

Idaho Risk Evaluation Manual for Petroleum Releases



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1410 North Hilton
Boise, Idaho 83706**

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Acronyms and Abbreviations

μg	Microgram
AST	Above Ground Storage Tank
ASTM	American Society for Testing and Materials
AUL	Activity and Use Limitation
BTEX	Benzene, Toluene, Ethyl Benzene, and Xylene
CAL-EPA	California Environmental Protection Agency
CAP	Corrective Action Plan
CAS	Chemical Abstract Service
cm ³	Cubic Centimeter
CLP	Contract Laboratory Program
COI	Chemical(s) of Interest
C _{cw}	Concentration in Groundwater (Between Source and Surface Water) at Alternate Point of Compliance
cm ²	Square Centimeter
CSF	Cancer Slope Factor
C _{soil}	Source Area Concentration in Soil
C _{swpoe}	Point of Exposure Concentration in Surface Water
DAF	Dilution Attenuation Factor
DEQ	State of Idaho, Department of Environmental Quality
DOE	U.S. Department of Energy
DQO	Data Quality Objective
Eh	Redox Potential
EPA	U.S. Environmental Protection Agency
EU	Exposure Unit
ft	Foot
gm	Gram
GW	Groundwater
GWP	Groundwater Protection
HI	Hazard Index
HQ	Hazard Quotient
IDAPA	Idaho Administrative Procedures Act
IDWR	Idaho Department of Water Resources
IELCR	Individual Excess Lifetime Cancer Risk
IRIS	Integrated Risk Information System
ISCE	Initial Site Characterization and Evaluation
IUPAC	International Union of Pure and Applied Chemists
IUR	Inhalation Unit Risk
kg	Kilogram

L	Liter
LNAPL	Light Non-Aqueous Phase Liquid
m	Meter
MCL	Maximum Contaminant Level
mg	Milligram
MTBE	Methyl Tertiary Butyl Ether
NA	Natural Attenuation
NAPL	Non-Aqueous Phase Liquid
NCEA	National Center for Environmental Assessment
NFA	No Further Action
NPDES	National Pollutant Discharge Elimination System
PAH	Polycyclic Aromatic Hydrocarbons
POC	Point of Compliance
POE	Point of Exposure
PSC	Petition for Site Closure
PST	Petroleum Storage Tank
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
QC	Quality Control
RA	Relative Absorption
RATL	Remedial Action Target Level
RBCA	Risk-Based Corrective Action
RCRA	Resource Conservation and Recovery Act
REDOX	Reduction-Oxidization
REM	Risk Evaluation Manual
RE	Risk Evaluation
RF	Reduction Factor
RfD	Reference Dose
RfC	Reference Concentration
RMP	Risk Management Plan
RNA	Remediation by Natural Attenuation
ROE	Route(s) of Exposure
RSL	EPA Regional Screening Level
RUSL	Residential Use Screening Level
SAB	EPA's Science Advisory Board
SCM	Site Conceptual Model
SF	Slope Factor
SVOC	Semi-Volatile Organic Chemical
STATECOMM	State Communications Center
SW	Surface Water
TEQ	Total Toxic Equivalency

TEF	Toxic Equivalency Factors
UCL	Upper Confidence Limit
UECA	Uniform Environmental Covenants Act
USACE	United States Army Corps of Engineers
VOC	Volatile Organic Compound

Introduction

In April 2009, the Idaho Legislature approved the Department of Environmental Quality (DEQ) Rules IDAPA 58.01.24, Standards and Procedures for Application of Risk Based Corrective Action at Petroleum Release Sites (the Rule). This rule required that DEQ prepare a risk evaluation manual for petroleum releases which would be used as guidance for implementation of the Rule. This document represents that implementation guidance. The Rule may be obtained at: <http://adminrules.idaho.gov/rules/2012/58/0124.pdf>

Organization of This Document

The document begins with a general description of the steps in the risk evaluation (RE) process, which is then followed by detailed implementation information for each step. DEQ has developed software that complements the process described and is provided at no charge. Contact DEQ regarding its availability.

Information in the body of this manual is supported by 12 appendices. Appendices A–D address default exposure factors, fate and transport parameter values, physical and chemical properties, and toxicity values. Appendix E presents models and equations. Appendix F provides the methodology and calculations for remedial action target levels (RATLs). Appendix G discusses the vapor intrusion pathway, and Appendix H addresses the application of natural attenuation. Appendix I describes the estimation of exposure point concentrations. A sample table of contents from a risk evaluation report is provided in Appendix J. Appendix K addresses practical quantitation limits, and Appendix L contains a quality assurance project plan (QAPP) template.

Section 1. Overview of the Risk Evaluation Process

1.1 Steps in the Risk Evaluation Process

The overall evaluation process for a site where a petroleum release is discovered and reported to DEQ is illustrated in Figure 1. The process consists of multiple steps, each of which is briefly described in the pages following Figure 1. In some cases, when adequate data are available concerning a release, the owner or operator (as defined IDAPA 58.01.24.010) of the release site may skip the screening level evaluation and proceed directly to the site-specific RE, a more detailed level of evaluation, without formally completing the intermediate steps. DEQ should be notified in these instances. A comparison of the two RE options, with the types of values, models, and other factors used in each option, is presented in Table 1.

1.1.1 Site Discovery

The risk-based site management process begins with the discovery of a petroleum release site. A petroleum release site may be discovered and reported to DEQ under a variety of circumstances. These include, but are not limited to, citizen complaints, investigations conducted as a part of real estate transactions, environmental impacts observed in surface water bodies, and notification of accidents and spills. It is the owner/operator's responsibility to ensure that DEQ is notified.

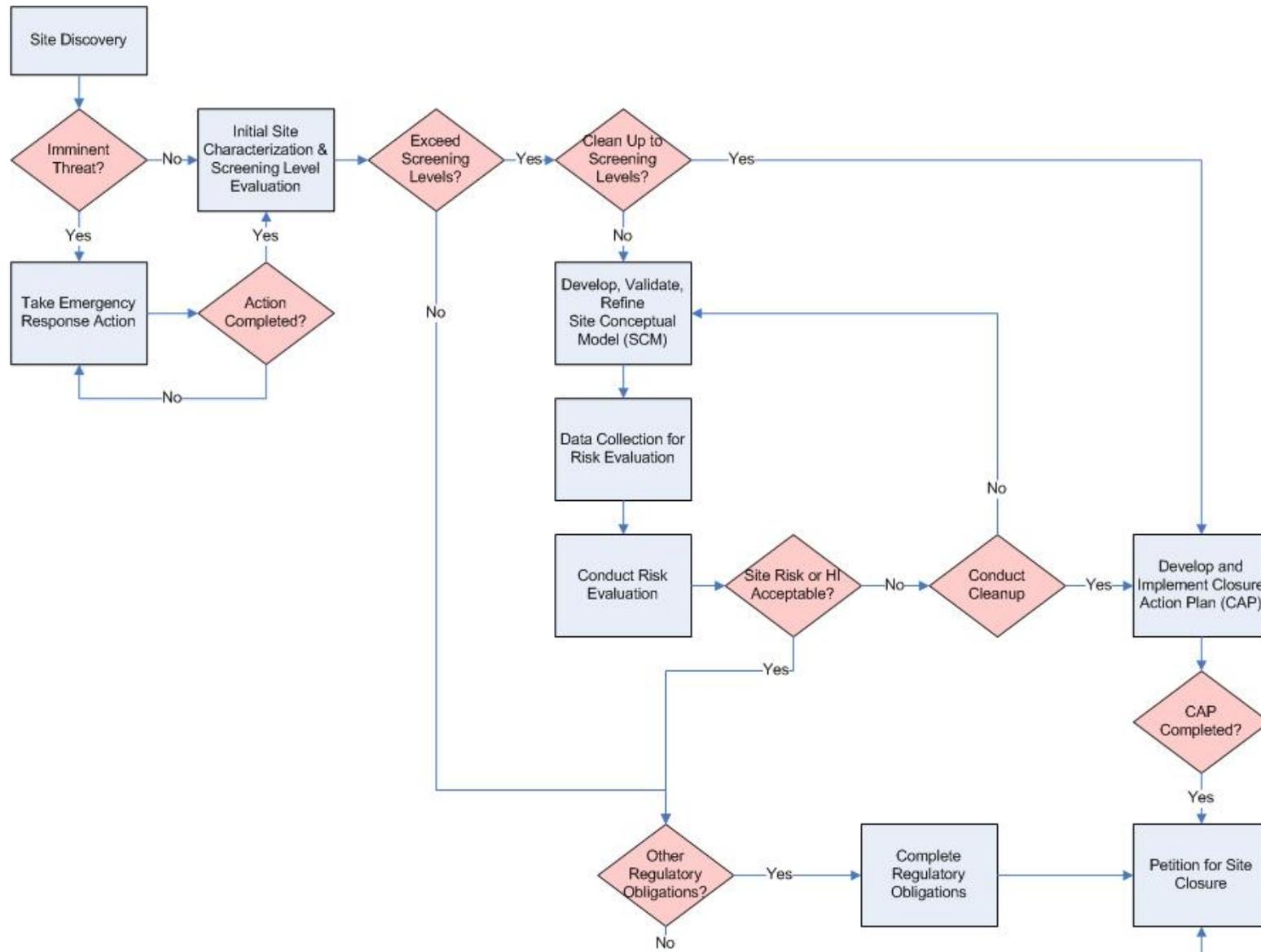


Figure 1. Idaho Petroleum Release Risk Evaluation Process Flowchart. This process allows for moving directly to a detailed risk evaluation without first completing a general screening level evaluation.

Table 1. Comparison of Risk Evaluation Options

Factors	Screening Level Evaluation	Site-Specific Risk Evaluation
Exposure Factors	Default	Site-specific/default
Toxicity Factors	Rule-specified values	Rule-specified values
Physical and Chemical Properties	Default	Default or DEQ accepted values
Fate and Transport Parameters	Default	Default/Site-specific
Unsaturated Zone Attenuation	None	None/Site-specific
Fate and Transport Models	Default	Default or other models acceptable to DEQ
Exposure Point Concentrations	Maximum	Statistical evaluation: Conservative Estimate of Mean:
Acceptable Target Risk	1×10^{-6}	Cumulative effects considered; target of 1×10^{-5}
Acceptable Target Hazard Quotient/Hazard Index	Hazard Quotient = 1	Cumulative effects considered; Hazard Index Target of 1
Groundwater Protection	Maximum contaminant level or risk based target levels	Maximum contaminant level or risk based target levels
Outcome of Evaluation	Either: <ul style="list-style-type: none"> • Petition for Site Closure, or • Risk Evaluation, or • Corrective Action Plan 	<ul style="list-style-type: none"> • Petition for Site Closure, or • Refine RE, or • Corrective Action Plan
Soil Concentration Protective of Groundwater	Default model with point of exposure at source	Default model with point of exposure determined as per Section 4. Flexibility in model may be used subject to DEQ approval
Surface Water Classification	See Section 4	See Section 4
Point of Exposure	Source	See Section 4
Activity and Use Limitations	None	See Section 6

1.1.2 Determination of Imminent Threat

Upon site discovery, the owner/operator should carefully evaluate the available information to determine whether the site poses any imminent threat to human health or safety, or to the environment. Threats include, but are not limited to, impacts to water wells; vapors or odors in residential and commercial structures; concentrations approaching explosive levels; impacts to a surface waterbody; and impacts to human health and the environment. If any imminent threats are identified, the owner/operator should notify DEQ or State Communications Center (STATECOMM) immediately (see Section 2) and take immediate steps to abate the threat. Documentation of abatement activities and confirmation that imminent threats have been removed should be provided to DEQ. Further details of this step are provided in Section 2.

1.1.3 Initial Site Characterization and Evaluation

Upon completion of the emergency response action, if any, it is necessary to perform an initial site characterization and evaluation (ISCE). As a part of the ISCE, media-specific data (for soil, soil vapor, and groundwater media) should be collected to characterize the source. This step is intended to identify the maximum contaminant concentrations for the identified petroleum products in soil and groundwater. Since a site may be a candidate for closure after the completion of the screening level evaluation (see , it is very important that the data collected at this time identify the maximum media-specific concentrations. Further details of this step are provided in Section 2.

1.1.4 Comparison with Screening Levels

This step involves the comparison of the maximum media-specific concentration of each contaminant, identified in the ISCE, with the screening levels developed by DEQ and presented in Table 2. There is a screening level for each contaminant in each media. The screening level is the lowest of the media-specific (soil, soil vapor, and groundwater) risk-based concentrations for the applicable exposure pathways. Screening levels are considered criteria that, if met (that is, maximum contaminant concentrations are below the screening levels), will allow unrestricted (residential) use of the property. Since exposure to these low concentrations (below the screening levels) of contaminants does not pose a threat to human health, if the owner/operator chooses to meet these criteria, they will not be required to evaluate site-specific exposure pathways and develop a site conceptual model (SCM), and no land use restrictions will be needed on the property.

When DEQ and the owner/operator agree that a petroleum release has been adequately characterized, DEQ will not require any further action of the owner/operator related to the release if the maximum contaminant concentrations in soil, surface water, and groundwater do not exceed the screening levels, subject to other applicable requirements, if any, as referenced in IDAPA 58.01.24.001.02. If any of the maximum soil, groundwater, or soil vapor concentrations exceed the screening levels, the owner/operator may either:

- adopt the screening levels as cleanup criteria and develop a corrective action plan (CAP) to achieve these levels, or
- perform a site-specific RE. Further details of this step are provided in Sections 3 and 4.

1.1.5 Development and Validation of a Site Conceptual Model

If the screening levels are exceeded, and the owner/operator chooses to conduct a more detailed (site-specific) RE, it is first necessary to develop and validate an SCM. An SCM provides the framework for the overall management of the site and should help guide data collection and risk management activities while the RE is being performed. The key elements of the SCM are:

- release scenario(s),
- source description,
- petroleum chemicals of interest (COI),
- an exposure model that incorporates the appropriate receptors,
- exposure pathways and routes of exposure (ROE),
- the site stratigraphy and hydrogeology, and
- the spatial and temporal distribution of the petroleum COI.

An important part of this step is to validate the SCM based on site-specific data. Further details of this step are provided in section 4.1.

1.1.6 Identify and Collect Data for Risk Evaluation

Depending on the site-specific conditions, the RE may require the collection of additional site-specific data. To prepare for conducting an RE, the owner/operator should review the SCM, identify requirements for filling data gaps, and collect additional data if necessary. This data will be used to calculate estimates of site-specific exposure point concentrations (see section 4.3.4 and Appendix I) and an estimate of the site-specific cumulative risk (see section 4.5) and, potentially, to develop RATL concentrations using the guidance provided in this document. Further details of this step are provided in section 4.2.

1.1.7 Site Specific Risk Evaluation

Conducting the RE requires developing site-specific estimates of exposure point concentrations for soil and groundwater, estimating site-specific cumulative risk, comparing these with acceptable target risk levels and, if necessary, developing media-specific RATL concentrations. RATLs are target concentrations developed by the owner/operator using a combination of conservative default and site-specific parameters. These concentrations depend on the receptor, media, pathway, and ROE and are developed for each petroleum COI and each media identified in the SCM. Using RATL concentrations instead of the defaults (the screening level criteria) may require that limitations be placed on activities and land uses that are allowed on the property. This step is discussed in section 4.6 and Appendix F.

1.1.8 Comparison with Acceptable Target Risk Levels and Decision Making

Once the site-specific cumulative risk has been estimated, it is compared to acceptable target risk levels, as specified in the Rule. If acceptable target risk levels are not exceeded, the site is eligible for closure, subject to other applicable requirements, if any, as referenced in IDAPA 58.01.24.001.02. If the site-specific cumulative risk exceeds the acceptable target risk levels, two options are available:

- Calculate and adopt media-specific RATL concentrations for each petroleum COI and develop and implement a CAP to achieve these concentrations.
- Refine the SCM and RE. It is possible that the site-specific cumulative risk is lower than initially estimated and may not pose an unacceptable risk, but this can only be determined with a more refined SCM and RE. This may involve the collection of additional data or the use of other models. Before collecting these additional data, it is optional to develop a work plan that outlines additional data needs and the overall approach for the refined evaluation. The plan may be submitted to DEQ for review and approval before proceeding with data collection and the evaluation. Although optional, the work plan and suggestions from DEQ may help with completing the required work more efficiently than might be the case without a DEQ-reviewed work plan. Details of this step, including the basic contents of a work plan, are included in section 4.7.

Upon completion of the RE, the owner/operator should provide recommendations to DEQ. In most cases, it is anticipated that DEQ and the owner/operator will work together to identify the best alternative. Note that it is not necessary to complete a screening level evaluation before conducting an RE, however, it is recommended that the owner/operator inform DEQ whether they will do a screening level evaluation or not. Often, DEQ can make suggestions to improve efficiency in the overall process.

1.1.9 Development and Implementation of a Corrective Action Plan

Based on the results of the RE process, the owner/operator proposes a set of remediation standards and prepares a CAP describing the measures that will be used to achieve the standards. The CAP is submitted to DEQ for approval. The CAP may include a combination of options for active remediation and passive remediation along with limitations on activities and land uses that were assumed in the RE step. Details of this step are included in Section 5.

1.1.10 Evaluation of Progress Toward Remedial Goals and Modification of the Corrective Action Plan if Necessary

The data collected during implementation of the CAP must be evaluated by the owner/operator and submitted to DEQ so that DEQ can determine whether the CAP is progressing as anticipated. Modifications to the CAP may be necessary in some circumstances. Circumstances that might require modifying the CAP include identification of significant deviations from the remedial strategy or unacceptable risk levels to receptors, by either DEQ or the owner/operator. Modification of the CAP also might be required if the data indicate that site cleanup is not progressing at the rate anticipated. In these cases, appropriate modifications to the CAP should be considered and an amended CAP should be submitted to DEQ for approval. The specific modifications to the CAP that are needed will vary from site to site.

1.1.11 Site Closure with a Corrective Action Plan

The primary objective of the CAP at any site is to ensure the long-term protection of human health and the environment, taking into consideration the current conditions at the site and conditions that are reasonable to expect in the future. When the regulatory obligations specified in the DEQ-approved CAP have been achieved, the site is eligible for closure. Closure typically involves the owner/operator submitting documentation that all the work specified in the CAP has been completed and all remedial action goals have been achieved accompanied with a request for site closure.

1.1.12 Certification by a Registered Professional

If work is performed that the State of Idaho requires a professional geologist or professional engineer (Idaho Code, Title 54, Chapters 12 and 28) to perform, the owner/operator shall employ the use of, and obtain certification from, a professional geologist or professional engineer registered in Idaho for that work.

Section 2. Site Discovery and Initial Steps

2.1 Determining Imminent Threats

The first step, once an impacted site has been identified or a release is known to have happened, is to determine whether contamination poses any imminent threat to human health or the environment. If so, abatement measures must be completed before any other activities. Examples of abatement measures include taking action to prevent further release into the environment, providing an alternate water supply if drinking water supplies are impacted, evacuating residents/commercial workers if they are or could be exposed to vapors at high concentrations, installing booms on surface waterbodies that have a sheen, or ventilating utility facilities where vapors are present. If there is an imminent threat, or uncertainty regarding potential threats, associated with a release, call DEQ or STATECOMM at 1-800-632-8000 or (208) 846-7610. Releases that do not pose an imminent threat do not have to be reported to STATECOMM, but do have to be reported to DEQ. Owner/operators shall follow the Petroleum Release Reporting, Release Response and Initial Abatement Measures as provided in IDAPA 58.01.02.851 and 852.

2.2 Initial Site Characterization

2.2.1 Site Characterization Introduction

Within the RE process, initial site characterization is performed after any necessary emergency response actions are completed. The overall objective of the initial site characterization is, at a minimum, to identify the maximum chemical concentrations on the site in each of the affected media. These maximum concentrations are then compared with screening level criteria to determine the need for any further action.

A brief description of the initial site characterization process is presented below.

2.2.2 Site Description and Adjacent Land Use

The owner/operator should conduct a thorough site reconnaissance and a historical review of site operations to identify source(s) of contamination on site. Sources may be identified based on knowledge of a known or documented release; location of certain structures that typically represent a contamination source such as underground storage tanks (USTs), pipes, pumps, etc.; interviews with current and former site employees who may have knowledge of source areas.

In addition to identifying sources, the owner/operator should collect data related to historic, current, and future land use on and adjacent to the site. A chronology of relevant site activities is often useful in understanding the site.

Based on this information, the owner/operator should identify the type of petroleum that may have been released at the site. Data collected during initial site characterization should, at a minimum, satisfy the following requirements:

- Quality Assurance/Quality Control (QA/QC) measures recommended by the United States Environmental Protection Agency (EPA) have been met,
- Analyte quantitation limits (the minimum amount that can be detected by the laboratory), where feasible, do not exceed screening levels,

- Appropriate petroleum COI have been identified and included for analysis,
- Source areas have been adequately characterized to identify the maximum concentration, and
- Analytical methods used are appropriate for petroleum COI at the site.

2.2.3 Soil Source Characterization

The owner/operator should collect soil data representative of the release's maximum concentration of petroleum COI. The exact number of samples, the analytical methods used, and the specific technology used to collect data will vary among sites. It is recommended, but not required, that the owner/operator develop a work plan and have it reviewed and approved by DEQ before beginning the work. At a minimum, the owner/operator should verbally confer with DEQ before collecting any data.

The overall intent of initial site characterization is to identify maximum concentrations of petroleum COI. However, for sites that will likely require further characterization, it may be efficient and cost-effective to collect additional data at this stage of the evaluation. Additional data may be used to identify the nature and extent of contamination and potential for exposure. For example, if contamination is suspected to exist in both surficial and subsurface soil zones, samples representing maximum concentrations in both zones should be collected.

2.2.4 Groundwater Source Characterization

In the initial site characterization, if there is evidence of possible groundwater impact from the site release, the owner/operator should collect groundwater samples below or immediately adjacent to the source. For sites with a very localized source, it may be sufficient to collect only one groundwater sample using a temporary well. Sites with multiple sources may require multiple wells and samples. For sites that will require further characterization, it may be more efficient and cost-effective to install at least three monitoring wells so the magnitude and the direction of groundwater flow can also be established.

2.2.5 Documentation of Initial Site Characterization

The owner/operator should document the initial site characterization results in a brief report that is submitted to DEQ. The chemical data collected should initially be evaluated using the screening levels as discussed in Section 3, all of which should be described in this report. The report should discuss:

- Site history,
- Site description,
- Current site use,
- Sources and petroleum COI identified at the site,
- Methods used to collect and analyze soil samples,
- Locations of all samples (identified on a site map), including sample depths,
- Results from soil chemical data analyses,
- Methods used to collect and analyze groundwater samples,
- Location, construction, and lithology of all wells,
- Results of groundwater chemical data analyses,
- Other site hydrogeological test data results, and
- QA/QC information.

Section 3. Screening Level Evaluation

Data collected during the initial site characterization is typically initially evaluated using screening levels. This evaluation is intended to achieve the following objectives of the screening level evaluation:

- Demonstrate that the site or portions of the site do not pose a threat to human health and hence does not require any further evaluation, and
- Identify areas of the site that need further evaluation.

These objectives are achieved by comparing the maximum site concentrations with the screening level values.

3.1 Screening Levels

The screening levels for the petroleum COI in the Rule have been developed by DEQ and are included in Table 2. The screening levels are risk-based target concentrations developed with the following:

- the assumption that receptors will be residential,
- conservative input parameter values,
- an acceptable target risk of 10^{-6} , and
- a hazard quotient (HQ) of 1.

Specific exposure factors and models used to develop screening levels are presented in Appendices A and E. Screening levels are the lowest target concentrations for the following exposure pathways and ROE for soil, soil vapor, and groundwater.

Specifically, screening levels for soil are the lowest of the following concentrations:

- Surficial and subsurface soil concentrations protective of exposure via groundwater ingestion at maximum contaminant levels (MCLs) or risk-based concentrations at the downgradient edge of the source or
- Subsurface soil concentrations protective of exposure via indoor inhalation of vapors emanating from soil for a residential scenario, or
- Surficial soil concentrations protective of combined ingestion, dermal contact, and outdoor inhalation exposures for a residential scenario.

Screening levels for groundwater are the lowest of the following concentrations:

- MCLs for chemicals that have them or calculated values for ingestion of water in a residential scenario, or
- Groundwater concentrations protective of exposure via indoor inhalation of vapors emanating from groundwater for a residential scenario.

Screening levels for soil vapor are protective of exposure via indoor inhalation of vapors emitted from contaminated soil or groundwater. Screening levels in sub-slab and near-source soil gas are derived by applying attenuation factors of 0.03, to the EPA Regional Screening Levels (RSLs) for both residential and industrial ambient air.

Table 2 lists the screening levels for unrestricted use. For comparison, Table 2 provides the risk-based concentrations in soil and groundwater for all the pathways and ROE listed above. The screening level values incorporated in the Rule are indicated in bold.

Because of the methods and assumptions used in the development of the screening levels and the current limitations of laboratory analytical methods, the calculated screening levels may be lower than the practical quantitation limit reported by a laboratory for selected chemicals. In these situations, site-specific review by DEQ will be required based on the criteria provided in Section 500 of the Rule and Appendix K.

Table 2. Screening Level Concentrations for Soil, Groundwater, and Soil Vapor

CHEMICAL	SOIL (mg/kg)			GROUNDWATER (mg/L)		TARGET SUB-SLAB AND NEAR-SOURCE SOIL GAS CONCENTRATIONS (ug/m ³)	
	Vapor Intrusion	Direct Contact	Groundwater Protection	Vapor Intrusion	Ingestion	Unrestricted Use	Commercial/Industrial
						Vapor Intrusion	Vapor Intrusion
Benzene	0.08	8.3	0.025	0.044	0.005	12	53
Toluene	1300	7930	6.6	340	1	170000	733333
Ethylbenzene	0.25	39	7.4	0.05	0.700	37	163
Xylenes	27	6100	93	8.7	10	3500	14667
Naphthalene	0.12	44	21	0.07	0.73	2.8	12
MTBE	2.4	340	0.08	6.8	0.04	360	1567
1,2-Dichloroethane	0.02	3.7	0.013	0.03	0.005	3.6	16
Ethylene Dibromide	0.001	0.27	0.00014	0.004	0.00005	0.16	0.67
Acenaphthene	NA	4470	200	NA	2.2	NA	NA
Anthracene	NA	22300	3200	NA	11	NA	NA
Benzo(a)anthracene	106	1.4	0.68	0.60	0.00022	0.56	6.67
Benzo(a)pyrene	NA	0.14	2.1	NA	0.0002	NA	NA
Benzo(b)fluoranthene	NA	1.4	2.29	NA	0.00022	NA	NA
Benzo(k)fluoranthene	NA	14	22.5	NA	0.0022	NA	NA
Chrysene	NA	139	69	NA	0.022	NA	NA
Fluoranthene	NA	2970	1400	NA	1.5	NA	NA
Fluorene	NA	2970	240	NA	1.5	NA	NA
Pyrene	NA	2230	1000	NA	1.1	NA	NA

Values in bold are current screening level values. Screening level values for sub-slab and near-soil gas concentration are equivalent to EPA Regional Screening Levels (EPA, 2018) for residential and industrial ambient air divided by an attenuation factor of 0.03.

NA: not applicable because the chemical does not meet EPA volatility criteria or does not have a Regional Screening Level for ambient air.

3.2 Comparison of Site Concentrations with Screening Levels

Based on the initial site characterization (discussed in Section 2), the owner/operator should identify the maximum soil and ground water petroleum COI concentrations at the site. These maximum concentrations are then compared with screening levels, obtained from Table 2.

If the maximum site concentration does not exceed the screening level for any petroleum COI in any media, the site is eligible for closure subject to other regulatory obligations (IDAPA 58.01.24.200) The owner/operator may request DEQ approval for site closure. If the maximum site concentration for any petroleum COI exceeds the screening level, the owner/operator must select one of the following options:

- Option 1: Adopt screening levels as cleanup remediation standards and develop a CAP (see Section 1).
- Option 2: Perform a more detailed, site-specific RE.

The owner/operator should clearly indicate to DEQ which option has been chosen.

3.3 Screening Level Evaluation Report

The owner/operator must submit a screening level evaluation report to DEQ if they have chosen option 1 above. The report should include, at a minimum:

- Site maps indicating land use, structures on site, locations and depths of samples, and locations of contaminant sources,
- A description of site history and activities leading to the release,
- A description of current land use adjacent to the site,
- A summary of initial site characterization results for soil and, as appropriate, groundwater,
- A discussion of data quality,
- A comparison of maximum soil and, as appropriate, groundwater concentrations with screening levels,
- A list of recommendations, and
- Laboratory reporting sheets, including QA/QC data.

Section 4. Site-Specific Risk Evaluation

Site-specific RE is needed only if the owner/operator chooses not to conduct a screening level evaluation or to use the default screening levels as the remediation standards.

Conducting a site-specific RE requires the completion of several important steps. These include developing an SCM, identifying the chemicals present in environmental media, assessing exposure and exposure pathways, assessing the toxicity of the chemicals present, characterizing human risks, and characterizing the impacts on or risks to the environment. This section describes each of these steps and also provides the suggested format for some of the deliverables (most of which are reports) that assist in developing and documenting the evaluation.

4.1 Site Conceptual Model

An SCM provides an overall understanding of the site and an SCM report can be a convenient format for compiling all the relevant data associated with a release. The SCM provides a framework for the entire project and can help identify specific data needs (the correct quality and quantity of data that will be needed). An SCM is necessary in the development of any data collection work plan and is also an important communication tool for regulators, owner/operators, and stakeholders.

In addition to basic site information (discussed in section 4.1.1), there are three key elements that should be included in the SCM. Each element will require certain types of data in order to validate the SCM. The amount of data required is typically based on site-specific considerations. The SCM is a dynamic entity that should be revisited and potentially refined any time additional data is collected for a site. The resulting SCM refinements should be incorporated, if necessary, into the RE.

The three key elements are:

- **Sources:** Contaminant source areas (nature, magnitude, and extent of release) and COI (see section 4.1.2).
- **Pathways:** Release fate and transport mechanisms, exposure pathways, and ROE (see section 4.1.3).
- **Receptors:** Characteristics of land use and likely receptors (see section 4.1.4).

More detailed information on these elements is provided below and in the sections on data requirements (section 4.2) and exposure assessment (section 4.3).

4.1.1 Site Characteristics

The following basic site characteristics should be included in the RE; each is described in the following sections:

- Site history and map,
- Ground surface conditions,

- Location of utilities on and adjacent to the site, and
- Location and description of site structures.

4.1.1.1 Site History and Map

The SCM should include a comprehensive chronology of events including remediation projects, tank removal activity, reported releases, etc. The chronology of events must be clearly and accurately documented.

All maps should be made to scale, with a bar scale and a north arrow. As appropriate, multiple site maps should be prepared to show sample collection points and locations of various site structures. A detailed facility map showing the layout of USTs, above ground storage tanks (ASTs), pipes, loading and unloading areas, sumps, paved and unpaved areas, canopy buildings, etc. should be prepared. A second facility map should be prepared to show locations of all on-site monitoring wells, water use wells, soil borings, soil vapor extraction wells, and soil excavation areas. All on-site structures should be clearly identified.

4.1.1.2 Ground Surface Conditions

Before conducting an RE, DEQ highly recommends the owner/operator and any other parties that will be involved make a site visit and walk through. It is important to document areas of the site that are paved, unpaved, landscaped, or covered with buildings. It is also highly useful to note the type, extent, slope, and general condition of the ground surface, and current land uses.

4.1.1.3 Location of Utilities on and Adjacent to the Site

Due to potential for preferential flow of contaminated groundwater and vapors into underground utility lines and conduits, a thorough documentation of the location of and potential impacts to underground utilities should be performed. Utilities may include phone lines, water lines, sanitary sewers, storm sewers, and natural gas lines. A combination of site observations, knowledge of buried utilities, and discussions with utility representatives and the site owner should reveal the utility locations.

At a minimum the following activities should be performed:

- Locate all underground utility lines and conduits within the area of known or potential soil and groundwater impact, both on site and off site, where the release may have migrated, or may migrate in the future.
- Determine the direction of flow in the utilities (water, storm water, and sewage).
- Identify utility lines/conduits on a base map that illustrates the extent of soil and groundwater impacts.
- Determine depth of utility lines/conduits relative to the depth of groundwater. Seasonal fluctuations of groundwater levels should be carefully evaluated. As appropriate, a cross-sectional diagram should be provided illustrating the depth to groundwater and the locations and depths of the lines/conduits.
- Determine any past impacts to utilities and any pertinent complaints that may have been previously filed with DEQ.

4.1.1.4 Existing Structures

The location, condition, and construction characteristics of each structure on and adjacent to the site should be described.

4.1.2 Contaminant Source Areas

This element of the SCM should include a discussion of the nature, location, timing, and magnitude of petroleum products spilled at the site. The petroleum COI should be determined. Any actions performed as a part of emergency response should be delineated and their impact on the source evaluated. The residual size of the source after any emergency or interim actions should be determined.

Knowledge about the nature, magnitude, and extent of the release is necessary to identify the petroleum source in soil and/or the groundwater at the site as well as to identify the petroleum COIs. The following information regarding a release, if available, is critical:

- Release location,
- Release quantity,
- Petroleum product released, and
- Interim corrective action measures performed.

Release-related information can be obtained by reviewing inventory records, interviewing current and past employees, and checking any spill incident reports filed with DEQ. Information related to site activities can also help identify source location and petroleum COIs.

4.1.2.1 Location of Release

The location of the release defines the source of the petroleum that is in the soil and potentially the groundwater. Likely release locations include, but are not limited to, corroded or damaged tanks, pipe bends and joints, and loading and unloading areas.

The owner/operator should review operational history to determine the likely location of the source. The assessment should focus on the identified release area; however, the exact location and timing of the spill source area may not be known. In these cases, soil and groundwater sampling should be used to identify the extent (vertical and horizontal) of residual soil and/or groundwater source. The exact number and location of necessary samples shall be determined on a site-specific basis using professional judgment. It will be important to understand the location and timing of past spills and releases in making decisions regarding assessment needs related to current releases. It is recommended, but not required, that the owner/operator consult with DEQ before conducting sampling. DEQ may be able to provide information at this point that can help the owner/operator improve the overall efficiency of sample collection or the entire RE.

4.1.2.2 Quantity of Release

The RE process does not necessarily require knowledge of the exact release quantity. However, an estimate of the amount released may help evaluate the severity of the impact and extent of contamination, and may help in planning site characterization measures. Estimation of release quantities is typically based on inventory records.

4.1.2.3 Chemicals of Interest and Spatial and Temporal Trends

This section should include a discussion of chemicals detected in each media and their spatial and temporal distribution. As appropriate, contour maps indicating concentrations of individual petroleum COIs may be useful. Graphs of petroleum COI groundwater concentrations in individual wells and concentration along the flow line (concentration vs. distance plots) may be useful as well. Based on data collected over time, it should be determined whether the chemical concentrations are stable, declining, or expanding.

Identification of specific petroleum product(s) spilled or released is important to identify the petroleum COIs. Evaluation of non-petroleum chemicals in addition to those in Subsection 800.01 (Table 1) may be required by DEQ when there is a reasonable basis based on site-specific information. A reasonable basis shall be demonstrated by DEQ when it can show documentation of releases or suspected releases of other non-petroleum chemicals. The environmental behavior (mobility, persistence, bio-degradation, and inter-media transport) of the petroleum product and its adverse environmental and human health effects depend on chemical properties and their concentrations in the petroleum product.

If a release can be identified as a single petroleum product based on a documented release, free product analysis, or location of impact (e.g., tank bottom of a particular product tank), only the COIs for that petroleum product need to be analyzed. If the product released cannot be conclusively identified, it is recommended that monitoring samples be analyzed for all petroleum COIs associated with the products suspected to have been stored at the site. Additional assessment may be required to identify the source of the release.

If previously collected data did not include all suspected site petroleum COIs, additional sampling may be necessary for petroleum COIs before an RE can be performed.

4.1.3 Pathways and Transport Mechanisms

The objective for this portion of the SCM is to describe site characteristics and mechanisms which have influenced or will influence the release, fate, and transport of chemicals of interest and to determine which exposure pathways and ROE will be most likely to occur.

4.1.3.1 Site Stratigraphy and Hydrogeology

The owner/operator should conduct a review of published literature and any investigations conducted on adjacent sites to determine regional hydrogeology, soil types, and aquifer characteristics. This evaluation should be used to determine the type and depth of aquifers in the area and whether they are confined, semi-confined, or unconfined. Regional information will help the owner/operator in efficiently collecting site-specific soil and groundwater information. The SCM should include a detailed discussion of site-specific stratigraphy and hydrogeology. Site stratigraphy should be determined based on boring logs and an adequate number of geologic cross sections.

The hydrogeologic discussion should include estimates of horizontal and vertical hydraulic gradients, seasonal variations in groundwater elevations and flow direction, and hydraulic conductivity of relevant water-bearing zones. How these characteristics may influence the fate and transport of chemicals to potential receptors should be discussed.

The survey should also locate potentially impacted surface waterbodies located within one-half (1/2) mile of the site. If a surface water body is identified, information including the type (perennial or intermittent), water flow rate, flow direction, depth of water, width or surface area of the water body, and water use should be provided. The location of the water body must be indicated on an area map.

4.1.3.2 Complete Exposure Pathways and Routes of Exposure

A complete exposure pathway involves a source of petroleum products, release and transport mechanisms, ROE, and potential receptors. The definition of complete exposure pathways starts with knowledge of the release, petroleum COIs, and site physical conditions (described above), then combines these with assumptions about land use and likely receptors. Exposure pathways and ROE are described and discussed in more detail in section 4.3.3.

The SCM should identify each of these components in its descriptions of exposure pathways. One example of a common exposure pathway would be leaching of petroleum chemicals from a gasoline release in soils (release) to the groundwater with subsequent transport (fate and transport) to a residential well where water is extracted for drinking water and ingested by residents (land use and likely receptors). Another would be volatilization of petroleum chemical vapors from a soil source with subsequent transport through the soil and into the air in an occupied structure where they are inhaled.

Another part of defining the complete or potentially complete exposure pathways and ROE in an SCM is identifying the locations where exposure to petroleum chemicals can occur and the media of concern at those locations. These known or potential exposure locations are commonly called exposure units. The exposure unit for each complete pathway and receptor should be described. The exposure unit may consist of a specific location such as a well or it may be an area, such as a parcel, over which receptors move. For large sites, it may be useful or necessary to subdivide the site into multiple exposure units. This may also be true at sites where impacts of the release have moved offsite.

Exposure pathways defined in the SCM are subsequently used in the exposure assessment phase of the RE, which is described in detail in section 4.3.

4.1.3.3 Protection of Groundwater

During the development of the SCM, it should be assumed groundwater may be used for drinking water. Consequently, if groundwater is not remediated to levels suitable for ingestion, the CAP must also include provisions in the final remedy for implementing limitations on activities and land uses. Such limitations are achieved through environmental covenants (activity and use limitations [AULs]) to prevent exposure via groundwater ingestion throughout the horizontal and vertical extent of the plume that has concentrations exceeding the criteria for groundwater ingestion presented in Table 2.

The SCM, as it relates to the use of groundwater, should include characterization and evaluation of the following groundwater aspects.

- The current and historical use of the groundwater for drinking water or irrigation.

- The location and approved use of existing groundwater wells within a one-half (1/2) mile radius from the release point at the contaminated site.
- The potential for communication between the impacted groundwater and other groundwater-bearing zones or surface water.
- The location of delineated source water protection areas for public drinking water systems.

This information, along with other data collected for the evaluation, will be used to determine if groundwater ingestion is a complete exposure pathway in the SCM, and will guide the selection and use of appropriate remedial target concentrations, measures, timeframes, and compliance conditions.

A water well survey should be conducted to identify all water use wells within a one-half (1/2) mile radius. Information sources include the U.S. Geological Survey, the Idaho Department of Water Resources (IDWR), water system operators, and local residents. If available, well characteristics including depth, water use, and screened interval should be documented. It is necessary to identify any dewatering wells located within a 1,000-foot radius of the site (or greater if the groundwater plume is extensive).

Land use considerations include, but are not limited to:

- Current zoning and land use. Consultation with local planning and zoning officials regarding future land use planning direction and interpretation of planning and zoning policies.
- Land use development trends. Conversion of agricultural land to residential land uses requires development of drinking water sources. The proximity of these conversions to urban centers and available public drinking water supplies should be taken into account.
- Local ordinances that include agreements with IDWR governing well drilling or state-designated restrictions or specifications for constructing wells into groundwater in a locality for drinking water purposes.
- The existence of source water assessment delineations and source water protection plans and ordinances associated with public drinking water supplies.
- The availability of alternative water supplies.

4.1.4 Land Use and Receptors

This portion of the SCM describes the current and future assumptions about land use as they relate to identifying potential receptors. The identification of land uses includes both the site of the release as well as adjacent properties which may be impacted by the release.

4.1.4.1 Land Use

Evaluating current and reasonably likely future land uses at and adjacent to the release site is a critical component when determining potential exposure points, exposure pathways, receptors, and exposure factors during the RE process and when determining cleanup concentrations.

Residential land use generally requires lower target concentrations. Cleanup to residential standards will usually allow unrestricted land use. Whenever assumed land use is other than

residential and cleanup is not to residential standards, DEQ may require that an AUL be imposed on the property through the use of an environmental covenant.

Residential land uses include use by sensitive subpopulations. Examples of land uses with sensitive subpopulations include but are not limited to hospitals, nursing homes, schools, childcare centers, farms with houses, and any other areas/structures with sensitive human activity.

The owner/operator should submit to DEQ illustrated land use maps clearly identifying current land uses at the site and the adjacent properties. One map should clearly show the area within one-half (1/2) mile of the known or likely extent of contamination. At sites where there is likelihood that the extent of impacts may be greater, due to the magnitude of the spill or other site-specific conditions, a land use map covering the entire impacted and potentially impacted area is necessary. A walking land use survey should be conducted for the area within a 500-foot radius of the source, with an emphasis on the down-gradient direction and potential offsite impacts. The survey should clearly identify the following: schools, hospitals, residences (apartments, single-family homes, and others), day care centers, nursing homes, and types of businesses. In addition to this survey, efforts should be made to identify structures with basements (which may enhance the transport of contamination) in areas in closer proximity to the source and where site conditions warrant it, such as where shallow groundwater or non-aqueous phase liquid (NAPL) is present. The map should also identify surface water bodies, parks, recreational areas, wildlife sanctuaries, wetlands, and agricultural areas.

Current land use refers to land use as it exists today and that can be readily determined by a site visit. A site visit should identify homes, playgrounds, parks, businesses, industries, or other land uses at, and in close proximity of, the release site. As appropriate, state or local zoning boards; the U.S. Census Bureau; zoning, topographic, land use, housing and other types of maps; and aerial photographs can provide information for determining land use.

Undeveloped land should be characterized by the most likely future use of that property, considering current zoning restrictions. If the undeveloped parcel is located in a predominantly nonresidential area, nonresidential classification may be appropriate. However, if the setting is more rural or land-use is mixed, the undeveloped land should be considered residential unless the owner/operator develops and implements an AUL as a part of a DEQ-approved CAP.

The exposures to be evaluated in an RE depend upon the activities that could occur under likely future uses of land and groundwater at the site. The future groundwater use should be consistent with the most likely future land use.

For example, consider property that is currently used as farmland. If the impacted farmland includes a residence, the current land use is residential. However, if the owner/operator provides information establishing clear plans to develop the residence into a nonresidential building in the near future, the likely future use may be evaluated as nonresidential.

While evaluating likely future land use(s) presents uncertainties, DEQ has identified certain factors that assist in this evaluation. These factors include, but are not limited to, local zoning ordinances; knowledge of current land use and changing land use patterns; zoning decisions; community master plans; interviews with current property owners; nonresidential appraisal

reports; proximity to wetlands, critical habitat, and other environmentally sensitive areas, such as source water protection areas; and the use of remedial action institutional controls at a site.

Assumed future land use designations other than residential must be justified and there should be a high likelihood that the land will be used for those purposes. Absent such a justification, DEQ will consider the residential land use scenario as the default future land use.

Site characterization will include a determination of the on-site and off-site areas of impact. These areas are considered in determining the pathway-specific exposure units for each type of receptor. Exposure units are discussed in more detail in section 4.3 and Appendix I.

4.1.4.2 Receptors

The objective of the RE is to quantify the adverse health effects to current and potential future receptors both onsite and offsite. For simplification, the following definitions should be used:

- **On-Site** –The area located within the legal property boundaries within which the source of the release is located. This includes soil, groundwater, surface water, and air within those boundaries. Adjacent property purchased subsequent to the release will be considered off-site.
- **Off-Site** –The areas of concern located outside the boundaries of the property where the release source is located. This includes soil, groundwater, surface water, and air located outside the property boundaries.

In a residential exposure scenario, risk is evaluated for either a child receptor or a composite receptor, depending on the specific exposure route, and whether the petroleum COI is noncarcinogenic, carcinogenic, or carcinogenic with a mutagenic mode of action. The composite receptor is based on an exposure duration of 30 years, and for some chemicals and exposure routes risk calculations incorporate modifications based on exposure occurring at different life stages.

For land uses other than residential, a typical receptor might be a commercial or industrial worker where the risk to adults is considered. Finally, under a construction scenario adult construction workers are considered. If warranted by site-specific conditions, other types of receptors may need to be defined and evaluated.

4.1.4.3 Ecological Risk Considerations

In addition to identifying potential impacts to human receptors the SCM should also attempt to identify potential pathways by which sensitive habitats, such as wetlands, surface water bodies, or other ecologically significant environments near the site, may be impacted by the release where wildlife may be the potential receptors.

Threatened and endangered species that may be exposed to site-specific chemicals should be identified. Note that within the RE process, protection of surface waters and streams is independent of ecological RE. As appropriate, a walking survey in the vicinity of the site may be necessary to identify ecological receptors.

Contact DEQ to obtain additional guidance on these issues.

4.2 Data Requirements and Evaluation

Once the SCM has been developed, an evaluation of data collection needs, data quality needs, and data collection methodology should be conducted. Depending on the amount and complexity of the proposed data collection effort, a work plan may be needed to guide the data collection process. The suggested contents of this work plan are discussed in section 4.7.

This section describes general data collection objectives and requirements for the RE process. This includes the general QA/QC considerations to help ensure the data collected is of sufficient quality and quantity to meet desired objectives, the categories of data necessary to meet these objectives, and data collection techniques.

Data collection objectives for RE include, but are not limited to:

- Accurately characterize the magnitude, nature, and extent of contamination, including the characterization of petroleum chemical concentrations for all impacted media, as appropriate,
- Allow the development and/or validation of an accurate SCM, and
- Develop sound estimates of risks posed by the release.

4.2.1 Data Collection Planning

Sound data collection planning involves a careful review of all available site information and data for its suitability in the RE. This process, in the context of the SCM, should identify any data gaps with the goal of determining the types, locations, quality, and numbers of samples or measurements needed.

Depending on what stage of the RE process is in for a given site, the relative importance of each objective described above will vary and specific data requirements will also vary. The goal of data collection for RE is to efficiently reduce uncertainty in those areas that contribute the most to potential or actual risk and for which the greatest uncertainty exists.

For example, it may be determined through the SCM that vapor intrusion represents the largest potential source of risk at a site, but little is known about subsurface conditions which may impact exposure point concentrations and only soil or groundwater data are available. In order to more realistically model this pathway, it may be most effective to better characterize subsurface stratigraphy and properties, document the conditions supporting biodegradation, and collect soil vapor data.

At many impacted sites, data collection efforts may have been conducted multiple times over an extended period of time. For example, interim corrective action measures may have been undertaken prior to planning for the RE. Soil and groundwater data collected prior to such activities may not be representative of current conditions and generally should not be used in RE. At such sites, collection of additional soil and groundwater concentration data may be needed after completion of interim corrective measures.

The exact number of samples required is a site-specific decision based on the balance between cost and representativeness and requires professional judgment and expertise. Numerous tools are available to assist in estimating the number of samples required for statistical analysis, but

none provide a definitive number and statistical analysis may not be practical in many cases. These tools include, but are not limited to, data quality objectives (DQO) and statistical and geo-statistical evaluation. Selected references to assist in developing and completing sound data collection efforts are listed in section 7.2.

4.2.2 Quality Assurance/Quality Control Considerations

The RE process relies on site-specific data to make decisions related to the magnitude of site risk, nature and extent of remedial activity, and site-closure. Thus it is very important that data be reliable, representative, complete, and of known quality.

In order to assure the data will be of appropriate quality, QA/QC activities must be applied to all environmental data collection activities throughout the RE process (site characterization, risk evaluation, remediation implementation, and monitoring).

Elements of QA/QC include:

- Using approved methodologies to collect data,
- Decontaminating field equipment as appropriate,
- Using EPA approved methods for laboratory analysis, and
- Including QA/QC samples, such as duplicates, equipment blanks, trip blanks, etc.

While the level of QA/QC applied to data collection efforts will vary (depending on factors such as site complexity, size of the release, and the immediacy of the response) all the elements of QA/QC described above that were used during a given data collection effort should be provided to DEQ when reporting the results of environmental sampling. This will allow an adequate review of the quality of the data used in the analysis.

If a work plan is submitted to DEQ for approval, it should include a QAPP. The QAPP integrates the appropriate technical and quality aspects of a project, including planning, implementation, and assessment. The purpose of the QAPP is to document planning for the collection of environmental data and to provide a project-specific “blueprint” for obtaining the type and quality of data needed for a specific decision or use. The QAPP documents the QA/QC procedures applied to various aspects of the project to assure that the data obtained are of the type and quality required.

The EPA has developed guidance for the development of QAPPs which can be obtained at: <http://www.epa.gov/quality/qs-docs/g5-final.pdf>.

To further assist in the development of a QAPP, DEQ has also developed an abbreviated QAPP template. The purpose of the template is to provide the user with an annotated outline format of a QAPP with all the required elements. From there, it is a simple matter to fill in appropriate site-specific information applicable to each element. The QAPP template is reproduced in Appendix L. This template is periodically updated. Contact DEQ for the latest version.

Documentation of all QA/QC efforts implemented during data collection, analysis, and reporting phases is important to data users, who can then consider the impact of these control efforts on data quality.

The QAPP is implemented during the data collection process. Problems can be identified and corrected at this stage. The impact of field and laboratory techniques and sampling and analysis conditions on data quality are determined using field and laboratory QC samples and periodic audits. Oversight and corrective action can prevent improper procedures or techniques from continuing.

Data verification, validation, and assessment should be performed to validate data quality and assess data quality and usability. Data verification and validation is particularly dependent on compliance with field and laboratory procedures for sample collection, identification, handling, preservation, chain of custody management, shipping, analysis, and reporting.

EPA provides several guidance documents to assist in performing data verification and validation (EPA, 1999; EPA, 2002a). The EPA Contract Laboratory Program National Functional Guidelines for Organic Data Review (EPA, 1999) provides guidance on data verification and validation of contract laboratory program (CLP) data, but may also be used as guidance for non-CLP data. EPA 2002a provides more generic guidance on conducting these tasks.

4.2.3 Documentation of the Data Collected

Once data have been collected, a field investigation report should be prepared and include:

- Dates when data were collected and names of individuals who collected the data.
- A list of data collected and reference to any work plan that may have been followed.
- All data collected, clearly tabulated, and contoured (if necessary),
- All boring logs and relevant cross-sections, where appropriate, to depict site stratigraphy,
- All QA/QC data, laboratory results, data validation and verification, assessment of data usability, and chain of custody forms,
- Contour maps of groundwater potentiometric surface indicating the predominant direction of groundwater flow, and
- A discussion of the SCM.

4.2.4 Data Collection Methods

The common categories of data that are the focus of data collection efforts for RE include:

- Vadose zone soil characteristics,
- Saturated zone characteristics, and
- Distribution of petroleum COIs in soil, soil vapor, groundwater, and surface water bodies.

DEQ has developed default values for many of the vadose and saturated zone characteristics that affect the fate and transport of petroleum COIs. These values are presented in Appendix B. For site-specific REs, these default values can be used or site-specific values can be established. This appendix describes typical collection methods for those properties of the vadose zone and saturated zone important for RE. It also addresses the collection of chemical concentration data from these media.

4.2.5 Vadose Zone Soil Characteristics

The vadose zone or unsaturated zone soil is the media through which petroleum COIs can migrate to the groundwater and vapors can move upward to the surface and into an enclosed space. Thus, characteristics of vadose zone soils have considerable impact on risk estimates and target concentration calculations. Relevant vadose zone characteristics include:

- Vadose zone thickness and depth to groundwater,
- Bulk density,
- Porosity,
- Water and air content, and
- Fractional organic carbon content.

In addition to parameters mentioned above, additional site-specific, pathway-specific parameters that may be valuable to measure include:

- Vapor permeability, effective diffusion coefficient, and building characteristics where indoor inhalation is a potentially complete pathway, and
- Infiltration rates for developing a detailed evaluation of the potential for leaching to groundwater.

4.2.5.1 Thickness of Vadose Zone and Depth to Groundwater

Vadose zone thickness is determined from boring logs. This thickness is the distance from the ground surface to the depth at which the water table is encountered, less capillary fringe thickness.

Depth to groundwater is used in estimating vapor emissions from groundwater. For indoor inhalation, depth to groundwater below the “floor” of an existing structure of concern or the most likely location of a future structure should be used.

For sites with considerable seasonal fluctuation in water table level, depending on the data available and the nature of the fluctuations, a yearly average depth or a time-weighted depth may be used. The vadose zone depth that is estimated should also form the basis for the selection of soil samples to be used in evaluation of subsurface soil vapor emissions to indoor air. Shallower water table depths often result in groundwater target levels set at lower concentrations to be protective of inhalation pathways.

4.2.5.2 Porosity

Porosity is the ratio of the volume of voids to the total undisturbed field volume of soil. Many laboratories use dry bulk density and specific gravity data to determine porosity using the following equation:

$$n = 1 - \rho_b / \rho_s \quad (4-1)$$

where,

n	=	porosity (cubic centimeter per cubic centimeter [cc/cc])
ρ_b	=	dry bulk density (grams per cubic centimeter [gm/cc])
ρ_s	=	specific gravity or particle density (gm/cc)

Dry bulk density is the dry weight of a soil sample divided by the field volume of the soil sample. An accurate measurement of bulk density requires determining the dry weight and volume of an undisturbed sample. This method involves collecting a core of known volume, using a thin-walled sampler, such as a Shelby tube or similar coring device, to minimize disturbance of the sample, and transporting the core to a laboratory for analysis. This method is described in American Society for Testing and Materials (ASTM) Method D2937-00, Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method (ASTM, 2000a).

The Standard Test Method for Specific Gravity of Soil, ASTM Method D854-00 (ASTM, 2002), may be used to determine specific gravity. If specific gravity is not assessed, then 2.65 gm/cc can be assumed as the particle density.

Consideration should be given to collecting multiple samples if multiple lithologies are present that might affect COI transport.

If site-specific values of porosity are not available, it should be estimated based on values provided in an appropriate literature source.

4.2.5.3 Volumetric Water Content/Moisture Content

Volumetric water content is the ratio of water volume to the total soil volume. The ASTM Method D2216-98, Standard Test Method for Laboratory Determination of Water [Moisture] Content of Soil and Rock by Mass (ASTM, 1998) is a gravimetric oven-drying method; however, the water content value used in most models is the volumetric water content.

Hence, it may be necessary to use the following equation to convert gravimetric water content to a volumetric basis:

$$\theta_{wv} = \theta_{wg} * \frac{\rho_b}{\rho_l} \quad (4-2)$$

where,

θ_{wv}	=	volumetric water content (cc water/cc soil)
θ_{wg}	=	gravimetric water content, typically reported by the laboratory (gm of water/gm of soil)
ρ_b	=	dry bulk density (gm of dry soil/cc of soil)
ρ_l	=	density of water (gm/cc)

Volumetric water content can also be measured in the field through the use of a variety of instruments such as a neutron probe, time domain reflectometer, or gypsum block sensors. For more information on these methods, see Part VII of Wilson et al. (2000).

4.2.5.4 Fractional Organic Carbon Content in Soil

Fractional organic carbon content is the organic carbon weight in the soil divided by soil weight and is expressed either as a ratio or as a percent. The Walkley Black Method (Page et al., 1982)

is a chemical oxidation method (rapid dichromatic oxidation) while ASTM Method 2974-00 is a furnace method (ASTM, 2000b) for determining fractional organic carbon content in soil. Results are usually reported as percent organic carbon content. The reported value can be converted to a fraction by dividing by 100.

If measurements of total organic matter content are available, they should be divided by 1.724 to estimate the fractional organic carbon content. This adjusts for the portion of soil organic matter that is actually carbon. Typically, total organic carbon content is estimated using ASTM Method 2974-00. Organic carbon content should be determined using soil samples not impacted by the release.

4.2.6 Saturated Zone Characteristics

Petroleum COIs that reach the water table typically travel horizontally through the saturated zone. However, if a vertical gradient is present, chemicals may also move vertically in the direction of the gradient. Saturated zone characteristics that determine the travel time and direction for the petroleum COIs include:

- Horizontal hydraulic conductivity,
- Horizontal and vertical hydraulic gradients (magnitude and direction), and
- Saturated zone soil characteristics (fractional organic carbon content and porosity).

4.2.6.1 Hydraulic Conductivity

Hydraulic conductivity is the discharge of water per unit area per unit hydraulic gradient in a subsurface formation. Estimates of site-specific hydraulic conductivity can be obtained by conducting aquifer tests such as slug or pump tests. Data gathered during the tests are then analyzed using appropriate methods. Slug tests are easier to conduct than pump tests, generate no wastewater for treatment, and may be more appropriate for low-permeability formations. The primary disadvantages are the small aquifer volume that is explored, resulting in the need to conduct multiple tests across the site. Properly conducted pump tests will often provide better estimates of hydraulic conductivity. The simplest pump tests are single-well short-duration (2 to 4 hours) tests. The best pump tests employ a pumping well and multiple observation wells and are of longer duration (12 hours or more). These tests will identify boundary effects. Regardless of the type of test conducted, different methods of data analysis will often yield different estimates of hydraulic conductivity. ASTM Method D4043 provides guidance on the selection of aquifer test methods (ASTM, 1996).

In the absence of these tests, estimates of hydraulic conductivity may be obtained from literature, with values corresponding to the type of soil in the saturated zone, using empirical equations based on the grain size distribution of the porous formation, or they may use specific capacity data from well logs of wells in the vicinity of the site that are representative of the aquifer being investigated. In either case, adequate references and justification for the value chosen should be provided.

4.2.6.2 Hydraulic Gradient

The magnitude and direction of the hydraulic gradient is estimated by comparing water levels measured in the monitoring wells. Typically, water level contour maps are prepared based on

measured data using a computer program or manual calculations along with professional judgment. Calculations done using automated procedures should be spot-checked with hand calculations. Three wells or more are needed to adequately estimate the direction of flow and magnitude of the gradient. When drawing the contour maps, care should be taken to ensure that the measurements used are from monitoring wells that are screened in the same interval or hydrologic unit.

For sites that have seasonal variation in hydraulic gradient, estimate the average hydraulic gradient for each season. Consideration should also be given to determining any vertical gradients. This requires a comparison of adjacent water levels in wells screened in different intervals.

In areas where the shallow aquifer has been impacted and a deeper aquifer is used for drinking water, the vertical gradient should be determined. When drilling deep wells, care should be taken to avoid cross contamination.

4.2.6.3 Saturated Zone Soil Characteristics

In addition to hydraulic conductivity, other important saturated zone soil characteristics include fractional organic carbon content, porosity, and bulk density. These parameters are required to quantify the movement of chemicals within the saturated zone. The laboratory methods to measure these parameters were discussed in section 4.2.5.

4.2.7 Indicators of Biodegradation

Biodegradation of petroleum chemicals occurs in all media (soil, soil vapor, groundwater). Depending on the media, different indicators (chemical concentrations, geochemical indicators, microorganisms, oxygen, and carbon dioxide) can be measured at a site to demonstrate the occurrence of biodegradation of these organic substances.

When evaluating the potential for biodegradation in groundwater, these indicators are commonly classified into three groups: primary, secondary, and tertiary lines of evidence. Data collected under each line of evidence can be evaluated qualitatively or quantitatively to determine the occurrence of biodegradation.

The primary line of evidence demonstrates spatial stability or a reduction in chemical concentrations at a site by evaluating measured concentrations within monitoring wells, groundwater velocity, rates of contaminant transport, and time of the release.

The secondary line of evidence refers to measurement of geochemical indicators including reduction-oxidization (REDOX) potential, dissolved oxygen, dissolved nitrates, manganese, ferrous iron, sulfate, and methane. These indicators should be measured in at least three wells located along the flow line, one of which should be located at a background or up-gradient location, one within the plume near the source, and one within the plume down-gradient from the source.

The tertiary line of evidence involves microbiological studies such as identification of types of subsurface microbial populations and microbe cell counts.

Commonly used methods to estimate biodegradation rates include mass balance analysis for expanding, stable, or shrinking plumes and plots of plume concentration vs. distance. Additional details on biodegradation for petroleum COIs in groundwater are provided in Appendix H.

When evaluating the potential for, or presence of, biodegradation in soil or soil vapor, the most common indicators used are soil vapor concentrations, oxygen, and carbon dioxide. These are commonly measured at multiple depths in the subsurface and related to a potential source. More information on evaluation of biodegradation of petroleum vapors in relation to the vapor intrusion pathway is provided in Appendix G.

4.2.8 Distribution of Petroleum Chemicals of Interest

Petroleum COI may be distributed between soil, soil vapor, groundwater, surface water, and sediments present at a release location. Knowledge of contaminant distribution entails a determination of the spatial extent and magnitude of concentrations in each of these media, where they are present.

4.2.8.1 Distribution of Petroleum Chemicals of Interest in Soil

Adequate soil concentration data are necessary to estimate risk to receptors, compare representative concentrations for each complete pathway to target levels, and define the soil source dimensions. Sufficient data should be collected to define horizontal and vertical extent of impacts. The vadose zone investigation(s) should be organized to:

- Identify the horizontal and vertical extent of soil impacts. Unless otherwise directed by DEQ, the extent of impact should be defined as those areas where petroleum COI concentrations exceed screening level concentrations.
- Identify areas of maximum concentration of petroleum COIs.
- Collect samples adequate to estimate exposure point concentrations for the potentially complete exposure pathways that have been defined based on the SCM.

To determine the spatial extent of contamination, soil borings should be drilled starting from the known or suspected source area and drilling outwards until borings with sample concentrations at or below screening levels are reached in all directions. To determine the vertical extent of contamination, soil borings should be extended to the base of petroleum impact and samples collected from surface and subsurface soil zones as explained in the following sections.

The soil analytical data should help identify the soil source area. If more than one source area is identified at a site, each source area should be evaluated separately. Once the soil source(s) is identified, source dimensions can be estimated. These dimensions are used in the computational software which accompanies the guidance and rule, along with other input parameters, to estimate risk and RATL concentrations protective of indoor inhalation and to evaluate the soil to groundwater leaching pathway. Depth to subsurface soil source (used to estimate the target concentrations) should be the depth, in the source area, from the surface to the zone where concentrations are above quantification limits. Professional judgment should be used in choosing the representative depth.

4.2.8.1.1 Surficial Soil Sampling

The RE process distinguishes between surficial soil and subsurface soil zones. Surficial soil is defined as the soil zone from the ground surface to 1 foot below ground surface. Pathways that may apply to the surficial soil zone include direct contact exposure via incidental ingestion, inhalation of vapors and particulates, dermal contact, and leaching of petroleum COIs to groundwater and surface water.

Evaluation of soil exposure pathways within the surficial soil zone requires collection of an adequate number of soil samples to estimate both maximum and representative concentrations of all potential petroleum COIs. Given the small vertical depth interval of this soil zone, close attention should be given to vertical variations in contamination. The acceptability of vertical depth-composite samples versus samples from discrete depth intervals is a site-specific decision. Criteria that influence this decision include the type of petroleum COIs, vertical extent of contamination, and areal extent of the contaminated zone. Sampling within the surficial soil zone is typically done from test pits using hand samplers such as trowels or corers.

The presence of impervious (paved) surfaces poses difficulties for sampling. In some cases, very permeable material may be located 2 inches below the pavement. Residues from the paved surface may also be present. When sampling beneath impervious surfaces, sampling should begin 2 inches or deeper below concrete or asphalt pavement. Cracked areas in impervious surfaces may represent conduits for chemical migration or leaching and should be evaluated during the selection of sampling locations.

4.2.8.1.2 Subsurface Soil Sampling

Soil below the surficial soil zone (more than one foot below ground surface) and extending to the water table is termed the subsurface soil zone. Pathways evaluated for this zone include volatilization from soil to indoor air and leaching to groundwater and surface water. Most receptors will not have direct exposure to this soil. However, some construction workers may be involved in excavation activities below the surficial soil zone and subsurface soil removed during excavation may be deposited at the surface allowing greater exposure. This possibility should be considered during the development of the SCM.

To test for indoor inhalation of vapors from subsurface soils, it is preferable to collect soil vapor data however soil data can also be used. Soil samples should be collected to characterize the complete horizontal and vertical extent of contamination. Soil moisture conditions and soil vapor permeability are also important parameters affecting soil vapor transport. If petroleum contamination exists adjacent to existing structures, additional sampling should be focused in these areas. More information on evaluation of the vapor intrusion pathway is provided in Appendix G.

To test for exposure to a construction or utility worker during excavation activities, soil samples should be collected from both surface and subsurface soil zones to depths where construction-related activities are likely to occur.

To test for leaching of petroleum COIs in soil to groundwater, it is critical to determine the thickness of the contaminated soil zone, the distance from the bottom of the contaminated zone to the water table, if any, and representative concentrations of petroleum COIs within the contaminated zone.

Soil sampling must be done in accordance with the following guidelines and procedures:

- Samples must be collected from the source area(s). Samples must be collected to determine the full horizontal and vertical extent of soil contamination. Sampling should strive to characterize any horizontal or vertical stratigraphic variation at the site that could impact petroleum COI fate and transport. Where required to fully characterize the vertical extent of contamination, borings should be extended to the water table and features such as the capillary fringe and any smear zone, if encountered, should be characterized. Vertical sampling intervals generally should not be greater than 5 feet.
- Soil borings should be logged and samples for laboratory analyses collected in accordance with current industry practice.
- All samples must be adequately preserved according to requirements of the laboratory analyses and analyzed within holding times required by each method. Sample analyses must be conducted in accordance with current, EPA Office of Solid Waste and Emergency Response SW-846 Methods, or other accepted methods.
- Adequate QA/QC procedures must be used to ensure sample quality and integrity. Section 4.2.2 contains additional information on QA/QC considerations.
- All sampling equipment must be decontaminated using current state of industry practice such as described in ASTM D-5088-90, Practice for Decontamination of Field Equipment Used At Nonradioactive Waste Sites (ASTM, 1990).
- Abandonment of boreholes that extend to the water table, which are considered wells by IDWR, should follow IDWR abandonment procedures (IDAPA 37.03.09.16). Appropriate methodology for abandoning other boreholes is described in detail in the Standard Guide for Decommissioning Ground Water Wells, Vadose Zone Monitoring Devices, Boreholes, and Other Devices for Environmental Activities, Standard Guide D5299-99 (ASTM, 1999a).

4.2.8.1.3 Subsurface Soil vapor Data

At sites where petroleum COIs in soil or groundwater are volatile and there is concern about potential indoor inhalation of vapors, it may be useful to assess soil vapor concentrations. For details about these samples, refer to Appendix G (Evaluation of the Vapor Intrusion Pathway).

4.2.8.1.4 Logging of Soil Boreholes

Each soil boring must be logged to record depths correlating with changes in lithology (with lithologic descriptions), soil vapor (e.g., photo-ionization detector) analyses, occurrence of groundwater, total depth, visual and olfactory observations, and any other pertinent data.

When a monitoring well is installed, as-built diagrams with depth to groundwater and construction details must be submitted for each well. A continuous soil profile from at least one boring with detailed lithologic descriptions may be useful. Particular emphasis should be placed on characteristics that control chemical migration and distribution, such as zones of greater or lesser permeability, changes in lithology, correlation between soil vapor concentrations and different lithologic zones, obvious areas of soil discoloration, organic content, fractures, and other lithologic characteristics.

4.2.8.2 Distribution of Petroleum Chemicals of Interest in Groundwater

Adequate groundwater samples should be collected to delineate the extent of free product, dissolved contaminant plumes in all directions, maximum petroleum COI concentrations, and representative concentrations based on the SCM. This sampling should take into account knowledge of the soil source and the direction of groundwater flow.

4.2.8.2.1 Groundwater Sampling

If groundwater has been impacted, temporary sampling points may be used to screen levels of groundwater impacts and to assist in determining optimal locations of permanent monitoring wells. A sufficient number of monitoring wells should be installed to identify source areas and to document petroleum COI migration and groundwater flow. The monitoring wells should be installed in accordance with current IDWR rules (IDAPA 37.03.09) and industry standards such as ASTM D 5092-95, Standard Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers (ASTM, 1995b). EPA documents such as the Resource Conservation and Recovery Act (RCRA) technical guidance for groundwater monitoring (EPA, 1986, 1992a) are also useful references.

Adequate numbers of monitoring wells must be installed to sufficiently delineate the horizontal and the vertical extent of the groundwater plume. The number and location of wells should also allow a site-specific estimate of the direction of groundwater flow. Well placement and design must consider the concentration of petroleum COIs in the source area, and the occurrence of NAPL at the site.

Well casing and screen materials must be properly selected. The screen interval length should be minimized to the extent possible but should be set at least 2 to 3 feet above the expected high water table and encompass the range of expected variation in water table depth. EPA (1992) recommends screen interval lengths of 10 to 15 feet except where specific monitoring objectives or site knowledge result in other requirements. Wells must be properly developed and gauged after installation. A site survey must be conducted to establish well casing elevations. Based on the groundwater elevations, groundwater flow direction and gradient should be determined and plotted on a map.

Groundwater samples must be collected in accordance with the following guidelines and procedures:

- Monitoring wells must be purged of an adequate number of well volumes prior to collecting a sample (usually 3 to 5 volumes). Low-flow purging and sampling techniques (EPA, 2002b) may also be acceptable when included in a DEQ-approved QAPP.
- Samples must be collected using EPA approved methods and equipment.
- All samples must be adequately preserved according to the requirements of the laboratory analyses and analyzed within holding times required by each method.
- Sample analyses must be conducted in accordance with EPA Office of Solid Waste and Emergency Response SW846 Methods, or other accepted methods.
- Adequate QA/QC procedures must be used to ensure sample quality and integrity. See section 4.2.2 for additional information on QA/QC considerations. All sampling equipment must be decontaminated using current state of industry practice such as

described in ASTM D-5088-90, Practice for Decontamination of Field Equipment Used At Nonradioactive Waste Sites (ASTM, 1990).

- If the plume is not delineated in all directions, locations of new monitoring wells must be chosen based on groundwater flow direction and location of the soil source area.

4.2.8.3 Surface Water and Sediment Sampling

Appropriate samples should be collected when petroleum COI migration is known or suspected to have impacted surface water. Water samples should be collected from upstream and downstream of a groundwater discharge point. Sediment samples should be collected if the SCM indicates a potential for releases to surface water.

In places where a groundwater plume may discharge into a stream, it is necessary to estimate the discharge concentration into the stream. This can be achieved by installing one or more monitoring wells or temporary wells within the plume adjacent to the stream.

4.3 Exposure Assessment

The goals of the exposure assessment portion of the RE are to:

- Characterize the physical setting,
- Identify potentially exposed populations,
- Identify complete or potentially complete exposure pathways,
- Estimate exposure concentrations, and
- Estimate petroleum chemical intakes.

The exposure assessment uses much of the data collected in support of and assumptions contained in the SCM (described earlier in section 4.1). A graphical display of the SCM like the sample shown in Figure 2 is helpful for assessing exposure.

4.3.1 Physical Setting

Characterization of the physical setting for exposure assessment identifies those site factors which may influence the fate and transport of chemicals from the source to a receptor. These factors include climate, meteorology, geologic and hydrogeologic setting, soil types, biodegradation potential, and surface water hydrology. When these factors are considered in the context of the media from which petroleum COIs are released (surficial soils, subsurface soils, groundwater, surface water, etc.), the transport mechanisms for the petroleum COIs from each media (leaching, groundwater transport, volatilization, etc.), and the chemical concentrations and distribution of the petroleum COIs in each media, the potential for a chemical to reach a receptor can be assessed. A more thorough discussion of the data needs related to description of the physical setting can be found in section 4.1 (Site Conceptual Model).

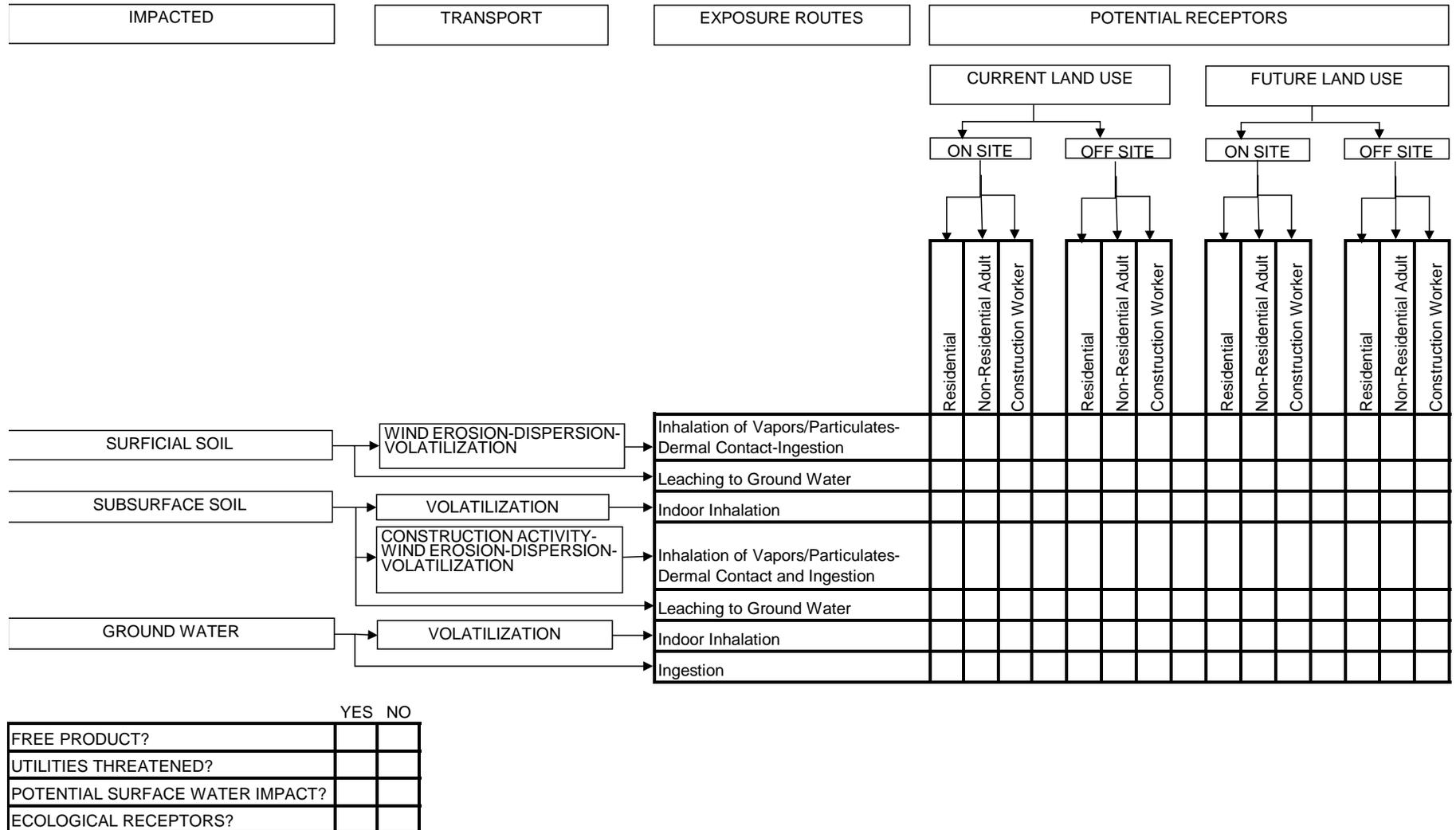


Figure 2. Sample Graphical Display of a Site Conceptual Model

4.3.2 Potentially Exposed Populations/Receptors

Potential exposure populations/receptors should be identified from the information contained in section 4.1 (Site Conceptual Model).

4.3.3 Exposure Pathways

A receptor comes in contact with petroleum COIs through a complete exposure pathway. If some but not all of the following elements are present, the pathway is incomplete. For a pathway to be complete, all of the following must be present:

1. a source of petroleum,
2. a mechanism by which the petroleum is released,
3. a transport medium through which petroleum travels from the point of release to the receptor location,
4. an ROE by which the petroleum chemical enters the receptor's body (ingestion, inhalation, or dermal contact) and
5. a potential receptor.

If the migration of petroleum chemicals to a receptor or contact by a receptor is not possible (e.g., due to formal engineering controls such as a paved site that will prevent human contact with petroleum-contaminated soil) under current and most likely future land use conditions, the site-specific petroleum COI concentrations may not pose a risk.

DEQ has identified the most commonly encountered exposure pathways for various environmental media for which an evaluation must be conducted. These pathways are discussed below. At sites where receptors, exposure pathways, or ROE other than those discussed below are important, the owner/operator must identify them and discuss their quantitative evaluation with DEQ. In some cases it may be determined that one or more of the pathways are incomplete and therefore do not need to be quantitatively evaluated. Adequate justification for exclusion of these pathways must be provided to and approved by DEQ.

4.3.3.1 Pathways for Surficial Soils (0–1 foot below ground surface)

Surficial soils are defined as soils extending from the surface to 1 foot below ground surface. For construction worker exposure, however, the applicable depth is the depth of excavation. The exposure pathways associated with impacted surficial soils include:

- Groundwater protection (leaching of petroleum chemicals from soil to groundwater with subsequent potential ingestion of groundwater),
- Surface water protection (leaching of petroleum chemicals from soil to groundwater with subsequent migration to a surface waterbody), and
- Ingestion of soil, outdoor inhalation of vapors and particulate emissions from soil, and dermal contact with soil.

4.3.3.2 Pathways for Subsurface Soils (1 foot below ground surface to the water table)

Subsurface soils are defined as soils extending from 1 foot below the ground surface to the water table. The exposure pathways associated with subsurface soils include:

- Indoor inhalation of vapor emissions from soil,
- Groundwater protection (leaching of petroleum chemicals from soil to groundwater with subsequent potential ingestion of groundwater), and
- Surface water protection (leaching of petroleum chemicals from soil to groundwater with subsequent migration to a surface waterbody).

4.3.3.3 Pathways for Groundwater

Potentially complete exposure pathways for impacted groundwater include:

- Indoor inhalation of vapor emissions from groundwater, and
- Current and/or future ingestion of water on or off site.

Appendix G describes in detail the process used to evaluate potential exposure via indoor inhalation of vapors from soil and groundwater.

4.3.3.4 Pathways for Surface Water and Sediments

Depending on the beneficial use designation of impacted surface waters, complete pathways for surface water include:

- Intentional ingestion of surface water and ingestion of fish when surface water is used as a drinking water supply, and
- Ingestion of fish from surface waters designated for recreational use.

4.3.3.5 Other Exposure Pathways

Other complete or potentially complete exposure pathways, such as ingestion of produce grown in impacted soils, ingestion of fish, contact with contaminated sediments, or use of groundwater for irrigation purposes, should be evaluated on a case-by-case basis. The owner/operator should contact DEQ for further guidance.

4.3.4 Exposure Point Concentrations

Exposure point concentrations are the average petroleum chemical concentrations to which receptors could be exposed over a specified duration within a specified geographical area. The geographical area about which a receptor moves and within which a receptor contacts contaminated media during the specified exposure duration is termed an exposure unit (EPA, 2001). The exposure unit of all receptors must be considered and described. The exposure unit, or spatial area over which a given receptor is likely to be exposed, must be established for on-site receptors as well as any off-site impacted or potentially impacted receptors and for each exposure pathway or ROE. The same site may have different exposure units for current and future use scenarios.

A detailed discussion of the estimation of exposure point concentrations and the use of exposure units for RE is provided in Appendix I. This appendix describes the sources of uncertainty which affect the estimation of exposure point concentrations, strategies to reduce this uncertainty, and methodologies to evaluate data quality. It also provides guidance on the selection of appropriate data for various ROE and appropriate statistical methods for analysis of available data.

The RE report should clearly identify specific data and methods used to estimate the exposure point concentrations, and provide a rationale for the method and data used. The following information should be provided in a table:

- Media
- ROE/pathway
- Receptor
- Data used
- Method of estimation

Table 3 shows how such a table might be constructed with examples of the type of information that would be supplied.

Table 3. Example Table Describing Derivation of Exposure Point Concentrations

Media	Route of Exposure	Receptor	Data Obtained From	Method
Surficial Soil	Direct Contact	Construction Worker	Unpaved Area	Average
Subsurface Soil	Indoor Inhalation	Commercial Worker	Building Footprint	Maximum
Groundwater	Ingestion	Residential	Source Area	Upper Confidence Limit
Soil Vapor	Indoor Inhalation	Commercial Worker	Sub-slab and near soil gas samples	Maximum

As presented in Table 3, an exposure point concentration is estimated for each complete ROE. Various methods available to estimate the exposure point concentrations are discussed in Appendix I. Use of the maximum concentration as the exposure point concentration is most conservative and also the easiest to calculate when compared with other ways of calculating exposure point concentration (average, area-weighted average, upper limit of the confidence interval around the mean). Thus, if the risk that is calculated using the maximum concentration is acceptable, considerable computational effort can be avoided.

4.3.4.1 Soil

Exposure point soil concentrations used to evaluate protection of the groundwater pathway should be calculated based on soil data collected within the source area only.

Soil data from the most recent investigation (assuming it was a comprehensive investigation) should be used. The use of older soil data (more than 4 years old), while discouraged, may be

acceptable if site conditions that would result in an increase in petroleum COI concentrations (such as a new release) have not changed. If a new release has or may have occurred, additional soil assessment activities that adequately characterize current conditions should be performed. New data collection efforts may be documented in a work plan and submitted for approval by DEQ.

4.3.4.2 Groundwater

Based on the SCM, several exposure point groundwater concentrations at a site may have to be estimated. These could include exposure point concentrations for the source area, at compliance locations, for protection of indoor inhalation on-site and off-site, and for off-site areas. Estimation of these concentrations will often require the use of fate and transport models, discussed in section 4.3.5.

In order to account for site-specific conditions such as source characteristics in relation to the depth to groundwater and the age of the release, it is typically necessary to perform multiple sampling events over time to ensure that the potential for the release to impact groundwater has been accounted for and that groundwater concentrations are representative. However, if these factors can be accounted for, it may be possible to perform an RE using data from one sampling event. If temporal data indicate significant variability, additional sampling events may be required prior to conducting the RE. Subsequent to RE, DEQ may require additional monitoring data to be collected. If recent groundwater data (less than one year old) is unavailable, current data may be necessary for the RE. The owner/operator may elect to document data collection objectives in a work plan submitted to DEQ for review and approval.

4.3.4.3 Point of Exposure and Point of Compliance

The point of exposure (POE) is the location where a receptor has or could come in contact with petroleum COIs under current and likely future conditions. A separate POE is associated with each complete exposure pathway-receptor combination identified in the SCM. For direct exposure pathways, the POE is located at the source of the petroleum COIs. For example, for the ingestion of surface soil, the POE is at the same location as the soil source. For indirect exposure pathways, the POE and the source of petroleum COIs are physically separate. For example, for the case of indoor inhalation of vapors from soil, the POE is inside the building (the breathing space) whereas the source is the soil below and adjacent to the building. The POE location for the protection of the groundwater for groundwater ingestion is discussed in section 4.3.3.3.

A point of compliance (POC) is a location where concentrations are measured to determine if compliance with remedial goals has been achieved. Concentration measurements at the POC may be in any media (e.g., soil, groundwater, soil vapor, etc.). The location of a POC may be identical to the POE or may be located between the source and the POE. In the latter case, the target concentrations at the POC are back-calculated to ensure that the concentrations at the POE do not exceed the target concentration at the POE. For example, for the protection of the groundwater pathway, the POC well may serve as a sentry well for protection of the POE. The calculated target levels for the POC are then compared to measured concentrations. POC locations may be predetermined based on program-specific requirements. Most sites, particularly those involving groundwater impacts, will have multiple POC locations.

4.3.4.4 Estimating Point of Compliance Well Concentrations

As a part of the RE process, it is necessary to designate and monitor appropriate POCs. The POCs, located onsite and/or offsite, are used to provide additional assurance that approved concentrations at a selected POE are not exceeded. Monitoring of POC locations is required, and data obtained are compared with approved RATL concentrations. Monitoring of POC locations must be continued until the concentrations stabilize below approved levels. Concentrations at the POC may also be used to determine the need for additional remedial activities.

4.3.5 Fate and Transport and Exposure Models

Different types of models or equations, uptake equations, risk equations, and fate and transport models, are required to calculate chemical intake, risk, exposure point concentrations, and target concentrations. Fate and transport models simulate the transfer of chemicals from one media (such as soil) to another (air). They also are used to simulate the movement of chemicals within a given media, such as the transport of chemicals in groundwater from a source area to a POE. They allow the estimation of concentrations at points distant from the source. A schematic and the equations for each of these models are presented in Appendix E. DEQ has selected the following default fate and transport models:

Indoor Inhalation of Volatile Emissions from Soil and Water: This pathway requires an emissions model and an indoor air-mixing model. These models are combined together and included in the Johnson and Ettinger Model (Johnson and Ettinger, 1991; EPA, 2003). The Johnson and Ettinger Model does not include the effects of attenuation by biodegradation, which may be significant for petroleum COI.

Surficial Soil Outdoor Inhalation: This pathway requires an emissions model for vapors, an emissions model for particulates, and an outdoor air-mixing model. The vapor emissions model used is based on the volatilization model developed by Jury et al. (1983) for an infinite source, the particulate emissions model is the Cowherd model (Cowherd, et al., 1985), and the outdoor air-mixing model is based on a simplified form of the Gaussian Dispersion model. These models are presented in Soil Screening Guidance: Technical Background Document (EPA, 1996a).

Leaching to Groundwater: This pathway uses a three-phase equilibrium partitioning equation to convert soil concentrations to leachate concentrations. These leachate concentrations are then used with a dilution attenuation model to simulate mixing of leachate with regional groundwater. Models used are described in Soil Screening Guidance: Technical Background Document (EPA, 1996).

Horizontal Migration in Groundwater: The Domenico steady-state analytical infinite-source model is used to quantify down-gradient migration of chemicals (Domenico, 1982, 1990). This model incorporates the processes of advection, sorption, three-dimensional dispersion, and degradation.

Alternative models may be used with prior DEQ approval.

4.3.5.1 Fate and Transport Parameters

Fate and transport parameters are necessary in the models used to estimate exposure point concentrations and compliance point concentrations for indirect pathways such as vapor intrusion and protection of groundwater. These parameters characterize the physical site properties such as depth to groundwater, soil porosity, and infiltration rate. DEQ has selected the conservative default values listed in Appendix B. Justification for these parameters is included in Appendix B. For RE, a combination of site-specific and default values for these parameters is typically used. However, the value of each parameter used, whether site-specific or default, must be justified based on site-specific conditions. Where fate and transport models other than those selected by DEQ are used, the specific fate and transport parameters required to calculate exposure point concentrations and risk may vary and have specific data collection requirements.

4.3.5.2 Physical and Chemical Properties of the Petroleum Chemicals of Interest

The development of target levels requires the selection of values for the physical and chemical properties of petroleum COIs. Values of these parameters are listed in Appendix C. To use different values, the owner/operator must provide sufficient justification to DEQ. The use of different values will be allowed only with prior DEQ approval. DEQ will update the data in Appendix C as new information becomes available.

4.3.6 Estimation of Chemical Intake

Risk evaluation requires quantifying the magnitude, frequency, and duration of exposure for the receptor populations and exposure pathways selected for analysis. Oral exposures are quantified on a dose per unit body weight basis while inhalation exposure is based on concentration in air.

4.3.6.1 Exposure Factors

In order to determine receptor and pathway-specific intake estimates, it is necessary to select values for a number of exposure parameters in the equations used to calculate intake. The selection of values for the following parameters is based on an assessment of recommendations in various guidance documents, as well as the open scientific literature. When determining these values, it is often necessary to make assumptions. Details and rationale regarding these assumptions are provided in Appendix A. Exposure assumptions for surface water related pathways are incorporated into the toxics criteria for surface water discussed in section 4.6.

Exposure factors describe the physiological and behavioral characteristics of the receptor. These factors include the following:

- Water ingestion rate,
- Body weight,
- Exposure duration for each ROE,
- Exposure frequency,
- Soil ingestion rate,
- Exposure times for indoor/outdoor inhalation,
- Dermal relative absorption factor,

- Skin surface area for dermal contact with soil,
- Soil-skin adherence factor, and
- Oral relative absorption factor.

A list of default exposure factors values selected by DEQ and justification for their choice is presented in Appendix A. Site-specific values of exposure factors, other than default values, may be used. However, the owner/operator must submit a proposal for the use of alternative values to DEQ for approval, and approval must be obtained before using alternative values for exposure factors.

4.4 Toxicity Assessment

4.4.1 Chemical-Specific Toxicological Factors

The toxicity of chemicals with carcinogenic adverse health effects is quantified using cancer slope factors (CSF) for oral and dermal ROE, or inhalation unit risk (IUR) for the inhalation route. A CSF is an upper-bound estimate of the probability of a response (developing cancer) per unit intake of a chemical over a lifetime. The IUR is the upper-bound excess cancer risk estimated to result from continuous exposure to a chemical at a concentration of 1 $\mu\text{g}/\text{m}^3$ in air.

For chemicals that cause noncarcinogenic health effects, toxicity is typically quantified by reference doses (RfD) for oral and dermal ROE, and reference concentrations (RfC) for the inhalation ROE. The RfD is an estimate of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without risk of adverse health effects during a lifetime. Since RfDs are based on oral exposure, they are modified for use in dermal exposure assessment to take account of differences between gastrointestinal and dermal absorption. The RfC is an estimate of a continuous inhalation exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of adverse health effects over a lifetime.

The primary source of information for toxicity factors for the petroleum COI is the EPA RSL tables (RSL) (EPA, 2018) found at:

http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm

Toxicity factors selected by DEQ for the petroleum COIs are presented in Appendix D.

Table 4. Default Toxicity Values for Risk Evaluation.

DEFAULT TOXICITY VALUES FOR RISK EVALUATION							
CHEMICALS	CAS Number ^a	Oral Slope Factor (SF _o) (kg-day/mg)	Inhalation Unit Risk (IUR) (ug/m ³)	Oral Reference Dose (RfD _o) (mg/kg-day)	Inhalation Reference Concentration (RfC) (mg/m ³)	Oral RA ^b Factor (RAF _o)	Dermal RA Factor (RAF _d)
Benzene	71-43-2	0.055	7.8E-06	0.004	0.03	1	0
Toluene	108-88-3	NA	NA	0.08	5.0	1	0
Ethylbenzene	100-41-4	0.011	2.5E-06	0.1	1.0	1	0
Total Xylenes	1330-20-7	NA	NA	0.2	0.1	1	0
Naphthalene	91-20-3	NA	3.4E-05	0.02	0.003	1	0.13
MTBE ^c	1634-04-4	0.0018	2.6E-07	NA	3.0	1	0
1,2-Dichloroethane	107-06-2	0.091	2.6E-05	0.006	0.007	1	0
Ethylene Dibromide	106-93-4	2	6.0E-04	0.009	0.009	1	0
Acenaphthene	83-32-9	NA	NA	0.06	NA	1	0.13
Anthracene	120-12-7	NA	NA	0.3	NA	1	0.13
Benz(a)anthracene	56-55-3	0.1	1.1E-04	NA	NA	1	0.13
Benzo(a)pyrene	50-32-8	1	1.1E-03	3.0E-04	NA	1	0.13
Benzo(b)fluoranthene	205-99-2	0.1	1.1E-04	NA	NA	1	0.13
Benzo(k)fluoranthene	207-08-9	0.01	1.1E-04	NA	NA	1	0.13
Chrysene	218-01-9	0.001	1.1E-05	NA	NA	1	0.13
Fluoranthene	206-44-0	NA	NA	0.04	NA	1	0.13
Fluorene	86-73-7	NA	NA	0.04	NA	1	0.13

Pyrene	129-00-0	NA	NA	0.03	NA	1	0.13
Notes:							
a Chemical Abstract Service							
b Relative Absorption							
c Methyl tert-butyl ether							
NA: No data available							
Source of toxicity values is the Regional Screening Level Summary Table (May 2018) found at the U.S. EPA Regional Screening Table website. The website is located at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm .							

4.4.2 Carcinogens with a Mutagenic Mode of Action

Current EPA guidance for risk assessment of carcinogens addresses the potential for increased susceptibility to cancer from exposure to carcinogens that occurs early in life (EPA, 2005a; EPA, 2005b). When information is available to establish the mode of action of a chemical for early-life and adult exposures, it may be appropriate to develop separate risk estimates for childhood exposure and exposure occurring later in life. When the mode of action cannot be established, risk estimates are based on a lifetime daily average exposure without adjustment. Currently, there is sufficient information to develop separate risk estimates only for chemicals having a mutagenic mode of action.

Specifically, when data indicate a mutagenic mode of action for a chemical, meaning that the chemical interacts directly with DNA, available studies indicate higher cancer risk for a given exposure when it occurs early in life compared to a similar exposure in adulthood. Among the petroleum chemicals of interest, the following carcinogenic chemicals are considered mutagens:

- Benzo(a)anthracene
- Benzo(a)pyrene
- Benzo(b)fluoranthene
- Benzo(k)fluoranthene
- Chrysene

For these chemicals, the following adjustments are made to risk estimates:

- For exposures between birth and two years of age, a ten-fold adjustment (multiplication factor) is applied. Toxicokinetic and toxicodynamic differences between children and adults are greatest for this age group.
- For exposures occurring to those in the age categories of two to six years of age and between six and sixteen years of age, a three-fold adjustment is applied.
- For exposures occurring after 16 years of age, no adjustment is applied.

These adjustments are combined with corresponding age-specific exposure parameters to assess cancer risk. For a standard residential exposure scenario of 30 years, a ten-fold adjustment is made for the first two years, a three-fold adjustment is made for the next fourteen years, and no adjustment is made for the final fourteen years of the exposure period.

The screening levels are based on unrestricted (residential) exposure; therefore they incorporate the adjustments described here. The effect of the adjustments will be a somewhat higher estimate of risk for a given exposure (and thus somewhat lower screening levels) compared to risk estimates without age-specific adjustment. Calculated risk estimates for residential exposure will incorporate these adjustments, but nonresidential risk estimates will not, as they are based on adult exposure.

4.5 Risk Characterization

The process of risk characterization consists of combining the intake estimates developed through the exposure assessment and toxicity information for the petroleum COIs and calculating carcinogenic risk and noncarcinogenic hazard. Calculations are made for each pathway-receptor combination and are summed to calculate a cumulative risk and a hazard index (HI) for each receptor. These risk results are then presented and discussed in a risk summary and are compared to acceptable target risk levels.

Risk and hazard calculations are completed using a standard set of risk equations provided by the EPA in their User's Guide for RSLs (EPA, 2012) and presented in Appendix E. Estimates made using these equations should be presented using one significant figure, although an additional significant digit should be carried through the supporting calculations, such as when summing risks from multiple petroleum chemicals or pathways, in order to minimize rounding errors. For example, calculated cancer risks would be presented as 1×10^{-4} and HQs or HIs would be expressed as 2, 0.7, or 0.03.

This risk-based decision-making process specifies the acceptable risk levels for both carcinogenic and noncarcinogenic health effects. For carcinogenic effects, risk is quantified using the individual excess lifetime cancer risk (IELCR) that represents an increase over background in the probability of an individual developing cancer due to exposure to specific petroleum COI through a specific exposure pathway. Since a receptor may be exposed to multiple petroleum chemicals through multiple ROEs, the acceptable risk level should account for the effect of simultaneous exposure to multiple petroleum chemicals and multiple ROEs. Overall site carcinogenic risk is calculated as the sum of the individual chemical risk estimates. The probability of a receptor getting cancer is thus the sum of the probabilities of getting cancer from exposure to each petroleum chemical through each exposure route. In this calculation there is an assumption of independence of action of the individual chemicals. If the carcinogenic actions of different petroleum chemicals are not independent there is the possibility of synergistic interaction in which case risk may be underestimated. However, information is generally not available to address this possibility.

For noncarcinogenic effects, risk is quantified using an HQ that represents the ratio of the estimated dose of a petroleum chemical for a ROE to the reference or allowable dose. When a

receptor is exposed to multiple chemicals and multiple ROEs, individual HQs are added together to estimate the HI.

For site-specific REs, the following target risk criteria must be satisfied at the POE:

Acceptable Target Risk Level: For combined exposure to all carcinogens and ROE, IELCR must be less than or equal to 1×10^{-5} for a receptor at a reasonable maximum exposure.

Acceptable HI: The summation of HQs for all petroleum chemicals that have noncarcinogenic health effects and ROE must be less than or equal to 1.

The target risk level and HI must be met for each current and potential future receptor at the site. If the initial calculated HI exceeds 1 further evaluation, including analysis of mode of action and target organ for each petroleum chemical, can be completed. If this analysis indicates sufficient independence of target organs and mode of action for different chemicals, it may be acceptable to present separate HQs, and/or one or more HI for subsets of the chemicals. This kind of analysis should be performed by a toxicologist.

In addition to the target risk levels, DEQ requires that MCLs, or comparable risk-based values for groundwater ingestion, be met at the POE when there is a high probability of groundwater use. When there is a low probability of groundwater use for drinking water, alternate risk-based groundwater target concentrations, based on the other potentially complete exposure pathways identified for the site, must be met at the POE. Similarly, for impacts to surface water bodies, calculated target concentrations must be met.

The risk summary should include an analysis and discussion of the sources of uncertainty so that the risk estimates can be placed in perspective. The uncertainty analysis can be qualitative or quantitative in nature. It is more important during the analysis to identify the key site-related parameters and assumptions in the SCM that contribute the most to the uncertainty than to precisely quantify the degree of uncertainty (EPA, 1989). It is typically the case that there is insufficient information available at a given site to be able to reliably quantify the uncertainty in a given risk estimate, such as through conducting a probabilistic risk assessment or sensitivity analysis. The typical sources of uncertainty that are included in the analysis include the petroleum COIs selected and their estimated site concentrations, the toxicity values used, the fate and transport models used to estimate exposure point concentrations, the exposure parameter values used in the exposure assessment, and the summing of risks from multiple pathways or petroleum chemicals.

4.6 Risk-Based Target Levels

As described in the Risk Characterization section 4.5, if the calculated risk or hazard for all petroleum COIs and complete ROE for identified potential receptors exceeds the Acceptable Target Risk or Hazard Levels and corrective action is required, then risk-based target concentrations (RATLs) to achieve these targets should be calculated. Ingestion of water is not included in this calculation. The procedure used to calculate RATLs requires chemical-specific toxicological factors, receptor-specific exposure factors, fate and transport parameters, physical and chemical properties of the petroleum COIs, and mathematical models. In calculating risk-

based target concentrations, all of these factors, properties, and models are typically the same as used for calculations of other risk-based levels.

Target concentrations should be estimated using an allocated risk process that apportions the acceptable target cumulative risk and HI among the different chemical-pathway combinations. The primary goal is to develop target concentrations in all media such that the acceptable target risk levels and hazard levels are met. There is no standard way to apportion the cumulative risk. To develop RATL concentrations, the default option selected by DEQ apportions cumulative risk and HI equally among all contributing petroleum chemical-pathway combinations such that those petroleum chemicals which contribute the greatest proportion of the total risk have the most stringent remediation standards. This methodology is described in detail, with examples, in Appendix D and is implemented in the computational software provided by DEQ to complement this guidance.

If a petroleum COI has toxicity that is based on both carcinogenic and noncarcinogenic effects, the applicable RATL for that chemical should be the lower of the two calculated allowable concentrations.

Site-specific considerations may result in an owner/operator choosing to utilize a different method for calculating target concentrations. For example, at a site having volatile and semi-volatile petroleum COIs contributing to the cumulative risk, the owner/operator may choose a technology that specifically reduces the volatile chemical's concentrations but marginally reduces the concentration of the semi-volatile chemical. A different owner/operator may choose to significantly reduce the concentration of the semi-volatile chemical and marginally reduce the concentration of the volatile chemical. The two strategies will result in different cleanup levels for each chemical; however, both will be acceptable provided cumulative risk meets the acceptable target risk criteria.

4.6.1 Developing RATL Concentrations for Groundwater and Surface Water Protection

For groundwater and surface water protection, target concentrations are calculated using somewhat different procedures, described below.

4.6.1.1 Groundwater Protection

The RATL concentrations for groundwater ingestion are equivalent to the federal MCLs or a risk-based calculated equivalent. MCLs are health-protective target concentrations promulgated by the EPA and adopted by the state of Idaho for the protection of drinking water and specified groundwater resources. For any petroleum COI that has an MCL, the RATL concentration for groundwater ingestion is equal to the MCL. For any petroleum COI that does not have an MCL, the risk-based equivalent level is calculated using the following input values and equations:

- A target risk level of 1×10^{-6} for carcinogenic effects and an HQ of 1 for noncarcinogenic effects,
- The residential exposure factors in Appendix A,
- The toxicity values in Appendix D, and
- Risk equations for the direct ingestion of water.

Calculations are made for residential receptors.

The RATL concentrations will apply at the POE. The POE will be the down-gradient property boundary, as it existed when the release occurred, or the nearest down-gradient location where a well exists or could be reasonably placed. Depending on site-specific conditions it is also possible to have multiple points of exposure.

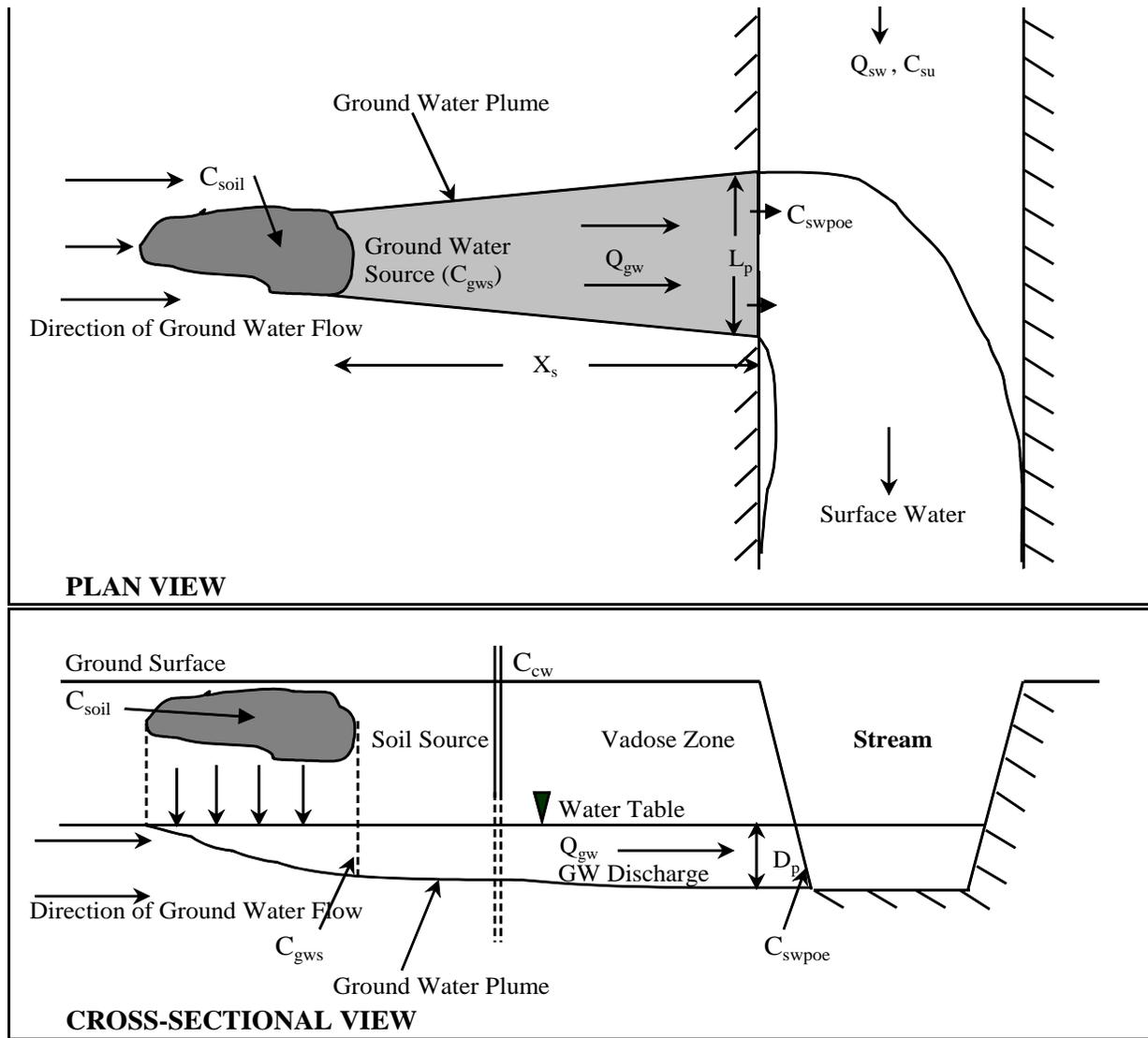
4.6.1.2 Surface Water Protection

Potential impacts to streams and other surface waterbodies from a petroleum release must be evaluated and surface water quality must be protected as per IDAPA 58.01.02 (Water Quality Standards and Wastewater Treatment Requirements). The primary receptors and ROE for potentially impacted surface waters evaluated in the RE process are described in section 4.6.1.2.1. Other ROE, such as contact with contaminated sediments or overland flow discharge, are evaluated on a case-by-case basis.

This section describes the evaluation of potential impacts to surface water via discharge of impacted groundwater to a surface waterbody. A schematic illustrating this exposure pathway is shown in Figure 3. This figure shows the relevant compliance and exposure locations and associated concentrations. Within the RE process, protection of surface waterbodies requires the owner/operator to determine or calculate the applicable surface water standards at the point where groundwater discharges into a surface waterbody (C_{swpoe}). Once the appropriate surface water standard is determined, compliance with the standard may be achieved in a number of ways. These include measuring surface water concentrations at the point of groundwater discharge, measuring groundwater concentrations at the point of discharge into the surface waterbody, or determining appropriate alternate concentrations in other media and at POC locations. Selection of alternate locations may be most appropriate for those sites where contamination has not yet reached a surface waterbody. Alternate concentrations (or RATLs) and POC locations can include:

- Source area soils (C_{soil}), or
- Compliance points in groundwater at different distances between the surface water and the source (C_{cw}) other than the point where groundwater discharges into the surface waterbody.

The owner/operator can back-calculate allowable soil (C_{soil}) and compliance well concentrations (C_{cw}) using dilution attenuation factors (DAFs). Specific equations, combining the Summer's mixing model and the Domenico analytical groundwater transport model, are presented in Appendix E. If measured concentration(s) at the soil source or the compliance well exceeds corresponding allowable concentrations, cleanup to RATL concentrations or performance of a more detailed, site-specific evaluation to refine DAFs are options.



Explanation of Symbols

- Q_{sw} = Stream flow upstream of the point of ground water discharge
- C_{su} = Concentration upstream of the ground water discharge
- Q_{gw} = Impacted ground water discharge into the stream
- C_{sw} = Allowable downstream concentration after uniform mixing
- C_{swpoe} = Allowable concentration at the point of ground water discharge to the stream
- C_{gws} = Allowable concentration in the ground water at the edge of the soil source
- C_{soil} = Allowable soil concentration at the source protective of the stream
- C_{cw} = Allowable soil concentration in ground water at different distances between the stream and the source
- L_p = Width of ground water plume discharging to the stream
- D_p = Thickness of ground water plume discharging to the stream
- X_s = Distance from the downgradient edge of the ground water source to the stream

Figure 3. Schematic of Leachate Migration from the Soil Source to the Stream

4.6.1.2.1 Surface Water Quality Standards

The allowable concentration at the point of groundwater discharge into the surface water (C_{swpoe}), or the surface water quality standard, depends on the beneficial use designations of the surface waterbody as per IDAPA 58.01.02.100 and criteria assigned to protect those beneficial uses (IDAPA 58.01.02.200-250).

Beneficial uses include:

- Aquatic life: Cold water, salmonid spawning, seasonal cold water, warm water, or modified.
- Recreation: Primary contact or secondary contact.
- Water supply: Domestic, agricultural, or industrial.

Each beneficial use has associated numerical and narrative criteria. Numerical criteria are specified values that are not to be exceeded. For narrative criteria involving toxic substances, concentrations are not specified, but must be low enough to ensure that designated beneficial uses are not impaired. When necessary, development of numeric criteria for toxic substances is governed by IDAPA 58.01.02.210.05.

The allowable concentrations for certain toxic substances associated with these beneficial uses are tabulated in IDAPA 58.01.02.210.01.b .

4.6.2 Determination of Applicable Risk Based Levels

The calculated allowable RATL concentrations for protection of groundwater and/or surface water and those calculated for other potentially complete exposure pathways are compared to determine which media-specific concentrations will guide the cleanup. Typically, the lower of these concentrations will be selected.

Using groundwater as an example, target POE concentrations will be based on the most limiting concentrations determined from evaluation of the complete or potentially complete pathways in addition to the groundwater ingestion pathway. These pathways may include indoor inhalation of vapors volatilized from groundwater, groundwater impacts to surface water, impacts to deeper groundwater systems with the potential for use as drinking water supplies, and also incidental ingestion of and dermal exposure from irrigation water. Also included is potential impairment of other beneficial uses of groundwater such as for agricultural or industrial water supplies.

The applicable POE will be based on the location of the plume (on-site vs. off-site) and which pathway(s) and receptors are limiting with respect to risk and allowable groundwater concentration. In many cases, particularly if a plume has migrated off-site, there may be multiple POE and pathways that will need to be considered.

For example, a petroleum-sourced volatile organic compound (VOC) plume may have migrated off-site into a residential area and have the potential to discharge to a down-gradient stream. Source area groundwater concentrations on-site must be controlled such that concentrations at the POE where groundwater discharges to the stream meet applicable criteria. In addition, unless vapor intrusion has been separately addressed, such as through the use of soil vapor, residential

vapor intrusion criteria in groundwater would need to be met at the down-gradient boundary of the source property and commercial criteria for on-site POE.

4.7 Deliverables

The primary deliverables associated with conducting a site-specific RE typically include an optional work plan for the collection and evaluation of data, an optional data collection report, and the required RE report. In many cases, the results of a data collection effort are combined with the RE report. If the results of the RE report indicate the need for corrective action, a CAP must also be developed and submitted. The contents of CAPs are discussed in Section 5. This section describes the contents of a work plan.

4.7.1 Work Plan

A work plan may be desirable where extensive data collection activities or significant departures from default exposure assumptions or modeling are being proposed.

As appropriate, a work plan to fill identified data gaps may be prepared and submitted to DEQ for review. The amount of detail to be included in the work plan will vary among sites. At sites where a considerable amount of data has already been collected, the work plan may be a brief letter indicating activities to be performed to fill in the data gaps. For a complex or large site, a very detailed work plan, including the SCM, data collection methodology, analysis methods, a data QAPP, and a health and safety plan may need to be developed.

An RE work plan should address each item discussed in sections 4.7.1.1 through 4.7.1.11 as appropriate to the purpose and goals of the RE.

4.7.1.1 Purpose and Goals

The purpose and goals of the work plan should be clearly stated. If the purpose is to fill data gaps, then a listing and description of the data gaps should be provided along with an explanation as to why they constitute data gaps and how the work proposed will fill those gaps.

If the purpose of the work plan is to propose use of alternative models, exposure factors, physical and chemical properties, toxicity factors, or methods of calculating remedial target concentrations, then a rationale should be provided as to why the alternatives proposed are needed. A short description of the scope and nature of the work proposed should be provided.

4.7.1.2 Site Background

This portion of the work plan may refer to documents previously submitted to DEQ; it is not necessary to repeat the entire site background description. Reference should be made to document(s) that contain a comprehensive chronology of site investigations.

4.7.1.3 Site Conceptual Model

A concise summary of the existing SCM should be provided. In those cases where the goal of the work plan is to revise a previously completed RE, then an SCM already exists that can be referenced rather than repeated. If validation or revision of a previous SCM is necessary, those

aspects of the current SCM that are the target of the work plan should be described. Refer to section 4.1 for the suggested content of the SCM.

4.7.1.4 Exposure Factors

If alternate exposure factors values are proposed in the work plan these factors must be justified and acceptable to DEQ. The default exposure factor values are listed in Appendix A.

4.7.1.5 Physical and Chemical Properties

Owner/operators should use the default physical and chemical properties for the petroleum COIs as listed in Appendix C.

4.7.1.6 Toxicity

The Rule specifies that toxicity values for petroleum chemicals listed in Appendix D must be used in the RE.

If additional chemicals need to be included in the RE, as provided for in Section 100.02 of the Rule, their physical chemical properties and toxicity values should be obtained from the EPA RSL website (EPA, 2018).

4.7.1.7 Fate and Transport Models

If alternative models are being proposed, the work plan should include reasons for using alternative models; it should demonstrate that the proposed models will better simulate site-specific conditions, and that the sufficient site-specific data are available or will be collected to justify the use of the proposed model. Alternative models must be approved by DEQ before they are used.

4.7.1.8 Fate and Transport Parameters

Data collection may be proposed to collect site-specific values in lieu of using DEQ default values for fate and transport parameters (listed in Appendix B) used in models for the RE. The parameters for which values are to be obtained should be specified and the methodology used to obtain those values described.

DEQ accepts the use of chemical-specific biological decay rates or attenuation factors in the fate and transport models. Use of decay rates in a RE must use values supported by site-specific information. Refer to Appendices G and H for data necessary to demonstrate occurrence of natural attenuation and methods to calculate decay rates. Examples of this type of information include, but are not limited to:

- Consistent stable or decreasing concentration (above the Residential Use Screening Levels [RUSLs]) trends in properly located and constructed monitoring wells, and
- Measurements of natural attenuation parameters that provide evidence of biodegradation.

4.7.1.9 Calculating RATL Concentrations

The process of calculating target concentrations (RATLs) is described in section 4.6 and Appendix F. If a method of apportioning risk and calculating RATLs different than the DEQ

default method is desired, the proposed methodology and rationale for the choice should be described.

4.7.1.10 Methodology and Quality Control

Work plans in support of data collection efforts should describe the methodology that will be used to obtain the data and provide a clear description of the level of data quality required to meet the stated objectives, and how this data quality will be achieved and ensured.

4.7.1.11 Schedule and Deliverables

The optional work plan should include an overall project schedule and deliverables that will be submitted to DEQ. The schedule should include any agency meetings necessary during work plan implementation.

4.7.2 Implementing the Work Plan

Upon receipt of a work plan approval, the owner/operator should implement the work plan according to the schedule in the work plan. In case there are delays, it is the owner/operator's duty to inform DEQ of the delay and revised schedule. If there were deviations in the work performed from that specified in the approved work plan, DEQ should be notified of the deviations and their impact on the goals and purposes of the work plan.

Upon completion of work specified in the work plan, the owner/operator should document the results and submit them to DEQ. If the purpose of the work plan included data collection, the data collection results can be summarized in a separate data collection report or incorporated into a revised RE report.

4.7.3 Risk Evaluation Report

The RE for a site must be clearly and concisely documented and submitted to DEQ for review. An example outline of an RE report is presented in Appendix J.

Section 5. Developing and Implementing Corrective Action Plans

Development and implementation of a CAP may be necessary if, after the screening level evaluation or site-specific RE, concentrations exceed screening levels or an unacceptable risk is identified and the owner/operator has chosen not to perform additional evaluation. The owner/operator must then develop cleanup criteria (also referred to as remediation standards) and create a CAP to achieve those standards or to ensure that the remaining risk is acceptable. The risk management strategy described in the CAP depends on the results of the RE (which pathways, petroleum chemicals, and media are responsible for the unacceptable risk) and other circumstances unique to the site.

5.1 Contents of a Corrective Action Plan

As required in the Rule, the CAP must include:

- A description of remediation standards selected, points of exposure, and points of compliance,
- A description of the remedial strategy and actions to be taken to achieve the remediation standards,
- Current and future land use and use of groundwater and surface water both onsite and offsite,
- AULs that will be required as part of the remedial strategy and the associated environmental covenants,
- Estimated timeline for completion of remedial actions,
- The monitoring plan to gauge effectiveness of the remedial strategy, and
- A description of practical quantitation limits and background concentrations as they apply to the remediation.

Additional elements that should also be a part of the plan include:

- A brief site description,
- A brief description of the RE approved by DEQ, including assumptions used for receptors and land use, and a list of approved cleanup levels for specific pathways, media, chemicals, and specific areas of the site (if applicable),
- A clear description of reasons a CAP is needed,
- An identification of the area(s) to be managed under the CAP,
- A description of the strategy selected to achieve cleanup goals, including a comparison and evaluation of remedial alternatives considered in development of the overall strategy. A rationale for the strategy selected should be presented; any data collected in support of or to determine the feasibility of a particular remedial measure such as pilot testing, should be presented,
- A description of what QA/QC measures will be implemented to ensure that data collected in support of remedial decision making is of adequate quality,
- A description of project closure requirements, and
- A reporting schedule to document progress of the corrective action.

5.2 Implementing a Corrective Action Plan

The CAP should not be implemented until approved by DEQ. Within 30 days of receiving a CAP, DEQ must provide an approval, an approval with modifications, or a rejection (specifying reasons for the rejection) in writing. Provisions are made in the Rule (Section 200.04) for extending this timeframe.

While DEQ is reviewing the CAP, implementation of interim corrective action measures may take place. However, as provided in IDAPA 58.01.02.852.06.c, owner/operators may, in the interest of minimizing environmental contamination and promoting more effective cleanup, begin cleanup of soil, surface water, and groundwater before the CAP is approved provided that they fulfill certain conditions including:

- Notifying DEQ of their intention to begin cleanup;
- Compliance with any conditions imposed by DEQ, including halting cleanup or mitigating adverse consequences from cleanup activities; and

- Incorporation of these self-initiated cleanup measures in the CAP that is submitted to DEQ for approval.

Typical interim corrective actions include excavating and disposing contaminated soil, removing free product, extracting soil vapor, and pumping and treating groundwater.

Upon approval of the CAP, the owner/operator must implement the plan according to the proposed schedule. All performance data should be submitted to DEQ in a timely manner. This data should be carefully evaluated by both the owner/operator and DEQ to determine if the CAP is progressing as anticipated. Major deviations in schedule or plan implementation should be communicated to DEQ for review and approval well in advance of proposed implementation, along with recommended modifications if necessary. The specific modifications that may be needed will vary from site to site.

When the CAP has been successfully implemented, the owner/operator should document these conditions in a completion report along with a petition to DEQ for site closure.

Section 6. Activity and Use Limitations

An AUL is a restriction or obligation, with respect to real property, that is created by an Environmental Covenant pursuant to the Uniform Environmental Covenants Act (UECA), Chapter 30, Title 55, Idaho Code. It is available at:

<http://legislature.idaho.gov/idstat/Title55/T55CH30.htm>

The purpose of AULs is to reduce the potential for exposure to contaminants at a release site. AULs are also commonly referred to as “institutional controls.” AULs are typically proposed to DEQ for approval through the RE process. Non-remedial land use restrictions (e.g., local zoning ordinances) may reinforce the sustainability of AULs; however, they are not considered sufficient by themselves. These types of non-remedial land use restrictions, such as zoning ordinances, may change or be removed without DEQ approval and therefore are not approved by DEQ as part of a CAP. However, non-remedial land use restrictions may be relevant to evaluating current and reasonably likely future use and exposure scenarios at a site.

6.1 Environmental Covenants

Owner/operators may propose an Environmental Covenant as part of the CAP which will include the AUL language. Any proposed Environmental Covenant must be consistent with UECA. Each proposed Environmental Covenant is reviewed and evaluated on a site specific basis.

Following is a *non-exclusive* list of the types of activity and use limitations that may be included in an Environmental Covenant:

- Restrictions on Water Use:
 - Prohibit use
 - Limit use
 - Monitor use
 - Report use
 - Operation and maintenance procedures for physical controls and devices
 - Prohibit well installation and operation
 - Abandon an existing well.
- Restrictions on Land Use:
 - Prohibit, or require DEQ approval for, disturbance of soil, cap, or vegetation
 - Limit activities and land use
 - Limit structures and buildings.
- Actions Regarding Access:
 - Right of Access necessary to implement the activity and use limitation
 - Limit or deny public access.
- Obligations to perform certain actions in order to maintain the effectiveness of an approved corrective action. For example, this may involve the need to do periodic inspections and maintenance in order to ensure that a cover or barrier retains its primary

function. In this case there might be a specific reference in the Environmental Covenant to an Operations and Maintenance Plan, developed as part of the corrective action.

DEQ has an Environmental Covenant template that owner/operators can use when proposing activity and use limitations as part of a CAP. The DEQ website includes a copy of the latest Environmental Covenant template at <http://www.deq.idaho.gov/environmental-covenants>. The owner/operator can propose an environmental covenant consistent with UECA for consideration and approval by DEQ.

6.2 Specific Application of Activity and Use Limitations at Petroleum Release Sites

Section 600.01 of the Rule outlines the circumstances under which AULs will be included as part of a CAP. These include:

- Where the assumed onsite land use for the purpose of the RE is not residential and either the maximum media concentrations exceed the screening levels or the calculated risk for a residential receptor is unacceptable
- Where off-site groundwater concentrations exceed RUSLs or risk-based concentrations, and
- Where DEQ determines, based on the proposed CAP, that such AULs are required to assure the continued protection of human health and the environment or the integrity of the cleanup action.

6.3 Use of Activity and Use Limitations at Impacted Neighboring Properties

Implementability and enforceability issues become more complicated when an owner/operator proposes use of AULs on impacted neighboring properties. It is the owner/operators' obligation to negotiate language and reach agreement with both the impacted property owner and DEQ.

6.4 Non-Remedial Land Use Restrictions

Non-remedial land use restrictions (e.g., local zoning ordinances) may reinforce the sustainability of AULs; however, they are not considered sufficient by themselves. These types of non-remedial land use restrictions, typically implemented by other governmental agencies, may change or be removed without DEQ approval and therefore are not approved by DEQ as part of a CAP. The presence of such non-remedial restrictions may be relevant when determining the current and likely future uses of impacted properties.

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Appendix A: Default Exposure Factors

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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 2011) that Americans are getting heavier, and currently the actual average adult body weight is 80 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 2011). 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. These exposure times are used in the inhalation portion of the direct contact equations used to derive screening levels and risk.

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 2004). 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 2004). 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 2004).

Table 1. Default Exposure Factors

Exposure Parameter	Symbol	Units	Default Value	Reference
Averaging Time (AT)				
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)
Body Weight (BW)				
Child	BWc	kg	15	EPA 1991a (p. 15)
Adult	BWa	kg	70	EPA 1991a (p. 15)
Exposure Duration (ED)				
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)
Exposure Frequency (EF)				
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
Exposure Frequency for Direct Contact Pathways (EF)				
Resident	EFres	days/yr	270	Professional judgment
Nonresidential Worker	EFd	days/yr	180	Professional judgment
Construction Worker	EFd	days/yr	30	Professional judgment
Soil Ingestion Rate (IR)				
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)
Daily Water Ingestion Rate (IRw)				
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 Time for Inhalation (ET)				
Resident (child)	ETo-c	hr/day	Outdoor: 2 Indoor: 24	EPA 1997 (p. 15-17)

Exposure Parameter	Symbol	Units	Default Value	Reference
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
Oral Relative Absorption Factor (RAF)				
Oral Relative Absorption Factor	RAFo	—	Assume 100%	EPA 2004 (p. 4-2)
Dermal Relative Absorption Factor (RAF_d)				
Volatile organic compounds	RAF _d	—	0	EPA 2004 (pg. 3-18)
Benzo(a)pyrene and other polynuclear aromatic hydrocarbons	RAF _d	—	0.13	EPA 2004 (Exhibit 3-4)
Soil-to-Skin Adherence Factor (M)				
Residential (child)	Mc	mg/cm ²	0.2	EPA 2004 (p.3-14)
Residential (adult)	Ma	mg/cm ²	0.07	EPA 2004 (p. 3-14)
Nonresidential Worker	M	mg/cm ²	0.2	EPA 2004 (p. 3-17)
Construction Worker	M	mg/cm ²	0.3	EPA 2004 (Exhibit 3-3)
Skin Surface Area for Dermal Contact with Soil (SA)				
Child Receptors	SAC	cm ² /day	2800	EPA 2004 (Exhibit 3-5)
Adult Receptors	SAA	cm ² /day	5700	EPA 2004 (Exhibit 3-5)
Nonresidential Worker Receptors	SA	cm ² /day	3300	EPA 2004 (Exhibit 3-5)
Construction Worker Receptors	SA	cm ² /day	3300	EPA 2004 (Exhibit 3-5)

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.

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Appendix B: Default Fate and Transport Parameter Values

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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 screening 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 simulations were run until steady-state conditions were achieved, and the moisture content at that time was noted. These values ($0.17 \text{ cm}^3/\text{cm}^3$, low precipitation, and $0.20 \text{ cm}^3/\text{cm}^3$, high precipitation) are consistent with field capacity (0.33 bar) moisture content values for sandy loam texture class soils presented by Rawls et al. (1982).

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.

The default value for fractional organic carbon content in the vadose zone (0.001) was selected from the statistical analysis of national soil survey data by Carsel et al. (1988). It represents the median value for subsoils with sandy loam textures.

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. For structures with finished basements, reasonable values for basement depth below grade of 200 cm and height of enclosed space of 366 cm (EPA 2003) can be assumed. Structures with crawl spaces are not as readily characterized because of the common occurrence of earthen floors and variable size and ventilation. 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 this area were one story. A slab-on-grade foundation and indoor building height of 8 feet were assumed. These values can be modified during the development of a site-specific evaluation to accommodate actual structure conditions.

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 ^a	Default Value	Reference
Soil Parameters				
<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 ²	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 _{unsat}	—	1	No attenuation in the unsaturated zone is assumed to occur.
Total soil porosity in the vadose zone	θT	cm ³ /cm ³ -soil	0.39	EPA 2003
Volumetric water content in vadose zone	θ _{ws}	cm ³ /cm ³	0.17	Professional judgment, see discussion
Volumetric air content in vadose zone	θ _{as}	cm ³ /cm ³	0.22	Calculated
Dry soil bulk density	ρ _s	g/cm ³	1.64	Nielson and Rogers 1990; Hers 2002
Fractional organic carbon content in the vadose zone	foc	g-C/g-soil	0.001	Carsel et al. 1988
Volumetric water content in the foundation/wall cracks	θ _{wcrack}	cm ³ /cm ³	0.17	Assumed equal to that in the adjacent soil
Volumetric air content in the foundation/wall cracks	θ _{acrack}	cm ³ /cm ³	0.22	Calculated
Volumetric water content in capillary fringe zone	θ _{wcap}	cm ³ /cm ³	0.32	EPA 2003
Volumetric air content in capillary fringe zone	θ _{acap}	cm ³ /cm ³	0.07	EPA 2003
<i>Saturated Zone Soil</i>				
Dry soil bulk density	ρ _{ss}	g/cm ³	1.64	Nielson and Rogers 1990; Hers 2002
Fractional organic carbon content	focs	g-C/g-soil	0.001	Professional judgment, see discussion
Total soil porosity	θTs	cm ³ /cm ³ -soil	0.39	Nielson and Rogers 1990; Hers 2002

Parameter	Symbol	Units ^a	Default Value	Reference
Volumetric water content	θ_{wss}	cm ³ /cm ³	0.39	Equivalent to total porosity
Volumetric air content	θ_{ass}	cm ³ /cm ³	0.0	
Air Property				
Viscosity of air		g/cm-sec	1.8E-4	
Ground Water Parameters				
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	δ_{gw}	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
Enclosed Space Parameters				
<i>Area of the Enclosed Space Below Grade</i>				
Residential—Slab on Grade	AB	cm ²	1488400	Calculated
Residential—Basement	AB	cm ²	2464400	Calculated
Nonresidential	AB	cm ²	4652649	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 ²	744	Calculated
Nonresidential	Acrack	cm ²	2326	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

Parameter	Symbol	Units ^a	Default Value	Reference
<i>Width of Enclosed Space</i>				
Residential	WB	cm	1220	DOE 1995
Nonresidential	WB	cm	2157	DOE 2001
<i>Height of Enclosed Space</i>				
Residential—Slab on Grade	HB	cm	244	EPA 2003
Residential—Basement	HB	cm	366	EPA 2003
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 ²	40	EPA 2003
Cowherd Particulate Emission Model				
Inverse of the mean concentration at the center of a square source	Q/C	(g/m ² -sec)/(kg/m ³)	69.41	EPA 1996
Fractional vegetative cover	V	m ² /m ²	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
Averaging Time For Vapor Flux				
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
Ground Water Protection				
Distance to the point of exposure	Xpoe	cm	0	Professional judgment
Distance to the point of compliance	Xpoc	cm	0	Professional judgment

^a cm = centimeters; g = grams; C = carbon; m = meters; sec = seconds; kg = kilograms

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Appendix C: Default Physical and Chemical Properties

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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) ^a	Diffusion Coefficient in Air (square centimeters/second)	Diffusion Coefficient in Water (square centimeters/second)
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	9.5E+01	0.09	1.0E-05
Benzo(a)anthracene	56-55-3	228.3	0.0094	4.9E-04	176900	1.1E-07	0.026	6.7E-06
Benzo(a)pyrene	50-32-8	252.3	0.0016	1.9E-05	587400	5.5E-09	0.048	5.6E-06
Benzo(b)fluoranthene	205-99-2	252.3	0.0015	2.7E-05	599400	5.0E-07	0.048	5.6E-06
Benzo(k)fluoranthene	207-08-9	252.3	0.0008	2.4E-05	587400	9.6E-11	0.048	5.6E-06
Chrysene	218-01-9	228.3	0.002	2.1E-04	180500	6.3E-09	0.026	6.7E-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	1.1E+01	0.043	1.0E-05
Fluoranthene	206-44-0	202.3	0.26	3.6E-04	55450	5.0E-06	0.028	7.2E-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	2.49E+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	2.7E-01	383	8.8 E+00	0.069	8.5E-06

Note: Values for physical and chemical properties (with the exception of vapor pressure) are taken from the U.S. Environmental Protection Agency regional screening levels website (accessed May 2018) chemical specific parameter supporting table

^a 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).

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Appendix D: Default Toxicity Values

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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 2018:

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 dermal relative absorption factors for volatile organic compounds based on the rationale that these compounds would tend to be volatilized from the soil on skin. Based on this rationale, the dermal relative absorption factors for volatile organic compounds is assumed to be zero.

Chemicals	CAS Number	Oral Slope Factor (kg-day/mg) ^a	Unit Inhalation Risk (µg/m ³) ^b	Oral Reference Dose (mg/kg-day) ^c	Inhalation Reference Concentration (mg/m ³) ^d	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	0.1	1.1E-4	NA	NA	1	0.13
Benzo(a)pyrene	50-32-8	1	1.1E-3	0.0003	NA	1	0.13
Benzo(b)fluoranthene	205-99-2	0.1	1.1E-4	NA	NA	1	0.13
Benzo(k)fluoranthene	207-08-9	0.01	1.1E-4	NA	NA	1	0.13
Chrysene	218-01-9	0.001	1.1E-5	NA	NA	1	0.13
1,2-Dichloroethane	107-06-2	9.1E-2	2.6E-5	6.0E-3	7.0E-3	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

^a kg-day/mg = kilogram-day per milligram

^b µg/m³ = microgram per cubic meter

^c mg/kg-day = milligram per kilogram-day

^d mg/m³ = milligram per cubic meter

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Appendix E: Models and Equations

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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 [mg/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 [mg/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

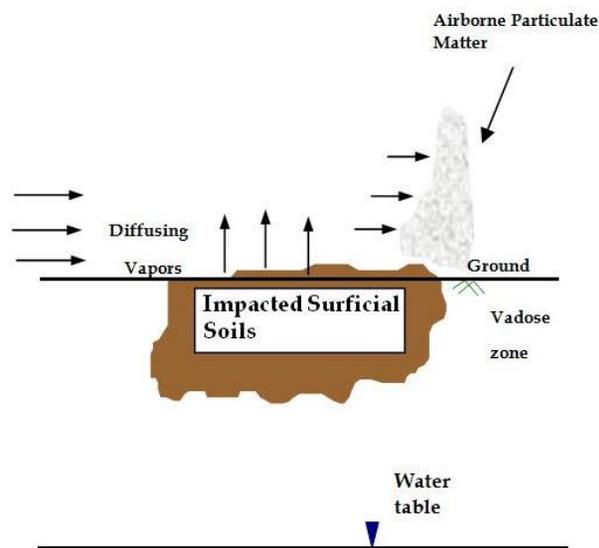
Carcinogenic effects

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

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 [(m³-air)/(kg-soil)]
- PEF = Particulate emission factor [(m³-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/m³]
- IUR = Chemical-specific inhalation unit risk [(μg/m³)⁻¹]
- 365 = Conversion factor [days/year]

1.3 Direct Ingestion of Surficial Soil

Carcinogenic effects

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

Noncarcinogenic effects

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

Where:

- RBTLs* = 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)]⁻¹
 365 = Conversion factor [days/year]
 10⁻⁶ = 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

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

Source: Modified from EPA 1989, p. 6-41; See also EPA 2007, Appendix D, p. D-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 [cm²/day]
 M = Soil to skin adherence factor [mg/cm²]
 RfD_o = Chemical-specific oral reference dose [mg/(kg-day)]
 SF_o = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]⁻¹
 365 = Conversion factor [days/year]
 10^{-6} = Conversion factor [kg/mg]

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

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

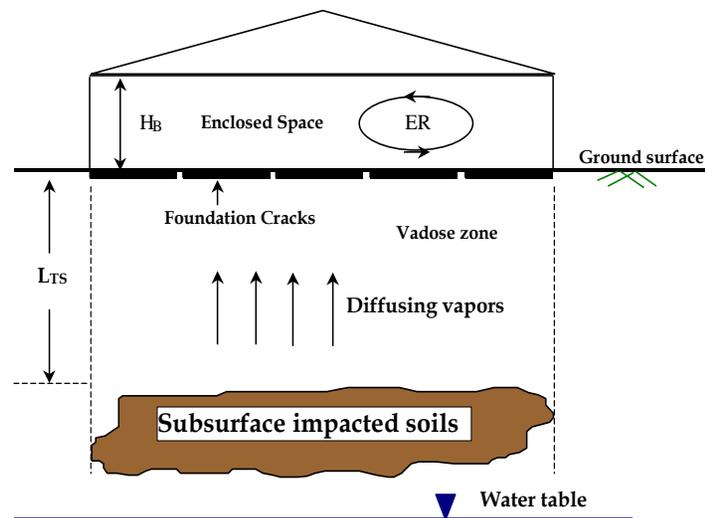
Where:

- $RBTL_{si}$ = 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^3 -air]
 α = Chemical-specific 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:

- ρ_s = Dry soil bulk density [g-soil/ cm^3 -soil]
 H = Chemical-specific Henry's Law constant [(L- H_2O)/(L-air)]
 θ_{as} = Volumetric air content in the vadose zone soils [cm^3 -air/ cm^3 -soil]
 θ_{ws} = Volumetric water content in vadose zone soils [cm^3 - H_2O / cm^3 -soil]
 K_D = $f_{oc} \times K_{oc}$ = Chemical-specific soil-water sorption coefficient [cm^3 - H_2O /g-soil]



1.7 Ground Water Concentrations Protective of Indoor Vapor Inhalation

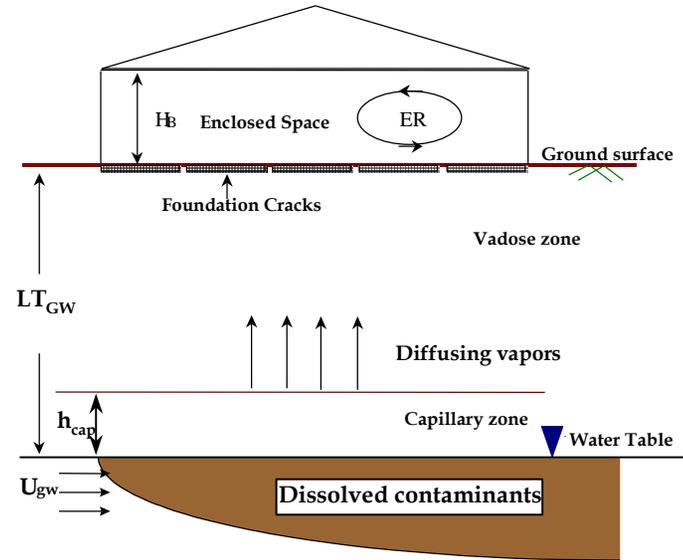
$$RBTL_{wi} = \frac{RBTL_{ai} * EF}{\alpha}$$

Where:

- $RBTL_{wi}$ = Risk-based target level for indoor inhalation of vapors from ground water [mg/L-H₂O]
- $RBTL_{ai}$ = Risk-based target level for indoor inhalation of air (mg/m³-air)
- α = Chemical-specific 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)*0.001m³/L

Where:

H = Henry's Law Constant [-]



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-H₂O]
 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)]⁻¹
 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

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

$C_{building}$ = Steady-state vapor-phase concentration in the building [mg/L]

α = 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-H₂O)/(L-air)]

ρ_s = Dry soil bulk density [g-soil/cm³-soil]

θ_{ws} = Volumetric water content in vadose zone soils [cm³-H₂O/cm³-soil]

K_d = $f_{oc} \times K_{oc}$
= Chemical-specific soil-water sorption coefficient [cm³-H₂O/g-soil]

θ_{as} = Volumetric air content in vadose zone soils [cm³-air/cm³-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 [cm²/s]

D_{crack}^{eff} = Effective diffusion coefficient through cracks [cm²/s]

A_B = Area of the enclosed space below grade [cm²]

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

L_T = Source-building separation [cm]

Q_{soil} = Volumetric flow rate of soil gas into the enclosed space [cm³/s]

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

A_{crack} = Total area of cracks [cm²]

1.9 Johnson and Etinger 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 ³ /s]
L_B	=	Length of building [cm]
W_B	=	Width of building [cm]
H_B	=	Height of building [cm]
ER	=	Air exchange rate [1/s]
Q_{soil}	=	Volumetric flow rate of soil gas into the enclosed space [cm ³ /s]
π	=	3.14159
ΔP	=	Pressure differential between the soil surface and the enclosed space [g/cm-s ²]
k_v	=	Soil vapor permeability [cm ²]
X_{crack}	=	Floor-wall seam perimeter [cm]
μ	=	Viscosity of air [g/cm-s]
Z_{crack}	=	Crack depth below grade [cm]
r_{crack}	=	Equivalent crack radius [cm]
D_T^{eff}	=	Total overall effective diffusion coefficient [cm ² /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 ² /s]
n	=	Number of soil layers [-]
D_s^{eff}	=	Effective diffusion coefficient in soil [cm ² /s]
D_{ws}^{eff}	=	Effective diffusion coefficient in capillary fringe [cm ² /s]
h_{cap}	=	Thickness of capillary fringe zone [cm]
D_{cap}^{eff}	=	Effective diffusion coefficient in the capillary fringe soil [cm ² /s]
D_{crack}^{eff}	=	Effective diffusion coefficient in the foundation/wall cracks [cm ² /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:

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

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

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

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

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

Source: EPA 2003

- $C_{building}$ = Steady-state vapor-phase concentration in the building [mg/L]
- α = 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-H₂O)/(L-air)]
- ρ_s = Dry soil bulk density [g-soil/cm³-soil]
- θ_{ws} = Volumetric water content in vadose zone soils [cm³-H₂O/cm³-soil]
- K_d = $f_{oc} \times K_{oc}$
- = Chemical-specific soil-water sorption coefficient [cm³-H₂O/g-soil]
- θ_{as} = Volumetric air content in vadose zone soils [cm³-air/cm³-soil]
- ΔH_c = Initial thickness of contamination [cm]
- τ_D = Time for source depletion [seconds]
- τ = Exposure interval [seconds]
- D_T^{eff} = Total overall effective diffusion coefficient [cm²/s]
- D_{crack}^{eff} = Effective diffusion coefficient through cracks [cm²/s]
- A_B = Area of the enclosed space below grade [cm²]
- $Q_{building}$ = Building ventilation rate [cm³/s]
- L_T^0 = Source-building separation at time = 0 [cm]
- Q_{soil} = Volumetric flow rate of soil gas into the enclosed space [cm³/s]
- A_{crack} = Total area of cracks [cm²]
- 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 [mg/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 [mg/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

2.2 Outdoor Inhalation of Vapors and Particulates from Surficial Soil

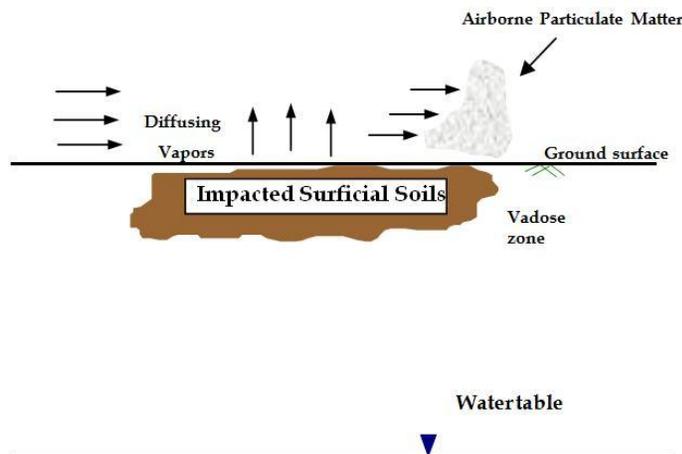
Carcinogenic effects

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

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 [(m³-air)/(kg-soil)]
- PEF = Particulate emission factor [(m³-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/(m³)]
- IUR = Chemical-specific inhalation unit risk [$\mu\text{g}/\text{m}^3$]⁻¹
- 365 = Conversion factor [days/year]

2.3 Direct Ingestion of Surficial Soil

Carcinogenic effects

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

Where:

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

Noncarcinogenic effects

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

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)]⁻¹
 IR_{s-aa} = Age-adjusted soil ingestion rate [mg-yr/kg-day]
 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]

2.4 Dermal Contact with Surficial Soil

Carcinogenic effects

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

Where:

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

Noncarcinogenic effects

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

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 [-]
- RAF_o = Oral relative absorption factor [-]
- M_c = Resident child soil-to-skin adherence factor [mg/cm²]
- M_a = Resident adult soil-to-skin adherence factor [mg/cm²]
- RfD_o = Chemical-specific oral reference dose [mg/(kg-day)]
- SF_o = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]⁻¹
- SA_{aa} = Age-adjusted skin surface area [mg-yr/ kg-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]
- SA_c = Resident child skin surface area [cm²/day]
- SA_a = Resident adult skin surface area [cm²/day]
- 365 = Conversion factor [days/year]
- 10⁻⁶ = Conversion factor [kg/mg]

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

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

Where:

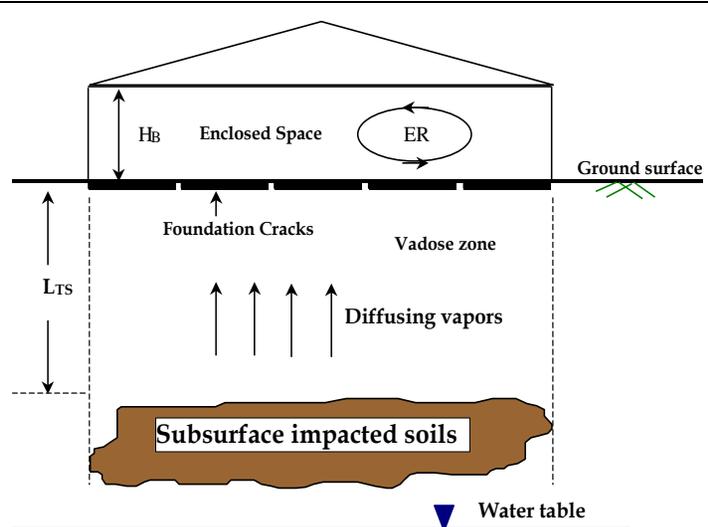
- $RBTL_{si}$ = Risk-based target level for indoor inhalation of vapors from subsurface soils [mg/kg-dry soil]
 $RBTL_{ai}$ = Risk-based target level for indoor inhalation of air [mg/m^3 -air]
 α = Chemical-specific attenuation factor from subsurface soil to indoor (enclosed space) air derived from the 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:

- ρ_s = Dry soil bulk density [$\text{g-soil}/\text{cm}^3$ -soil]
 H = Chemical-specific Henry's Law constant [(L-H₂O)/(L-air)]
 θ_{as} = Volumetric air content in the vadose zone soils [cm^3 -air/ cm^3 -soil]
 θ_{ws} = Volumetric water content in vadose zone soils [cm^3 -H₂O/ cm^3 -soil]
 K_D = $f_{oc} \times K_{oc}$ = Chemical-specific soil-water sorption coefficient [cm^3 -H₂O/g-soil]

Source: Modified from EPA 2003



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-H₂O]

$RBTL_{ai}$ = Risk-based target level for indoor inhalation of air (mg/m³-air)

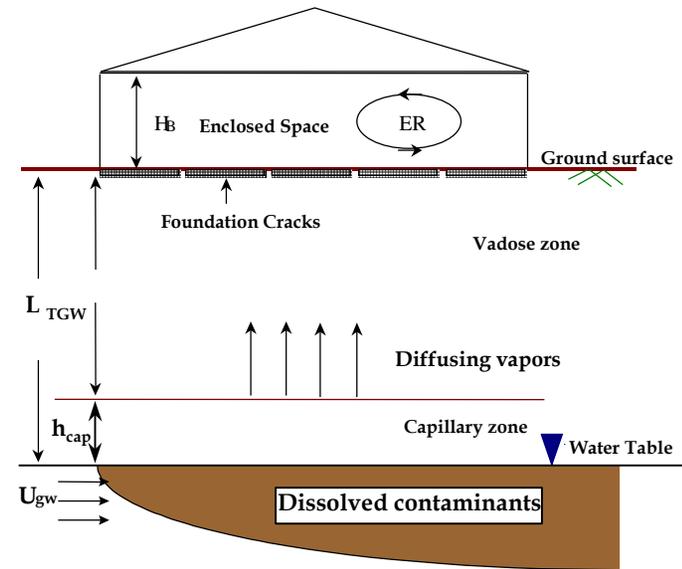
α = Chemical-specific attenuation factor from ground water to indoor (enclosed space) air derived from the Johnson-Ettinger model [-]

EF = Equilibrium factor to convert vapor target level to water target level

$$= (1/H) * 0.001 \text{m}^3/\text{L}$$

Where:

H = Henry's Constant [-]



Source: Modified from EPA 2003

2.8 Direct Ingestion of Ground Water

Carcinogenic effects

$$RBTL_{w-adj} = \frac{TR \times AT_c \times 365}{IR_{w-aa} \times SF_o}$$

Where:

$$IR_{w-aa} = \frac{ED_c \times EF_{res} \times IR_{w-c}}{BW_c} + \frac{ED_a \times EF_{res} \times IR_{w-a}}{BW_a}$$

Noncarcinogenic effects

$$RBTL_w = \frac{THQ \times AT_{nc} \times 365 \times RfD_o \times BW_a}{IR_{w-a} \times EF_{res} \times ED_a}$$

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

Where:

- $RBTL_{w-adj}$ = Age-adjusted risk-based target level for ingestion of ground water [mg/L-H₂O]
- $RBTL_w$ = Risk-based target level for ingestion of ground water [mg/L-H₂O]
- 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]
- RfD_o = Chemical-specific oral reference dose [mg/(kg-day)]
- SF_o = Chemical-specific oral cancer slope or potency factor [mg/(kg-day)]⁻¹
- IR_{w-aa} = Age-adjusted ground water ingestion rate [L/kg]
- IR_{w-c} = Resident child ground water ingestion rate [L/day]
- IR_{w-a} = Resident adult ground water ingestion rate [L/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]
- EF_r = Exposure frequency for a resident [days/year]
- 365 = Conversion factor [days/year]

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:

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

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]
- α_x = Longitudinal dispersivity [m] ($\alpha_x = x/10$)
- α_y = Lateral dispersivity [m] ($\alpha_y = x/30$)
- α_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]
- δ_{gw} = Ground water mixing zone thickness [m]
- DAF = C/C_o

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:

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

Where:

- U_{gw} = ground water Darcy velocity [m/s]
- R = retardation factor in the saturated zone [-]
- θ_T = 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-H₂O)/mg/kg-soil]
- $DAF_{Summers}$ = Dilution attenuation factor in the mixing zone [-]
- $K_{Water-soil}$ = Water-soil partitioning coefficient [(mg/kg-soil)/(mg/L-H₂O)]
- ρ_s = Dry soil bulk density [g-soil/cm³-soil]
- θ_{ws} = Volumetric water content in vadose zone soils [cm³-H₂O/cm³- soil]
- K_d = $f_{oc} \times K_{oc}$
= Chemical-specific soil-water sorption coefficient [cm³-H₂O/g-soil]
- H = Chemical-specific Henry's Law constant [(L-H₂O)/(L-air)]
- θ_{as} = Volumetric air content in the vadose zone soils [cm³-air/cm³-soil]
- U_{gw} = Ground water Darcy velocity [cm/yr]
- δ_{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-H₂O]
 ρ_s = Dry soil bulk density [g-soil/cm³-soil]
 H = Chemical-specific Henry's Law constant [(L-H₂O)/(L-air)]
 θ_{as} = Volumetric air content in the vadose zone soils [cm³-air/cm³-soil]
 θ_{ws} = Volumetric water content in vadose zone soils [cm³-H₂O/cm³-soil]
 K_d = $f_{oc} \times K_{oc}$
 = Chemical-specific soil-water sorption coefficient [cm³-H₂O/g-soil]

Source: ASTM 1995

3.4 Soil and Ground Water Concentration for Ground Water Protection

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

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

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

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:

ρ_{ss} = Dry soil bulk density of the saturated zone soil [g-soil/cm³-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 [-]

θ_{TS} = Total soil porosity in the saturated zone [cm³/cm³-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 [(m³-air)/(kg-soil)]
- Q/C = Inverse of the mean concentration at the center of square source [cm²/s]
- D_A = Apparent diffusivity [cm²/s]
- τ = Averaging time for vapor flux [s]
- ρ_s = Dry soil bulk density [g-soil/cm³-soil]
- K_d = Chemical-specific solid-water sorption coefficient [cm³-H₂O/g-soil]
- D^a = Chemical-specific diffusion coefficient in air [cm²/s]
- D^w = Chemical-specific diffusion coefficient in water [cm²/s]
- θ_T = Total soil porosity in the impacted zone [cm³/cm³-soil]
- θ_{as} = Volumetric air content in the vadose zone soils [cm³-air/cm³-soil]
- θ_{ws} = Volumetric water content in the capillary fringe soils [cm³-H₂O/cm³-soil]
- H = Chemical-specific Henry's Law constant [(L-H₂O)/(L-air)]
- 10^{-4} = Conversion factor [m²/cm²]

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 [(m³-air)/(kg-soil)]
Q/C = Inverse of the mean concentration at the center of square source [(g/m²-s)/(kg/m³)]
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 [m²-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 [cm²/s]
D^a = Chemical-specific diffusion coefficient in air [cm²/s]
D^w = Chemical-specific diffusion coefficient in water [cm²/s]
θ_{as} = Volumetric air content in capillary fringe soils [cm³-air/cm³-soil]
θ_{ws} = Volumetric water content in capillary fringe soils [cm³-H₂O/cm³-soil]
θ_T = Total soil porosity in the impacted zone [cm³/cm³-soil]
H = Chemical-specific Henry's Law constant [(L-H₂O)/(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 [cm²/s]
- h_{cap} = Thickness of capillary fringe [cm]
- D_{cap}^{eff} = Effective diffusion coefficient through capillary fringe [cm²/s]
- D_s^{eff} = Effective diffusion coefficient in soil based on vapor-phase concentration [cm²/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 [cm²/s]
- D^a = Chemical-specific diffusion coefficient in air [cm²/s]
- D^w = Chemical-specific diffusion coefficient in water [cm²/s]
- θ_{acap} = Volumetric air content in capillary fringe soils [cm³-air/cm³-soil]
- θ_{wcap} = Volumetric water content in capillary fringe soils [cm³-H₂O/cm³-soil]
- θ_T = Total soil porosity [cm³/cm³-soil]
- H = Chemical-specific Henry's Law constant [(L-H₂O)/(L-air)]

Source: ASTM 1995

4.3.4 Effective Diffusion Coefficient In Foundation/Wall Cracks

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

Where:

- D_{crack}^{eff} = Effective diffusion coefficient through foundation cracks [cm^2/s]
- D^a = Chemical-specific diffusion coefficient in air [cm^2/s]
- D^w = Chemical-specific diffusion coefficient in water [cm^2/s]
- θ_{acrack} = Volumetric air content in foundation/wall cracks [$\text{cm}^3\text{-air}/\text{cm}^3\text{-total volume}$]
- θ_{wcrack} = Volumetric water content in foundation/wall cracks [$\text{cm}^3\text{-H}_2\text{O}/\text{cm}^3\text{-total volume}$]
- θ_r = Total soil porosity [$\text{cm}^3/\text{cm}^3\text{-soil}$]
- H = Chemical-specific Henry's Law constant [(L-H₂O)/(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:

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

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

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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 1×10^{-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 _{site} = SUM(SUM)	HI _{site} = 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:**Error! Objects cannot be created from editing field codes.**

$p_{i,j}$ = 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 _{site} = 8E-5	HI _{site} = 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 7×10^{-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 .

$$Risk_{i,j}^{allocated} = \frac{1 \times 10^{-5}}{6} = 1.7 \times 10^{-6}$$

$$HQ_{i,j}^{allocated} = \frac{1}{9} = 0.11$$

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-5/1.7E-6 = 6.0	N/A	2E-5/1.7E-6 = 12	N/A	—	N/A
C2	N/A	1/0.11 = 9.0	N/A	3/0.11 = 27	N/A	1/0.11 = 9.0
C3	N/A	1/0.11 = 9.0	—	1/0.11 = 9.0	N/A	3/0.11 = 27
C4	1E-5/1.67E-6 = 6.0	N/A	1E-5/1.7E-6 = 6.0	N/A	1E-5/1.7E-6 = 6.0	N/A
C5	2E-5/1.67E-6 = 12	1/0.11 = 9.0	N/A	1/0.11 = 9.0	N/A	1/0.11 = 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,

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

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 _c	RATL _{nc}	RATL _c	RATL _{nc}	RATL _c	RATL _{nc}
C1	1/6.0 = 0.17	N/A	2/12 = 0.17	N/A	—	N/A
C2	N/A	2/9.0 = 0.22	N/A	4/27 = 0.15	N/A	2/9.0 = 0.22
C3	N/A	3/9.0 = 0.33	—	6/9.0 = 0.67	N/A	3/27 = 0.11
C4	4/6.0 = 0.67	N/A	8/6.0 = 1.3	N/A	4/6.0 = 0.67	N/A
C5	5/12 = 0.42	5/9.0 = 0.56	N/A	10/9.0 = 1.1	N/A	5/9.0 = 0.56

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

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Technical Guide For Addressing Petroleum Vapor Intrusion At Leaking Underground Storage Tank Sites

U.S. Environmental Protection Agency
Office of Underground Storage Tanks
Washington, D.C.

June 2015

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Acronyms

1,2-DCA	1,2-Dichloroethane (also known as ethylene dichloride or EDC)
ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	Benzene, Toluene, Ethylbenzene, Xylenes (there are three isomers of xylene)
CFR	Code of Federal Regulations
CSM	Conceptual Site Model
EDB	Ethylene Dibromide (also known as 1,2-dibromoethane)
IUR	Inhalation Unit Risk
ILCR	Incremental Lifetime Cancer Risk
IRIS	Integrated Risk Information System
ITRC	Interstate Technology & Regulatory Council
JEM	Johnson-Ettinger Model
LNAPL	Light Non-Aqueous Phase Liquid
MTBE	Methyl Tertiary-Butyl Ether
NAPL	Non-Aqueous Phase Liquid
OIG	Office of Inspector General
OSWER	Office of Solid Waste and Emergency Response
OUST	Office of Underground Storage Tanks
PHC	Petroleum Hydrocarbon
PPRTV	Provisional Peer Reviewed Toxicity Value
PVI	Petroleum Vapor Intrusion
RBC _v	Risk-based Concentration, Soil Vapor
RfC	Reference Concentration (inhalation)
RSL	Regional Screening Level (for Chemical Contaminants at Superfund Sites)
SIM	Selective Ion Monitoring
TAME	Tertiary-Amyl Methyl Ether
TBA	Tertiary-Butyl Alcohol
TEL	Tetraethyl Lead
TMB	Trimethylbenzene
TML	Tetramethyl Lead
TPH	Total Petroleum Hydrocarbons
UST	Underground Storage Tank
VI	Vapor Intrusion
VISL	Vapor Intrusion Screening Level
VOC	Volatile Organic Compound

Disclaimer

This document presents current technical recommendations of the U.S. Environmental Protection Agency (EPA) based on our current understanding of petroleum vapor intrusion (PVI) into indoor air from subsurface sources. This document provides technical information to EPA, state, tribal, and local agencies. It also informs the public and the regulated community on how EPA intends to implement its regulations. This guidance document does not impose any requirements or obligations on the EPA, the states, or local or tribal governments, or the regulated community. Rather, the sources of authority and requirements for addressing subsurface vapor intrusion are the relevant statutes and regulations. Decisions regarding a particular situation should be made based upon statutory and regulatory authority. Decision-makers retain the discretion to adopt or approve approaches on a case-by-case basis that differ from this document. Contact information for your state's UST-implementing agency may be found at <http://www.epa.gov/oust/states/statcon1.htm>. EPA may revise this document in the future, as appropriate.

Recommendations

This document provides technical information to regulatory personnel from the U.S. Environmental Protection Agency (EPA) and state¹, tribal, and local agencies for investigating and assessing petroleum vapor intrusion (PVI) at sites where petroleum hydrocarbons (PHCs) have been released from underground storage tanks (USTs). This document is comprised of two parts: *Recommendations*, which provides a description of EPA's recommended approach for addressing PVI, and *Supporting Technical Information*, which provides detailed technical information supporting the recommendations.

Background

In 2002, EPA's Office of Solid Waste and Emergency Response (OSWER) issued draft vapor intrusion guidance, *OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Draft Vapor Intrusion Guidance)* (EPA, 2002).² This draft guidance explicitly states that it is not recommended for addressing petroleum vapor intrusion (PVI) at UST sites regulated under Subtitle I of the Solid Waste Disposal Act through the Hazardous and Solid Waste Amendments of 1984.

In 2009, EPA's Office of Underground Storage Tanks (OUST), at the request of partners and stakeholders, initiated a collaborative effort to develop a technical guide for petroleum vapor intrusion. Further highlighting the need for information on PVI, EPA's Office of Inspector General later that year released an evaluation report, *Lack of Final Guidance on Vapor Intrusion Impedes Efforts to Address Indoor Air Risks* (Report No. 10-P-0042).³ The report included recommendations, one of which was for EPA to issue final vapor intrusion guidance that incorporates information on how risks from petroleum hydrocarbon vapors should be addressed. In response to stakeholder requests, EPA's Office of Underground Storage Tanks developed this technical guide, which is a companion to OSWER's more general vapor intrusion guide.⁴ Together, these two documents replace the 2002 Draft Vapor Intrusion Guide.

EPA developed the two guides to address different scenarios and meet the needs of different audiences. The UST program regulates a very large universe of sites, typically gas stations, which share many similar characteristics, including small release volumes (compared to pipelines and tank farms, for example) and the potential for aerobic biodegradation of petroleum vapors. Based on these facts, and to meet the request of UST regulators and practitioners, EPA developed a guide specifically focused on petroleum UST releases. This PVI guide provides screening criteria based on physical separation distances between vapor sources and potential receptors. EPA OUST derived the screening criteria from an analysis of a large

¹ The term *state* refers to regulatory agencies of states, territories, and the District of Columbia.

² The OSWER draft guidance is accessible at <http://www.epa.gov/osw/hazard/correctiveaction/eis/vapor/complete.pdf>

³ The OIG report is accessible at <http://www.epa.gov/oig/reports/2010/20091214-10-P-0042.pdf>

⁴ *OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway From Subsurface Sources To Indoor Air* (OSWER Publication 9200.2-154), accessible at <http://www.epa.gov/oswer/vaporintrusion/>.

data set of samples from leaking UST sites.⁵ In contrast, the OSWER Vapor Intrusion Guide addresses a wide variety of sites and a broader range of contaminants.

Overview Of Petroleum Vapor Intrusion

Vapor intrusion is the general term given to migration of volatile organic chemicals (VOCs) from any subsurface contaminant source, such as contaminated soil or groundwater, through the soil and into an overlying building. There are two general classes of VOCs that account for a large number of soil and groundwater contamination sites in the United States:

- Petroleum hydrocarbons (PHCs) and non-PHC fuel additives
- Chlorinated solvents (e.g., the dry cleaning chemical tetrachloroethylene, also known as perchloroethylene, (PCE), and the degreasing solvents trichloroethylene (TCE), 1,1,1-trichloroethane (TCA)).

In this guide, petroleum vapor intrusion (PVI) is defined as the intrusion of vapors from subsurface PHCs and non-PHC fuel additives into overlying or nearby buildings or structures.

Vapors emanating from petroleum-contaminated soil or groundwater that enter buildings may result in indoor air concentrations that pose a risk to building occupants. PVI may pose both immediate threats to safety (e.g., fire or explosion potential from petroleum vapors or methane) and possible adverse health effects from inhalation of toxic chemicals (e.g., exposure to benzene from gasoline). PVI may be associated with three groups of volatile chemicals:

- PHCs found in gasoline, diesel, and jet fuel (e.g., benzene, trimethylbenzenes (TMBs), naphthalene)
- Volatile chemicals other than PHCs that may be found in petroleum fuels, such as ethers, alcohols, and other fuel additives (e.g., methyl tertiary-butyl ether (MTBE), tertiary-butyl alcohol (TBA), ethylene dibromide (EDB), and 1,2-dichloroethane (1,2-DCA))
- Methane, which is generated from anaerobic biodegradation of PHCs and other constituents of petroleum fuels (especially ethanol), and organic matter in soil

In contrast to chlorinated solvents, PHCs generally biodegrade rapidly under aerobic conditions and if biodegradation is complete, produce only water and carbon dioxide. If biodegradation is incomplete a variety of intermediate degradation products may be formed, but these are usually less toxic than the parent PHCs.⁶ If chlorinated solvents biodegrade it is usually under

⁵ *Evaluation Of Empirical Data To Support Soil Vapor Intrusion Screening Criteria For Petroleum Hydrocarbon Compounds* (EPA 510-R-13-001), accessible at http://www.epa.gov/oust/cat/pvi/PVI_Database_Report.pdf

⁶ Some petroleum hydrocarbons may also degrade anaerobically and may produce methane, particularly if the source is from an ethanol-blended gasoline. A recent modeling study cautions that for releases of high ethanol fuel blends (i.e., greater than E-20) advective methane transport may result in methane buildup inside buildings and pose a risk of explosion (Ma, et al., 2014, Numerical Model Investigation for Potential Methane Explosion and Benzene Vapor Intrusion Associated with High-Ethanol Blend Releases, *Environmental Science and Technology* 48(1):474-481).

anaerobic conditions, which is slower and may produce intermediate degradation products that are more toxic than the parent compounds.

The aerobic biodegradability of PHCs typically reduces the potential for PVI and justifies a different approach for addressing PVI than for vapor intrusion from chlorinated solvents and other non-aerobically biodegradable VOCs.⁷

Scope And Applicability

This PVI guide focuses on releases of petroleum-based fuels (e.g., gasoline, diesel), including both PHCs and non-PHC fuel additives, from underground storage tanks (USTs) regulated under Subtitle I of the Solid Waste Disposal Act of 1984, which are typically located at gas stations.⁸ This guide applies to new and existing releases of PHCs and non-PHC fuel additives from leaking USTs and to previously closed sites where the implementing agency has reason to suspect that there may be a potential for PVI. Although EPA developed the PVI guide based on data from typical UST sites, this technical guide may also be helpful when addressing petroleum contamination at comparable non-UST sites. Petroleum contamination at sites that are not comparable to UST sites (such as refineries, petrochemical plants, terminals, aboveground storage tank farms, pipelines, and large scale fueling and storage operations at federal facilities), or sites with releases of non-petroleum chemicals including comingled plumes of petroleum and chlorinated solvents regardless of the source, should be addressed under OSWER's more general vapor intrusion guide.

This PVI guide does not impose legally binding requirements on implementing agencies or the regulated community. Decision-makers retain the discretion to adopt or approve approaches on a case-by-case basis that differ from this technical guide.

Recommended Actions For Addressing PVI

Addressing the potential for PVI is an integral part of the normal response to a suspected or confirmed release from any Subtitle I regulated UST system. At any leaking UST site, it is important to have a thorough understanding of the release (i.e., source, composition, and magnitude) and other factors that may influence the distribution and transport of contaminants that impact human safety and health. Until it is clear that human health and the environment are adequately protected from adverse impacts caused by the release, appropriate site characterization, risk assessment, and corrective action activities should continue.

⁷ For more information on the differences between PHCs and chlorinated solvents, see *Petroleum Hydrocarbons And Chlorinated Solvents Differ In Their Potential For Vapor Intrusion* (<http://www.epa.gov/oust/cat/pvi/pvicvi.pdf>)

⁸ EPA's UST regulations are contained in 40 CFR Parts 280, 281, and 282.50-282.105 (see <http://www.epa.gov/oust/fedlaws/cfr.htm>). Definitions of key terms such as UST and petroleum are found in 40 CFR 280. These definitions may change if the regulations are revised in the future.

EPA recommends the following actions for situations in which EPA, state, tribal, and local agencies are investigating releases of petroleum-based fuels (including addressing potential risks due to PVI) at leaking UST sites or where 40 CFR 280 requires⁹ UST owners and operators to undertake release investigation and corrective action activities:

✓ **Assess and mitigate immediate threats to safety – see Section 1 (p.11)**

Identify whether there is a potential threat of explosion or fire due to the presence of flammable PHCs and non-PHC fuel additive vapors or methane¹⁰. A threat could be indicated by reports of the presence of odors, disagreeable taste of water, or visible signs of PHC contamination by building occupants. If so, alert first responders so they can, if necessary, evacuate these buildings until the potential threat to human safety from fire or explosion due to PVI has been assessed and mitigated as needed.

✓ **Conduct a site characterization and develop a conceptual site model (CSM) – see Section 3 (p.39)**

Site characterization data should be integrated into a conceptual site model (CSM). This includes characterization of the physical, biological, and chemical systems at the site, with emphasis on determining the spatial and temporal relationships between receptors and sources of contamination. The CSM should be used as the basis for planning the PVI investigation and making informed risk management decisions about the site and the threat posed by PVI to nearby receptors. EPA recommends that the site characterization include:

- Determining the full extent and location of contamination and its nature
- Assessing the potential for biodegradation of PHCs (and non-PHC fuel additives)
- Defining the hydrologic and geologic characteristics of the site
- Identifying potential receptors in the vicinity
- Determining whether preferential transport pathways are present and connect PHC vapor sources with potential receptors¹¹
- Considering whether there are any other factors that may preclude the use of screening criteria

⁹ In the case of a suspected or confirmed release from a regulated UST system, Subparts E and F of 40 CFR 280 require owners and operators to investigate, report, and perform corrective action (including recovery of light non-aqueous phase liquid (LNAPL) to the maximum extent practicable) if contamination is present, and submit timely reports of activities and findings to the implementing agency.

¹⁰ Note that methane cannot be detected based on odor, taste or visible signs. Methane-detecting devices must be used. For additional information on evaluating the presence of methane and potential hazards, see ASTM's "New Practice for Evaluating Potential Hazard Due to Methane in the Vadose Zone", which is accessible at <http://www.astm.org/DATABASE.CART/WORKITEMS/WK32621.htm>.

¹¹ Preferential transport pathways can short-circuit the protectiveness provided by the extent of the lateral inclusion zone and the vertical separation distances described in this guide. If preferential transport pathways connect a vapor source directly to a building, indoor air sampling paired with sub-slab vapor sampling is recommended.

✓ **Delineate a lateral inclusion zone – see Section 4 (p.44)**

Delineate a lateral inclusion zone to focus the investigation on buildings located within these boundaries. The lateral inclusion zone is based on the spacing between clean monitoring points; the closer the spacing of the clean monitoring points, the less extensive the lateral inclusion zone.

✓ **Determine vertical separation distances for each building within the lateral inclusion zone – see Section 5 (p.48)**

Further narrow the investigation to potential receptors (e.g., buildings) within the lateral inclusion zone and directly overlie contamination. For such buildings, determine the vertical distance between the contamination and the building basement, foundation, or slab. This distance is determined by collecting soil gas, soil, and groundwater samples as necessary. The thickness of clean soil separating contamination from the deepest point of the building basement, foundation, or slab is the vertical separation distance.

Additional investigation is generally unnecessary if the vertical separation distance is greater than 6 feet for dissolved contamination beneath buildings of any size, or 15 feet for light non-aqueous phase liquid (LNAPL) if the overlying building has at least one side shorter than 66 feet in length. If the distance to contamination is less than the appropriate vertical separation distance (i.e., 6 feet or 15 feet; see **Section 5**), then additional investigation is recommended.

✓ **Evaluate vapor source and attenuation of PHC vapors – see Section 5 (p.48), Section 8 (p.66), Section 9 (p.75), Section 10 (p.81), Section 12 (p.100), and Section 13 (p.106)**

If contamination (either dissolved, or LNAPL whether mobile or residual) is in direct contact with a building EPA recommends indoor air sampling. In the case of direct contact, sub-slab samples cannot be collected because there is no subsurface soil between the contamination and the building. Where contamination is not in direct contact with an overlying building, then choose one of two options: (1) collect near-slab (exterior) shallow soil gas samples paired with deep (source) soil gas samples, or (2) collect indoor air samples paired with sub-slab soil gas samples. If the potential for PVI cannot be ruled out based on near-slab and deep soil gas sampling, then EPA recommends indoor air sampling paired with sub-slab vapor sampling. If the attenuation factor calculated from results of analysis of the chosen pair or vapor samples indicates that there may be a potential for PVI above applicable exposure limits, EPA recommends gathering additional information and data to determine whether mitigation is appropriate.

- ✓ **Mitigate PVI, as appropriate – see Section 1 (p.11)**
Mitigation involves interruption of the transport pathway for vapors between the source of contamination and potential receptors. Select a remedial design that is appropriate for the building and site. As necessary, establish institutional controls to limit or prohibit access to affected areas. Remediate the source of the contamination, including recovery of LNAPL (if present) to the maximum extent practicable.

Community Engagement

When conducting PVI assessments and follow-up actions, it is important to consider proactive community engagement. EPA acknowledges there is no single correct approach to engage the potentially impacted community in cleanup decisions. Community engagement can occur at any step in the process and may occur more than once. It is generally recognized that earlier and more frequent communication yields positive results, particularly for sites that pose a threat to human health or the environment, or when the public expresses an elevated level of concern or interest in the site. Depending on site circumstances, obtaining meaningful community input is a sound approach that may result in better-informed decisions. EPA developed several community engagement resources, which are available on the Office of Underground Storage Tanks website: [Community Engagement And The Underground Storage Tank Program](#).¹² Some of the resources include:

- [Guidelines For Tailoring Community Engagement Activities To Circumstances At Leaking Underground Storage Tank Sites](#).
- [Community Engagement Resources \(Toolbox\) For Underground Storage Tank Programs](#).

Table 1 and **Figure 1** briefly outline the **Recommended Actions for Addressing PVI**. Note that this process is not necessarily linear and some of these activities may occur in a different order or recur throughout the PVI investigation; this is especially true for community engagement. Additional technical information is presented in the second part of this guide, *Supporting Technical Information*.

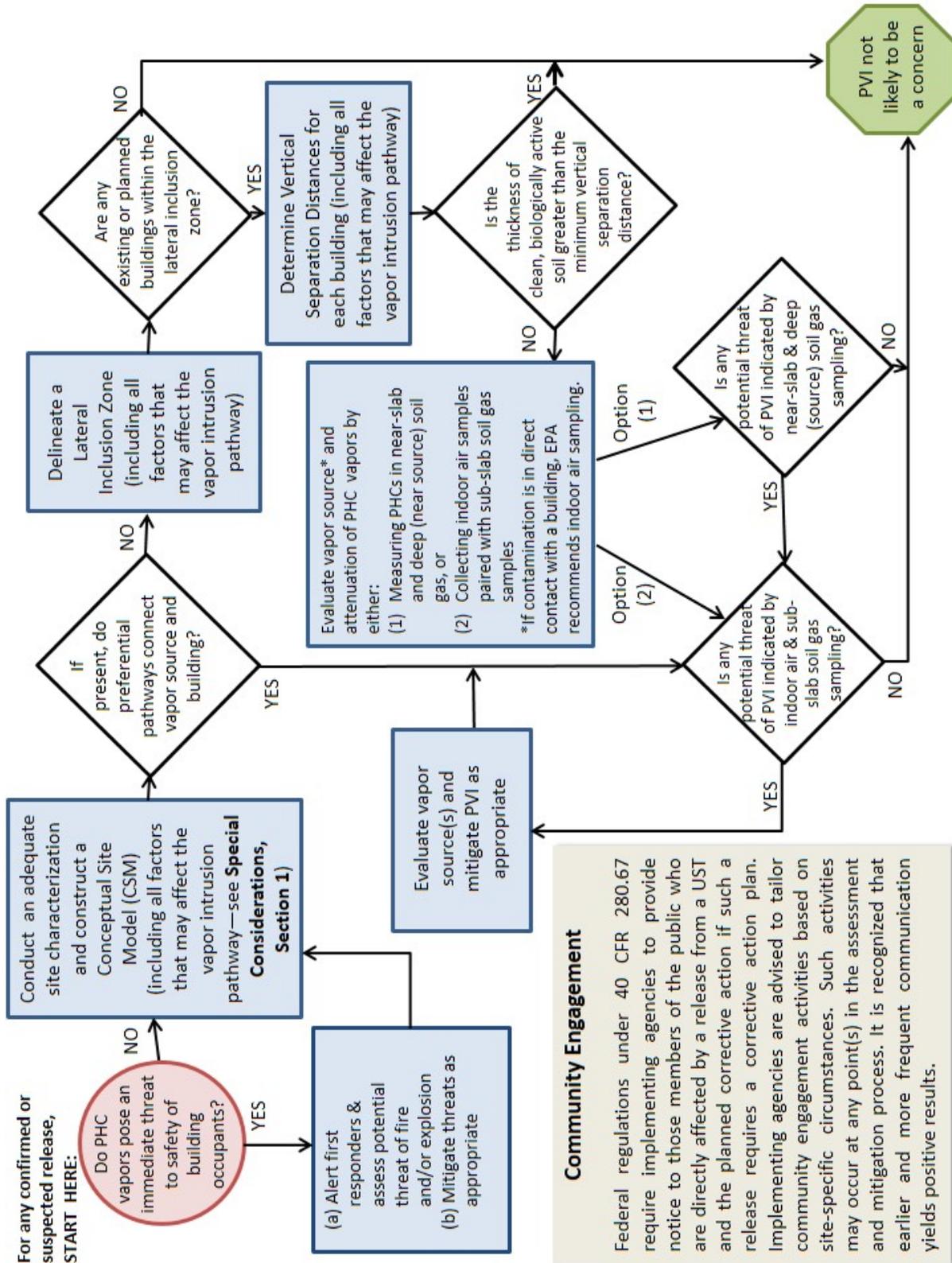
¹² The URL for this web site is <http://www.epa.gov/oust/communityengagement/index.htm>.

Table 1. Recommended Actions For Addressing PVI At Leaking Underground Storage Tank Sites

Recommended Actions	Purpose And Objectives	Procedures
<p>Assess and mitigate immediate threats to safety (see Section 1, p.11)</p>	<p>Identify potential threat of explosion or fire due to petroleum vapors or methane. Threat may be indicated by:</p> <ul style="list-style-type: none"> • LNAPL visible in building, possibly as sheen in sump • Noticeable petroleum odor; headache, dizziness, or nausea • Atypical, unusual, or disagreeable taste or smell in the water supply <p>NOTE: Methane cannot be detected on the basis of odor, taste, or visible signs</p>	<ul style="list-style-type: none"> • Investigate all reports of petroleum odors and other indicators within buildings • Detection of the presence of methane; requires specialized devices • Alert first responders so that they can, if necessary, evacuate building occupants as necessary until the potential for fire or explosion has been assessed and mitigated as needed
<p>Conduct a site characterization and develop a conceptual site model (CSM) (see Section 3, p.39)</p>	<p>Characterize the physical, biological and chemical systems at the site, with emphasis on determining the spatial and temporal relationship between receptors and sources of contamination by:</p> <ul style="list-style-type: none"> • Determining the full extent and location of contamination and its nature • Assessing the potential for biodegradation of PHCs • Defining the hydrologic and geologic characteristics of the site • Identifying potential receptors in the vicinity • Identifying whether preferential transport pathways are present and connect PHC vapor sources with potential receptors. Preferential transport pathways include both natural (i.e., geologic) and man-made (i.e., underground utilities, excavations) features. 	<ul style="list-style-type: none"> • Collect sufficient site data and information to construct CSM • Identify data gaps • Update CSM as new data become available • Where preferential transport pathways connect PHC vapor sources to receptors (e.g., buildings), indoor air sampling paired with sub-slab vapor sampling is recommended
<p>Delineate a lateral inclusion zone (see Section 4, p.44)</p>	<p>Screen out buildings that are not likely to be impacted by PVI to narrow the investigation to only those buildings that have a greater potential for PVI and for which further investigation should be conducted.</p> <p>The lateral inclusion zone is site-specific and:</p> <ul style="list-style-type: none"> • Based on the extent of contamination and distance between clean monitoring points • Decreases in extent as additional data are collected to reduce uncertainty in the CSM 	<ul style="list-style-type: none"> • Construct lateral inclusion zone based on distance between clean monitoring points (includes consideration of the presence of preferential transport pathways)
<p>Determine vertical separation distances (see Section 5, p.48)</p>	<p>Further screen out buildings that are not likely to be impacted by PVI to focus the investigation on potential receptors that overlie contamination in the dissolved, vapor, and/or LNAPL phase. The vertical separation distance is:</p> <ul style="list-style-type: none"> • The thickness of clean, biologically-active soil 	<ul style="list-style-type: none"> • For each building within the lateral inclusion zone, collect additional soil gas, soil, and groundwater samples as necessary to determine the vertical separation distance. Additional investigation is generally unnecessary

Recommended Actions	Purpose And Objectives	Procedures
	<p>(see Section 9, p.75) separating contamination from overlying buildings or other potential receptors</p> <ul style="list-style-type: none"> • Determined by site-specific sampling to determine the depth at which contamination is present 	<p>If the distance to contamination is greater than:</p> <ul style="list-style-type: none"> • 6 feet for dissolved contamination beneath buildings of any size, or • 15 feet for LNAPL if the overlying building has at least one side shorter than 66 feet in length • If the distance to contamination is less than those indicated above, then additional investigation is recommended.
<p>Evaluate vapor source and attenuation of PHC vapors (see Section 5, p.48, Section 8, p.66, Section 9, p.75, Section 10, p.81, Section 12, p.100, and Section 13, p.106)</p>	<p>Carefully evaluate the potential for PVI into those buildings identified as being the most likely to be impacted by PVI. This is a building-by-building evaluation based on sampling conducted within close proximity to the building or inside the building as necessary.</p>	<p>If contamination is in direct contact with building basement, foundation, or slab, then collect indoor air samples. Otherwise choose either option (1) or (2) below:</p> <ol style="list-style-type: none"> 1. Collect near-slab soil gas samples coupled with deep (source) soil gas samples. If a potential threat of PVI is indicated, then proceed to option 2. 2. If not, PVI is not likely to be a concern. 2. Collect indoor air samples paired with sub-slab soil gas samples. If these results indicate a potential threat of PVI, mitigate PVI as appropriate.
<p>Mitigate PVI as appropriate (see Section 1, p.11)</p>	<p>Interrupt the pathway between the source of contamination and potential receptors.</p> <ul style="list-style-type: none"> • Numerous approaches depending on building characteristics 	<ul style="list-style-type: none"> • Select a remedial design that is appropriate for building and site • Remediate source of contamination, including recovery of LNAPL (if present) to the maximum extent practicable • Establish institutional controls to limit or prohibit access to affected areas of building, as necessary

Figure 1. Flowchart For Addressing PVI At Leaking Underground Storage Tank Sites



Supporting Technical Information

The following sections provide technical information in support of EPA’s recommended actions as outlined in **Table 1** (p.7) and depicted in **Figure 1** (p.9). Each section presents information in a standardized format, which is easy to follow and allows for future revisions, as necessary.

Additional sources of information may be found in the Petroleum Vapor Intrusion Compendium (<http://www.epa.gov/oust/cat/pvi/>), located on the Office of Underground Storage Tanks (OUST) website (<http://www.epa.gov/oust/>).

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1. Petroleum Vapor Intrusion (PVI)

Description

Petroleum vapor intrusion (PVI) occurs when vapors from petroleum hydrocarbons (PHCs) migrate through the subsurface into overlying or nearby buildings. Fuels such as gasoline, diesel, aviation gasoline, and jet fuel are comprised primarily of PHCs with some non-petroleum based additives. Under certain circumstances, PVI may result in indoor air concentrations that pose a risk to building occupants. PVI may pose immediate threats to safety (e.g., fire or explosion potential from petroleum vapors or methane) or possible adverse health effects from inhalation of toxic chemicals (e.g., exposure to benzene from gasoline). Vapor concentrations generally decrease with increasing distance from a subsurface vapor source due to aerobic biodegradation, and eventually at some distance the concentrations become negligible.

Composition Of Petroleum Fuels

Petroleum fuels are comprised of hundreds of individual compounds. PHCs present in petroleum fuels generally belong to one of two major groups: aromatics and aliphatics. The aromatic PHCs are characterized as having one or more benzene rings. Benzene, toluene, ethylbenzene, and the three isomers of xylene are collectively referred to as BTEX. The aliphatics are non-aromatic PHCs consisting of straight-chains, branched chains, or non-aromatic rings. Although BTEX represent the group of PHCs that receive the most attention at typical leaking underground storage tank (UST) sites, they are not the only compounds that may pose a risk to human health.¹³ Petroleum fuels may also contain a variety of non-PHC volatile organic chemicals (VOCs) as additives to enhance performance. Fuel oxygenates such as methyl

¹³ The federal UST program does not prescribe human health values for contaminants; implementing authorities should use exposure values and attenuation factors appropriate for the contaminants present and the characteristics of exposure (e.g., residential vs industrial). Although there is a lack of toxicological data for many PHCs, EPA provides some information that may be applicable. For example, EPA provides vapor intrusion screening levels (VISLs) for a variety of volatile chemicals known to pose a potential cancer risk or noncancer hazard through the inhalation pathway. These VISLs, which are calculated by the VISL Calculator (EPA, 2014b), are generally recommended, medium-specific, risk-based screening-level concentrations intended for use in identifying areas or buildings that may warrant further investigation and mitigation of vapor intrusion, as appropriate. VISLs are calculated for concentrations of volatile chemicals in groundwater, soil gas (exterior to buildings and sub-slab), and indoor air for default target risk levels and exposure scenarios. The VISL Calculator does not account for biodegradation so attenuation factors may need to be adjusted for biodegradable chemicals. The VISL Calculator draws on toxicity values from Regional Screening Levels (RSLs) for Chemical Contaminants at Superfund Sites, accessible at http://www.epa.gov/req3hwmd/risk/human/rb-concentration_table/index.htm. Both the *VISL Calculator User's Guide* (EPA, 2014a) and *VISL Calculator* (EPA, 2014b) may be downloaded from EPA's web site: <http://www.epa.gov/oswer/vaporintrusion/guidance.html>. RSLs are drawn from a variety of sources according to EPA's three-tiered hierarchy of toxicity data (see "[Human Health Toxicity Values in Superfund Risk Assessments](#)" OSWER Directive 9285.7-53, 2003). Tier 1 (highest quality data) is EPA's Integrated Risk Information System (IRIS), accessible at <http://www.epa.gov/iris/>. Tier 2 are Provisional Peer Reviewed Toxicity Values (PPRTVs), accessible at <http://hhpprtv.ornl.gov/> (also see EPA, 2009). Tier 3 include toxicity values from other sources such as the Agency for Toxic Substances and Disease Registry (ATSDR). Several states have also developed toxicity values, including California (CA DTSC, 2009), Hawai'i (HI DOH, 2008, 2012), Massachusetts (MA DEP, 2003), New Jersey (NJ DEP, 2013), and Washington (WA DEC, 2006). Links to these sources are provided under *References Cited* at the end of this section.

tertiary-butyl ether (MTBE) and tertiary-butyl alcohol (TBA), and the lead scavengers¹⁴ ethylene dibromide (EDB), and 1,2-dichloroethane (1,2-DCA), plus other PHCs (e.g., naphthalene), may also pose a risk to human health. If present, their vapor intrusion potential should be assessed (see **Section 10**, p.81). The presence of biodegradable VOCs other than benzene may result in depletion of oxygen that is necessary for aerobic biodegradation of benzene, potentially resulting in farther migration of benzene vapors.

Phase Partitioning

When petroleum fuels are released into the subsurface from a leaking UST, PHCs may partition into several phases:

- Globules of light non-aqueous phase liquid (LNAPL) trapped within soil pore spaces (i.e., residual LNAPL)
- Dissolved in soil moisture
- Adhered onto the surface of, or absorbed into, soil solids
- Vapors in soil gas
- Accumulations of mobile LNAPL on and in the capillary fringe¹⁵
- Dissolved in groundwater

Low volume releases may result in contamination of only soil (including soil gas and soil moisture) and remain in the vadose zone. If the volume of a fuel release is sufficient, the fuel may accumulate on and in the capillary fringe and become mobile LNAPL. The mobile LNAPL generally spreads in the direction of groundwater flow, and may accumulate in monitoring wells. Temporal fluctuations in the elevation of the water table typically create a vertical smear zone of residual LNAPL contamination both above and below the average water table elevation. The more soluble components of the LNAPL mass dissolve into groundwater and are transported down gradient by the flowing groundwater as an aqueous phase. The remaining LNAPL mass will contain a sizeable fraction of aliphatic and relatively insoluble PHCs (e.g., naphthalene), especially if the source is large or unweathered (Lahvis, et al., 2013; EPA, 2013a). PHCs in the residual phase (both above and below the water table), the mobile phase (i.e., free product, LNAPL plume), and the dissolved phase (i.e., contaminant plume) all can serve as sources of PHC vapors. **Figure 2** illustrates the typical distribution of petroleum fuels in the subsurface resulting from a leaking UST. See **Section 2** (p.33) for a more detailed discussion of typical PVI scenarios.

¹⁴ Older sites, where leaded gasoline was released to the subsurface, should be assessed for EDB and 1,2-DCA as they may represent a potential source of vapors (see **Section 10**). For more information about lead scavengers, see Appendix F in *Evaluation Of Empirical Data To Support Soil Vapor Intrusion Screening Criteria For Petroleum Hydrocarbon Compounds* (EPA, 2013) and EPA's Lead Scavengers web site at <http://www.epa.gov/oust/cat/leadscav.htm>.

¹⁵ Mobile LNAPL is often referred to as free product, especially in older documents and 40 CFR 280.

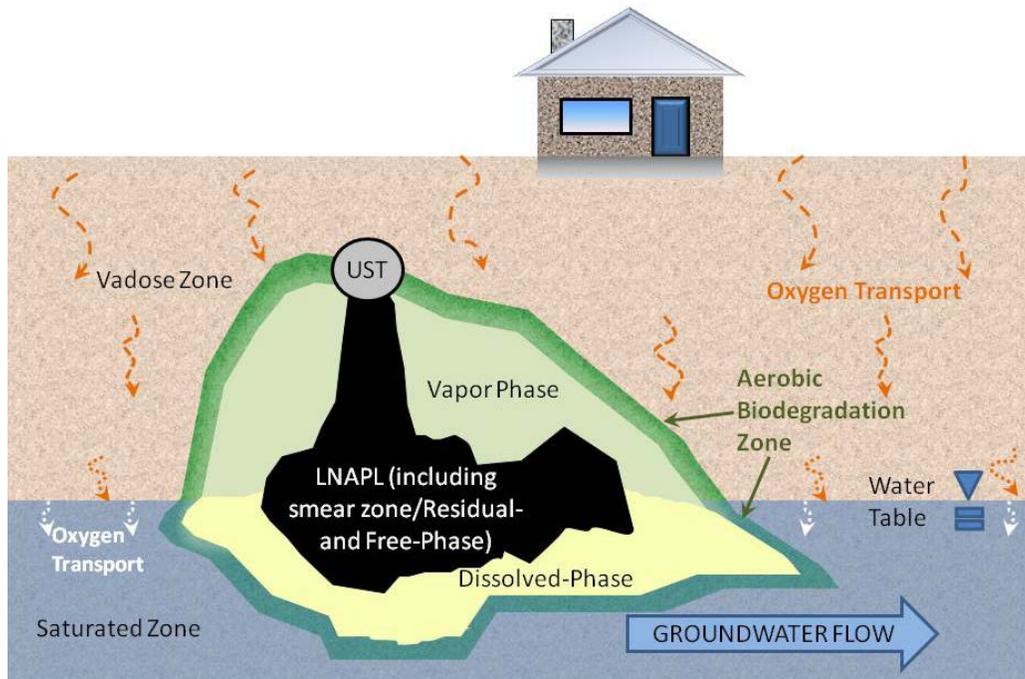


Figure 2. Conceptual Model Of Typical Petroleum Hydrocarbon Release

Aerobic biodegradation of PHCs along the perimeter of the vapor and dissolved plumes may limit the spread of subsurface contamination. Effective oxygen transport (dashed arrows) maintains aerobic conditions in the biodegradation zone. Petroleum LNAPL collects at the capillary fringe between the saturated and unsaturated zones (EPA, 2012).

Vapor Migration

Vapor migration results from two processes: diffusion and advection. Diffusion is the process whereby net transport of vapors from a source area of higher concentration (e.g., LNAPL, residual LNAPL, or dissolved plume) to an area of lower concentration occurs as a result of random molecular motion. Diffusion can also lead to chemical migration into buildings directly through a dirt floor or crawlspace, or through openings in the building slab and foundation such as passages for utility lines, sumps, and elevator pits. Also, intact concrete has appreciable permeability to diffusive gas movement (Kobayashi and Shuttoh, 1991; Sanjuan and Munoz-Martialay, 1996; and Tittarelli, 2009) and the permeability increases substantially when cracks are present (Daoud and Renken, 1999; EPA, 1995).

Advection refers to the movement of soil gas in response to pressure gradients. Advection can be an important mechanism for drawing soil gas and contaminant vapors through cracks in the basement floor or foundation into the building or back into the soil beneath the building. Heating and cooling systems can create differential pressures inside the building. When the pressure inside the building is lower than the pressure in the subsurface, vapors are drawn into the building. Conversely, when the pressure inside the building is greater than the pressure in

the subsurface, air within the building may be forced into the subsurface causing some degree of reoxygenation (Lundegard, Johnson, and Dahlen, 2008). Wind or changes in barometric pressure may also drive advective transport of oxygen into the subsurface beneath the building (Lundegard, Johnson, and Dahlen, 2008; Patterson and Davis, 2009; McHugh, DeBlanc, and Pokluda, 2006; Luo and Johnson, 2011; Robinson, Sextro, and Riley, 1997; Luo, et al., 2009; and Hong, Holton, and Johnson, 2012) (see **Section 11**).

Biodegradation Of PHCs

Biodegradation of PHCs is recognized as one of the primary mechanisms by which petroleum and other hydrocarbon pollutants are removed from the environment (Baedecker, Cozzarelli, and Hoppel, 1987; Leahy and Colwell, 1990). The biodegradability of PHCs often reduces the potential for human exposure from PVI (McHugh, et al., 2010; EPA, 2012; Interstate Technology & Regulatory Council [ITRC], 2014). Microorganisms are widely distributed in the environment and most are recognized as having some ability to metabolize PHCs (Gale, 1951; Ward, Singh, and Van Hamme, 2003; Prince, 2010). Although most microbes degrade a narrow range of organic compounds, they typically exist as a mixed consortium that collectively can biodegrade a wide range of organic compounds. Biodegradation progresses through stages with certain microbes being predominant until environmental conditions (e.g., availability of specific hydrocarbons, micronutrients, electron acceptors) become unfavorable for them at which time different microbes then become dominant (Wang and Deshusses, 2006; Suflita and Mormile, 1993; Corseuil, et al., 1998; Moyer, et al., 1996; Boopathy, 2004; Alexander, 1980; Prince, Parkerton, and Lee, 2007; Prince, 2010; and Bekins, et al., 2001). Thus, aerobic and anaerobic microbes may coexist with one class essentially dormant while the other is active.

Gasoline and diesel fuel (including biodiesel) may be completely biodegraded under aerobic conditions (Hult, 1987; Prince and Douglas, 2010; Prince, Parkerton, and Lee, 2007; Marchal, et al., 2003), though diesel fuel is more difficult and slower to biodegrade (Marchal, et al., 2003).¹⁶ The end products of complete biodegradation (mineralization) of PHCs are water and carbon dioxide. Mineralization of PHCs is almost always the consequence of microbial activity (Alexander, 1981). If aerobic biodegradation of PHCs is incomplete, a variety of intermediate degradation products may be formed, but none of these are more toxic than the parent PHCs.

Aerobic biodegradation is well documented for many individual PHCs and classes of PHCs including:

- N-alkanes (Bouchard, et al., 2005; Prince, Parkerton, and Lee, 2007; Bailey, Jobson, and Rogers, 1973; Hult, 1989; Baedecker, et al., 2011)
- Branched alkanes (Prince and Douglas, 2010; Prince, Parkerton, and Lee, 2007); cycloalkanes (Bouchard, et al., 2005)

¹⁶ The rate of aerobic biodegradation slows down with decreasing concentration of oxygen. Many aerobic microorganisms continue to function at concentrations as low as 0.1 mg/L of available oxygen, which is equivalent to an air concentration of 0.2%. For more information see research by Alagappan and Cowan (2004), Miralles-Wilhelm, Gelhar, and Kapoor (1997), and Mohamed, Saleh, and Sherif (2010).

- Aromatics (Wang and Deshusses, 2007; Phelps and Young, 1999; Landmeyer and Bradley, 2003; Lahvis, Baker, and Baehr, 2004; Lahvis, Baehr, and Baker, 1999; Bailey, Jobson, and Rogers, 1973; ZoBell, 1946; Corseuil, et al., 1998; Richnow et al., 2003)
- Naphthenes (Prince, Parketon, and Lee, 2007; Bailey, Jobson, and Rogers, 1973; Anderson, et al., 1999; ZoBell, 1946)
- Phenols (ZoBell, 1946; Basha, Rajendran, and Thangavelu, 2010)
- Trimethylbenzenes (Chen, et al., 2009)

Though aerobic biodegradation has been studied for over a century, anaerobic biodegradation of PHCs has been recognized only within the past three decades (Widdel, Boetius, and Rabus, 2006; Spormann and Widdel, 2000; and Townsend, et al., 2003). Anaerobic microorganisms degrade PHCs by using an electron acceptor other than oxygen (e.g., sulfate, nitrate, ferrous iron, or carbon dioxide). Anaerobic biodegradation is a slower process than aerobic biodegradation (Widdel, Boetius, and Rabus, 2006; Bailey, Jobson, and Rogers, 1973; and Lanham et al., 2013) and anaerobes grow slower than their aerobic counterparts (Widdel, Knittel, and Galushko, 2010). Instead of water and carbon dioxide, complete anaerobic biodegradation of PHCs (and naturally-occurring organic matter in soil, such as peat) can produce methane (Zengler, et al., 1999), especially with a release of an ethanol-blended gasoline (Jewell and Wilson, 2011; Ma, et al., 2012; Ma, et al., 2014). Incomplete anaerobic biodegradation of PHCs can produce compounds of higher toxicity, but these vapors are readily biodegraded in the vadose zone under aerobic conditions, and thus should not present a threat of vapor intrusion. Anaerobic biodegradation is typically the predominant mechanism of biodegradation in the source zone (Anderson and Lovley, 1997). Additional references documenting anaerobic biodegradation of PHCs are listed under *Additional Information* at the end of this section.

Importance

Important factors cited by Lahvis and Baehr (1996) and Suarez and Rifai (1999) as being influential for aerobic biodegradation of PHC vapors include:

- Vapor source hydrocarbon concentration, flux, and composition (including methane)
- Oxygen demand (i.e., the oxygen required to biodegrade the available hydrocarbons and any other organic matter present) and oxygen availability
- Soil type and properties (including texture and moisture content)
- Availability of essential micronutrients
- Ambient temperature in the subsurface
- The pH of the soil and groundwater

Additional factors cited by EPA (2012) as influencing the potential for PVI include:

- Size and characteristics of the building and adjacent land surface
- Distance between the vapor source and the building

Assessment

An assessment of the potential for PVI is not an isolated activity, but rather an integral part of the normal response to a suspected or confirmed release of PHCs from a leaking UST. At any leaking UST site (including abandoned sites or those that will be redeveloped for other uses), it is important to have a thorough understanding of the nature and magnitude of the release; the physical, biological, and chemical characteristics of the subsurface environment; an understanding of the preferential pathways for contaminant transport; and locations of receptors in the vicinity of the release. This is determined through collection and analysis of samples of soil, soil gas, groundwater, and sometimes LNAPL. Any other conditions (e.g., seasonal, weather-related; see **Section 11**, p.96) that may influence the transport of contaminants and potentially impact the safety and health of nearby building occupants should also be investigated.

Vapors emanating from dissolved-phase sources are primarily water soluble compounds, the more soluble aromatic hydrocarbons (e.g., BTEX) and other volatile and semi-volatile hydrocarbons and fuel additives (Lahvis, et al, 2013; EPA, 2013a). Vapors emanating from LNAPL sources contain a significantly larger fraction of aliphatic compounds and relatively insoluble hydrocarbons, especially if the source is large or unweathered (Lahvis, et al., 2013; EPA, 2012). Analyses of samples of soil, soil gas, groundwater, and LNAPL collected during site characterization (see **Section 3**, p.39) will provide information on specific contaminants that may warrant assessment for potential vapor intrusion.

Special Considerations

Several factors may preclude the effectiveness of aerobic biodegradation to mitigate the threat of vapor intrusion. They include:

- Source volume and composition (including PHCs and non-PHC fuel additives)
- Soil properties (moisture content, permeability, high organic carbon content, especially peat)
- Large building size
- Extensive impermeable surface covering (e.g., asphalt, concrete)
- Preferential transport pathways (including both natural and man-made)

If present, these factors may reduce the potential for biodegradation of PHC vapors and warrant additional investigative steps (e.g., collection of soil gas samples—see **Section 8**, p.66) to determine if the use of screening criteria (e.g., vertical separation distance) is appropriate.

The age and volume of release should be determined or estimated. When the release is relatively recent or if the volume of the release is relatively large¹⁷, there is greater potential for PVI than for smaller or older releases, which may be more weathered. Large volume PHC

¹⁷ The adjective *large* refers to either the total volume of the release or the areal extent (footprint) of the LNAPL mass in the subsurface.

releases may require a greater separation distance for biodegradation to be effective due to increased oxygen demand (EPA, 2013a).

Biodegradation of recent releases of high ethanol blended gasoline (i.e., E-20 or greater) may consume oxygen that would otherwise be available for biodegradation of PHCs resulting in an increased potential for PVI (Ma et al., 2014). In addition, the biodegradation of ethanol may result in the advective transport of methane and a potential risk of explosion. Thus, larger separation distances may be necessary to mitigate the threat of explosion or PVI at sites where high ethanol blended fuel has been released into the subsurface (Ma et al., 2014).

Preferential transport pathways may be either natural (e.g., fractures in rock, solution channels in karst terrain, bedding planes, joints, high permeability layers) or man-made (e.g., utility corridors including sewer lines themselves, trenches, excavations). Because they increase the speed at which the contaminants move through the subsurface, preferential transport pathways can potentially short circuit protectiveness that would otherwise be provided by biodegradation of PHCs and other fuel additives in homogeneous soils. Typically, it is difficult to detect and map natural preferential transport pathways, and contamination may present itself in unexpected locations. Local government offices have maps of utility corridors that can provide information on the presence and location of man-made preferential transport pathways.¹⁸

Recommended Steps For Addressing The Potential Risk From PVI

EPA recommends the following actions for situations in which EPA, state, tribal, and local agencies are investigating releases of petroleum-based fuels (including addressing potential risks due to PVI) at leaking UST sites or where 40 CFR 280 requires¹⁹ UST owners and operators to undertake release investigation and corrective action activities:

✓ ***Assess and mitigate immediate threats to safety***

Some releases from UST systems are discovered through noticeable sensory indicators on neighboring properties. Indicators may include sight, smell, taste, or physiological effects (e.g., dizziness, headache, nausea, vomiting, and confusion). The presence of odors does not necessarily correspond to adverse health or safety impacts from PVI, as the odors could be the result of indoor vapor sources. However, it is generally prudent to investigate any reports of odors in close proximity to UST systems as the odor threshold for some chemicals exceeds their acceptable health-based concentrations. PHC odors are a nuisance and may trigger the need

¹⁸ A federally mandated national call center was established to ensure that utility lines are marked before digging or boring. Dial 811 to have the locations of utilities marked before conducting site work that involves digging or boring. For more information, visit <http://www.call811.com/default.aspx>

¹⁹ In the case of a suspected or confirmed release from a regulated UST system, Subparts E and F of 40 CFR 280 require owners and operators to investigate, report, and perform corrective action (including recovery of LNAPL to the maximum extent practicable) if contamination is present, and submit timely reports of activities and findings to the implementing agency.

for abatement or mitigation even if the concentration in indoor air is below acute or chronic health-based levels.

In confined spaces, the presence of flammable PHC vapors and non-PHC fuel additive vapors or methane may pose a threat of fire or explosion and endanger building occupants. Federal regulations (40 CFR 280.61) require that immediate action be taken to prevent any further release of the regulated substance into the environment and that fire, explosion, and vapor hazards be identified and mitigated (*Federal Register*, 1988). Section 280.64 requires that free product (mobile LNAPL) be recovered to the maximum extent practicable and that records be kept of the volumes recovered. First responders, typically fire department personnel, should be notified if there are reports of either odor from petroleum or the presence of an oily sheen on basement floors or in sumps, drains, or elevator pits. It may be necessary to evacuate building occupants until the threat from fire or explosion has been mitigated. Since methane is odorless and colorless, monitoring devices are required if methane is suspected.

✓ **Conduct a site characterization and develop a conceptual site model (CSM)**

Once the immediate threats to safety have been mitigated (or it is determined that immediate threats do not exist), determine whether there is a long-term threat to human health and the environment from intrusion of petroleum vapors. Site characterization²⁰ and CSM development provide information about the full extent and location of the contamination; the nature and characteristics of the contamination; the characteristics of the site that influence contaminant migration, including the potential for biodegradation of PHCs; and the locations of receptors. Information derived from the CSM helps ensure that sources, pathways, and receptors throughout the site are considered; this knowledge can lead to selection of the most appropriate sampling locations and techniques. A systematic soil gas sampling program may also aid in defining the full extent and location of contamination, detecting the presence of preferential transport pathways, and locating pockets of PHC vapors. Preferential transport pathways are avenues of least resistance to the migration of contaminants whether in the dissolved phase, LNAPL phase, or vapor phase. They include both natural and man-made features such as:

- | Natural | Man-made |
|---|--|
| <ul style="list-style-type: none">• gravel lenses and channels• solution channels in karst terrain• bedding planes• fractures, joints, and faults in consolidated rock | <ul style="list-style-type: none">• utility corridors (including sewer lines themselves) and trenches• elevator pits• sumps and drainage pits• other types of excavations |

²⁰The term *site characterization* is used throughout this document for consistency. *Site characterization* is often used interchangeably with *site assessment*, *site evaluation*, *site investigation*, and sometimes *site check* as they all mean assembling and collecting information and data about a site.

Preferential transport pathways increase the speed at which contamination moves through the subsurface such that contaminants may not biodegrade by the time they reach receptors. They can also allow atypical movement, which in some cases may be opposite groundwater flow (ITRC, 2014). Because preferential transport pathways can short-circuit the protectiveness provided by lateral and vertical separation distances described in this PVI guide, indoor air sampling is recommended in situations where they connect vapor sources and receptors. See **Section 3** (p.39) for more information about site characterization and CSMs.

✓ ***Delineate a lateral inclusion zone***

Based on the CSM, delineate a lateral inclusion zone. The lateral inclusion zone is the area surrounding a contaminant mass through which petroleum vapors may travel, intrude into buildings, and potentially pose a threat to human health and the environment. Buildings directly above contamination sources, whether as mobile LNAPL, residual LNAPL, or PHCs dissolved in groundwater, are considered within the lateral inclusion zone. Buildings outside this zone generally may be excluded from further assessment for PVI unless:

- Site conditions change (e.g., groundwater flow direction changes, contaminant plume migrates beyond the lateral inclusion zone, development or redevelopment of nearby properties)
- Preferential transport pathways are present

In such instances, additional investigation may be warranted to more fully evaluate the risk from PVI. See **Section 4** (p.44) for more information on delineating a lateral inclusion zone.

✓ ***Determine vertical separation distances***

The vertical separation distance is the thickness of clean, biologically active soil (see **Section 9**, p.75) between a contaminant mass and the lowest point of an overlying receptor (e.g., building basement floor, foundation, or crawl space surface). Consolidated rock is not soil and should not be included in the vertical separation distance. For example, for a situation in which there is 3 feet of soil above fractured rock and the depth to contaminated groundwater is 7 feet, the vertical separation distance is 3 feet, not 7 feet. Some buildings within the lateral inclusion zone will overlie PHC contamination that exists as either a mobile LNAPL mass, residual soil contamination (including the smear zone), or dissolved in a groundwater plume. However, not all of these buildings will be threatened by PVI due to aerobic biodegradation of PHCs provided there is sufficient vertical separation distance between the receptor and the vapor source. The vertical separation distance between contamination and overlying buildings is determined as part of the normal site characterization process. The full extent and location of contaminant sources should have been adequately mapped in the subsurface and the nature and characteristics of the contamination should have been determined during site characterization and conceptual site model development (see **Section 3**, p.39).

EPA (2013a) presents analysis of petroleum vapor source data and soil gas data from a number of leaking UST sites across the United States. The report findings support screening criteria for dissolved and LNAPL PHC releases from leaking USTs. For dissolved PHC sources that are separated from overlying buildings by more than 6 feet of clean, biologically active soil, the potential threat of PVI is negligible and further investigation for PVI is generally unnecessary. For LNAPL sources that are separated from overlying buildings by more than 15 feet of clean, biologically active soil, the potential threat of PVI is negligible and further investigation for PVI is generally unnecessary. These separation distances are believed to be sufficiently protective in most situations because they include a number of built-in safety factors, which are discussed in more detail in **Section 5** (p.48). If the distance separating the source of PHC vapors and overlying buildings is less than 6 feet for dissolved sources and 15 feet for LNAPL sources, additional investigation is recommended.

EPA (2013a) recognizes that there are a number of precluding factors that may justify a greater vertical separation distance in some cases. These factors include:

- Influence of methanogenesis on oxygen demand (especially for higher ethanol blends of gasoline)
- Effect of extensive high organic matter content soils (e.g., peat) with potentially high natural oxygen demand
- Reduced oxygen flux caused by certain geologic conditions (e.g., low permeability surface layer overlying coarse-grained soils, soil moisture from precipitation (Luo et al., 2009))
- Limited knowledge of vapor attenuation behavior in fractured rock
- Limited soil gas data for non-UST (e.g., petroleum refinery, fuel terminal) sites
- Limited data on vapor attenuation behavior of aliphatic compounds
- Lack of soil vapor data for the lead scavengers ethylene dibromide (EDB) and 1,2-dichloroethane (1,2-DCA) (see **Section 10**, p.81, for more information on these contaminants)

Other site characteristics that may warrant additional investigation include exceptionally dry soils (<2 percent soil moisture), areas covered by extensive impervious paving or large buildings, and presence of preferential transport pathways (see **Section 3**, p.39). Also, soil gas movement may vary seasonally in response to differential pressures created by heating and cooling of overlying buildings (see **Section 11**, p.96).

✓ ***Evaluate vapor source and attenuation of PHC vapors***

Where contamination is not in direct contact with an overlying building, EPA recommends one of two options: (1) collection of near-slab (exterior) shallow soil gas samples paired with deep (near source) soil gas samples, or (2) collection of indoor air samples paired with sub-slab soil

gas samples to evaluate attenuation of PHC vapors and the potential for PVI.²¹ When collecting soil gas samples²², use option 1 under the following conditions (EPA, 2013b):

- A building, with the shortest side no longer than 66 feet, overlies LNAPL and the vertical separation distance is less than 15 feet, but not in direct contact with the building basement floor, foundation, or crawl space surface.
- A building, of any dimension, overlies dissolved PHC contamination and the vertical separation distance is less than 6 feet, but not in direct contact with the building basement floor, foundation, or crawl space surface.

Use option 2 for buildings larger than 66 feet on a side or if near-slab soil gas samples from around smaller buildings do not clearly demonstrate that biodegradation is sufficient to mitigate the threat of PVI by reducing PHC concentrations to below applicable human health thresholds (see Footnote #13).

The purpose of collecting paired samples is to enable determination of a building-specific vapor intrusion attenuation factor. Generic attenuation factors that do not account for biodegradation of PHCs are conservative and, likely overestimate the transfer of contaminants from soil gas to indoor air in most buildings. Attenuation factors (see **Section 12**, p.100) that account for biodegradation can be derived from models such as *BioVapor* or *PVIScreen* (see **Section 13**, p.106). Additional information may be found in Wilson *et al.* (2014).

If contamination (either dissolved, or LNAPL whether mobile or residual) is in direct contact with a building basement floor, foundation, or crawlspace surface, EPA recommends indoor air sampling (these samples cannot be paired with subsurface soil gas samples because there is no clean, biologically active soil between the contamination and the building). Information on collecting and analyzing sub-slab vapor samples and indoor air samples is beyond the scope of this document, but is provided in other documents, for example ITRC (2014) and EPA (2015).

Indoor air in many buildings will contain detectable levels of a number of vapor-forming compounds whether or not the building overlies a subsurface source of vapors, because indoor air can be impacted by a variety of indoor and outdoor sources. The composition of outdoor air surrounding a building is referred to as ambient air throughout this document. The combined contribution of indoor and outdoor sources of vapors to indoor air concentrations is referred to as background throughout this document. To differentiate and quantify the relative contribution of contaminants from PVI versus background sources, indoor air samples must be collected in conjunction with sub-slab (or near-slab, as appropriate) soil gas samples. ITRC

²¹ Implementing authorities may opt for sub-slab soil gas and indoor air sampling in any situation they deem necessary to protect the safety and health of building occupants.

²² Soil gas samples should be analyzed for oxygen, carbon dioxide, PHCs (and any other fuel constituents likely to be present including fuel additives), and methane. As a quality assurance/quality control check, nitrogen can be added to the analyte list at a nominal cost. This will enable determination of whether significant concentrations of other gases are unaccounted for as these gases should account for nearly 100 percent of the total present. (See **Section 8**).

(2014) and EPA (2015) provide information on background sources, techniques, and methods to account for background contributions to indoor air concentrations.

Information on historic concentrations of background vapors is presented in *Background Indoor Air Concentrations of Volatile Organic Compounds in North American Residences (1990 – 2005): A Compilation of Statistics for Assessing Vapor Intrusion* (EPA, 2011b). In addition, the Montana Department of Environmental Quality (MT DEQ, 2012) conducted an extensive investigation of the indoor air quality of typical uncontaminated buildings in Montana. The objective of these studies is to illustrate the ranges and variability of VOC concentrations in indoor air resulting from sources other than vapor intrusion. While these studies provide expected ranges of indoor air contaminants, EPA recommends building-specific sampling (rather than using literature values) to characterize actual contaminant levels. If measured indoor air concentrations are found to greatly exceed the historic range of background levels, there is a greater likelihood that the indoor air concentrations are the result of vapor intrusion. Studies such as EPA (2011) and MT DEQ (2012) can be employed to determine whether measured indoor air concentrations exceed the historic range of background concentrations.

If the attenuation factor calculated from results of analysis of the chosen pair or vapor samples indicates that there may be a potential for PVI above applicable exposure limits, EPA recommends additional investigation to determine whether mitigation is appropriate.

✓ ***Mitigate petroleum vapor intrusion, as appropriate***

If contaminant concentrations represent a potential threat of fire or explosion (i.e., vapor concentrations are more than 10% of the lower explosive limit), or indoor air sampling indicates that PVI is occurring, EPA recommends that active mitigation measures be immediately initiated. ITRC (2014) and EPA (2015) provide information on mitigation and remediation of vapor intrusion. In addition, the source of contamination should be remediated per Subpart F of the Federal Regulations (40 CFR 280.60 through 280.67) (Federal Register, 1988). In particular, 40 CFR 280.64 requires the recovery of LNAPL to the “maximum extent practicable”.

See the following sections for more information on the factors discussed in the paragraphs above:

- **Section 3** (p.39) Site Characterization and Conceptual Site Model (CSM)
- **Section 4** (p.44) Lateral Inclusion Zone
- **Section 5** (p.48) Vertical Separation Distance
- **Section 6** (p.57) Mobile and Residual Light Non-Aqueous Phase Liquid (LNAPL)
- **Section 7** (p.61) Groundwater Flow and Dissolved Contaminant Plumes.
- **Section 8** (p.66) Soil Gas Profile
- **Section 9** (p.75) Clean, Biologically Active Soil

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2. Typical PVI Scenarios

Description

The potential for PVI is primarily a function of the location of the contamination source relative to a potential receptor, source volume and strength, and the source mass distribution in the subsurface. Source concentrations are typically much higher for LNAPL sources than for dissolved-phase sources. Higher source concentrations will generate higher rates of mass diffusion (flux). The higher mass flux will also be more sustained over time because LNAPL sources will contain significantly more mass compared to dissolved-phase sources. Oxygen demand and the potential for encountering anaerobic conditions are also uniquely different between LNAPL and dissolved-phase sources. For both dissolved and LNAPL sources, the biodegradation reaction front is relatively narrow, but it occurs higher in the unsaturated zone (closer to land surface) over an LNAPL source than it does over a dissolved-phase source (**Figure 3**).

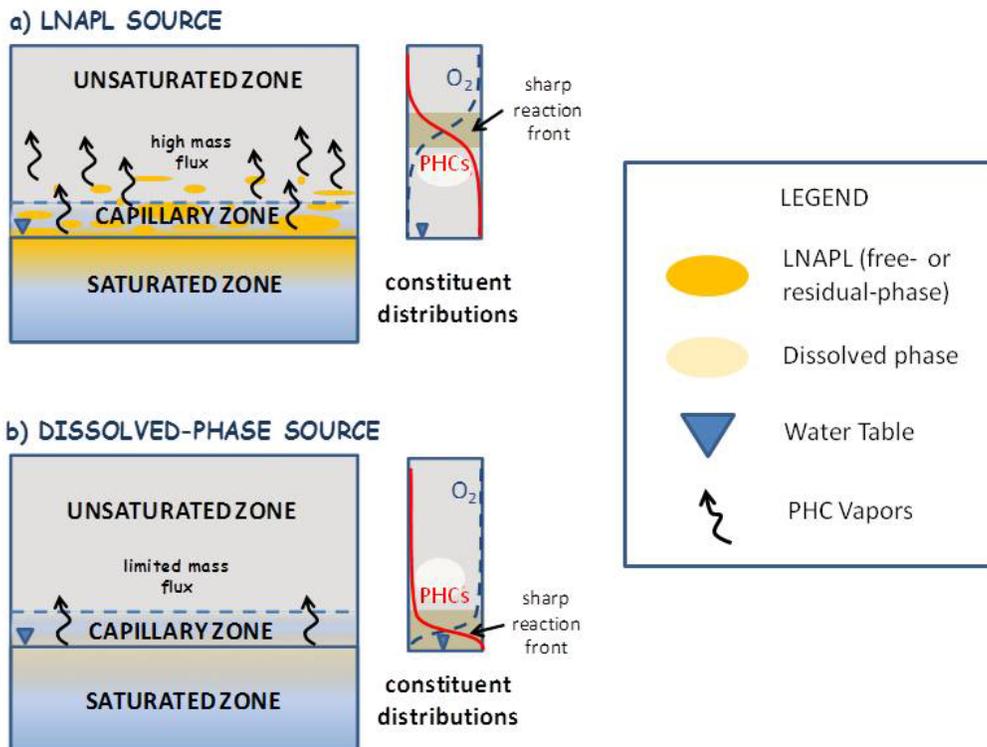


Figure 3. Difference In Potential For PVI Based On Type Of Source: a) LNAPL, b) Dissolved Phase (Source: Lahvis, et al., 2013. Reprinted from *Groundwater Monitoring & Remediation* with permission of the National Ground Water Association. Copyright 2013.)

LNAPL sources may be distributed both above and below the capillary fringe as a result of smearing from water-table fluctuations. This phenomenon will tend to enhance mass flux to the unsaturated zone because of direct partitioning between LNAPL (residual) and vapor phases. Conversely, the mass flux will be more limited for dissolved-phase sources because vapor transport through water is reduced relative to diffusion in soil gas (Golder Associates, 2006; Lahvis and Baehr, 1996). Vapor diffusion is limited by low effective air-phase porosity (i.e., high moisture saturation) and biodegradation in the capillary zone.

Importance

Relatively few confirmed occurrences of PVI at petroleum sites are reported in the literature (EPA, 2013, Section 2.6, p.9). The most likely scenarios for PVI to occur are shallow PHC sources directly beneath buildings and mobile LNAPL or groundwater plumes with high concentrations of PHCs that are in direct contact with buildings (Davis, 2009; and McHugh, et al., 2010). A study by Peargin and Kolhatkar (2011) suggests that a dissolved source with benzene greater than 1 mg/L may behave like a LNAPL source in terms of vapor-generating capability.

Assessment

Recommended steps for investigating PVI are discussed in **Section 1** (p.11). Application of the screening criteria allow for the determination of which buildings are threatened by PVI. Using this approach, resources can be appropriately focused on those buildings potentially impacted by PVI.

Figure 4 presents typical scenarios of the spatial relationship between PHC sources and potential receptors. However, it is not intended to be a comprehensive depiction of all possible configurations of such a relationship.

Table 2 summarizes the characteristics of these six scenarios relative to lateral and vertical distances from contamination and necessary investigation activities.

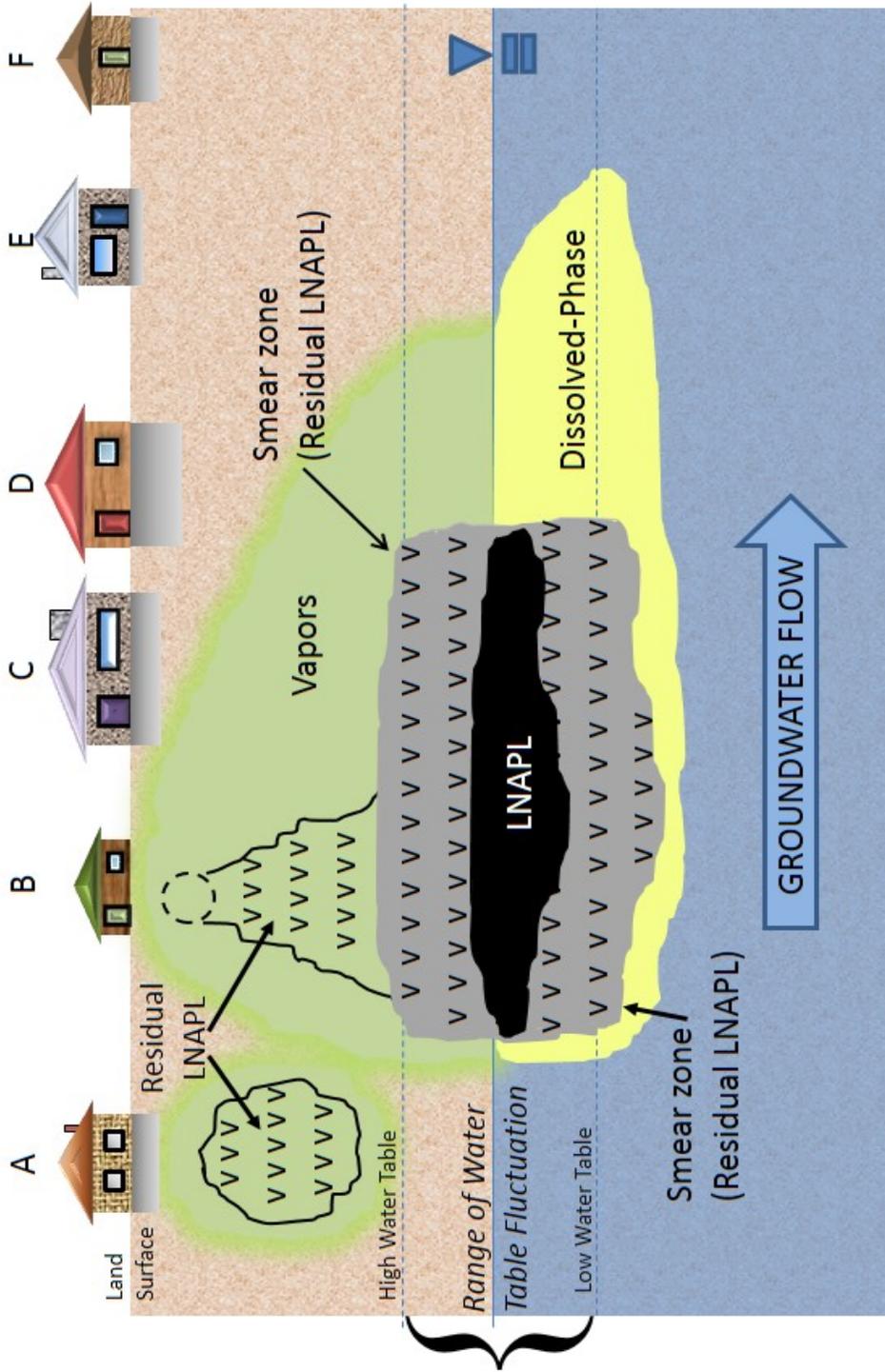


Figure 4. Typical Scenarios Of Potential PVI Sources And Potential Receptors

Table 2. Summary Of Characteristics Of Typical Scenarios Of Petroleum Vapor Sources And Potential Receptors.

Scenario (as illustrated in Figure 4)	Contamination Beneath Building? (building is within lateral inclusion zone)	Potential For PVI	Near-Slab* Soil Gas Sampling Recommended?
A	Yes; shallow residual LNAPL in the vadose zone	High	Yes, if vertical separation distance is less than 15 feet from the top of residual LNAPL, otherwise No
B	Yes; residual including smear zone, LNAPL, dissolved in groundwater	High	Yes, if vertical separation distance is less than 15 feet from the top of the smear zone, otherwise No
C	Yes; smear zone, LNAPL, dissolved in groundwater	Medium	Yes, if vertical separation distance is less than 15 feet from the top of the smear zone, otherwise No
D	Yes; dissolved in groundwater	Low	Yes, if vertical separation distance is less than 6 feet from the historical high water table elevation, otherwise No
E	Maybe; plume may be diving beneath water table	Low – None	Yes, if vertical separation distance is less than 6 feet from the historical high water table elevation, otherwise No
F	No	None	No
<p>*Near-slab soil gas samples should be collected from each side of the potentially impacted building and as close to the building as possible. These samples should be paired with deep (near source) soil gas samples. If these samples do not clearly demonstrate that biodegradation is sufficient to mitigate the threat of PVI into the building, EPA recommends collection of indoor air samples paired with sub-slab soil gas samples.</p>			

Special Considerations

While biodegradation may reduce the potential for human exposure to petroleum vapors, its effectiveness in mitigating PVI may be limited by precluding factors such as:

- Migration of contaminants, especially plumes in flowing groundwater
- Presence of non-PHC chemicals that biodegrade too slowly (or the rate is not known with certainty)
- Presence of preferential transport pathways
- Extensive impermeable surface cover, or very large buildings
- Presence of higher blends of ethanol in gasoline that consumes oxygen that would otherwise be available for aerobic biodegradation of PHCs
- Generation of methane from higher blends of ethanol in gasoline that exerts high oxygen demand and presents a vapor intrusion threat itself
- Soils with high organic content (e.g., peat) that exert a high oxygen demand
- Soil conditions that are inhospitable to microorganisms such as insufficient soil moisture
- Insufficient thickness of clean, biologically active soil
- LNAPL source is relatively unweathered and rich in volatile PHCs

Recommendation

EPA recommends conducting an adequate PVI investigation and following the steps described in **Section 1** (p.11) to determine which buildings may be at risk for PVI.

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3. Site Characterization And Conceptual Site Model (CSM)

Description

Site characterization is the process by which site-specific information and data are gathered from a variety of sources to characterize the physical, biological, and chemical systems at a contaminated site. A conceptual site model (CSM) integrates all data and information into a three-dimensional picture of site conditions that illustrates contaminant distributions, release mechanisms, migration routes, exposure pathways, and potential receptors (EPA, 2012; ITRC, 2014). The CSM uses a combination of text and graphics to portray both known and hypothetical information (EPA, 2011). The CSM documents current conditions at the site and is supported by maps, cross-sections, and site diagrams. The CSM illustrates potential human and environmental exposure through contaminant release and migration toward receptors (EPA, 1995, 1996a). The CSM should be refined as new data are collected.

Importance

At any leaking UST site, it is important to have a thorough understanding of the full extent and location of contamination (including both PHCs and non-PHC fuel additives), the characteristics of the site that influence contaminant migration (especially the presence of preferential transport pathways), and the locations of potential receptors. A CSM helps ensure that sources, pathways, and receptors throughout the site have been considered; this knowledge can lead to selection of the most appropriate sampling locations and techniques. The CSM assists the site manager in evaluating the interaction of different site features. Risk assessors use conceptual models to help plan for risk assessment activities (EPA, 1995). The CSM is the basis for making informed risk management decisions about the site and the threat posed by PVI to nearby buildings and their occupants. In addition, remedial action costs are influenced by the quality of the CSM (EPA, 1996b).

Assessment

An investigation for PVI potential is not separate from the normal response to a confirmed UST release; an adequate site characterization is essential in order to construct an accurate CSM. A primary objective of site characterization is delineation of the aerial and vertical extent of contamination in the subsurface (per 40 CFR 280.65(a)) so that lateral and vertical separation distances can be accurately determined.²³ It is also important to determine whether preferential transport pathways are present and, if so, delineate them to determine if they connect vapor sources directly to potential receptors. Site characterization generally proceeds in a systematic manner, often beginning in or near the source area and working outward and in the downgradient direction in which groundwater flows.

²³ The separation distances described in this document (**Section 5**, Table 3, p.52) and the protectiveness provided by clean, biologically active soil against vapor intrusion by PHCs may be insufficient to protect against vapor intrusion by non-PHC fuel additives. Additional investigation should be conducted where certain additives are present (see **Section 10**, p.81).

All information and data about the site should be integrated into a CSM, which is continually updated and refined to account for changing conditions and new information. Basic activities associated with developing a CSM include:

- Identification of potential contaminants²⁴
- Identification and characterization of the source of contaminants
- Characterization of the geochemical parameters that affect biodegradation
- Characterization of the geologic and hydrogeologic characteristics of the subsurface
- Delineation of potential migration pathways, including preferential transport pathways, through environmental media
- Establishment of background levels of contaminants and areas of contamination for each contaminated medium
- Identification and characterization of potential receptors
- Determination of the limits of the study area or system boundaries

Tracking contaminant migration from sources to receptors is one of the most important uses of the CSM (ASTM, 2008). Uncertainties associated with the CSM should also be identified as well as the efforts taken to reduce uncertainties to acceptable levels (ASTM, 2008). As new information and data become available, the CSM should continually be refined (EPA, 1993; ITRC, 2007). ITRC (2014), EPA (2013, 2015), and Wilson et al., (2014) provide additional information about developing CSMs.

Special Considerations

The separation distances described in this document (**Section 5**, Table 3, p.52) and the protectiveness provided by clean, biologically active soil against vapor intrusion by PHCs may be insufficient to protect against vapor intrusion by non-PHC fuel additives. Additional investigation should be conducted where certain additives are present (see **Section 10**, p.81).

The presence and locations of preferential transport pathways should be identified and incorporated into the CSM. All new information and data about a site, including potential future land uses, should also be identified to refine the CSM.

Recommendation

Per Subparts E and F in 40 CFR 280.50 through 280.67 (see <http://www.epa.gov/oust/fedlaws/cfr.htm>), EPA recommends that an adequate site characterization considers the following:

- §280.52(b) Release Investigation and Confirmation Steps:
“Owners and operators must measure for the presence of a release where contamination is most likely to be present at the UST site. In selecting sample types, sample locations, and measurement methods, owners and operators must consider the nature of the stored

²⁴ The list of potential contaminants should include BTEX and other PHCs as well as non-PHC fuel additives likely to have been present in the fuel stored at the site. See **Section 1** (p.11) and **Section 10** (p.81) for more information.

substance, the type of initial alarm or cause for suspicion, the type of backfill, the depth of ground water, and other factors appropriate for identifying the presence and source of the release.”

- §280.62(a)(5) Initial Abatement Measures and Site Checks

“Measure for the presence of a release where contamination is most likely to be present at the UST site, unless the presence and source of the release have been confirmed in accordance with the site check required by §280.52(b) or the closure site assessment of §280.72(a). In selecting sample types, sample locations, and measurement methods, the owner and operator must consider the nature of the stored substance, the type of backfill, depth to ground water and other factors as appropriate for identifying the presence and source of the release. . .”

- §280.63(a)(1-4) Initial Site Characterization

“. . . owners and operators must assemble information about the site and nature of the release, including information gained while confirming the release or completing the initial abatement measures. . . This information must include, but is not necessarily limited to the following: (1) Data on the nature and estimated quantity of release; (2) Data from available sources or site investigations concerning the following factors: surrounding populations, water quality, use and approximate locations of wells potentially affected by the release, subsurface soil conditions, locations of subsurface sewers, climatological conditions, and land use; (3) Results of the site check required under §280.62(a)(5); and (4) Results of the free product investigations. . .”

- §280.64 Free product removal

“At sites where investigations under §280.62(a)(6) indicate the presence of free product, owners and operators must remove free product to the maximum extent practicable as determined by the implementing agency while continuing, as necessary, any actions initiated under §§280.61 through 280.63, or preparing for actions required under §§280.65 through 280.66. In meeting the requirements of this section, owners and operators must: . . . (d) Unless directed to do otherwise by the implementing agency, prepare and submit to the implementing agency, within 45 days after confirming a release, a free product removal report that provides at least the following information: . . . (2) The estimated quantity, type, and thickness of free product observed or measured in wells, boreholes, and excavations;”

- §280.65(a) Investigation for soil and ground water cleanup

“In order to determine the full extent and location of soils contaminated by the release and the presence and concentrations of dissolved product contamination in the groundwater, owners and operators must conduct investigations of the release, the release site, and the surrounding area possibly affected by the release. . .”

- §280.66(b)(1-6) Corrective Action Plan

“In making this determination, the implementing agency should consider the following factors as appropriate: (1) The physical and chemical characteristics of the regulated

substance, including its toxicity, persistence, and potential for migration; (2) The hydrogeologic characteristics of the facility and the surrounding area; (3) The proximity, quality and current and future uses of nearby surface water and ground water; (4) The potential effects of residual contamination on nearby surface water and ground water; (5) An exposure assessment; and (6) Any information assembled in compliance with this subpart.”

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4. Lateral Inclusion Zone

Description

The lateral inclusion zone is the area surrounding a contaminant source through which vapor-phase contamination may travel and intrude into buildings. Determination of the lateral distance within which buildings and other structures may be threatened by PVI is site-specific. In general, with increasing confidence in the site characterization and the CSM, there can be a corresponding decrease in the distance the lateral inclusion zone extends from clean monitoring points.²⁵ All buildings within the lateral inclusion zone should be further assessed to determine if they are separated from vapor sources by an adequate vertical separation distance (see **Section 5**, p.48). Further assessment may be unnecessary for those buildings outside the lateral inclusion zone unless preferential transport pathways are present. If contaminated groundwater is the source of vapors, migration of the contaminant plume (in the longitudinal, transverse, and vertical directions) should be assessed when evaluating the potential for future risks.

Importance

The lateral inclusion zone is a screening criterion to help determine which sites should definitely be assessed further for PVI; which sites might need additional site characterization and assessment for PVI; and which sites can reliably be excluded from consideration for further evaluation of PVI. All buildings that overlie, or are reasonably expected to overlie, contamination, whether LNAPL or the dissolved phase, are considered to be within the lateral inclusion zone.

Assessment

Lateral separation distance is schematically depicted in **Figure 5**. Though in theory the length of the lateral separation distance may be on the same scale as the vertical separation distance (EPA, 2013a; ITRC, 2014), a greater lateral distance is generally warranted in the down gradient direction (Lahvis, et al, 2013; EPA, 2013a). This is because the lateral boundaries of a migrating plume are more difficult to accurately delineate, as they are not stationary. Groundwater elevations fluctuate which may result in changes in the direction and velocity of groundwater flow. The lateral and down gradient investigation should continue until the full extent and location of contamination is determined. This is typically achieved by surrounding the dissolved-phase plume with clean monitoring points.

Both mobile LNAPL and dissolved contaminant plumes are dynamic and may move from one monitoring event to the next. As discussed in **Section 7** (p.61), periodic monitoring of groundwater flow directions and plume migration should be conducted, possibly over more than one annual cycle.

²⁵ A *monitoring point* is defined as a sampling point at which soil and groundwater samples are collected (typically from monitoring wells, though not exclusively) and which define the full extent and location of contamination. A *clean monitoring point* is defined by dissolved benzene concentration less than 5 µg/L and soil TPH concentration less than 20 mg/Kg.

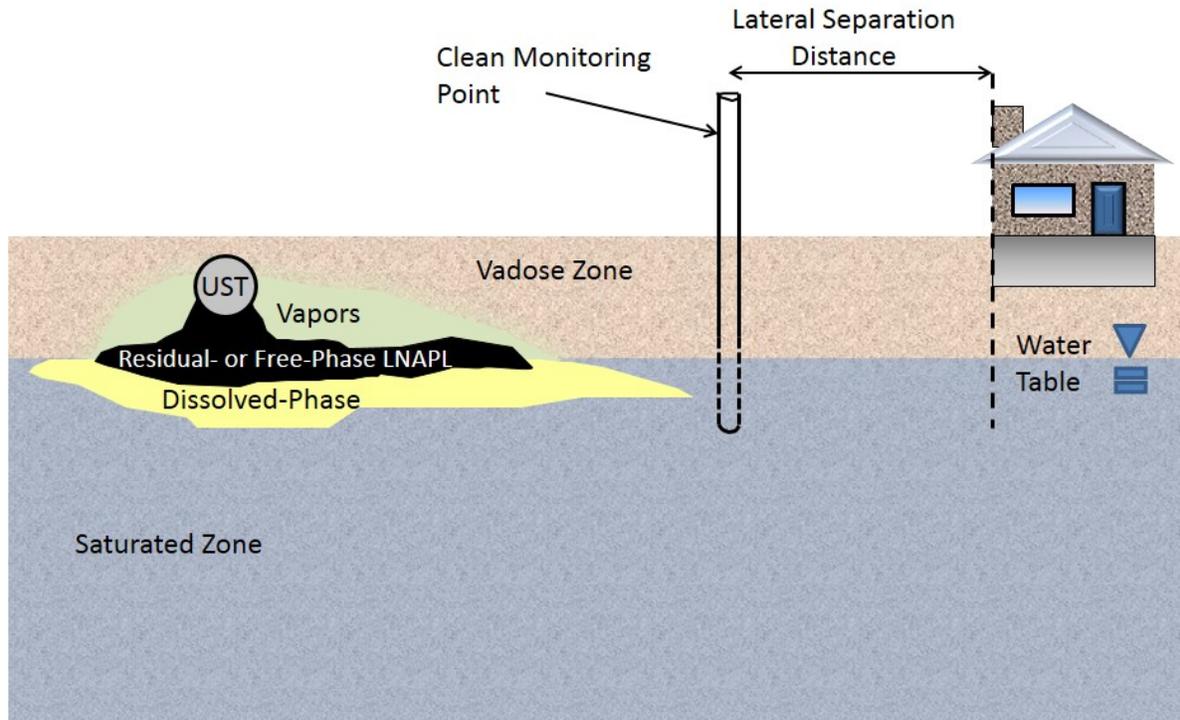


Figure 5. Lateral Separation Distance Between Source Of PHC Contamination And Hypothetical Receptor

Special Considerations

It can be difficult to accurately determine the exact location of contamination relative to potential receptors. This is in part due to the dynamic nature of contaminant plumes (both LNAPL and dissolved PHCs); the presence of heterogeneities and preferential transport pathways in geologic material; and the distance between monitoring points, such as soil borings and monitoring wells. It may be necessary to assess some nearby buildings for PVI before all site characterization activities have been completed.

It is important to consider whether, and what type of preferential transport pathways are present and could facilitate the migration of petroleum vapors. The presence of preferential transport pathways may circumvent the protectiveness that a sufficiently thick layer of clean, biologically active soil would otherwise provide. Preferential transport pathways such as utility conduits typically enter buildings through holes in the foundation or slab and can facilitate the entry of PHC vapors into the building. For example, if the transport of vapors from the source

area to the building could occur along utility conduits, then vapor sampling inside those utility conduits (e.g., sewers) should be considered. Field instrument screening at utility access points may help determine if the utility is acting as a conduit for vapors. Although specific guidance for utility sampling is beyond the scope of this document, EPA recommends that any utility sampling program include safety precautions to protect personnel (e.g., oxygen and combustible gas monitoring, confined-space entry requirements) and to avoid damage to utilities. For guidance on utility sampling, see *A Practical Strategy for Assessing the Subsurface Vapor-to-Indoor Air Migration Pathway at Petroleum Hydrocarbon Sites* (API, 2005).

Lateral separation distances that are usually protective against PVI may not be sufficiently protective in situations where methane is produced in large quantity, such as sites where high-ethanol blends of gasoline (i.e., E-20 or greater) have been released (Ma et al., 2014), and at sites where non-PHC fuel additives are present (see **Section 10**, p.81). In both of these cases, additional investigation should be conducted to assess the potential for vapor intrusion.

Another consideration is changing site conditions. Factors to consider in deciding whether to include sites for further evaluation of PVI may include future land use—that is, whether: future new buildings will be constructed within the lateral inclusion zone, utility trenches will be excavated through or near previous contamination, groundwater usage will potentially be increased, and additional releases of contaminants may occur.

Recommendation

Delineation of a lateral inclusion zone is site-specific. EPA recently published *An Approach for Developing Site-Specific Lateral and Vertical Inclusion Zones within which Structures Should be Evaluated for Petroleum Vapor Intrusion due to Releases of Motor Fuel from Underground Storage Tanks* (EPA, 2013b). This Issue Paper describes a procedure for constructing a lateral inclusion zone that decision makers may find useful. EPA recommends that all buildings within the lateral inclusion zone be further assessed to determine if they are separated from vapor sources by an adequate vertical separation distance. Further assessment may be unnecessary for those buildings outside the lateral inclusion zone unless:

- Preferential transport pathways are present that connect PHC vapor sources to receptors
- Impermeable surface cover (e.g., concrete, asphalt, ice, very large buildings) is so extensive that there is concern whether there is sufficient oxygen in the subsurface to support biodegradation
- Soil conditions are inhospitable to microorganisms (e.g., dry soils with less than 2 percent soil moisture by dry weight) such that biodegradation is insufficient to mitigate the threat of PVI

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5. Vertical Separation Distance

Description

The vertical separation distance is the thickness of clean, biologically active soil (see **Section 9**, p.75) between the highest vertical extent of a contaminant source and the lowest point of an overlying building. This lowest point could be a building basement floor, foundation, or crawlspace surface.

Importance

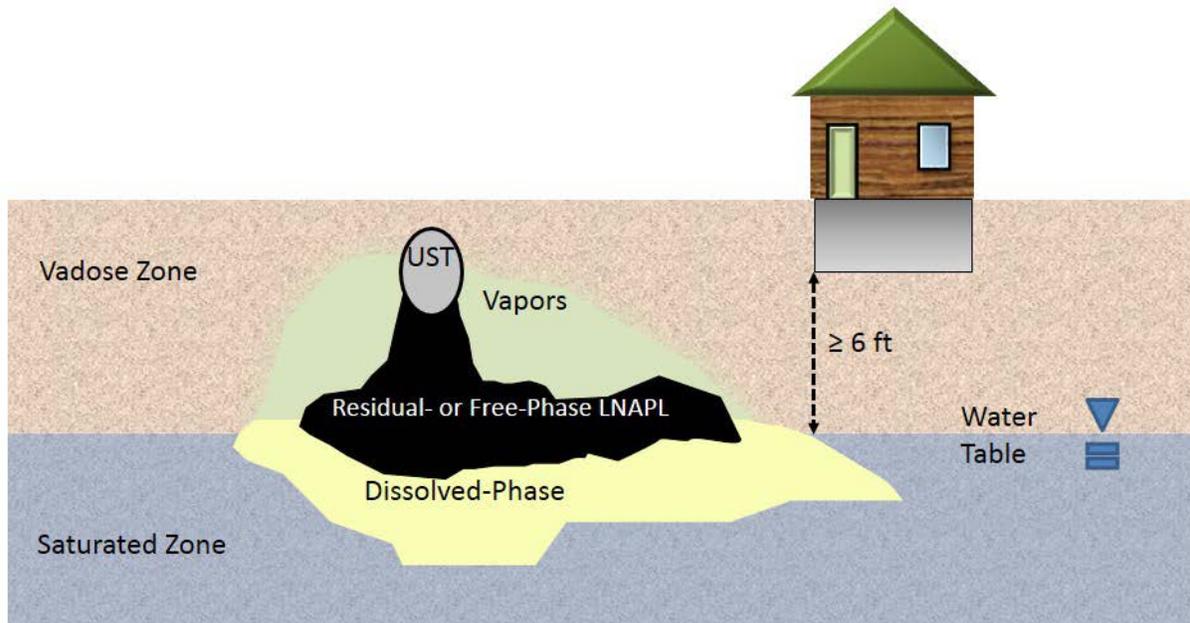
If the thickness of clean, biologically active soil is sufficient and oxygen and soil moisture are present, aerobic biodegradation will usually degrade vapor-phase PHCs before they can intrude into buildings. EPA (2013a) presents a compilation and analysis of soil gas data from a large number of sites that represent many different hydrogeologic settings where gasoline was released from USTs.²⁶ This analysis builds on the work of Davis (2009, 2010, 2011a, and 2011b). In addition, EPA (2013a) summarizes the results of a number of parallel efforts (Lahvis, et al., 2013; Peargin and Kolhatkar, 2011; Wright, 2011, 2012). Although these studies used somewhat different data sets, there is a high degree of consistency among them. This consistency supports the establishment of vertical screening distances based on whether PHC contamination is present as LNAPL or dissolved PHCs; that is, the thickness required to aerobically biodegrade PHCs is directly related to the strength of the source. Because LNAPL sources are capable of producing higher concentrations of vapors compared to dissolved sources, the necessary separation distance between receptors and LNAPL is greater than the necessary separation distance between dissolved sources and receptors. At sites where non-PHC fuel additives are present (see **Section 10**, p.81), the vertical separation distance may not be sufficient to protect against vapor intrusion. In this case, additional investigation should be conducted to assess the potential for vapor intrusion.

Assessment

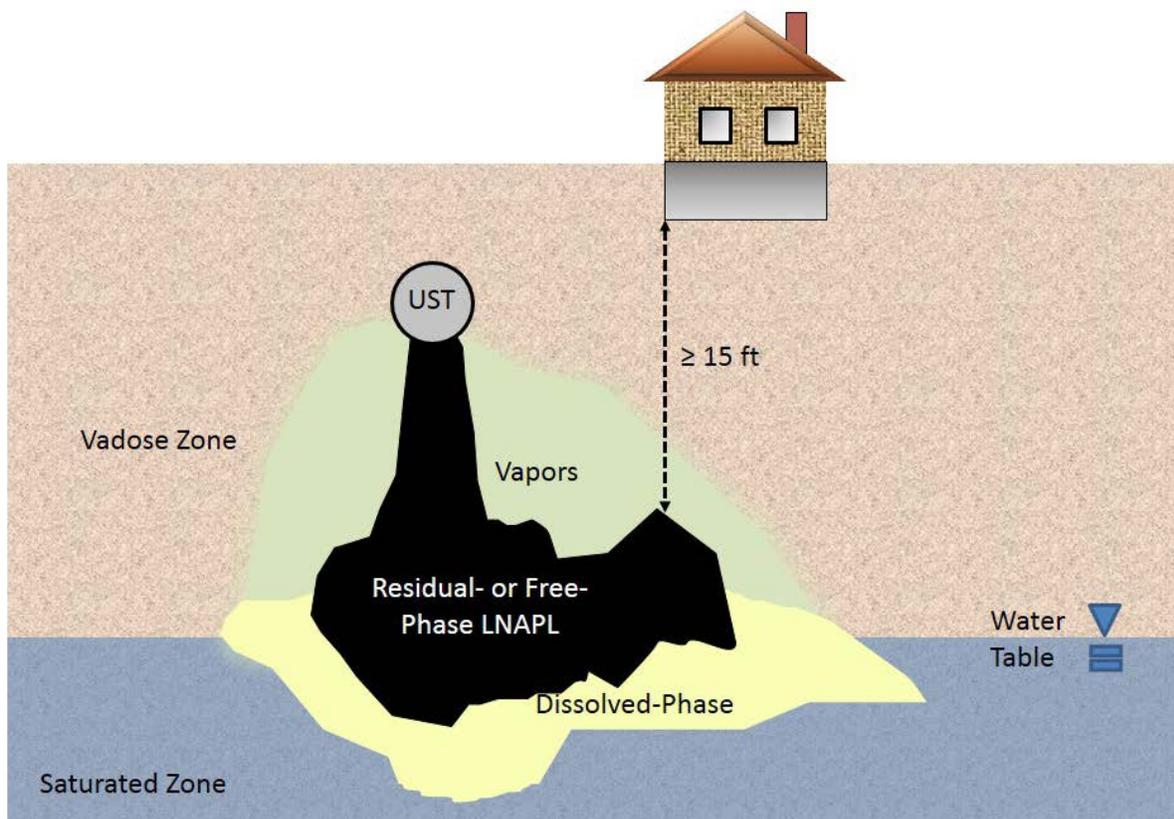
The vertical separation distance is measured from the lowest point of the overlying building basement floor, foundation, slab, or crawlspace surface and the highest vertical extent of contamination. For dissolved sources this is the historic high water table elevation; for LNAPL sources this is the top of the smear zone or residual LNAPL in the source area. Vertical separation distances for dissolved plumes and LNAPL sources are schematically depicted in **Figure 6a and 6b**, respectively. Both mobile LNAPL and dissolved contaminant plumes are dynamic and may move from one monitoring event to the next. As discussed in **Section 7** (p.61), periodic monitoring of groundwater flow directions and plume migration are recommended, possibly over more than one annual cycle.

The presence of LNAPL may be determined from direct or indirect evidence. Direct evidence includes measureable accumulations of free product in monitoring wells, an oily sheen or floating globules on the water table, and petroleum hydrocarbon-saturated bulk soil samples.

²⁶ The final report (EPA, 2013a) addresses the peer review comments received. The report, database, and peer review record are accessible on EPA's PVI Compendium Web page: <http://www.epa.gov/oust/cat/pvi/index.htm>.



(a) Vertical separation distance for dissolved-phase source of PHCs.



(b) Vertical separation distance for LNAPL (residual or mobile phase) source of PHCs.

Figure 6. Vertical Separation Distances Between Source Of PHC Contaminants And Hypothetical Receptor: (a) Dissolved Source, (b) LNAPL Source.

Lahvis et al. (2013) caution that the presence or absence of free-phase LNAPL in monitoring wells may not be a reliable indicator of the presence of residual-phase LNAPL. The absence of LNAPL can only be determined through analysis of core samples. This is important to recognize because free-phase and residual LNAPL have a greater vapor-generating capability than dissolved sources. Indirect evidence includes high concentrations of benzene and other PHCs, often measured as TPH.²⁷ There is considerable variation and uncertainty in LNAPL thresholds determined from indirect evidence and Lahvis et al. (2013) suggest that multiple indicators of the presence of LNAPL be evaluated. EPA (2013a) selected a benzene concentration of 5 mg/L to differentiate between dissolved and LNAPL sources. A study by Peargin and Kolhatkar (2011) suggests that a dissolved source with benzene greater than 1 mg/L may behave like a LNAPL source in terms of vapor-generating capability. For more information on indicators of LNAPL, see **Section 6** (p.57).

Special Considerations

Preferential transport pathways such as utility conduits typically enter buildings through holes in the foundation or slab and can facilitate the entry of PHC vapors into the building. Consideration should be given to field instrument screening at utility access point(s) as an initial step to determine if the utility is acting as a conduit for vapors. If the transport of vapors from the source area to the building could occur along utility conduits, then vapor sampling inside the utility conduits, manholes, or sumps should be considered in addition to vadose zone and sub-slab soil gas sampling. Any utility sampling program should include safety precautions to protect personnel (e.g., oxygen and combustible gas monitoring, confined-space entry requirements) and to avoid damage to utilities. Specific guidance for utility sampling is available in *A Practical Strategy for Assessing the Subsurface Vapor-to-Indoor Air Migration Pathway at Petroleum Hydrocarbon Sites* (API, 2005).

Vertical separation distances that are usually protective against PVI may not be sufficiently protective in situations where methane is produced in large quantity, such as sites where high-ethanol blends of gasoline (i.e., E-20 or greater) have been released (Ma et al., 2014), or beneath very large buildings, or where the ground surface is covered by extensive impermeable material (e.g., pavement) (EPA, 2013c).

In addition, consideration should be given to whether future new buildings will be constructed within the lateral inclusion zone and whether they may be impacted by PVI.

²⁷ Toxicological data for TPH fractions may be found in EPA (2009, 2013b), ATSDR (1999), Tveit et al. (1999), and HI DOH (2012). More recently, Brewer et al. (2013) have developed a quantitative method for risk-based evaluation of TPH in PVI investigations.

Recommendation

EPA recommends using the criteria presented in **Table 3** to determine the necessary vertical separation distance between PHC contamination from leaking USTs and an overlying building foundation, basement, or slab. These distances are 6 feet for dissolved vapor sources (beneath buildings of any size) and 15 feet for LNAPL sources (beneath buildings up to 66 feet on the shortest side).²⁸ Where the respective vertical separation distance is met or exceeded, generally no further investigation for PVI is necessary if there are no precluding factors present (e.g., preferential transport pathways) and the PCH source is not a high-ethanol blend (i.e., E-20 or greater) of gasoline. If the applicable separation distance is not met and where contamination is not in direct contact with an overlying building, then choose one of two options: (1) collect near-slab (exterior) shallow soil gas samples paired with deep (source) soil gas samples, or (2) collect indoor air samples paired with sub-slab soil gas samples. If the potential for PVI cannot be ruled out based on near-slab and deep soil gas sampling, then EPA recommends indoor air sampling paired with sub-slab vapor sampling. If the attenuation factor calculated from results of analysis of the chosen pair or vapor samples indicates that there may be a potential for PVI above applicable exposure limits, EPA recommends gathering additional information and data to determine whether mitigation is appropriate.

Although biodegradation is known to occur for many individual non-PHC fuel additives and classes of additives, the rate of biodegradation in soil gas has not necessarily been rigorously quantified; this is especially true for the lead scavengers EDB and 1,2-DCA. Therefore, for these two chemicals in particular, vertical separation distances recommended in this guide may not be sufficient for petroleum fuel releases that contain EDB and 1,2-DCA and additional investigation may be necessary to assess their potential for vapor intrusion (See **Section 10**, p.81 for more information).

²⁸ See *3-D Modeling of Aerobic Biodegradation of Petroleum Vapors: Effect of Building Area Size on Oxygen Concentration Below the Slab* (EPA 510-R-13-002)(EPA, 2013c).

Table 3. Recommended Vertical Separation Distance Between Contamination And Building Basement Floor, Foundation, Or Crawlspace Surface.

Media	Benzene	TPH	Vertical Separation Distance (feet)*
Soil (mg/Kg)	≤10	≤ 100 (unweathered gasoline), or ≤ 250 (weathered gasoline, diesel)	6
	>10 (LNAPL)	> 100 (unweathered gasoline) >250 (weathered gasoline, diesel)	15
Groundwater (mg/L)	≤5	≤30	6
	>5 (LNAPL)	>30 (LNAPL)	15

The thresholds for LNAPL indicated in this table are indirect evidence of the presence of LNAPL. These thresholds may vary depending on site-specific conditions (e.g., soil type, LNAPL source). The value of 5 mg/L benzene is from EPA (2013a, p.31). A study by Peargin and Kolhatkar (2011) suggests that a dissolved source with benzene greater than 1 mg/L may behave like a LNAPL source in terms of vapor-generating capability. Decision-makers may have different experiences with LNAPL indicators and may use them as appropriate. For more information, see **Section 6** (p.57) and **Figure 7** in particular.

Bulk soil samples should be analyzed for Total Petroleum Hydrocarbon (TPH) and BTEX (plus any other potential contaminants). The objective of measuring TPH is to quantify the total vapor phase concentration of PHCs. TPH may be analyzed by methods appropriate for the type of fuel released. These methods may be designated as TPH-gasoline (or sometimes gasoline range organics or GRO), TPH-diesel (or sometimes diesel range organics or DRO). Method TO-15 (see <http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-15r.pdf>) by itself only measures a small fraction of PHCs that may be present in the vapor-phase. TO-15 analyses require a correction factor to estimate bulk TPH. An extended TO-15 analysis can provide such an estimate. For more information on TPH in vapor intrusion studies, see Brewer et al. (2013).

*The vertical separation distance represents the thickness of clean, biologically active soil between the source of PHC vapors (LNAPL, residual LNAPL, or dissolved PHCs) and the lowest (deepest) point of a receptor (building basement floor, foundation, or crawlspace surface).

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6. Mobile And Residual Light Non-Aqueous Phase Liquid (LNAPL)

Description

LNAPLs released from petroleum USTs are typically fuel products such as gasoline and diesel fuel. Fuel products are comprised of a large number of volatile and semi-volatile PHCs and synthetic additives. Among these compounds are some that are volatile and some that are semi-volatile. Newer, unweathered releases typically contain a higher proportion of more volatile PHCs than do older releases that may be more weathered and depleted in the more volatile PHCs. Similarly, gasoline contains a higher proportion of more volatile PHCs than does diesel fuel and other middle distillates such as heating oil and kerosene. Vapors emanating from dissolved-phase sources are primarily BTEX and other aromatic hydrocarbons, and relatively water-soluble PHCs. Vapors emanating from LNAPL sources contain the same constituents in addition to a sizeable fraction of aliphatic and relatively insoluble hydrocarbons (e.g., naphthalene), especially if the source is large or unweathered (Lahvis, et al., 2013; EPA, 2013).

Importance

Depending upon the volume of the release and the characteristics of the soil, PHC vapors from LNAPL sources can reach concentrations high enough to deplete oxygen needed by microorganisms to biodegrade them. Compared to a dissolved plume, a LNAPL plume from a leaking UST does not typically migrate far from the site of release (e.g., the leaking UST or connected piping). However, the larger the mass of the release the greater the potential for the LNAPL plume to migrate. When LNAPL underlies a receptor or comes into direct contact with a basement, foundation, or slab, there is increased potential for explosive levels of vapors to accumulate within the building or other structure.

Residual PHCs are non-mobile in the subsurface and occur when the release stops prior to the accumulation of a sufficient amount of LNAPL for flow to occur, or when a fluctuating water table smears the LNAPL across the water table and reduces the LNAPL saturation of the soil. This smearing inhibits the lateral migration of LNAPL. Although residual contamination is not free flowing, residual sources represent a large mass of contaminants that can persist for long periods of time and generate considerable volumes of PHC vapors as well as dissolved-phase contaminants.

Monitoring wells with residual LNAPL may not have a measurable accumulation of LNAPL so they look exactly like monitoring wells with only dissolved contamination (that is, there is no measurable LNAPL in the monitoring well). However, due to the presence of residual LNAPL, the vapor source area acts like a free-phase LNAPL source in terms of vapor-generating character (Lahvis, et al., 2013). A study by Peargin and Kolhatkar (2011) suggests that a dissolved source with benzene concentration greater than 1 mg/L may have the same vapor-generating capacity as a LNAPL source. This situation is depicted in **Figure 7**.

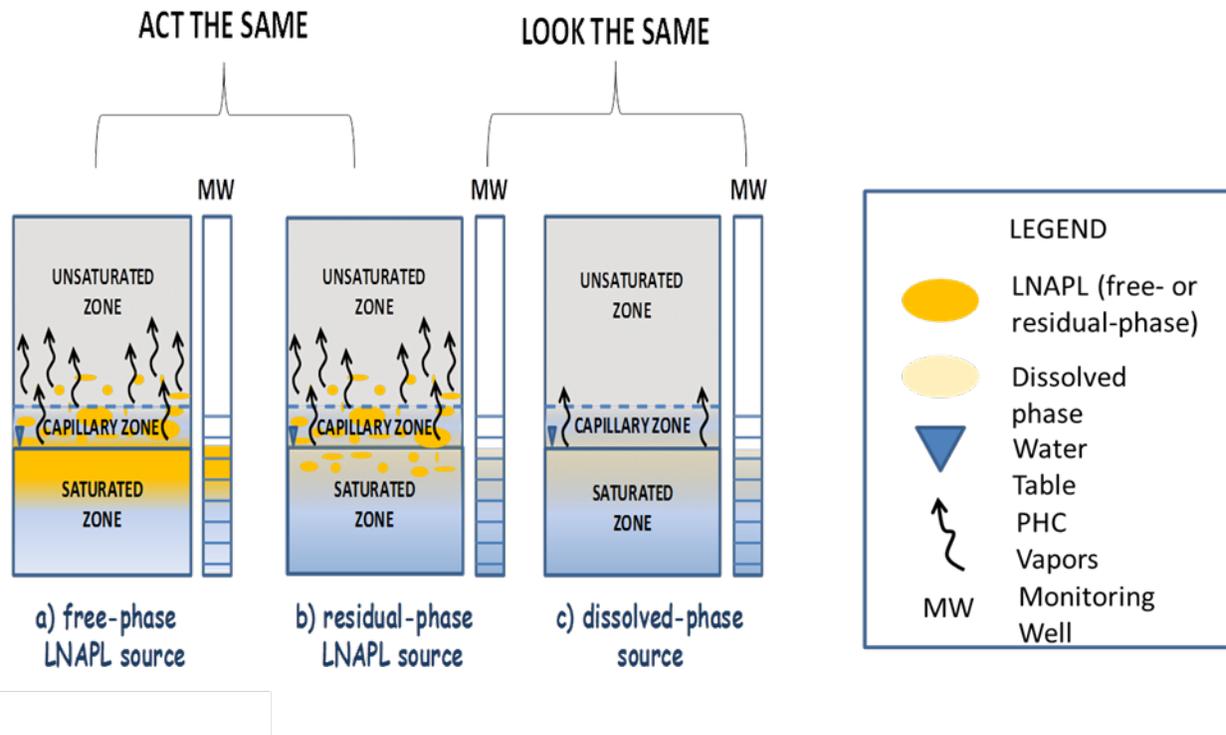


Figure 7. Conceptual Model Illustrating The Potential For Vapor Intrusion For a) Free-Phase LNAPL Source, b) Residual-Phase LNAPL Source, And c) Dissolved-Phase Source (Source: Lahvis, et al., 2013. Reprinted from *Groundwater Monitoring & Remediation* with permission of the National Ground Water Association. Copyright 2013.)

Assessment

The distinction between petroleum contamination present as LNAPL and contamination present purely as a dissolved phase is important. Unfortunately, there is no precise concentration threshold between dissolved phase PHCs and PHCs present in a mixed phase that includes LNAPL.²⁹ EPA (2013) used a threshold for the benzene groundwater concentration equal to 5 mg/L and a total petroleum hydrocarbon (TPH) threshold groundwater concentration of 30 mg/L for identification of LNAPL sites. The TPH threshold adopted by EPA (2013) is based on the calculated approximate average ratio of the concentration of benzene to TPH in groundwater at UST sites. A site with a LNAPL source was identified on the basis of either the benzene or TPH groundwater concentration exceeding the threshold. The thresholds adopted for identifying LNAPL sites based on soil concentrations are 10 mg/Kg benzene, 100 mg/Kg TPH for unweathered gasoline, and 250 mg/Kg TPH for diesel or weathered gasoline.

²⁹ Table 4 in EPA (2013) presents a variety of direct and indirect indicators of LNAPL. For example, Bruce, et al. (1991) suggest groundwater concentrations greater than one-fifth (0.2) of the effective solubility of LNAPL as indirect evidence of the presence of LNAPL. However, because the effective solubility depends on characteristics of the LNAPL mass (e.g., composition, weathering); there is uncertainty in the threshold. Additional discussions of screening concentrations for LNAPL are presented in *Evaluating Hydrocarbon Removal from Source Zones and its Effect on Dissolved Plume Longevity and Concentration* (API, 2002), and ITRC (2014).

Special Considerations

Direct means for detecting the presence of LNAPL include measurable accumulations of free product in monitoring wells, an oily sheen on the water, and saturation of bulk soil samples.³⁰ The presence of residual LNAPL may not be recognizable from monitoring well data. This is because the soil is not sufficiently saturated with LNAPL to allow it to flow into wells. Lahvis et al. (2013) suggest that multiple indicators (both direct and indirect) be evaluated to determine whether or not LNAPL is present.

Recommendation

EPA recommends subsurface sampling to determine the full extent and location of LNAPL (both mobile LNAPL and residual). LNAPL may be present even when there is no measureable accumulation of free product in a monitoring well. In addition, federal regulations (40 CFR 280.64) require that when free product is present, it must be “removed to the maximum extent practicable as determined by the implementing agency.” Effective source removal will mitigate a long term source of PHC vapors as well as mitigate dissolved and residual LNAPL contamination.

EPA recommends analyzing bulk soil samples collected in the source area for TPH (e.g., gasoline or diesel depending on which fuels were stored on site) and specific petroleum constituents (e.g., BTEX and other volatile and semi-volatile organic chemicals, and fuel additives). EPA also recommends analysis of LNAPL samples (if present) to determine the degree of weathering and potential for vapor generation.

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³⁰ Consistent with the findings in EPA (2013) EPA recommends that these same thresholds also be applied for PVI investigations conducted using this guide. These thresholds are presented in **Table 3** in **Section 5** (p.52).

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7. Groundwater Flow And Dissolved Contaminant Plumes

Description

Contaminant plumes are dynamic, three-dimensional distributions of contaminants in groundwater. Contaminants dissolved in groundwater can migrate with flowing groundwater thereby spreading contamination. In some aquifers, where the direction and speed of groundwater flow are stable, the plumes are usually long and narrow. Other plumes appear to spread in both the transverse as well as the longitudinal direction. This apparent transverse dispersion may be the direct result of changes in the direction of groundwater flow. What may appear to be transverse dispersion is actually longitudinal dispersion occurring in different directions as the direction of flow changes (EPA, 2005; Wilson, 2003).

Importance

The potential for PVI from dissolved PHC contaminant plumes is typically limited to sites where there are high concentrations of dissolved contaminants or the plume is in direct contact with a building foundation, basement, or slab. A study by Peargin and Kolhatkar (2011) suggests that a dissolved source with benzene greater than 1 mg/L may have the same vapor-generating capacity as a LNAPL source.

Assessment

Contaminant plumes generally necessitate three-dimensional monitoring to assess the transient behavior of groundwater flow and the movement of contaminant plumes (EPA, 2004a, b). Contaminant plumes migrate with flowing groundwater, which can exhibit seasonal variations as well as responses to pumping, tides, or stage of a nearby river.³¹ Groundwater flow directions can and often change over time, and may necessitate periodic monitoring over more than one annual cycle to understand the groundwater flow regime at a given site.

(Note: This monitoring need not delay additional investigation activities and measures to mitigate or remediate threats to safety and health.) As the plume migrates, appropriate adjustments to the sampling plan should be made to ensure that potential receptors are

³¹ Groundwater flow directions can change frequently and relatively quickly. Changes in groundwater flow directions may be more prevalent than is realized, because the variation in the direction of groundwater flow is rarely evaluated in any formal way (EPA, 2005). Wilson (2003) studied data from a site in North Carolina where groundwater flow was influenced by the stage of a nearby river. Over the course of one year of monthly monitoring, groundwater flow directions fluctuated by 120 degrees. Wilson et al. (2005) also studied data from a gas station site in New Jersey. Over a six-year period groundwater monitoring data were collected on 23 occasions; the predominant flow direction was 90-degrees from the presumed direction on which the conceptual model was constructed, and the direction of flow fluctuated by nearly 180 degrees. Mace et al. (1997) studied the variation in groundwater flow directions at 132 gas stations in Texas. Fluctuations in flow directions occurred over a range of 120 degrees. Goode and Konikow (1990) characterized a site where PHCs leaked to the water table. Groundwater flow directions changed nearly 90 degrees in less than four months in response to changing flow conditions in a nearby intermittent stream.

protected. If new PHC releases to groundwater occur, then appropriate mitigation steps can be implemented.

Plume monitoring networks should be able to detect changes in plume boundaries as well as fluctuations in the concentrations of geochemical parameters and contaminant concentrations. Collection of samples from the contaminant plume is needed to determine the extent of contamination and provide information that can be used to estimate the vapor generation capacity of the dissolved contamination. The contaminant plume should be surrounded by sampling points that are free of contamination (i.e., *clean monitoring points*).

Conventional monitoring wells may provide an incomplete picture of the true distribution of contaminants in groundwater. If the length of the screen in a monitoring well is long compared to the thickness of the plume of contamination, the sample obtained will be diluted by the inflow of clean(er) groundwater from above or below the plume. Also, plumes may dive below the screened interval of the wells leading to the false impression that the plume is shorter than it actually is (EPA, 2005).

Special Considerations

Dissolved plumes are dynamic and contamination may migrate beneath buildings over time. This is best evaluated by determining the range of fluctuation in groundwater flow direction and water table elevations beneath buildings over at least one annual cycle. However, in the interim, the remaining PVI-related activities should continue. Preferential transport pathways, if present, may facilitate the intrusion of petroleum vapors into buildings.³² When contaminant plumes intersect preferential transport pathways, the spread of contamination can be very rapid compared to the velocity of groundwater flow through the soil.

Volatilization of contaminants from the plume into soil gas is greatly reduced when a plume dives beneath the water table surface. Volatile contaminants diffuse more slowly through the water column than through soil gas.

Recommendation

EPA recommends groundwater monitoring and sampling to determine the depth to contaminated groundwater and the vertical distribution of contaminants in the water column beneath overlying buildings³³. Due to the transient nature of groundwater migration, EPA recommends periodic monitoring and sampling over more than one annual cycle to fully

³² Dissolved petroleum contaminants may threaten building inhabitant's health through their water supply rather than through vapor intrusion. Exposure may occur from wells drawing from a contaminated plume, or contamination permeating the water supply piping. Though fuel constituents generally impart a disagreeable odor and taste, building occupants may still be exposed to potentially harmful levels of contaminants. Such exposure may occur when PHCs volatilize from the dissolved phase during showering or washing clothes and dishes, or through ingesting contaminated water. Identifying the mechanism of exposure is important because methods for remediation/mitigation of PVI will be different than treatment or remediation of contaminated groundwater.

³³ If groundwater samples contain greater than 30 mg/L TPH (or greater than 5 mg/L benzene), it is possible that residual LNAPL is present (see **Section 6**, p.57).

understand the groundwater flow regime at a given site. Where the respective vertical separation distance (see **Section 5**) is met or exceeded, generally no further investigation for PVI is necessary if there are no precluding factors present (e.g., preferential transport pathways) and the PCH source is not a high-ethanol blend (i.e., E-20 or greater) of gasoline. If the applicable separation distance is not met and where contamination is not in direct contact with an overlying building, then choose one of two options: (1) collect near-slab (exterior) shallow soil gas samples paired with deep (source) soil gas samples, or (2) collect indoor air samples paired with sub-slab soil gas samples. If the potential for PVI cannot be ruled out based on near-slab and deep soil gas sampling, then EPA recommends indoor air sampling paired with sub-slab vapor sampling. If the attenuation factor calculated from results of analysis of the chosen pair or vapor samples indicates that there may be a potential for PVI above applicable exposure limits, EPA recommends gathering additional information and data to determine whether mitigation is appropriate.

Even in cases where there is no threat of PVI from contaminated groundwater, EPA recommends that the plume be assessed to determine if remediation is necessary to prevent ingestion of contaminated drinking water and protect and restore actual or potential sources of drinking water.

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8. Soil Gas Profile

Description

Aerobic biodegradation of PHC vapors occurs in many subsurface environments (Lahvis, Baker, and Behr, 1998; McHugh, et al., 2010; Roggemans, 1998; Roggemans, Bruce, and Johnson, 2002; ZoBell, 1946; Atlas, 1981; Leahy and Colwell, 1990; DeVaul, 2007). The soil gas profile can provide confirmation that aerobic biodegradation is occurring in the subsurface.

Decreasing oxygen concentration and increasing carbon dioxide and methane concentrations indicate biodegradation of PHCs (Hult and Grabbe, 1988). Shallow soil gas typically contains water vapor and fixed gases: nitrogen, oxygen, carbon dioxide, carbon monoxide, and argon. These gases infiltrate into the soil from the atmosphere. Vapor phase PHC contamination may be the result of volatilization from mobile LNAPL released into the subsurface, residual soil contamination (including the smear zone), and dissolved phase contamination. The lower proportion of volatile hydrocarbon compounds in diesel fuel will lead to a comparatively smaller vapor plume in comparison to the release of a similar volume of gasoline (Prince and Douglas, 2010; Marchal, et al., 2003). In addition to PHCs, soil gas may also contain degradation products from the breakdown of PHCs and naturally occurring organic matter. The principal gases resulting from the biodegradation of PHCs are carbon dioxide (under aerobic conditions) or methane (under anaerobic conditions).

Figure 8 presents a characteristic vertical concentration profile in the unsaturated zone; oxygen concentrations decrease with depth and PHCs (including methane) and carbon dioxide

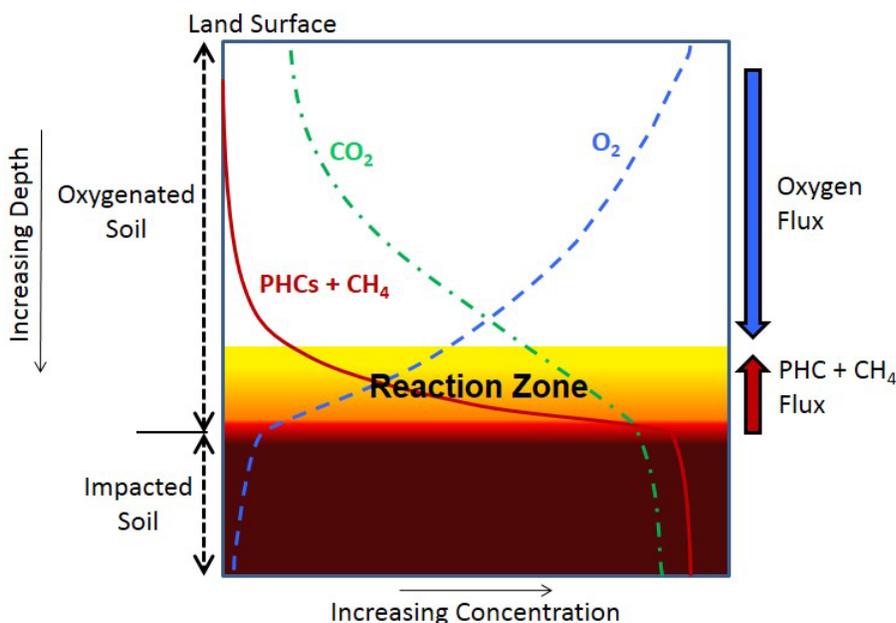


Figure 8. Typical Vertical Concentration Profile In The Unsaturated Zone For PHCs (Plus Methane), Carbon Dioxide And Oxygen

concentrations increase with depth toward the source of contamination. This typical vertical profile may vary somewhat in shape depending on site-specific conditions (Roggemans, Bruce, and Johnson, 2002). During aerobic biodegradation in unsaturated soils, PHCs degrade, oxygen is consumed, and carbon dioxide is produced. The aerobic biodegradation zone is within oxygenated soil (generally greater than 1 percent oxygen in soil gas). In the oxygenated soil zone (where aerobic biodegradation occurs between land surface and the depth of impacted soil) the decrease in PHC concentrations is typically quite rapid and occurs over a narrow interval (the reaction zone in **Figure 8**) (Abreu, Ettinger, and McAlary, 2009).

The impacted soil zone, which is anaerobic, is characterized by the maximum PHC concentrations (and often LNAPL) and biodegradation is slow (EPA, 2012a). Generally, PHC vapor concentrations will be much greater adjacent to a LNAPL source than adjacent to a dissolved hydrocarbon plume. If PHC concentrations are high enough, available oxygen may be depleted, which in turn limits aerobic biodegradation. The core of any PHC contaminant mass is typically depleted with respect to oxygen, thus anaerobic biodegradation of LNAPL or other organic sources (e.g., ethanol) can produce significant amounts of methane (Anderson and Lovley, 1997; Wiedemeier, et al., 1999; Koenigsberg and Norris, 1999; Ma et al., 2014). Methane readily biodegrades under aerobic conditions and, when present, will create an additional oxygen demand (Jewell and Wilson, 2011; Ma, et al, 2012). High concentrations of methane, oxygen, and a source of ignition can create a fire or explosion hazard in confined spaces (e.g., utility vaults and passages, basements, or garages) (Ma et al., 2014). For additional information on evaluating the presence of methane and potential hazards, see ASTM's "*New Practice for Evaluating Potential Hazard Due to Methane in the Vadose Zone*".³⁴

Differences between near-slab soil gas profiles and sub-slab soil gas profiles are reported in two EPA modeling studies: the conceptual model scenarios report EPA (2012b) and the building size modeling report for PVI (EPA, 2013a). However, EPA (2012b) assumed that building foundations, basements, and slabs were impermeable and, thus, oxygen transport was not simulated through the foundation, basement, or slab into the subsurface beneath the building. Simulations presented in EPA (2013a) allowed for oxygen transport using reasonably expected oxygen permeability values for concrete (Fischer et al., 1996; McHugh, DeBlanc, and Pokluda, 2006; Lundegard, Johnson, and Dahlen, 2008; Patterson and Davis, 2009; Tittarelli, 2009). When oxygen transport is accounted for, the differences in soil gas profiles were less pronounced between near-slab and sub-slab samples very close to the building basement and slab. Thus, near-slab soil gas samples can be substituted for sub-slab samples in situations where dissolved contamination is present within 6 feet of (but not in contact with) a building basement floor, foundation, or crawlspace surface, and where LNAPL is present within 15 feet of (but not in contact with) a building basement floor, foundation, or crawlspace surface. For dissolved sources this holds for buildings of any size, and for LNAPL sources it applies to buildings with the shortest side being no longer than 66 feet (EPA, 2013a). Deep soil gas samples are needed to determine the depth to contaminated soil and the thickness of clean,

³⁴ The new ASTM methane guide is accessible at <http://www.astm.org/DATABASE.CART/WORKITEMS/WK32621.htm>

biologically active soil necessary to attenuate PHC vapors. Shallow soil gas samples should be paired with deep (near source) soil gas samples to evaluate the strength of the PHC vapor source and the attenuation of PHC vapors.

Importance

The potential for PVI is a function of the oxygen demand exerted by all biodegradable vapors, not just the key chemicals of potential concern (Jewell and Wilson, 2011; Ma, et al., 2012). When present, volatile PHCs and methane also exert an oxygen demand that may limit aerobic biodegradation of benzene (Abreu, Ettinger, and McAlary, 2009; Wilson, 2011). An estimate of the biodegradation rate can be determined from the stoichiometric relationship between the flux of oxygen, carbon dioxide, and methane (Lahvis and Baehr, 1996). PHC vapor concentrations generally decrease with increasing distance from a subsurface vapor source. At a relatively short distance from the source, concentrations of PHCs in soil gas will typically fall below potentially significant levels of concern provided that oxygen replenishment is adequate to ensure complete aerobic biodegradation. Lahvis, Baehr, and Baker (1999) observed that PHC vapors from a dissolved plume were almost completely degraded within 1 meter (3.3 feet) above the water table and that significant transport of PHC vapors may only be significant if the vapor source is LNAPL. This is consistent with the findings of EPA's (2013b) PVI database analysis report and Lahvis et al. (2013).

Assessment

Soil gas samples provide information on the distribution of contamination near the source area, whether biodegradation is occurring, and how effective it is in reducing the potential for PVI. When there is an impermeable surface cover adjacent to a building, soil gas probes should be installed beneath the surface in order for the soil gas profile to adequately characterize conditions below the surface. For very large buildings, or where there is extensive impermeable surface cover and the vapor source is relatively shallow, additional investigation is recommended to verify that biodegradation is occurring beneath the building.³⁵ Vapor samples should be analyzed for PHCs (and non-PHC fuel additives), methane, oxygen, and carbon dioxide (Lahvis, Baehr, and Baker, 1999).

³⁵ EPA (2013a) presents modeling results for a variety of soil types, building sizes, vapor source strengths, and vertical separation distances. These results, while not exhaustive, indicate that for dissolved sources and very large buildings, an oxygen shadow does not form, thus the subsurface stays sufficiently oxygenated to support aerobic biodegradation and preclude the potential for PVI. For LNAPL sources, an oxygen shadow was not observed to form beneath buildings up to 66 feet on the shortest side. This length represents the threshold below which oxygen replenishment is sufficient to support aerobic biodegradation; above this length oxygen replenishment may be impeded and there may be insufficient oxygen present to support aerobic biodegradation. For larger buildings underlain by LNAPL within 15 feet of the foundation, basement, or slab, sub-slab soil gas sampling paired with indoor air sampling is necessary to assess whether PVI is occurring. Another potential concern for large buildings and extensive, impermeable surface cover (e.g., asphalt, concrete) is formation of a moisture shadow, which represents soil moisture content too low to support microbial biodegradation (see **Section 9**, p.75, for more information).

An estimate of the total oxygen demand can be determined in two ways: sample for methane and petroleum hydrocarbons (PHCs); or sample and measure the oxygen demand for all the organic compounds in the soil gas at the source.³⁶ If methane and all the PHCs in soil gas are measured, these concentrations should be converted to an equivalent concentration of benzene and summed. The total oxygen demand of the aggregate of methane and the PHCs (expressed as an equivalent concentration of benzene) can be used to determine an attenuation factor (α) that can be used along with the actual concentration of benzene in soil gas at the source to determine whether aerobic biodegradation is capable of degrading the PHC vapors to acceptable concentrations (see **Section 12**, p.106, **Figure 9**, p.101, and **Figure 10**, p.103).

In some cases, relatively shallow soil gas samples (less than five feet below ground surface) will be needed to characterize active biodegradation zones in the shallow soil (e.g., in the presence of shallow contamination sources). Some state regulatory programs do not allow soil gas sampling at depths less than 5 feet based on the concern that accurate sampling may not be possible at shallow depths because air from the surface may leak into the sample. However, recent research has shown that the collection of accurate shallow-soil gas samples is possible at depths as shallow as 2 feet below ground surface using appropriate field methods (e.g., leak testing), such as those documented in *Temporal Variation of VOCs in Soils from Groundwater to the Surface* (EPA, 2010). It is also possible under certain conditions to collect representative soil gas samples using previously installed groundwater monitoring wells (see Wilson et al., 2014).

Special Considerations

There are several factors that can limit replenishment of oxygen to deep soils. These include presence of low permeability layers, concrete or asphalt covering at the surface, high soil moisture from a recent rainfall event or from irrigation, and buildings that are so large that oxygen is depleted beneath the center of the building (Patterson and Davis, 2009). However, a recent study by EPA (2013a) indicates that for an oxygen shadow³⁷ to form beneath a building, the PHC vapor source must be shallow LNAPL and the building must be greater than 66 feet in length on the shortest side. For simulations with dissolved sources, no oxygen shadow formed even under a square building with sides that were 2,073 feet in length.

At sites with a new release or unweathered LNAPL source, the oxygen demand will be high. It is important to determine whether temporal variations in oxygen flux into the vadose zone will limit the effectiveness of aerobic biodegradation, potentially resulting in intermittent vapor intrusion impacts. For such sites, more than one round of soil gas monitoring may be needed to confirm that aerobic biodegradation consistently prevents PVI impacts at the site.

³⁶ EPA recommends using modified Method TO-15 (see <http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-15r.pdf>) for organic compounds. The concentration of methane measured as a fixed gas can then be added to the results of TO-15 to give an approximation of TPH.

³⁷ For the purposes of this modeling study, an oxygen shadow is defined as less than 1 percent oxygen.

Recommendation

EPA recommends that soil gas samples be analyzed for PHCs, non-PHC fuel additives, methane, oxygen, and carbon dioxide. Sampling for nitrogen (and other fixed gases) in soil gas can provide a check on the quality of the analyses since the sum of these gases should be 100 percent. If they are substantially less than 100 percent, then some constituents are unaccounted for and the analyses should be interpreted with caution.

For buildings of any size within the lateral inclusion zone if the vertical separation distance between the building basement, foundation, or slab and dissolved contamination is less than 6 feet, but not in contact with the building EPA recommends that near-slab soil gas samples paired with deep (near source) soil gas be collected. For buildings up to 66 feet on the shortest side that directly overlie LNAPL masses, and the vertical separation distance is less than 15 feet (but the building is not in direct contact with LNAPL), EPA recommends collection of near-slab soil gas samples paired with deep (near source) soil gas samples. Near-slab soil gas samples should be collected from each side of the building and as close to the building as practicable. If the attenuation factor calculated from results of analysis of the chosen pair or vapor samples indicates that there may be a potential for PVI above applicable exposure limits, EPA recommends gathering additional information and data to determine whether mitigation is appropriate. If contamination is in direct contact with an overlying building (and thus, collection of shallow soil gas samples is not possible), indoor air sampling is recommended.

In addition, for very large buildings or where there is extensive impermeable surface covering, EPA recommends that near-slab or sub-slab soil gas samples be collected if there is concern that these conditions may impede the flux of oxygen to the subsurface and create an oxygen or soil moisture shadow.

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9. Clean, Biologically Active Soil

Description

For a PVI investigation, clean soil does not necessarily mean that it is contaminant-free, but rather that the level of any contamination present is low enough so that the biological activity of the soil is not diminished and the subsurface environment will support sufficient populations of microorganisms to aerobically biodegrade PHC vapors. This means that LNAPL is not present. The oxygen demand of all of the contamination present in the soil should not deplete the available supply of oxygen to such an extent that the rate of biodegradation is reduced.

Effective aerobic biodegradation of PHCs depends on the soil having sufficient oxygen and enough moisture to provide a habitat for adequate populations of active microorganisms. Although most soils contain indigenous microorganisms capable of degrading PHC vapors, typically there is an acclimation period between the time they are exposed to the PHC vapors and the time they begin to biodegrade the vapors. Prior exposure to PHCs has been observed to both increase the number of microbes and the microbial mass available for biodegradation of the PHCs and consequently speed up the degradation rate (ZoBell, 1946; Moyer, et al., 1996; Phelps and Young, 1999; and Siddique, et al., 2007).

The habitat of soil bacteria is the thin film of water held to the surface of soil particles by capillary attraction. EPA (2013a) notes that soil moisture content greater than 2 percent is adequate to support biodegradation activity (Leeson and Hinchee, 1996), although biodegradation is limited when the moisture content is at or below the permanent wilting point (Zwick, et al., 1995; Holden, Halverson, and Firestone, 1997). Adequate soil moisture is also indicated if the landscape supports the growth of non-irrigated vegetation (Riser-Roberts, 1992).

Certain geologic materials do not qualify as biologically active soil and should not be included in the vertical separation distance (see **Section 5**, p.48). These geologic materials include:

- Coarse sand and gravel with a low content of silt, clay, and organic matter, and low moisture content that is less than 2 percent dry weight
- Fractured, faulted, or jointed consolidated rock
- Consolidated rock with solution channels (i.e., karst)

Importance

Effective aerobic biodegradation of PHCs depends on a thick layer of soil having sufficient oxygen and enough soil water to provide a habitat for adequate populations of active microorganisms. If oxygen is present, these organisms will generally consume available PHCs. Furthermore, aerobic biodegradation of petroleum compounds can occur relatively quickly, with degradation half-lives as short as hours or days under some conditions (DeVaul, 2007).

Some petroleum compounds can also biodegrade under anaerobic conditions; however, above the water table, where oxygen is usually available in the soil zone, this process is less important because it is generally much slower than aerobic biodegradation (Widdel, Boetius, and Rabus, 2006; Bailey, Jobson, and Rogers, 1973; and Bruce, Kolhatkar, Cuthbertson, 2010).

Assessment

Scientific research and site characterizations have demonstrated that microorganisms capable of aerobically degrading many PHCs are present in nearly all subsurface soil environments (ZoBell, 1946; Atlas, 1981; Wilson, et al., 1986; Leahy and Colwell, 1990; Bedient, Rifai, and Newell, 1994; EPA, 1999). A number of well-characterized field studies demonstrate extensive aerobic biodegradation of PHC vapors in unsaturated soils (Kampbell, et al., 1987; Ostendorf and Kampbell, 1991; Ririe and Sweeney, 1995; Ririe, et al., 1998; Ostendorf, et al., 2000; Hers, et al., 2000; Roggemans, Bruce, and Johnson, 2002; Sanders and Hers, 2006; Davis, Patterson, and Trefry, 2009; Patterson and Davis, 2009; Lahvis, Baehr, and Baker, 1999; and Lavhis and Baehr, 1996). Several of these studies document vapor concentrations at least two to three orders of magnitude lower than would be predicted to occur merely by simple diffusion in the absence of biodegradation.

EPA (2013a) presents findings of an analysis of a large number of vapor samples from leaking UST sites. These results, which are consistent with several recent analyses of different PVI databases (and which are summarized in the report), indicate that in most settings, PHC vapors are biodegraded over relatively short distances in clean, biologically active soil.

Special Considerations

Preferential transport pathways are avenues of least resistance to the migration of contaminants whether in the dissolved phase, LNAPL phase, or vapor phase. The presence of preferential transport pathways can increase the speed at which contamination moves through the subsurface such that contaminants may not biodegrade by the time they reach receptors. Preferential transport pathways include both natural and man-made features (e.g., solution channels, gravel layers, utility corridors and excavations). Natural geologic materials such as coarse sand and gravel with a low content of silt and clay; fractured consolidated rock; or consolidated rock with solution channels, may not have enough soil moisture in contact with soil gas to support adequate densities of biologically active microorganisms. Particularly in cases with shallow contamination, site investigations should evaluate whether a sufficiently thick layer of clean, biologically active soil is present below buildings in the lateral inclusion zone.

In addition, beneath very large buildings or under areas of extensive impermeable surface cover, soil moisture content may be lower than optimal³⁸ to support an adequate population of biologically active microorganisms necessary to degrade PHC vapors and prevent PVI (see Tillman and Weaver, 2007; EPA, 2013b).

³⁸ Such reduced soil moisture beneath large buildings is referred to as a *soil moisture shadow*.

Recommendation

Based on EPA (2013a), clean, biologically active soil does not contain LNAPL, EPA recommends LNAPL thresholds of 100 mg/Kg TPH (fresh gasoline) and 250 mg/Kg TPH (weathered gasoline and diesel). Except for the geological materials identified in *Special Considerations*, most soils contain indigenous microorganisms, sufficient oxygen, and adequate soil moisture necessary for degrading PHC vapors. Thus, it is typically not necessary to run microcosm studies or plate counts to test for microbial presence. However, if the conditions at the site are uncertain for supporting aerobic biodegradation, EPA recommends that appropriate samples be collected and analyzed to verify conditions at the site.

Due in part to difficulties in measuring this level of accuracy in the field, EPA recommends vertical separation distances of 6 feet for purely dissolved sources of PHCs and 15 feet for LNAPL sources. These distances are believed to be conservative in most environmental settings. The vertical separation distances described in this guidance (see **Table 3** in **Section 5**, p.52) should not be used at sites where the geologic materials may not have enough soil moisture in direct contact with soil gas. EPA recommends collection and analysis of adequate soil samples for soil moisture, which should be greater than 2 percent by dry weight. In situations where densities of biologically active microorganisms may not be adequate to biodegrade PHCs then soil gas samples should be collected following the recommendations in **Section 8**. If the attenuation factor calculated from results of analysis of the chosen pair or vapor samples indicates that there may be a potential for PVI above applicable exposure limits, EPA recommends gathering additional information and data to determine whether mitigation is appropriate.

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10. Non-PHC Fuel Additives

Description

Petroleum fuels are comprised of hundreds of compounds; both natural components of petroleum as well as a number of synthetic (non-PHC) additives intended to improve certain performance properties of the fuel. Contaminants other than PHCs may be present at a site as the result of releases of petroleum fuels that contain additives, including alcohols (e.g., ethanol and tertiary-butyl alcohol [TBA]), ethers (e.g., MTBE), organic lead (e.g., the tetraalkyl lead compounds: tetraethyl lead [TEL], and tetramethyl lead [TML]), and lead scavengers (e.g., ethylene dibromide [EDB] and 1,2-dichloroethane [1,2-DCA]).³⁹ Non-petroleum contaminants may also be from releases of substances (e.g., chlorinated solvents) other than petroleum fuels. Their presence may be from prior uses of the site or as the result of migration from an off-site source (e.g., dry cleaner, chemical plant, landfill).⁴⁰

Importance

When assessing the potential threat of vapor intrusion, the presence of non-PHC fuel additives may pose a variety of additional challenges. Depending on the class of additive, the challenges include:

- Uncertainty regarding the aerobic biodegradation rates of some additives as well as some that do not biodegrade aerobically (or do not biodegrade quickly enough) in the shallow subsurface
- Biodegradation of an additive such as ethanol that consumes oxygen that would otherwise be available for biodegradation of other PHCs and produces a VOC (methane), which may migrate into buildings and hasten the spread of PHC vapors
- Toxicity levels of some additives are below the detection limit of conventional analytical methods

³⁹ Although leaded gasoline, which also contains the lead scavengers EDB and 1,2-DCA, is no longer used for automotive fuel, it is still used for certain off-road applications such as automobile racing and in aviation fuel (Avgas). At these and older automotive fuel sites where leaded gasoline was released to the subsurface, lead scavengers may be present and could represent a potential source of vapors that should be assessed. For more information about lead scavengers, see Appendix F in *Evaluation Of Empirical Data To Support Soil Vapor Intrusion Screening Criteria For Petroleum Hydrocarbon Compounds* (EPA, 2013).

⁴⁰ While these substances are not the primary focus of a petroleum UST release investigation (including site characterization and subsequent cleanup, if necessary), there is the possibility that their presence may be detected through the use of certain analytical methods for identification of contaminants in groundwater, soil, and vapor samples. In particular, both EPA methods 8260B (EPA, 1996a) and 8021B (EPA, 1996b) can detect a number of volatile chlorinated solvents that are not associated with petroleum fuels or typically stored in USTs. The Leaking Underground Storage Tank Trust Fund cannot be used to assess or cleanup contamination from non-UST and non-petroleum sources. Volatile chlorinated solvents (e.g., PCE, TCE, TCA, Carbon tetrachloride, Chloroform) also do not biodegrade under aerobic conditions, therefore their potential for vapor intrusion should instead be assessed using the *OSWER Final Guidance For Assessing and Mitigating the Vapor Intrusion Pathway From Subsurface Sources to Indoor Air* (OSWER Publication 9200.2-154)(EPA, 2015). Should any contaminants from non-UST sources be discovered at a leaking UST site, contact the appropriate state or federal implementing agency.

The separation distances described in this document (**Section 5**, Table 3, p.52) and the protectiveness provided by clean, biologically active soil against vapor intrusion by PHCs may be insufficient to protect against vapor intrusion by non-PHC fuel additives. Additional investigation should be conducted where certain additives are present. The following narrative provides additional information on several additives and introduces the Vapor Intrusion Screening Levels (VISL) Calculator, which may be particularly useful when investigating vapor intrusion from non-PHC fuel additives.

Although biodegradation is known to occur for many individual additives and classes of additives,⁴¹ the rate of biodegradation in soil gas has not necessarily been rigorously quantified; this is especially true for the lead scavengers EDB and 1,2-DCA. Therefore, for these two chemicals in particular, vertical separation distances recommended in this guide may not be sufficient for petroleum fuel releases that contain EDB and 1,2-DCA and additional investigation may be necessary to assess their potential for vapor intrusion. Note: Though the use of ethers and lead scavengers in gasoline has been reduced or eliminated in recent years, these compounds may still be present at some older petroleum release sites (Weaver, et al., 2005, 2008, 2009; EPA, 2008).

Alternative fuels, especially those that contain higher percentages of ethanol present a challenge because ethanol readily biodegrades to create methane (Jewell and Wilson, 2011; Ma, et al., 2012 and 2014; Freitas, et al., 2010). The use of ethanol in motor fuels is increasing. Methane generation may be more significant at sites where large volumes of ethanol-blended gasoline (and higher ethanol content fuels, greater than E-20) have been released into the subsurface (Ma et al., 2014). Methane production can increase soil gas pressures and may result in advective soil gas flow toward receptors. In such situations, intrusion of methane into confined spaces may result in the accumulation of very high concentrations creating a risk of fire and explosion. In addition, methane also biodegrades under aerobic conditions and depletes oxygen that otherwise could be available for the biodegradation of PHCs.

The depletion of oxygen may result in PHC vapors being transported farther than they otherwise would be, possibly increasing the threat of PVI.

⁴¹ Aerobic biodegradation has been observed for the lead scavengers EDB (Prince and Douglas, 2010; Pignatello, 1986), and 1,2-DCA (Falta, 2004); the ethers MTBE (Prince and Douglas, 2010; Wang and Deshusses, 2007; Phelps and Young, 1999; Landmeyer and Bradley, 2003; Landmeyer, et al., 2010; Bradley and Landmeyer, 2006; Kuder, 2005; Lesser, et al., 2008; Baehr, Charles, and Baker, 2001) and Tertiary-amyl methyl ether (TAME) (Landmeyer, et al., 2010); the alcohols Ethanol (Powers, et al., 2001; Corseuil et. al, 1998), TBA (Wang and Deshusses, 2007; Landmeyer, et al., 2010), and Methanol (Powers, et al., 2001); and some organic lead compounds (Prince and Douglas, 2010; Gallert and Winter, 2004). Although anaerobic biodegradation is slower than aerobic biodegradation, anaerobic biodegradation may be a significant mechanism for destruction of non-PHCs fuel additives (and PHCs, especially in source areas.) Selected references on anaerobic biodegradation of various non-PHC fuel additives are listed under *Additional Information* at the end of this section.

Thus, separation distances that are usually protective against PVI may not be sufficiently protective in situations where methane is produced in large quantity (Ma et al., 2014). For additional information on sampling for the presence of methane, assessing potential risks, and how to manage the risks, see ASTM's "*New Practice for Evaluating Potential Hazard Due to Methane in the Vadose Zone*".⁴²

Finally, in addition to the uncertainties regarding the rates of biodegradation of the lead scavengers EDB and 1,2-DCA, existing analytical methods are not able to detect them at very low concentrations representative of a cancer risk level of 1E-06. However, EPA (2013) suggests that although there are no soil gas data for lead scavengers in the PVI database, "a screening approach is feasible where groundwater concentrations are measured to determine the potential for vapor intrusion risks from EDB and 1,2-DCA." (see Section F.6). This approach is illustrated in the *Assessment* subsection through a sequence of equations and detailed discussion of the results for EDB and 1,2-DCA.

Assessment

Federal UST regulations (40 CFR 280.52(b)) stipulate that when conducting an investigation of a release from a regulated UST, investigators "must measure for the presence of a release where contamination is most likely to be present. In selecting sample types, sample locations, and measurement methods investigators must consider the nature of the stored substance, the type of initial alarm or cause for suspicion, the type of backfill, the depth of groundwater, and other factors appropriate for identifying the presence and source of release". Results of this sampling should also identify which contaminants should be assessed for potential vapor intrusion.

Once the candidate contaminants have been identified, the next step is to determine the target indoor air screening level for each of them. While the federal UST program does not prescribe human health values for contaminants, implementing authorities should use exposure values appropriate for the contaminants present and the characteristics of exposure (e.g., residential vs industrial). EPA provides a source of such exposure values in the Vapor Intrusion Screening Levels (VISL) Calculator.⁴³ VISLs for human health protection are generally recommended, medium-specific, risk-based screening-level concentrations intended for use in identifying areas or buildings that may warrant further investigation and mitigation as appropriate.

These VISLs are calculated and documented in the VISL Calculator and are based on:

⁴² The new ASTM methane guide is accessible at <http://www.astm.org/DATABASE.CART/WORKITEMS/WK32621.htm>

⁴³ The VISL Calculator provides recommended, but not mandatory, screening levels for use in evaluating the vapor intrusion pathway at Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) sites. The user's guide for the VISL Calculator provides additional information about derivation of the indoor air and subsurface screening levels (EPA, 2014a). Both the VISL Calculator (EPA, 2014b) and user's guide may be downloaded from EPA's website: <http://www.epa.gov/oswer/vaporintrusion/guidance.html>.

Current toxicity values selected considering OSWER's hierarchy of sources for toxicity values (EPA, 2003)⁴⁴

- Physical-chemical parameters for vapor forming chemicals
- EPA recommended approaches for human health risk assessment

The VISLs include target indoor air screening levels for long-term (i.e., chronic) exposures that consider the potential for cancer and non-cancer effects of vapor-forming chemicals. The VISLs also include subsurface screening levels for comparison to sampling results for sub-slab soil gas, "near-source" soil gas, and groundwater. These subsurface screening levels are back-calculated from the target indoor air screening levels for chronic exposures using medium-specific, generic attenuation factors that reflect generally reasonable worst-case conditions (EPA, 2015, Appendix B). VISLs are not automatically response action levels, although EPA recommends that similar calculation algorithms be employed to derive cleanup levels (see EPA, 2015, Section 7.6 for more information).

The VISL Calculator allows users to specify an exposure scenario, target risk for carcinogens (TCR) and target hazard for non-carcinogens (THQ), and the average groundwater temperature at a site, and calculates screening levels for the target indoor air concentration, sub slab and exterior soil gas concentrations, and ground water concentration.

In the VISL Calculator, target indoor air concentrations are calculated using the equations presented in **Table 4**. For carcinogens, the inhalation unit risk (IUR) is the appropriate toxicity value. For non-carcinogens, the reference concentration (RfC) is the appropriate toxicity value. Each of these toxicity values is weighted by the appropriate exposure factors to determine the target indoor air screening concentrations. The smaller value (between $C_{ia,c}$ and $C_{ia,nc}$) is used as the target indoor air screening value.

Example calculations using the equations in **Table 4** are presented in **Table 5** for EDB and 1,2-DCA in indoor air under a residential exposure scenario. Note that the cancer screening levels ($C_{ia,c}$) are consistently lower than the non-cancer screening levels ($C_{ia,nc}$), thus the cancer screening levels would generally be used to assess risk to receptors for a given chemical.

⁴⁴ OSWER's toxicity data hierarchy is three-tiered. Tier 1 are values from EPA's Integrated Risk Information System (IRIS). The IRIS database is web accessible at <http://www.epa.gov/iris/>. Tier 2 are Provisional Peer Reviewed Toxicity Values (PPRTVs), which are accessible at <http://hhpprtv.ornl.gov/>. Tier 3 are "Other" sources, such as the Agency for Toxic Substances and Disease Registry (ATSDR), and various states (e.g., California (CA DTSC, 2009), Hawai'i (HI DOH, 2011, 2012), Massachusetts (MA DEP, 2009), New Jersey (NJ DEP, 2013), Washington (WA DEC, 2006). Links to these sources are provided under *References Cited* at the end of this section.) EPA's Regional Screening Levels (RSLs) for Superfund Sites compiles available toxicity information based on this hierarchy. The VISL Calculator draws on these RSL tables for toxicity values that are used to calculate VISLs. RSLs are accessible at http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm.

Table 4. Equations For Target Indoor Air Screening Concentrations For Volatile Chemicals

Cancer	$C_{ia,c} = \frac{TCR \cdot ATc \cdot 365 \text{ (days/year)} \cdot 24 \text{ (hours/day)}}{EF \cdot ED \cdot ET \cdot IUR}$
Non-Cancer	$C_{ia,nc} = \frac{THQ \cdot RfC \cdot ATnc \cdot 365 \cdot 24 \cdot 1000 \text{ (ug/mg)}}{EF \cdot ED \cdot ET}$
<p>$C_{ia,c}$ is the indoor air concentration for cancer risk, and $C_{ia,nc}$ is the indoor air concentration for non-cancer risk; the smaller value is used as the indoor air screening value. ATc and ATnc are the averaging times for cancer and non-cancer, respectively, and EF, ED and ET are exposure parameters (exposure frequency, duration, and time). The exposure factors should be consistent with those in Human Health Evaluation Manual, Supplemental Guidance: Update of Standard Default Exposure Factors OSWER Directive 9200.1-120 http://www.epa.gov/oswer/riskassessment/pdf/superfund-hh-exposure/OSWER-Directive-9200-1-120-ExposureFactors.pdf</p>	

Table 5. Example Target Residential Indoor Air Concentrations For EDB And 1,2-DCA

Chemical	$C_{ia,c}$ ($\mu\text{g}/\text{m}^3$)	$C_{ia,nc}$ ($\mu\text{g}/\text{m}^3$)
1,2-Dibromoethane (EDB)	4.7E-03	9.4
1,2-Dichloroethane (1,2-DCA)	1.1E-1	7.3
Values (and units) of other variables used in these example residential calculations (equations in Table 4) are:		
Variable	Cancer (c)	Non-Cancer (nc)
IUR(c) or RfC(nc) (EDB)	$6.0\text{E-}04 \text{ (}\mu\text{g}/\text{m}^3\text{)}^{-1}$	9 (mg/m^3)
IUR(c) or RfC(nc) (1,2-DCA)	$2.6\text{E-}05 \text{ (}\mu\text{g}/\text{m}^3\text{)}^{-1}$	7 (mg/m^3)
TCR(c) or THQ(nc) (unitless)	10^{-6}	1.0
ATc or ATnc (years)	70	26
ED (years)	26	26
EF (days/year)	350	350
ET (hours/day)	24	24

After target indoor air screening levels (C_{ia}) have been established, the next step is to determine vapor source concentrations and assess whether these are high enough to potentially pose a threat of vapor intrusion. The equations in **Table 6** are used by the VISL Calculator to calculate groundwater and soil gas screening levels based on target indoor air screening levels. These groundwater and soil gas screening levels can then be compared to actual field measurements of groundwater and/or soil gas concentrations. If the measured concentrations are greater than the screening levels, then there is a potential for vapor intrusion, otherwise not.⁴⁵

Table 6. Equations For Groundwater And Soil Gas Screening Levels Based On Target Indoor Air Screening Levels.

Ground Water Concentration	$C_{gw} = \frac{C_{ia}}{\alpha_{gw} \cdot 1000 \cdot HLC}$
Soil Gas Concentration	$C_{sg} = \frac{C_{ia}}{\alpha_{sg}}$
<p>C_{ia} is the target indoor air screening level concentration ($\mu\text{g}/\text{m}^3$). C_{gw} is the screening concentration in groundwater ($\mu\text{g}/\text{L}$). C_{sg} is the screening concentration in soil gas ($\mu\text{g}/\text{m}^3$). HLC is the unitless Henry's Law constant. α_{gw} and α_{sg} are the groundwater and soil gas vapor intrusion attenuation factors, respectively (both unitless). 1,000 is the number of liters per m^3 (to convert from units of $\mu\text{g}/\text{m}^3$ to $\mu\text{g}/\text{L}$).</p>	

⁴⁵ An individual subsurface sampling result that exceeds the respective, chronic screening level does not establish that vapor intrusion will pose an unacceptable human health risk to building occupants. Conversely, these generic, single-chemical VISLs do not account for the cumulative effect of all vapor-forming chemicals that may be present. Thus, if multiple chemicals that have a common, non-cancer toxic effect are present, a significant health threat may exist at a specific building or site even if none of the individual substances exceeds its VISL (see discussion of non-cancer hazard index in EPA (2015) Section 7.4.1).

These equations also may be rearranged to calculate a potential upper-bound indoor air screening concentration based on actual field measurements of groundwater and/or soil gas concentrations. For groundwater, the equation is rearranged like this:

$$(upper\ bound)C_{ia} = C_{gw} \cdot \alpha_{gw} \cdot 1000 \cdot HLC$$

Note that in order to calculate a screening level concentration in groundwater, a value for Henry's Law constant (HLC) is necessary.⁴⁶

For soil gas the equation is rearranged like this:

$$(upper\ bound)C_{ia} = C_{sg} \cdot \alpha_{sg}$$

Appropriate values for the field measured concentration in groundwater or soil gas, and for the respective attenuation factors are plugged into the equation to yield an upper bound indoor air screening level for C_{ia} . The respective upper-bound indoor air screening level (derived from either groundwater or soil gas sampling data) is then compared to the target indoor air screening concentration (C_{ia}) from the VISL Calculator. If the upper-bound value is greater than the target value, then there is a potential for vapor intrusion, otherwise not (see Footnote #45).

In both cases, if there is a potential for vapor intrusion and where contamination is not in direct contact with an overlying building, then paired vapor samples should be collected to assess vapor attenuation. These paired samples should either be (a) near-slab (exterior) shallow soil gas samples paired with deep (source) soil gas samples, or (b) indoor air samples paired with sub-slab soil gas samples.

Table 7 presents example screening concentrations of EDB and 1,2-DCA in groundwater and soil gas using the equations in **Table 6**. These values represent the upper-bound concentrations according to Henry's Law that could be present in groundwater and soil gas, respectively, and not result in indoor air concentrations in excess of the target screening levels (i.e., VISLs) presented in **Table 5**. If concentrations measured in groundwater (C_{gw}) exceed these thresholds, it is possible that the target indoor air concentration will also be exceeded and mitigation may be necessary.

⁴⁶ The VISL Calculator is one source of Henry's Law constants. Because these constants are temperature dependent, the VISL Calculator automatically calculates the correct constant based on a temperature that is selected by the user.

Table 7. Example Screening Concentrations For EDB And 1,2-DCA In Groundwater And Soil Gas

Chemical	C_{gw} ($\mu\text{g/L}$)	C_{sg} ($\mu\text{g/m}^3$)
1,2-Dibromoethane (EDB)	0.18	.16
1,2-Dichloroethane (1,2-DCA)	2.2	3.7

Target residential indoor air concentrations ($C_{ia,c}$) are from **Table 5**. Selected attenuation factors (α) are 0.001 for groundwater and 0.03 for soil gas. These are taken from the VISL Calculator and do not account for biodegradation. Dimensionless Henry's Law constants (HLC) for groundwater at 25°C are 0.0266 for EDB and 0.048 for 1,-DCA. These values are also taken from the current version of the VISL Calculator.

The lead scavengers present an additional challenge in that existing analytical methodology is not able to detect them at very low concentrations representative of a cancer risk level of 1E-06 for either EDB or 1,2-DCA. As shown in **Table 8**, Selective Ion Monitoring (SIM) is able to achieve a detection limit representative of the 1.0E-04 risk level for EDB and 1.0E-05 for 1,2-DCA. Commercial low level is able to achieve a detection limit representative of the 1.0E-05 risk level for 1,2-DCA. However, an analytical detection limit does not impact the risk level for a certain chemical. The chemical may be present at a concentration greater than the appropriate risk level concentration, but below the limit of detection, which may result in undetected risk to potential receptors. Approaches to compensate for such analytical limitations include using available modeling data and professional judgment to evaluate whether the chemical may be present and having samples reanalyzed by special analytical services. For the screening level assessment, the chemical should be carried through assuming that it is present at the concentration equivalent to the quantitation limit. This allows the risk at the quantitation limit to be compared to the risks associated with other chemicals at the site. At minimum, the chemical should be addressed qualitatively. These topics are beyond the scope of this PVI guide; additional information may found in EPA's *Risk Assessment Guidance for Superfund (RAGS)*.⁴⁷

⁴⁷ The *Risk Assessment Guidance for Superfund (RAGS)* document is accessible at <http://www.epa.gov/oswer/riskassessment/ragas/index.htm>. In particular see Section 5.3 in Part A, and Part F: Supplemental Guidance for Inhalation Risk Assessment.

Table 8. Comparison Of Risk Levels And Achievable Analytical Detection Limits For The Lead Scavengers EDB And 1,2-DCA In Indoor Air.

Compound	Target Indoor Air Concentration			Analytical Method		
	Risk Level 1.0E-04	Risk Level 1.0E-05	Risk Level 1.0E-06	Commercial conventional	Commercial low level	Commercial SIM
EDB	0.47	0.047	0.0047	3.8	0.77	0.23
1,2-DCA	11	1.1	0.11	2.0	0.40	0.12

NOTE: all values in $\mu\text{g}/\text{m}^3$
 1.0E-04 = increased lifetime cancer risk of 1 per 10,000
 1.0E-05 = increased lifetime cancer risk of 1 per 100,000
 1.0E-06 = increased lifetime cancer risk of 1 per 1,000,000
 Commercial conventional = EPA Method TO-15 (see <http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-15r.pdf>)
 Commercial low level = EPA Method TO-15 (modified)
 SIM = Selective Ion Monitoring
 The achievable detection limits in this table are representative of the general state of the technology as of the present date. Some laboratories may be able to achieve lower detection limits using modified techniques. Future technological improvements may also result in lower detection limits.

 Achievable
 Not Achievable

Special Considerations

VISL Calculator screening levels do not include the effects of biodegradation on the concentrations of vapors in soil that could potentially intrude into indoor air. The generic attenuation factors used in calculating VISLs (i.e., 0.001 for groundwater, 0.03 for soil gas) are conservative, and may overestimate the transfer of some contaminants (e.g., those that biodegrade aerobically) from soil gas to indoor air in some buildings. As a result these screening levels will usually overestimate the true indoor air concentrations of aerobically-biodegradable volatile contaminants (e.g., PHCs). Decision-makers may choose to use alternate approaches (e.g., attenuation factors that account for biodegradation) that may be more appropriate for specific sites where circumstances do not match the underlying assumptions used in calculating the VISLs.

When Information is available on the separation distance between the source of contamination and the receptor, on the total concentration of biodegradable compounds in soil gas, and on the rate constant for degradation of contaminant vapors in soil, it is possible to refine the estimate of the attenuation factor (α) between soil gas and indoor air for some VOCs and PHCs. Approaches to refine the estimate of the attenuation factor (α) for PHCs are discussed in **Section 12** (p.100) and by Wilson et al. (2014). Also see **Section 13** (p.106) for information on the use of models to estimate attenuation factors. However, until more is known about the rates of biodegradation of EDB and 1,2-DCA in soil gas, the separation distances for PHCs shown in Section 5 and the approaches described in **Section 12** or **Section 13** for determining attenuation factors are not recommended for these two contaminants.

In addition to concerns discussed earlier, other potential concerns with increasing ethanol content are in relation to (re)mobilization of LNAPL (McDowell, et al., 2003; Yu, et al., 2009) and increased solubility of PHCs (Powers, et al., 2001). The implications of these impacts may extend beyond vapor intrusion; see **Section 7** (p.61) for information about LNAPL and **Section 6** (p.57) for information about dissolved contaminant plumes.

Recommendation

EPA recommends that groundwater samples be analyzed for PHCs and non-PHC fuel additives (e.g., alcohols, ethers, organic lead, lead scavengers) typically found in petroleum-based fuels, when appropriate. At the present level of knowledge, the groundwater and soil gas screening levels in **Table 7** are the best values to use to determine whether indoor air target levels will be exceeded for EDB and 1,2-DCA. If measured concentrations of EDB and 1,2-DCA in groundwater exceed the screening levels in **Table 7**, EPA recommends gathering additional information and data to determine whether mitigation is appropriate. The methodology illustrated in the *Assessment* subsection above can be applied to any non-PHC (or any VOC for that matter) for which an appropriate toxicity value and attenuation factor are available.

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11. Seasonal And Weather Effects

Description

The generation and movement of petroleum vapors are subject to seasonal effects such as temperature trends and fluctuations; and weather effects such as precipitation, barometric pressure changes, and wind (Lundegard, Johnson, and Dahlen, 2008). Cycling of heating and cooling systems inside buildings in response to seasonal and weather effects may also influence vapor intrusion.

Importance

Biological processes slow down with decreasing temperatures, though microorganisms continue to biodegrade PHCs at environmentally significant rates even when temperatures are near freezing (Bradley and Chapelle, 1995; Bradley, Richmond, and Chapelle, 2005; Hers, et al., 2011). Bradley and Landmeyer (2006) documented microbial degradation of MTBE in the wintertime when groundwater temperatures were below 5°C.

There is conflicting evidence as to whether, and under what additional conditions, frozen or ice-covered soil reduces the movement of oxygen into the subsurface. Hers, et al. (2011) studied a residential site in Canada where subsurface oxygen readings taken throughout the winter did not indicate a decrease in oxygen content of soil gas and there was evidence that biodegradation was occurring. However, the residence was above a crawl space and the soil below the house was never covered by ice or snow. It is known that the air permeability of a snow layer is a complex function of pore size, grain size, ice fraction, and density (Armstrong, 2008; Bender, 1957; Conway and Abrahamson, 1984). Rike (2003) observed ongoing biodegradation in frozen arctic soils. In that study, a lengthy period of subfreezing soil temperatures at a petroleum contaminated site did not result in decreasing oxygen concentrations. In contrast, Freyman (1967) and Yanaia (2010) report that oxygen depletion has been observed in other studies of soils under ice sheets and snow cover. More study is needed to resolve this issue.

Precipitation events can impact biodegradation of petroleum vapors. A certain amount of soil moisture is necessary for microorganisms to live; not enough and they are not actively degrading PHC vapors; too much and reoxygenation is impeded, possibly leading to anaerobic conditions at greater depths (Silver, 1999; Ludemann, 2000; Pezeschki, 2001). Wind and barometric pressure changes can produce pressure gradients inside buildings. Negative pressure inside buildings can result in enhanced intrusion of PHC vapors. Positive pressure inside buildings can both prevent intrusion of PHC vapors into buildings and facilitate oxygen transport through cracks in the foundation into the subsurface. This can result in reoxygenation of the soil beneath the building that would otherwise be depleted of oxygen (Lundegard, Johnson, and Dahlen, 2008).

Heating systems in buildings, which operate most frequently during winter months, can create a chimney effect, whereby PHC vapors are pulled into buildings at much higher rates than they would ordinarily. Cooling systems, which operate only during summer months, can have the opposite effect, creating positive pressure gradients in basements that both prevent intrusion of PHC vapors into buildings and allow oxygen to enter the soil (Lundegard, Johnson, and Dahlen, 2008).

Assessment

Seasonal and weather conditions can influence the characteristics of PHC vapor migration over time. Data on temporal changes in temperature, barometric pressure, wind speed and direction, relative humidity, and precipitation can aid in correctly identifying trends and result in a more accurate CSM.

In addition, site characteristics that may indicate susceptibility to the effects of seasonal and weather factors should be assessed. These include:

- Poor drainage around the building indicated by flooded soils
- Area subject to permafrost/long lasting snow cover (based on altitude or latitude)
- Shallow and highly variable water table

Special Considerations

Seasonal effects may also influence the formation and migration of dissolved plumes and LNAPL. Changes in water table elevation can create a smear zone of residual LNAPL contamination. LNAPL in the smear zone can act as a long-term source of dissolved contamination during periods of high water table elevation and as a source of petroleum vapors during periods of low water table elevation when contaminants reemerge from a previously submerged condition. Groundwater levels in the vicinity of USTs may also be subject to the influence of water within the tank pit. After rainfall events (and potentially snowmelt) water levels within tank pits are typically above the level of ambient groundwater; consequently a groundwater recharge mound may form. This mound disrupts the local groundwater flow field and contaminants can migrate away from the tank excavation, potentially in all directions.

Recommendation

During site characterization activities, weather conditions such as temperature, barometric pressure, and wind speed/direction should be recorded to aid in recognizing the cause of trends or anomalies in the PVI data and not merely attributed to unknown factors. This information may be obtained from the National Oceanic and Atmospheric Administration (NOAA) (see <http://www.noaa.gov/wx.html>) or a nearby airport where weather data are recorded hourly.

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Web Resources

U.S. Geological Survey's Soil Surveys
<http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>

U.S. Department of Homeland Security Federal Emergency Management Agency's flood plain maps <https://msc.fema.gov/portal>

2012 U.S. Department of Agriculture Plant Hardiness Zone Map
<http://planthardiness.ars.usda.gov/PHZMWeb/>

12. Vapor Intrusion Attenuation Factor (α)

Description

When Johnson and Ettinger (1991) published their vapor intrusion model they introduced a parameter to relate the vapor concentration of a volatile chemical inside a building to its vapor concentration at the subsurface source. The parameter, designated alpha (α), is also called the vapor intrusion attenuation factor. It is defined mathematically as the concentration in indoor air divided by the concentration in soil gas at the source (with concentrations in the same units). The source is defined as the region of highest vapor concentration in the vadose zone. Large values of α (i.e., values approaching one) indicate that little attenuation is taking place, whereas small values of α (i.e., values much smaller than one) indicate that significant attenuation is taking place.

Importance

As part of a risk evaluation, the concentrations of a chemical in indoor air can actually be measured, or they can be predicted. The attenuation factor is used as a part of a risk evaluation to predict or estimate the concentration of a chemical in indoor air from the concentration measured in soil gas below or near a building. To predict the indoor air concentration, the measured concentration in soil gas is multiplied by the suitable attenuation factor.

Assessment

U.S. EPA (2013, Table 6-1) provides recommended vapor attenuation factors for risk-based screening of the vapor intrusion pathway for residential buildings. For example, the generic values of α in EPA (2015) are 1.0E-03 (0.001) for groundwater, 3.0E-02 (0.03) for sub-slab soil gas, and 3.0E-02 (0.03) for deep (near-source) soil gas. These values of α are derived from measurements made during case studies of the vapor intrusion of chlorinated solvents such as trichloroethylene (TCE), which are not biologically degraded in aerobic unsaturated soil or sediment. Likewise, values for concentrations in indoor air that are derived from the model of Johnson and Ettinger (1991) also do not include any consideration of biodegradation. As a result, the generic values of α in U.S. EPA (2015) and values for indoor air that are calculated using the Johnson and Ettinger model (JEM) overestimate the indoor air concentrations of PHCs. Thus, these values of α are not applicable to PVI from leaking USTs.⁴⁸ For additional information on estimation of sub-slab attenuation factors, see Brewer et al. (2014).

To provide estimates of α that are more suitable for PHCs, Abreu, Ettinger, and McAlary (2009) developed a three-dimensional computer model to predict the effects of biodegradation in the unsaturated zone below a building on the concentrations of chemicals in the indoor air of the building. They performed a series of model simulations to estimate semi-generic values of α from site-specific information on the vertical separation distance between the receptor building

⁴⁸ Attenuation factors that account for biodegradation can be derived from models such as *BioVapor* or *PVIScreen* (see **Section 13**, p.106 for more information). Additional guidance may be found in Wilson *et al.* (2014).

and the source, and the total concentration of biodegradable compounds in soil gas at the source of the hydrocarbons. **Figure 9** compiles the computer simulations conducted by Abreu, Ettinger, and McAlary (2009) of the attenuation factor during vapor intrusion into a building with a basement. This figure presents the concentration of biologically degradable hydrocarbon in an unconventional unit (mg/L as benzene).

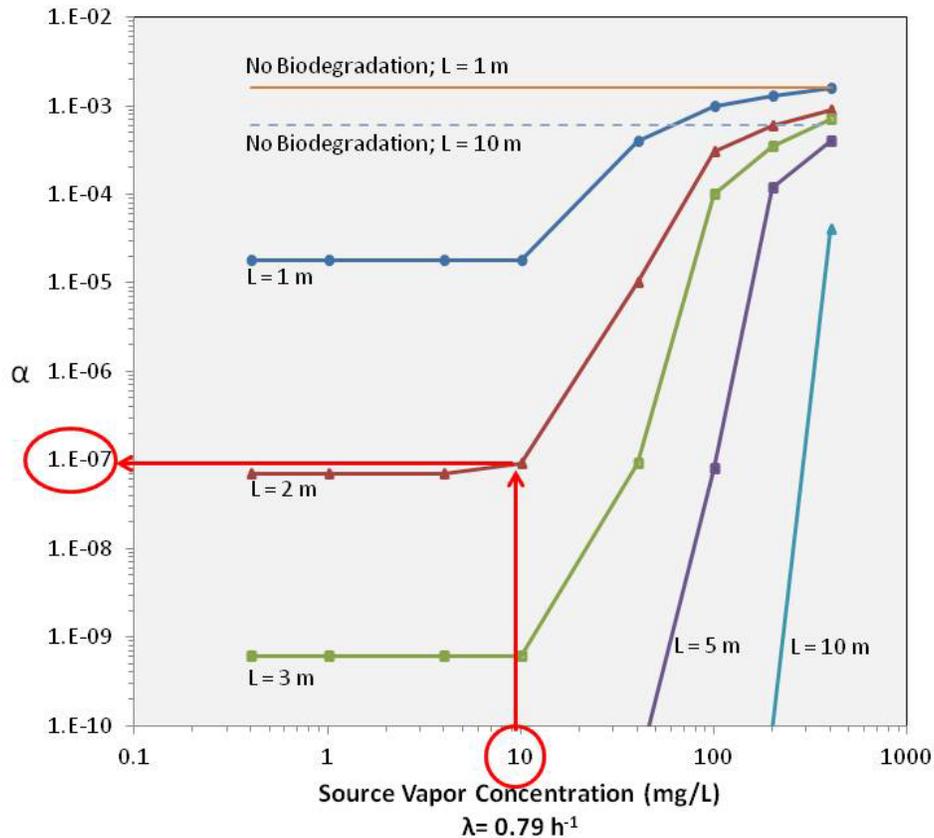


Figure 9. Relationship Between Source Vapor Concentration And Vapor Intrusion Attenuation Factor (α) As A Function Of Vertical Separation Depth Between Contaminant Source And Base Of Building (Receptor) (Source: modified from Abreu, Ettinger, and McAlary, 2009, Figure 7, page 114. Reprinted from *Groundwater Monitoring & Remediation* with permission of the National Ground Water Association. Copyright 2009.)

To generate **Figure 9**, Abreu, Ettinger, and McAlary (2009) used conservative assumptions for the rate of biodegradation. In this particular set of simulations, the first order rate constant for biodegradation (λ) was set at 0.79 h^{-1} , a reasonable average rate based on the range of rates published in the literature (DeVaul 2007). Model simulations assume the building has a basement and that it is surrounded by homogeneous, uniform sandy soil that is directly exposed to the atmosphere and that preferential pathways for vapor migration into the building or through the vadose zone are not present. As a result, the concentration of oxygen

in the soil gas in the topmost layer of exposed soil is the concentration of oxygen in the atmosphere. Compared to silty or clayey soils, sandy soils have more air filled porosity and as a result, vapors diffuse more rapidly through them (and they also allow more oxygen to diffuse from the atmosphere). The simulations assumed that the square building was 10 meters (33 feet) on each side.

Figure 9 can be used to estimate the value of α for situations where the total concentration of vapors at the source and the vertical separation distance between the contaminant source and the bottom of the building are known and all of the other input parameters match site conditions. For example, for a source vapor concentration of 10 mg/L and a vertical separation distance (L) of 2 meters (6.6 feet), the estimated value of α would be approximately 1.0E-07. To complete the exposure assessment, the measured concentration of benzene in soil gas at the source of contamination is multiplied by the value of α , to predict the indoor air concentration in a building.

Figure 10 is a redraft of **Figure 9**, where the source concentration of vapors is expressed in more conventional units for vapors in soil gas ($\mu\text{g}/\text{m}^3$). The oxygen demand of all the hydrocarbons that might be in soil gas is expressed as the concentration of TPH (gasoline) plus the concentration of methane. The concentration of TPH (gasoline) can be determined by modified EPA Method TO-15 (see <http://www.epa.gov/ttn/amtic/files/ambient/airtox/to-15r.pdf>) referenced to heptane. The concentration of methane can be determined as a fixed gas or by EPA Method 3C. The concentration of methane is multiplied by 1.136 to correct for the differences between the theoretical oxygen demand of methane and heptane.

Special Considerations

Figure 9 or **Figure 10** should only be used for UST sites with the same characteristics that were simulated by Abreu, Ettinger, and McAlary (2009). These conditions were relatively conservative. **Figure 9** and **Figure 10** are not appropriate for use at sites where the oxygen flux from the surface is impeded.

Some documents define the vapor intrusion attenuation factor differently than defined by Johnson and Ettinger (1991) and discussed in this section. The JEM (see **Section 13**, p.106) ignores background sources when estimating the indoor air concentration arising from vapor intrusion. When used in this PVI guide, the Greek letter alpha (α) refers strictly to attenuation during vapor intrusion, which might be observable if there were no background (ambient) vapor sources. In contrast, some empirical attenuation factors (sometimes designated *AF*) are based on indoor air concentrations that include both background sources and vapor concentrations that intrude into the building from a subsurface vapor source. Thus, when there is a measurable contribution from an ambient source, an attenuation factor such as *AF* (which includes the contribution of ambient sources) would be somewhat greater than the Johnson & Ettinger alpha (α), which would indicate less attenuation than is actually occurring.

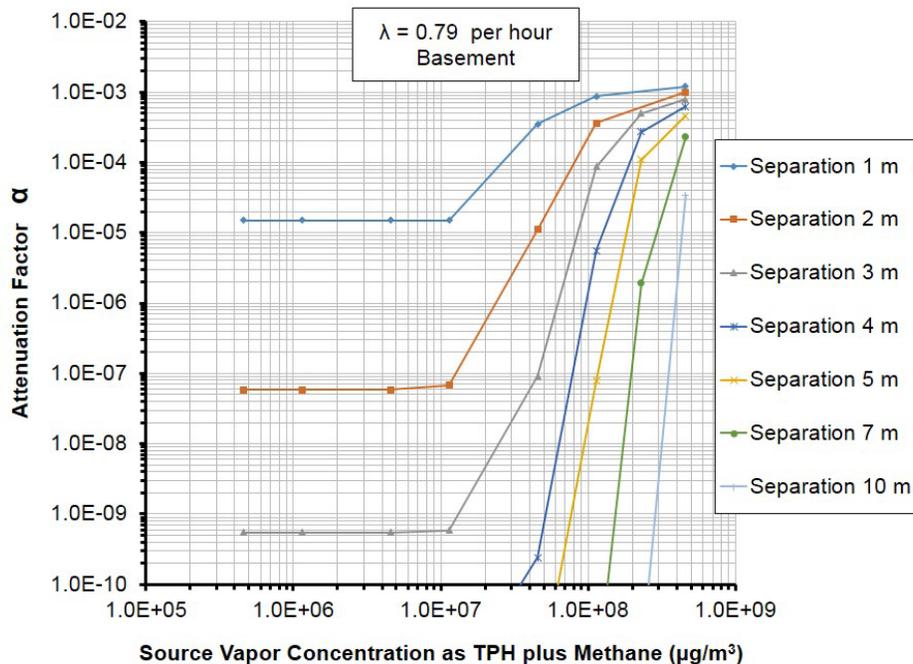


Figure 10. Rescaled Figure 9 That Expresses The Source Vapor Concentration In Conventional Units.

Recommendation

When evaluating the vapor source and attenuation of PHC vapors, paired vapor samples are required to measure the actual attenuation that occurs due to aerobic biodegradation. Where contamination is not in direct contact with an overlying building, choose one of two options: (1) collect near-slab (exterior) shallow soil gas samples paired with deep (source) soil gas samples, or (2) collect indoor air samples paired with sub-slab soil gas samples. Note that for option 2 if the measured concentration of vapor in indoor air is below the applicable allowable indoor concentration there is no need to measure sub-slab vapor concentration. If contamination is in direct contact with a building basement, foundation, or slab, it is necessary to collect indoor air samples as it will not be feasible to collect sub-slab vapor samples. If a generic vapor intrusion attenuation factor and the measured concentration of a PHC in shallow soil gas predict an acceptable concentration in indoor air, that prediction may be adequate to support a screening decision. However, generic attenuation factors may not be appropriately representative of conditions at a particular site.

Models may provide better estimates of α , but only if the actual conditions at a specific site match the assumptions of a particular model. For biodegradable PHCs it would be better to implement a transport and fate model that is designed to simulate the contribution of biodegradation. The three-dimensional models of Abreu, Ettinger, and McAlary (2009) and Verginelli and Baciocchi (2014) are potential options. BioVapor, a model developed by the American Petroleum Institute, is another option. U.S. EPA is developing a model called PVIScreen that is intended for this purpose. See **Section 13** (p.106) for more discussion of the appropriate use of computer models for PVI investigations.

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13. Computer Modeling Of Petroleum Vapor Intrusion

Description

A number of models have been developed and applied in estimating transport of volatile chemicals from subsurface soil and groundwater to indoor air (Bekele, et al. 2013). Lahvis (2011) presents a summary of 35 different analytical screening-level models, including a discussion of features, and assumptions. Models generally used for simulation of PVI are either the Johnson-Ettinger model (JEM) or BioVapor.

Johnson-Ettinger Model (JEM)

Johnson and Ettinger introduced one of the first vapor intrusion models in 1991. This model is referred to as the Johnson-Ettinger Model or JEM. Features of the JEM include:

- A steady or transient source of subsurface vapors from groundwater or residual chemicals
- Gaseous-phase diffusive vapor flow through a layer of soil
- Vapor transport through a slab-on-grade or basement foundation
- Building air exchange

The JEM presumes that the concrete foundation is impermeable and vapor movement occurs only through cracks and other openings. However, concrete is permeable to vapors and gases. Effective diffusion rates for intact air-dry concrete have been measured for hydrocarbons, oxygen, methane, and radon with an overall measured range from 1.08 to 15.6 cm²/hr (Haghighat, et al., 2002; Patterson and Davis, 2009; Kobayashi and Shuttoh, 1991; Tittarelli, 2009; Yu, et al., 1993). Thus, diffusive vapor flow for typical foundation areas and thicknesses can be significant (McHugh, de Blanc, and Pokluda, 2006; Luo, et al., 2012). Actual measurement of differential pressure across varied building foundations show a significantly variable component over time (Nazaroff, et al., 1985; Hintenlang and Al-Ahmady, 1992; Robinson, et al., 1997a,b; McHugh, de Blanc, and Pokluda, 2006; Lundegard, Johnson, and Dahlen, 2008; Patterson and Davis, 2009; Luo and Johnson, 2011).

For sites where PHCs are present and aerobic biodegradation of PHCs occurs in the vadose zone, comparisons to JEM consistently show the model to over-predict indoor air concentrations by at least several orders of magnitude (Fitzpatrick and Fitzgerald, 2002; Sinke, 2001; Ririe, Sweeny, and Daugherty, 2002; Hers, et al., 2003; Davis, 2006; Golder Associates, 2008; Davis 2009). The potential for over-prediction is greatest for sites with low concentrations of PHCs in soil and groundwater (API, 2009; Davis, 2009; Energy Institute, 2009).

The original model has been revised numerous times to attempt to account for biodegradation, which was not included in the original JEM (see Johnson, Kemblowski, and Johnson, 1998; Ririe, et al., 1998; Johnson, Hermes, and Roggemans, 2000; Spence and Walden, 2010; Parker, 2003; Environmental Systems and Technologies, 2004; DeVauil, 2007a; Mills, et al., 2007; Turczynowicz and Robinson, 2007; API, 2010; Lahvis, 2011). EPA also revised the original JEM.

The most current information on EPA's revised model may be found on EPA's website at http://www.epa.gov/oswer/riskassessment/airmodel/johnson_ettinger.htm.

BioVapor

The BioVapor model (DeVaull, 2007a; API, 2010) is a Microsoft Excel© macro that uses a conceptual model similar to the JEM. BioVapor includes the following features:

- A steady subsurface petroleum vapor source.
- Gaseous-phase diffusive vapor flow through a layer of soil.
- Vapor transport through a slab-on-grade or basement foundation.
- Building air exchange.

In contrast to JEM, BioVapor accounts for oxygen-limited, aerobic biodegradation. Aerobic biodegradation is included as a coupled reaction between petroleum vapors and oxygen. Oxygen availability in the subsurface is dictated by transport through and around the building foundation, and by diffusion into the soil. The BioVapor model requires estimates of chemical-specific aerobic degradation rates for vadose zone soils. DeVaull (2007a,b) provides default values based on measured data. DeVaull (2011) provides improved estimates of both median values and observed ranges for an expanded set of specific chemicals.

PVIScreen

PVIScreen (Weaver, 2015) is based on the equations of BioVapor but is coded in Java to improve computational efficiency and allow for implementation of algorithms to automate uncertainty analysis. Most computer models must be run multiple times with varying input parameters in order to conduct a typical sensitivity analysis. PVIScreen automates this function by treating input variables as ranges and then conducting a Monte Carlo analysis. The results, which are provided in a matter of seconds, are presented as the probability that the indoor air concentration is less than a risk-based level. This is in contrast to most models that provide single values for various output parameters. PVIScreen also allows for flexible unit choices and presents results in an automatically-generated report.

Importance

Vapor intrusion models that include oxygen limited biodegradation support development of petroleum-specific exclusion distance criteria (i.e., lateral inclusion zone—see **Section 4**, p.44; vertical separation distance—see **Section 5**, p.48). Model results are consistent with empirical exclusion distance values derived from several PVI field investigations. These include Lahvis, et al. (2013); Davis (2009); Peargin and Kolhatkar (2011); Wright (2011); McHugh, et al. (2010), and Verginelli and Baciocchi (2014). Site assessment and field data including the depth to contamination, source strength, and type (LNAPL or dissolved) are key parameters for determining these exclusion distance criteria.

Estimates using the BioVapor model indicate that for moderate or weak sources (especially dissolved plumes), biodegradation effectively eliminates the potential for PVI. Conversely, where vapor sources are both high in concentration and in close proximity to the bottom of a foundation, the BioVapor model predicts significant potential for PVI.⁴⁹ Notably, in these cases the BioVapor model predicts significantly higher potential for PVI below a foundation, where oxygen availability is more limited, than adjacent to the foundation where the soil surface is open to air and oxygen availability is greater. This prediction is consistent with measured vertical profiles of hydrocarbons and oxygen for high concentration vapor sources taken both below a foundation and beside a foundation (Patterson and Davis, 2009; Laubacher, et al., 1997).

Weaver (2012) presents results of a sensitivity analysis that indicates when biodegradation occurs, it dominates the other processes included in the BioVapor model. In these cases, the parameters representing aerobic biodegradation, source depth, and source strength dominate the model results. In the other cases where biodegradation is insignificant, building parameters become more important, as they are in the JEM (Tillman and Weaver, 2007).

More complex numerical models including oxygen-limited biodegradation have been developed and applied. Abreu and Johnson (2006) present results for a three-dimensional model. With matched model parameters, there is reasonable agreement between the three dimensional results and those predicted with the BioVapor model (DeVaull, 2007b) and PVI-Screen (Weaver, 2015). Each of these model results show similar sensitivities to changes in model parameters, and support the use of exclusion distances such as those recommended in this document (see **Section 4**, p.44, lateral inclusion zone, and **Section 5**, p.48, vertical separation distance).

Assessment

When selecting an appropriate computer model, the mathematical formulation needs to be consistent with conditions at the site and the CSM. If the computer model is not matched to conditions at the site, then error is likely introduced into the computer model results. This means that input parameters for the computer model should be representative of the actual physical, chemical, and biological properties of the site. Typically all factors influencing vapor intrusion are not included in currently available models. Even with more advanced modeling, resource limitations would prevent the detailed characterization necessary to determine representative values for some of the input parameters. Some of these factors include subsurface heterogeneity, variation in building operation, subsurface moisture content, variations in weather and others. For most other types of environmental models, limitations in characterization are mitigated by calibration to known endpoints, typically concentration distributions. Though calibration results may not be unique (that is the same results could potentially be obtained using different values for the same suite of input parameters), when these results match field conditions, a model is deemed to be useful for predictive simulations.

⁴⁹ Moderate or weak sources are associated with dissolved plumes. Strong sources are associated with LNAPL. **Table 3** on page 52 presents concentration thresholds associated with dissolved plumes and LNAPL.

Special Considerations

Most of the parameters describing model processes will not be known with certainty. A common limitation is that field measurements of all the input parameters (e.g., biodegradation rates, soil moisture content beneath buildings, air exchange rates) are typically not available, and those that are (e.g., source concentration) may be spatially or temporally variable. Literature values are typically substituted for site-specific data. This leads to uncertainty as to whether parameter values are truly representative of site conditions. Model results will likewise inevitably lack certainty (Bekele, et al, 2013). The importance of these (and other) parameters is determined through an uncertainty analysis. By determining the impact of parameter variability on the model results, the uncertainty analysis adds confidence to the conclusions drawn from the model.

Recommendation

An appropriate framework for the use of a mathematical model and understanding of model characteristics is critical when using the results of mathematical models for regulatory purposes (Hers, et al., 2003). The appropriate role for a model in a PVI investigation is as a means to explain observed behavior. EPA recommends the use of a model that considers aerobic biodegradation when assessing the potential for PVI. Regardless of which model is used to simulate PVI, EPA recommends that an uncertainty analysis be conducted to provide error bounds on predictions of the computer model.

Model results obtained by using site-specific inputs can provide results that inform decision-making. In particular, model results can be used to demonstrate that: sufficient oxygen exists to degrade petroleum contaminants, contaminant vapor distributions are plausible given conditions at the site, estimates of the vapor attenuation anticipated in the subsurface due to biodegradation are reasonable. Models may also be used for purposes such as improving a site-specific sampling strategy, validation (or refutation) of the CSM by comparing a model to measured soil gas data, and in estimating the effect of varied or changed site conditions (e.g., including construction of a new building on a brownfields site).

Model results can thus be used as one line of evidence that a building is not likely to be impacted by PHC vapors. At the present time and state of knowledge, EPA cautions that model results should not be used as the sole rationale for determining that a building is not threatened or impacted by PVI.

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Glossary

Note: Most of these definitions are from EPA's on-line glossaries (see http://iaspub.epa.gov/sor_internet/registry/termreq/searchandretrieve/termsandacronyms/search.do).

Absorption: the penetration of atoms, ions, or molecules into the bulk mass of a substance. In contrast, adsorption is the retention of atoms, ions, or molecules onto the surface of another substance

Advection: the process of transfer of fluids (vapors or liquid) through a geologic formation in response to a pressure gradient that may be caused by changes in barometric pressure, water table levels, wind fluctuations, or infiltration

Aerobic: able to live, grow, or take place only when free oxygen is present

Anaerobic: able to live, grow, or take place where free oxygen is not present

Analyte: the element, ion, or compound that an analysis seeks to identify; the element of interest

Attenuation: the reduction or lessening in amount (*e.g.*, a reduction in the amount of contaminants in a plume as it migrates away from the source)

Biodegradability (or biodegradation potential): the relative ease with which organic chemicals will degrade as the result of biological metabolism. With respect to petroleum hydrocarbons, although virtually all petroleum hydrocarbons are biodegradable, biodegradability is highly variable and dependent somewhat on the specific type of hydrocarbon. In general, biodegradability increases with increasing solubility; solubility is inversely proportional to molecular weight.

Biodegradation: a process by which microbial organisms transform or alter (through metabolic or enzymatic action) the structure of chemicals introduced into the environment

Biologically active soil: in the context of a PVI investigation means that the subsurface soil environment will support populations of microorganisms that are present in sufficient quantities to aerobically degrade PHC vapors before they intrude into a receptor. Effective aerobic biodegradation of petroleum hydrocarbons depends on the soil having sufficient oxygen and enough soil water to provide a habitat for adequate populations of active microorganisms. The presence of sufficient oxygen must be determined by the collection and analysis of soil gas. Soil that is too dry will not support microbial life. The soil generally will not be too dry for bacteria if the depth to the water table is less than 300 feet, or if the soil around the receptor supports the growth of plants characteristic of temperate climates. (NOTE that in hot, arid climates lack of soil moisture may inhibit biodegradation of PHCs)

Concentrations of carbon dioxide which are ten-fold higher than concentrations in the atmosphere are an acceptable indication that conditions support microbial respiration. The actual habitat of soil bacteria is the thin film of water held to the surface of soil particles by capillary attraction. Coarse sand and gravel with a low content of silt or clay or organic matter, or fractured consolidated rock, or consolidated rock with solution channels, may not have enough soil water in intimate contact with soil gas to support adequate densities of biologically active microorganisms. These geological materials do not qualify as "biologically active soil."

BTEX: acronym for the aromatic hydrocarbons benzene, toluene, ethylbenzene, and xylenes (three isomers)

Capillary fringe: the zone of a porous medium above the water table within which the porous medium is saturated by water under pressure that is less than atmospheric pressure. See also *vadose zone* and *unsaturated zone*.

Clean monitoring point: Concentration thresholds for “clean” monitoring points are: the BTEX concentration in groundwater is equal to or less than the respective maximum contaminant level (e.g., 5 µg/L for benzene); the TPH concentration in soil is less than 20 mg/Kg; there is no potential presence of liquid or residual phase LNAPL; the oxygen concentration is greater than 0.2 percent; and the combustible gas concentration in soil gas is less than 100 ppm (v/v).

Clean soil: In the context of a PVI investigation, clean soil does not necessarily mean that the soil is free from all contamination, but rather that any contamination present is at concentrations low enough that the biological activity of the soil is sufficient to biodegrade PHC vapors before they reach a receptor.

Computer model: a mathematical representation of a physical process or system. Computer models are based upon sound conceptual site models to provide meaningful information. As the complexity of computer models increases, so does the amount of data required, and the quality of the output from computer models is directly related to the quality of the input data. Because of the complexity of natural systems, models necessarily rely on simplifying assumptions that may or may not accurately represent the dynamics of the natural system. Calibration and sensitivity analyses are important steps in the appropriate use of models.

Conceptual site model (CSM): a three-dimensional representation that conveys what is known or suspected about potential contamination sources, release mechanisms, and the transport and fate of those contaminants. The conceptual model provides the basis for assessing potential remedial technologies at the site. “Conceptual site model” is not synonymous with “computer model”; however, a computer model may be helpful for understanding and visualizing current site conditions or for predictive simulations of potential future conditions.

Contamination: in the context of a PVI investigation, contamination means that: the BTEX concentration in groundwater is greater than the respective MCL; or the TPH concentration in soil is greater than 100 mg/Kg; or there is potential presence of liquid or residual phase LNAPL; or the combustible gas concentration in soil gas is greater than 100 ppm (v/v).

Diffusion: the process by which molecules in a single phase equilibrate to a zero concentration gradient by random molecular motion (Brownian motion). The flux of molecules is from regions of high concentration to low concentration and is governed by Fick's Second Law.

Dispersion: the process by which a substance or chemical spreads and dilutes in flowing groundwater or soil gas

Downgradient: in the direction of decreasing potentiometric head; the general direction of groundwater flow

First responder: refers to those individuals who in the early stages of an incident are responsible for the protection and preservation of life, property, evidence, and the environment. Typically these are police, firefighters, or emergency medical personnel.

Fixed gases: refers to the gases nitrogen, oxygen, argon, carbon dioxide, and carbon monoxide. The volume of these gases together accounts for virtually 100 percent of the composition of the earth's atmosphere. Presence and concentration of these gases are determined using gas chromatography (GC).

Flux: the rate of movement of mass through a unit cross-sectional area per unit time in response to a concentration gradient or some advective force

Free product: a petroleum hydrocarbon in the liquid ("free" or non-aqueous) phase (see also light non-aqueous phase liquid, LNAPL)

Gradient: the rate of change in value of a physical or chemical parameter per unit change in position. For example, hydraulic gradient is equal to the difference in head measured at two points (usually wells) divided by the distance separating the two points. The dimensions of head and distance are both lengths, therefore the gradient is expressed as a dimensionless ratio (L/L).

Groundwater: the water contained in the pore spaces of saturated geologic media

Henry's law constant: the ratio of the concentration of a compound in air (or vapor) to the concentration of the compound in water under equilibrium conditions

Henry's law: the relationship between the partial pressure of a compound and the equilibrium concentration in the liquid through a proportionality constant known as the Henry's law constant

Heterogeneous: varying in structure or composition at different locations in space

Homogeneous: uniform in structure or composition at all locations in space

Hydraulic gradient: the change in total potentiometric (or piezometric) head between two points divided by the horizontal distance separating the two points

Hydrocarbon: chemical compounds composed only of carbon and hydrogen

Inclusion zone: the area surrounding a contaminant mass through which vapor-phase contamination may travel and intrude into buildings and potentially result in adverse health effects to inhabitants

Indian country: (1) All land within limits of any Indian reservation under the jurisdiction of the United States government, notwithstanding the issuance of any patent, and, including rights-of-way running through the reservation; (2) All dependent Indian communities within the borders of the United States whether within the original or subsequently acquired territory thereof, and whether within or without the limits of a state; and (3) All Indian allotments, the Indian titles to which have not been extinguished, including rights-of-way running through the same.

Indigenous: living or occurring naturally in a specific area or environment; native

Isotropic: the condition in which hydraulic properties of an aquifer are equal when measured in any direction

Lateral inclusion zone: the area surrounding a contaminant mass and for which all buildings within its boundaries should be assessed for potential PVI. By definition, all buildings that overlie contamination in any phase are within the lateral inclusion zone.

Light non-aqueous phase liquid (LNAPL): contaminants that remain as the original bulk liquid with a density less than that of water (see also free product)

Microorganisms: microscopic organisms including bacteria, protozoans, yeast, fungi, mold, viruses, and algae

Permeability: a qualitative description of the relative ease with which rock, soil, or sediment will transmit a fluid (liquid or gas). Often used as a synonym for hydraulic conductivity or coefficient of permeability.

Petroleum: 40CFR280.12 defines the term *petroleum* to include crude oil or any fraction thereof that is liquid at standard conditions of temperature and pressure (60 degrees Fahrenheit and 14.7 pounds per square inch absolute).

Petroleum hydrocarbons (PHCs): hydrocarbons (i.e., compounds comprised of combinations of hydrogen and carbon atoms) that are components of petroleum (crude oil), including the various products that result from distillation of crude oil

Petroleum vapor intrusion (PVI): intrusion of petroleum hydrocarbon vapors into buildings or other structures

Porosity: the volume fraction of a rock or unconsolidated sediment not occupied by solid material but usually occupied by water or air (gas)

Preferential transport pathways: pathways through which contaminants may be transported at a higher rate than through surrounding materials. Preferential transport pathways are heterogeneities within geologic media and include features that are natural (such as facies changes, sand or gravel stringers, solution channels in karst, bedding planes and weathered surfaces, fractures, and joints) as well as man-made (such as utility corridors, trenches, other types of excavations).

Regulated substance: (a) Any substance defined in section 101(14) of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) of 1980 (but not including any substance regulated as a hazardous waste under subtitle C), and (b) Petroleum, including crude oil or any fraction thereof that is liquid at standard conditions of temperature and pressure (60 degrees Fahrenheit and 14.7 pounds per square inch absolute). The term regulated substance includes but is not limited to petroleum and petroleum-based substances comprised of a complex blend of hydrocarbons derived from crude oil through processes of separation, conversion, upgrading, and finishing, such as motor fuels, jet fuels, distillate fuel oils, residual fuel oils, lubricants, petroleum solvents, and used oils.

RfC (reference concentration, inhalation): an estimate (with uncertainty spanning perhaps an order of magnitude) of a continuous inhalation exposure of a chemical to the human population through inhalation (including sensitive subpopulations), that is likely to be without risk of deleterious noncancer effects during a lifetime

Selective ion monitoring (SIM): a mass spectrometry scanning mode in which only a limited mass-to-charge ratio range is transmitted or detected by the instrument, as opposed to the full spectrum range

Semi-volatile organic compound (SVOC): an organic compound which has a boiling point higher than water and which may vaporize when exposed to temperatures above room temperature. Semi-volatile organic compounds include phenols and polynuclear aromatic hydrocarbons (PAHs).

Site assessment: see site characterization

Site characterization: (verb) the process by which site-specific information and data are gathered from a variety of sources to characterize the physical, biological, and chemical systems at a contaminated site. A primary objective of site characterization is delineation of the areal (both horizontal—longitudinal and lateral—transverse) and vertical extent of contamination. This includes changes in plume boundaries, changes in geochemical parameters that affect biodegradation, and contaminant mass (or concentration) increases or decreases. (noun) The product (e.g., CSM, report) resulting from the site characterization process. (Note: Site assessment, site investigation, site evaluation, and site check are all synonyms of site characterization.)

Site check: see site characterization

Site evaluation: see site characterization

Site investigation: see site characterization

Soil moisture: the water contained in the pore spaces in the unsaturated zone

Solubility: the amount of mass of a compound that will dissolve in a unit volume of solution

Sorption: a general term used to encompass the processes of absorption, adsorption, ion exchange, and chemisorption

Source material: material that includes or contains contaminants that act as a reservoir (either stationary or mobile) for migration of contamination to the ground water, to surface water, to air, (or other environmental media), or acts as a source for direct exposure. Contaminated ground water generally is not considered to be a source material although non-aqueous phase liquids (NAPLS [occurring either as residual- or free-phase]) may be viewed as source materials.

Source zone: the impacted area immediately surrounding the source of a release of regulated substances comprising source materials

Total petroleum hydrocarbons (TPH): a measure of the concentration or mass of petroleum hydrocarbon constituents present in a given amount of air, soil, or water. (Note: The term total is a misnomer, in that few, if any, of the procedures for quantifying hydrocarbons are capable of measuring all fractions of petroleum hydrocarbons present in the sample. Volatile hydrocarbons are usually lost in the process and not quantified. Additionally, some non-petroleum hydrocarbons may be included in the analysis.)

Travel time: the time it takes a contaminant to travel from the source to a particular point downgradient

Tribe: Indian tribe or tribe means an Indian or Alaska Native tribe, band, nation, pueblo, village, or community that the Secretary of the Interior acknowledges to exist as an Indian tribe pursuant to the federally Recognized Indian Tribe List Act of 1944, 25 U.S.C. 479a.

Underground storage tank (UST): 40CFR280.12 defines an *underground storage tank* as any one or combination of tanks (including underground pipes connected thereto) that is used to contain an accumulation of regulated substances, and the volume of which (including the volume of underground pipes connected thereto) is 10 percent or more beneath the surface of the ground. This term does not include any: (a) Farm or residential tank of 1,100 gallons or less capacity used for storing motor fuel for noncommercial purposes; (b) Tank used for storing heating oil for consumptive use on the premises where stored; (c) Septic tank; (d) Pipeline facility (including gathering lines) regulated under: (1) The Natural Gas Pipeline Safety Act of 1968 (49 U.S.C. App. 1671, *et seq.*), or (2) The Hazardous Liquid Pipeline Safety Act of 1979 (49 U.S.C. App. 2001, *et seq.*), or (3) Which is an intrastate pipeline facility regulated under state laws comparable to the provisions of the law referred to in paragraph (d)(1) or (d)(2) of this definition; (e) Surface impoundment, pit, pond, or lagoon; (f) Storm-water or wastewater collection system; (g) Flow-through process tank; (h) Liquid trap or associated gathering lines directly related to oil or gas production and gathering operations; or (i) Storage tank situated in an underground area (such as a basement, cellar, mine working, drift, pit, or tunnel) if the storage tank is situated upon or above the surface of the floor. The term underground storage tank or UST does not include any pipes connected to any tank which is described in paragraphs (a) through (i) of this definition.

Unsaturated zone: the zone between land surface and the capillary fringe within which the moisture content is less than saturation and pressure is less than atmospheric. Soil pore spaces also typically contain air or other gases. The capillary fringe is not included in the unsaturated zone.

Vadose zone: the zone between land surface and the water table within which the moisture content is less than saturation (except in the capillary fringe) and pressure is less than atmospheric. Soil pore spaces also typically contain air or other gases. The capillary fringe is included in the vadose zone.

Vapor intrusion attenuation factor (α): a parameter defined by Johnson and Ettinger (1991) to relate the vapor concentration of a volatile chemical inside the building to its vapor concentration at the subsurface source. This parameter, designated alpha (α), is defined mathematically as the vapor concentration in indoor air divided by the vapor concentration in soil gas at the source (with concentration being in the same units), and thus it is a ratio. The source is defined as the region of highest vapor concentration. Therefore, α values are always less than one. The vapor intrusion attenuation factor is an inverse measurement of the attenuation: α values *decrease* with *increasing* attenuation and α values *increase* with *decreasing* attenuation. In other words, α values represent the fraction of soil gas contaminant that reaches indoor air. Large α values (i.e., values approaching 1) indicate that a large fraction of the soil gas contaminant has reached the indoor air; therefore, little attenuation is taking place, whereas small α values indicate that a small fraction of the soil gas contaminant has reached the indoor air; therefore, significant attenuation is taking place.

Vapor pressure: the force per unit area exerted by a vapor in an equilibrium state with its pure solid, liquid, or solution at a given temperature. Vapor pressure is a measure of a substance's propensity to evaporate. Vapor pressure increases exponentially with an increase in temperature.

Vertical separation distance: the thickness of clean, biologically active soil that separates the source of contamination from a building basement, foundation, or slab

Volatile: is a tendency of a substance to vaporize or the speed at which it vaporizes. Volatility is indicated by a substance's vapor pressure. Substances with a higher vapor pressure will vaporize more readily at a given temperature than substances with a lower vapor pressure. A volatile organic compound is an organic compound which has a boiling point below that of water and which can easily vaporize or volatilize.

Volatile organic compound (VOC): organic compound that at room temperature and normal atmospheric pressure produces vapors that escape easily from volatile liquid chemicals. Volatile organic compounds include a variety of chemicals such as gasoline, benzene, toluene, xylene, formaldehyde, tetrachloroethylene, and perchloroethylene.

Volatilization: the process of transfer of a chemical from the aqueous or liquid phase to the gas phase. Solubility, molecular weight, and vapor pressure of the liquid and the nature of the gas-liquid interface affect the rate of volatilization.

Water table: the water surface in an unconfined aquifer at which the fluid pressure in the pore spaces is at atmospheric pressure

Weathering: the process during which a complex compound is reduced to its simpler component parts, transported via physical processes, or biodegraded over time

Wilting point: the minimal point of soil moisture the plant requires not to wilt. Wilting point values under field conditions are not constant for any given soil, but are determined by the integrated effects of plant, soil and atmospheric conditions.

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

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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 provides general recommendations on procedures to accurately determine EPCs. These recommendations 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 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 pathway involving soil leaching and protection of ground water ingestion typically considers data over the entire soil profile from the source area. At the same site, soil EPC estimates for the direct contact route of exposure involving surficial soil 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. 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

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 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. The Interstate Technology Regulatory Council (ITRC) has developed a guide for incremental sampling methodology (ITRC 2012).

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>.

2.3 Arithmetic Average

Using the arithmetic average (or mean) 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 mean tend to converge as the number of samples approaches 20 to 30 (EPA 1992a).

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.

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), 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; ITRC 2012). 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.

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 for cases where other monitoring objectives, such as determining compliance with cleanup criteria or site closure, are the primary goals.

- 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. The need for additional monitoring is a site-specific determination that is dependent on a number of factors, including the magnitude of measured concentrations in relation to risk-based criteria, the degree to which samples are representative and address site factors such as seasonality, and the estimated travel time of contamination from the release area to ground water and to potential receptors. For example, four measurements, taken at appropriate intervals over the course of a year, show an increasing trend but are all below applicable risk criteria. Further monitoring to develop an EPC may not be necessary.
- 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.

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.

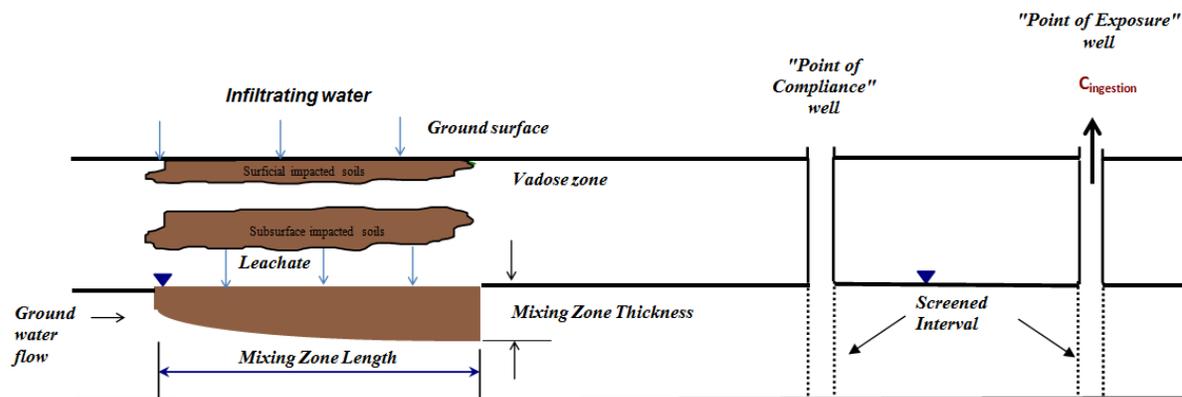


Figure 1. Schematic of soil leaching to ground water

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.

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 (DEQ 2009). Wells clearly not part of the source area of contamination should not be included in the calculations.

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,

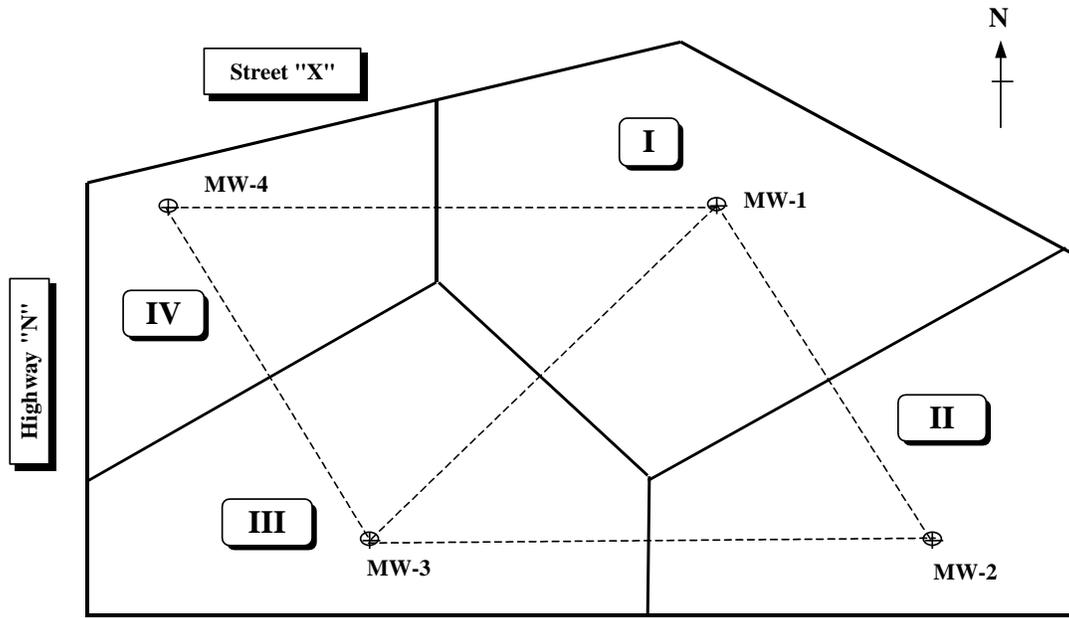
C_{area} = area-weighted average concentration over the EU [mg/kg]

A_i = area of each Thiessen polygon [m²]

A_{Total} = total area of the polygons (i.e., area of the EU) [m²]

$C_{avg,i}$ = 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	
TOTAL		1814	2852	
Area Weighted Average Concentration = $C_{area} = \frac{\sum_{i=1}^{i=n} (A_i * C_{avg,i})}{A_{Total}}$				1.57

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 (Burmaster and Thompson 1997).

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Appendix H: Application of Natural Attenuation

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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 1×10^{-5} atm-m³/mole) 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.

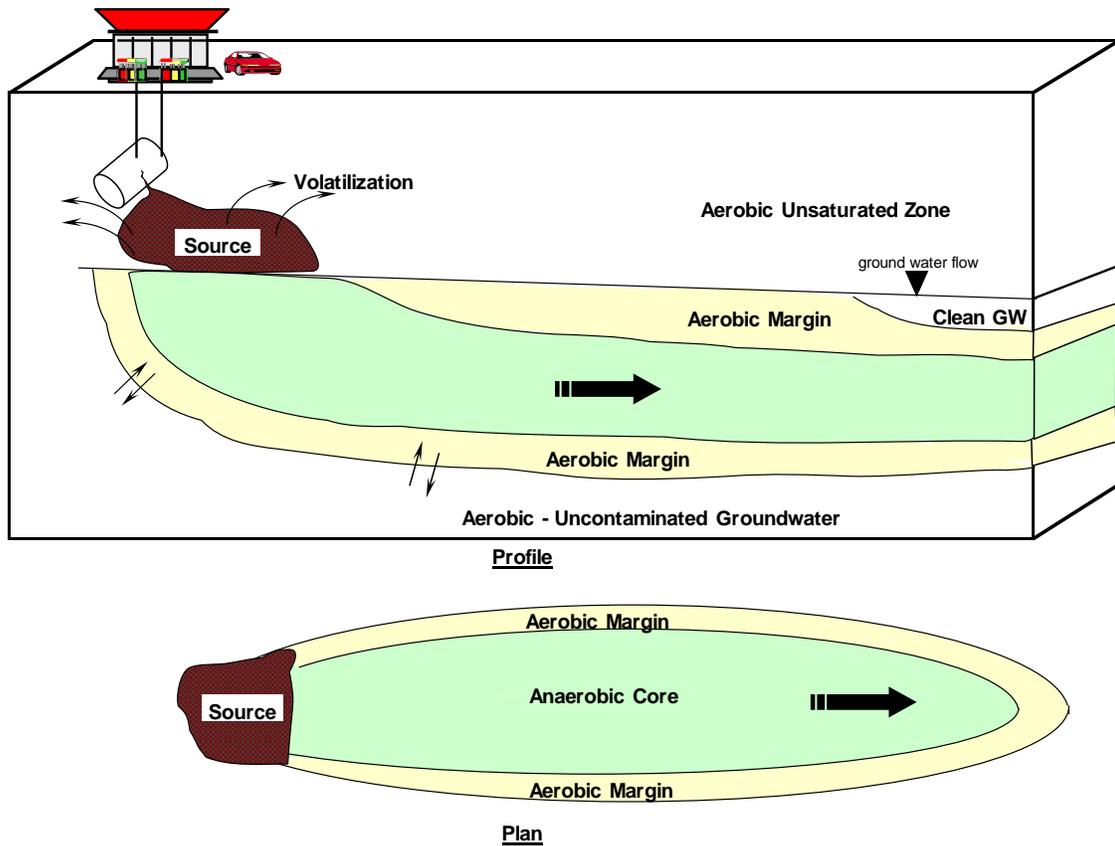


Figure 1. Schematic of a hydrocarbon release

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.

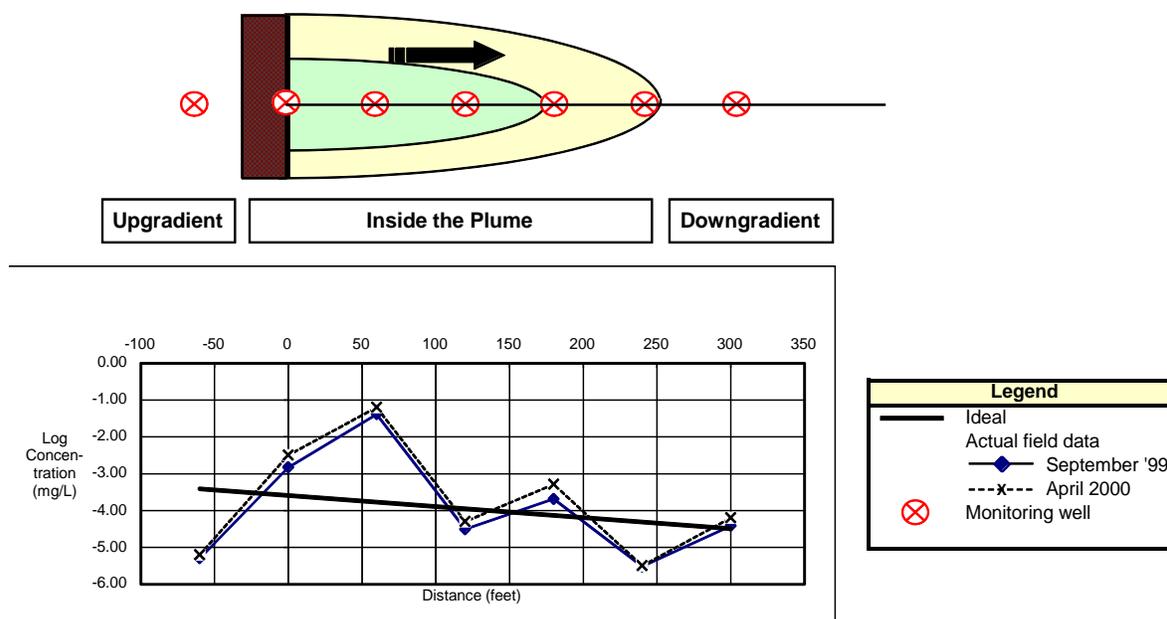


Figure 2. Concentration profile as a function of distance (ideal behavior and data from an actual site)

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 Kosteci 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 (NO_3^-) that is reduced to nitrogen (N_2)
- Manganese (Mn^{4+}) that is reduced to water soluble Mn^{2+}
- Ferric iron (Fe^{3+}) that is reduced to water soluble Fe^{2+}
- Sulfate (SO_4^-) that is reduced to sulfide (S^-)
- Carbon dioxide (CO_2) that may be used by methanogens to yield methane (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.

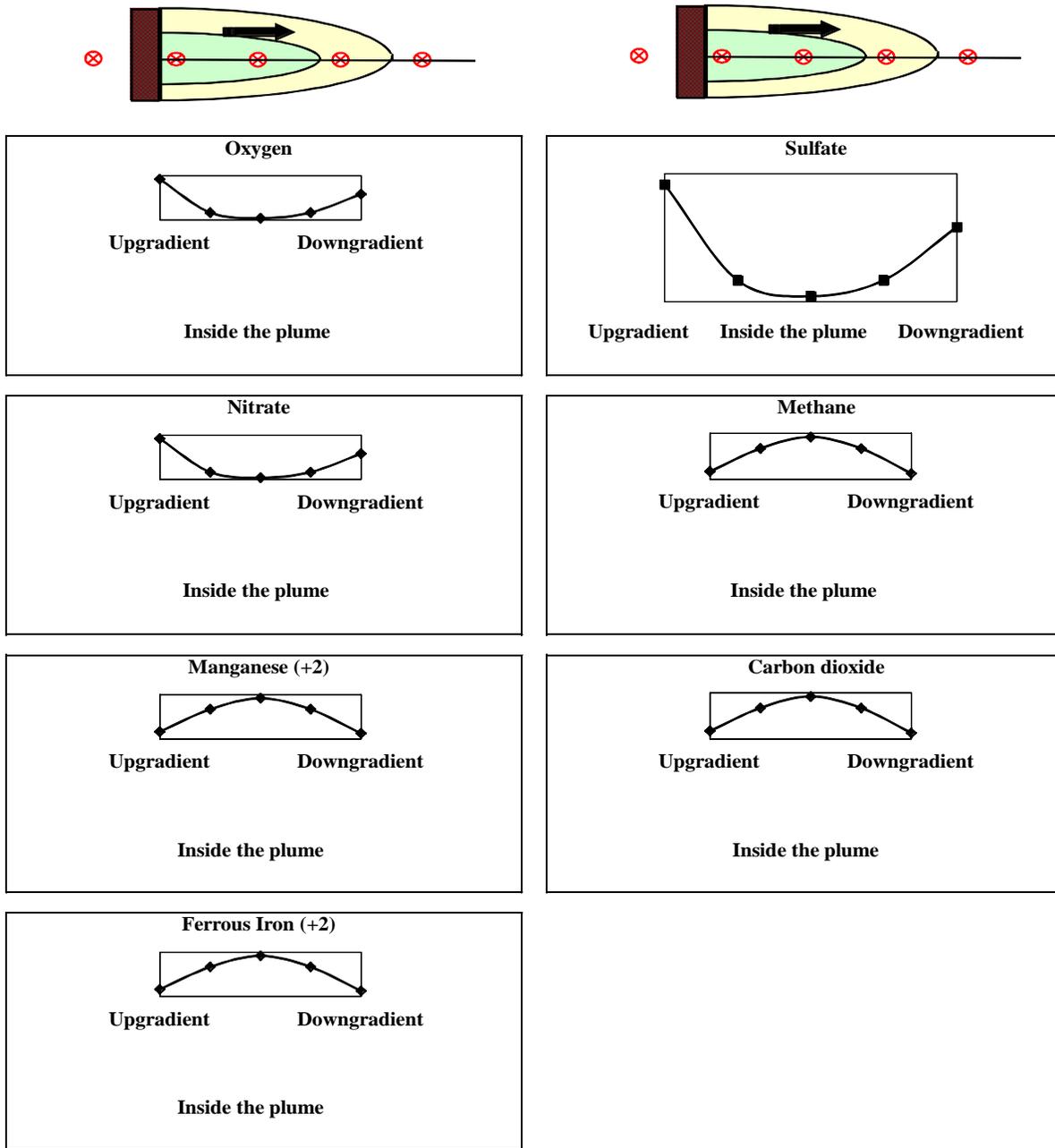


Figure 3. Expected pattern of natural attenuation indicators (secondary line of evidence)

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

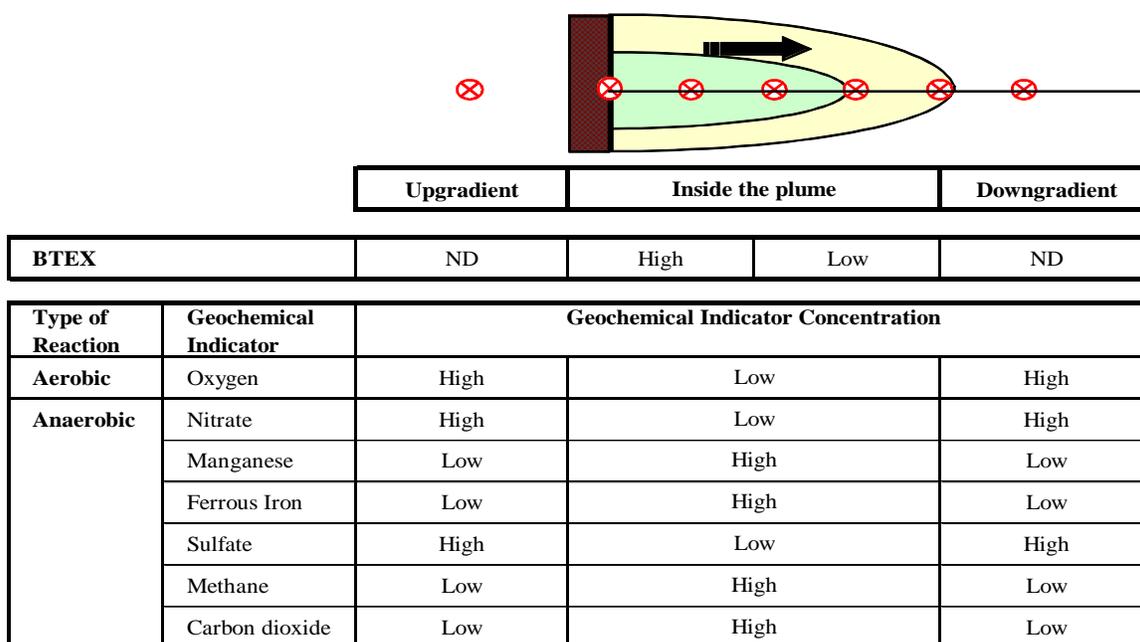
Secondary evidence of NA refers to measurements of electron acceptors and products of metabolism within the plume and their comparison with concentrations in the unimpacted area of the aquifer, where no biodegradation activity would be expected to occur.

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.

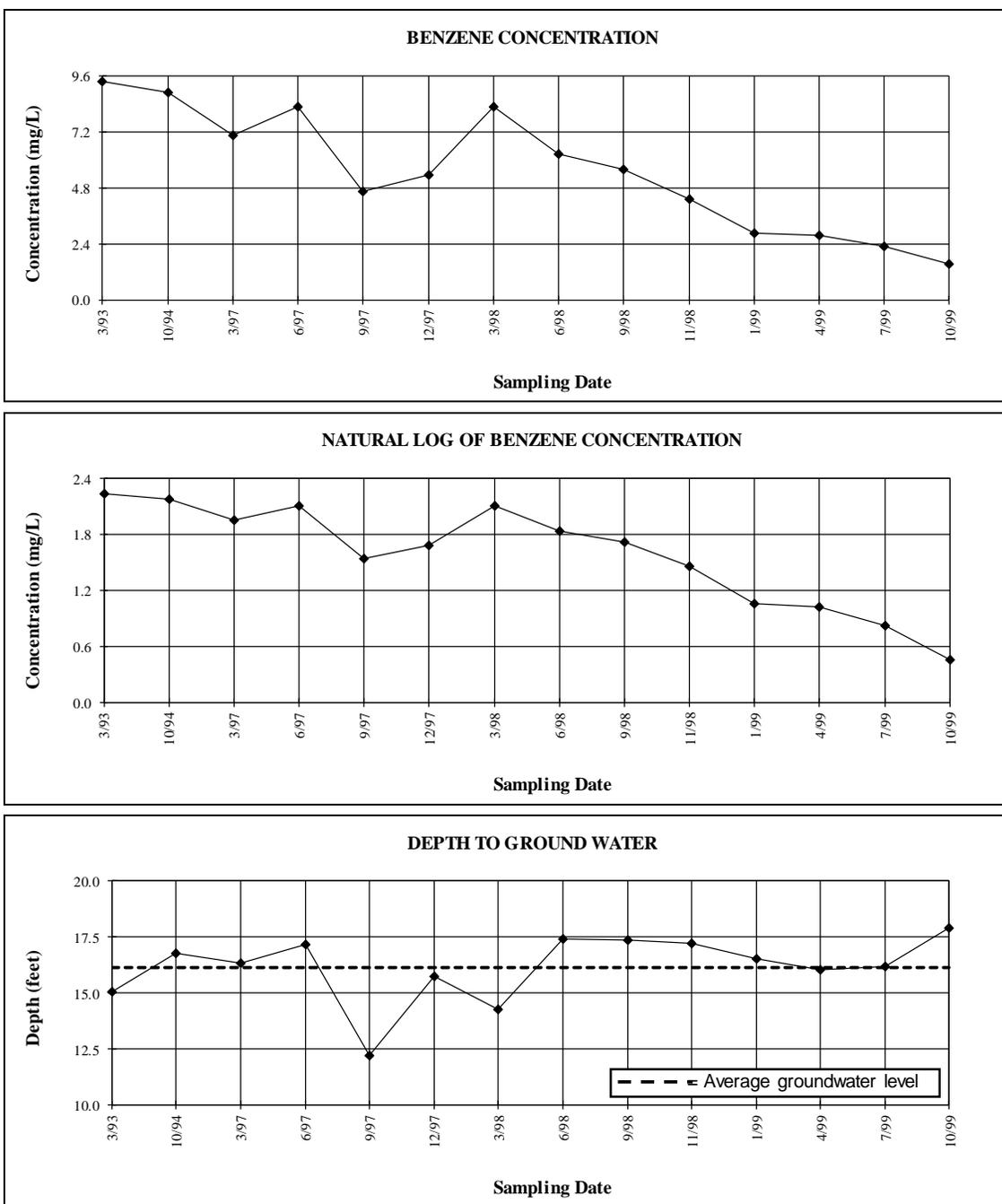


Figure 4. Concentration-versus-time plot of benzene

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:

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

Where:

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

α_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 (λ) 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.

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.

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Appendix K: Practical Quantitation Limits

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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 background on the concepts of PQLs, MDLs and Remediation Standards and provides guidance on using the above factors when a REM user is proposing PQLs as remediation standards.

Background— Practical Quantitation Limits, Method Detection Limits and Remediation Standards

What are PQLs and MDLs?

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.”

How are PQLs Derived?

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.

How did DEQ derive the PQLs and MDLs in Table 1?

For the petroleum chemicals of interest (COI) listed in the rule, the common analytical methods for soil and water employed at petroleum release sites are established by the U.S. Environmental Protection Agency (EPA) in SW-846 (EPA 2011). For soil vapor and ambient air other EPA methods are applied (EPA 1999). Table 1 lists these methods employed in the analysis of the petroleum COI along with typically achieved detection and quantitation limits.

These detection and quantitation 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).

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 achieved with 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.

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. Procedures such as sample dilution may allow quantification of petroleum COI concentrations but will also result 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 (BAA) and benzo(b)fluoranthene (BBF) in water and ethylene dibromide (EDB) in soil pose the greatest potential challenges with respect to PQL values meeting screening level concentrations.

For BAA and BBF, common practical quantitation limits in water using EPA Method 8270 with SIM (0.00005 mg/liter) slightly exceed the groundwater screening levels (0.00003 mg/liter) while the method detection limits (0.00002 mg/liter) are slightly below the screening values. At petroleum release sites where these chemicals are COI and groundwater analytical results for these chemicals are reported either as estimated values (between the quantitation and detection limits) or below the detection limit the screening levels will be assumed to have been achieved. Additional support for this determination is provided if all other PAH chemicals are also reported at concentrations below screening levels.

The most commonly used analytical method for EDB in soils (EPA Method 8260) has typical quantitation (0.001 mg/kg) and detection (0.0003 mg/kg) limits that exceed the soil screening level concentration (0.00014 mg/kg). The soil screening level for EDB is based on protection of groundwater. The groundwater quantitation limit for EDB is below groundwater screening level. Examination of Table 2 of the guidance shows that for EDB the soil quantitation limits are low enough to evaluate the other relevant pathways and routes of exposure, 0.27 mg/kg for direct contact and 0.001 mg/kg for vapor intrusion. At petroleum release sites where EDB is a COI and groundwater is potentially impacted and representative groundwater samples report EDB below the screening level but soil quantitation limits are above the soil screening level the groundwater results will take precedence.

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 or 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.

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 groundwater,
- 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 ($\mu\text{g}/\text{m}^3$)	PQL ($\mu\text{g}/\text{m}^3$)
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	8260	0.0003	0.001	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

Checklist for Proposals to Use PQLs as Remediation Standards

Proposals to DEQ for the use of PQLs as remediation standards at petroleum release sites should include:

- the results of any risk evaluation,
- the remediation standards developed from that process,
- the proposed PQL, and
- the site-specific issues, with supporting information, that justify the use of the proposed PQL(s) as a remediation standard(s).

The supporting information that should be provided in the proposal is listed below along with a discussion of how DEQ will evaluate that information along with potential solutions to various issues, as they may be relevant to the site being evaluated. Given the number and variety of factors which may arise regarding PQLs in relation to remediation standards both the list and the discussion are not considered all-inclusive.

1. Risk Evaluation

- Describe the conceptual site model.
- Identify the level of risk evaluation, the chemicals, media, and pathway or route of exposure that are at issue.
- State the magnitude of the proposed PQL and MDL vs. the remediation standard.

Screening Level Evaluation

For sites where a screening level evaluation has taken place and the proposal is to use PQLs in place of screening levels as remediation standards for specific COI and media, the information provided will be reviewed in a number of ways. The proposed PQLs will first be reviewed relative to the conceptual site model and the pathway/routes of exposure, which are the basis of the screening levels for the chemicals under consideration.

- If the PQL for a chemical exceeds a soil screening level based on groundwater protection but the PQL achieves the groundwater screening level (also based on groundwater protection) for the same chemical, the soil PQL may be used as the soil remediation standard for that chemical.
- If the PQL for a chemical exceeds a soil or groundwater screening level for other routes of exposure (groundwater ingestion, vapor inhalation, or direct contact), DEQ will review the magnitude of the difference between the PQL/MDL and the screening level (whether greater than or less than the screening level) for all COI with a common route of exposure to estimate the potential impact on the cumulative risk from that pathway.
- If the pathway or route of exposure for the media-specific screening level for that chemical can be considered incomplete and the PQL is below the

screening levels for any other complete/potentially complete pathways/routes of exposure for that chemical and media the PQL may be acceptable as a remediation standard. DEQ will use Table 2 of this guidance for evaluation. Alternatively, the screening level for the most appropriate pathway or route of exposure may be considered as a remediation standard.

If only a screening level evaluation has been done completion of a site-specific evaluation may revise the remediation standards and still allow unrestricted use of the site, if that is the desired/expected future land use condition.

Site-Specific Evaluation

PQL issues may be related to cleanup criteria from a site specific risk evaluation. Site specific evaluations depend on the calculation of cumulative risk to a receptor from all pathways/routes of exposure and chemicals, based on estimated exposure point concentrations. The calculation of exposure point concentrations can be influenced by the number of chemicals with PQL issues, proportion of samples with <PQL values, the magnitude of the PQL, and how these censored data are treated in the calculation procedure. If the calculations result in unacceptable risks cleanup levels for individual COI are calculated, some of which may be low enough to be exceeded by PQLs. DEQ will evaluate whether and to what extent < PQL data were used appropriately in these calculations, if the resultant calculated risks are over or under estimated, the degree to which the < PQL data contribute to overall risk, and whether the calculated cleanup criteria can be modified to avoid the PQL issue or if use of a PQL will not materially affect the protectiveness of the cleanup.

The assumptions of the conceptual site model and risk evaluation will be reviewed to determine if the land use scenarios, receptors, and input parameter values are appropriate. For example, while an assumption of residential use may be appropriate all of the specific pathways and routes of exposure assumed to be complete may not be. Exclusion of an inappropriate pathway may eliminate the specific PQL concern. Alternatively, the pathways/routes of exposure may be appropriate but the receptor/land use scenario may not be.

If the PQL for a COI is above a remediation standard but the MDL is at or below the standard there may be instances where sample results falling between these limits can be considered to have met the remediation standard. If a sample result is reported as an estimated value and that concentration is at or below the remediation standard the standard will have been met, Sample results reported as undetected (less than the detection limit, provided the limit is at or below the standard) will have met the standard.

Additional guidance on the treatment of PQL/MDL data and issues in site-specific risk evaluation are available in the EPA *Guidance for Data Useability in Risk Assessment (Part A)* (EPA 1992), the *Risk Assessment Guidance for Superfund*,

Volume I, Part A (EPA 1989), and the EPA ProUCL statistical software technical guide (EPA 2010).

2. Analytical Issues

- Identify the analytical methods used that are the basis of the PQL
- Provide all relevant QA/QC information from the laboratory sheets for the analyses in question including data quality assessment and summaries provided by the laboratory.

When reviewing the proposal DEQ will evaluate whether the data quality assessment and QA/QC accompanying the analytical results adequately explain and support the PQLs proposed. Generally, PQL proposals should be based on PQLs derived from undiluted samples. Elevated PQLs resulting from sample dilution are typically the result of an attempt to quantitate all the COI when the concentrations of one or more chemicals (some of which may not be COI) are highly elevated, often referred to as matrix interference.

Matrix interference can also occur due to the nature of the media (soils in particular) which can impair the quantitation of a COI. The matrix spike and matrix spike duplicate portions of the laboratory QA procedures can sometimes clarify whether there are matrix interferences and whether they are causing over or underestimation of actual concentrations of a COI.

3. Sampling

- Provide information on the number of sampling events completed to support the PQL proposal.
- Provide information on the sampling procedures and QA/QC measures implemented during each of the sampling programs undertaken at the release site. Copies of quality assurance project plans and evaluations of adherence to and departure from those plans for the site in question for each event should be included.

The owner/operator may select alternative sampling procedures, which may provide for a lower PQL. The PQLs for analysis of air and vapor samples can be dramatically affected by the volume of air which is sampled.

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.

References

- EPA (U.S. Environmental Protection Agency). 1989. *Risk Assessment Guidance for Superfund, Volume 1, Human Health Manual (Part A)*. United States Environmental Protection Agency. EPA/540/1-89/002.
- EPA (U.S. Environmental Protection Agency). 1992. *Guidance for Data Useability in Risk Assessment (Part A)*. United States Environmental Protection Agency. 9285.7-09A.
- EPA (U.S. Environmental Protection Agency). 1999. *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, Second Edition*. United States Environmental Protection Agency. EPA/625/R-96/010b.
- EPA (U.S. Environmental Protection Agency). 2001. *The Relationship Between SW-846, PBMS, and Innovative Analytical Techniques*. United States Environmental Protection Agency. EPA 542-R-01-015.
- 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). 2010. *ProUCL Version 4.1.00 Technical Guide (Draft), Statistical Software for Environmental Applications for Data Sets with and without Nondetect Observations*. United States Environmental Protection Agency. EPA/600/R-07/041.
- 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>

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Appendix L: Quality Assurance Project Plan Template

This appendix provides an example of the elements and general description of the content that should be included in a Quality Assurance Project Plan. It was current as of July 2012. Please contact DEQ to obtain a copy of the most current version.

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State of Idaho

Department of Environmental Quality

Quality Assurance Project Plan

Idaho Department of Environmental Quality

Title: Enter the title of your project here

Region/Division: Enter the name of the applicable Region or Division

Revision # Enter the document revision number. This number should increase by 1 each time the document is revised and approved.

Date: mm/dd/yyyy This date should be reasonably close to the final approval signature date

TRIM Record Number: To be filled in by staff member who enters document into TRIM

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THE INFORMATIONAL TEXT CONTAINED ON THE NEXT FEW PAGES (UP TO “SECTION 1 – TITLE AND APPROVAL PAGE”) IS INTENDED FOR USE BY STAFF TASKED WITH GENERATING A NEW PROJECT QAPP, AND SHOULD BE DELETED FROM THE DOCUMENT PRIOR TO FINALIZATION.

Example/Template QAPP – Rev 1.2 – 01/13/2012

The following few pages contain important information and general instructions for all Department of Environmental Quality (DEQ) personnel assigned the task of generating, reviewing, or approving a DEQ Quality Assurance Project Plan (QAPP). A thorough understanding of these instructions will expedite the QAPP development process, and all personnel involved in these tasks are highly encouraged to read these pages prior to initiating the process. Before submission of the QAPP for approval, these four pages of instructional notes should be deleted, including this page and all the following pages up to Section 1 – “Title and Approval Page”.

All DEQ staff involved in generating a project QAPP are also strongly encouraged to read the current revision of the DEQ Quality Management Plan (QMP), and the “EPA Guidance for Quality Assurance Project Plans, EPA QA/G-5” document, which explains each section of a project QAPP in more detail. These two documents can be accessed via hyperlinks located on the Inside DEQ Intranet “Quality Assurance” page, and on the last page of these instructions.

This document is intended to be both an example QAPP, and a template for use, by those who need to author a DEQ project QAPP. The format of this document is designed to comply with the DEQ Quality Management Plan, and to meet the minimum quality system requirements as established by the EPA. Previous versions of the DEQ QAPP outline should no longer be used.

In order to ensure progressive QAPP document improvement across the agency, the latest version of this example/template QAPP should be obtained from the DEQ intranet each time that a new project QAPP is to be developed. Through the incorporation of feedback and input from project personnel, this example/template QAPP will continue to improve over time.

The text in this document, which is highlighted in grey, is considered example language which must be revised and edited as necessary to reflect the needs of the actual individual project for which the new QAPP is being written. Text in this document that is NOT highlighted in grey is considered language that is critical to meeting the minimum intent of the DEQ QMP. Much of this non-highlighted language is expected to be applicable to most DEQ QAPP’s. If the non-highlighted text is edited to satisfy specific project requirements, the revision must address the intent of the original text in an equivalent or superior fashion.

The format (Sections 1 through 25) of this document shall not be changed, as it is specifically designed to comply with the DEQ QMP, and to meet current EPA requirements. Please also note that all sections in the included outline must be filled out, leaving no blank sections. If a section is not applicable to the project, an explanation of why that section is not relevant is required.

Through the use of this example/template QAPP, rather than a blank template, the individual project author will have the opportunity to use portions of the existing language that are applicable to their project. This example/template document is based on a Nitrate Priority Area QAPP, originally authored by the Boise Regional Office, and further enhanced by the Idaho Falls Regional Office. The example language serves to illustrate the level of detail necessary for a typical DEQ project QAPP.

Use of this example/template QAPP is intended to make the process of creating a new DEQ project QAPP simpler, more robust, and increasingly uniform throughout the agency. For additional guidance on what information should be included in each section of the example/template QAPP, please refer to the “EPA QA/G-5 Guidance for Quality Assurance Project Plans” document, which explains each section in more detail.

Please note that this example/template QAPP is not intended to be an “off-the-shelf” completed project QAPP. It is intended as an aid for QAPP development, and to help ensure a level of consistency across the agency. While it is not possible to develop an example QAPP that will satisfy the detailed needs of all projects which may arise in the performance of DEQ project work, the provided example language will guide project personnel in their efforts to produce an acceptable QAPP.

This example/template QAPP is also based upon the assumption that the project for which a QAPP is being developed uses a laboratory to analyze samples. Not all DEQ projects gather samples in the process of gathering project data. In cases where only data is gathered, some portions of the non-shaded language may not be applicable, and should be removed. However, please remember that no section can be left blank. If a section is not applicable to the project, an explanation of why that section is not relevant is necessary.

For projects requiring the use of existing data, DEQ QAPP authors should follow the steps outlined in Chapter 3 of the EPA “Guidance for Quality Assurance Project Plans” document (EPA QA/G-5).

As mentioned previously, this document will be revised on a regular basis, based on input from Regional and State Office staff. The DEQ will also be revising the entire DEQ Quality Management Plan (QMP), based on comments received from the EPA during the September 2011 Quality System Review (QSR) of the DEQ quality assurance program.

The DEQ QMP revision process will involve frequent consultation with the EPA, and will likely result in several changes to the current program. During this transitional period, the example/template QAPP may occasionally be revised to reflect the most significant changes made to the overall DEQ quality system.

Suggestions for improvement of this document, which meet EPA requirements, are highly encouraged. Please bring all suggestions to the attention of the DEQ Quality Assurance Director.

To help alleviate confusion with respect to the general roles of various project personnel, please refer to Table 2 of the example/template QAPP for an in-depth description of these roles and responsibilities.

The following links contain resources that will provide helpful information and guidance to all DEQ personnel tasked with generating a project QAPP. The first link provided below will bring the user to the “Quality Assurance” area of the “Inside DEQ” Intranet Page.

For DEQ personnel tasked with writing a project Quality Assurance Project Plan, the **EPA QA/G-5 Guidance document** provides clear and detailed explanations on how to fill out the required sections. This example/template QAPP only provides the framework for a project QAPP, the bulk of the information must be supplied by the author of the QAPP. The EPA QA/G-5 guidance document will be of significant assistance to the QAPP author, and use of that document (see link below) is highly recommended.

Link to the DEQ intranet page which provides several links to the major EPA and DEQ QA System documents:

<http://insidedeq.deq-intra/director/quality.htm>

Link to the “DEQ Quality Management Plan” (QMP):

This document describes the overall quality assurance system used by the DEQ. It provides the general description of how the DEQ quality assurance system functions, what the elements of the system are, and basic requirements for DEQ quality system documents.

http://insidedeq.deq-intra/director/quality/quality_mgmt_plan_07.pdf

Link to the EPA “Guidance for Quality Assurance Project Plans” (EPA QA/G-5) document:

In conjunction with the DEQ QMP, this document provides detailed guidance to project personnel with respect to how to write a project QAPP.

<http://www.epa.gov/quality/qs-docs/g5-final.pdf>

Link to the EPA page listing several resources related to writing a project QAPP:

<http://www.epa.gov/quality/qapps.html>

Link to the EPA Agency-wide quality system document resource page:

http://www.epa.gov/quality/qa_docs.html

Link to the EPA Quality System main page:

<http://www.epa.gov/quality/>

Note that for most of the EPA “Requirement” documents, there is a companion EPA “Guidance” document. These guidance documents generally have the same title as the requirements document, but have the letter “G” rather than “R” associated with their title. The EPA has many other quality system guidance and requirement documents, all of which can be easily found at the EPA Quality System main internet page (see link above).

(Links verified operational on 1-13-2012)

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1. Title and Approval Page

Quality Assurance Project Plan

Title: Enter the title of your project here

Region/Division: Enter the name of the applicable Region or Division

Revision # Enter the document revision number. This number should increase by 1 each time the document is revised and approved

Date: mm/dd/yyyy This date must be the same as that used on the cover page and header. This date should be reasonably close to the final approval signature

Approval Signatures

Note: This QAPP becomes effective on the date of the last approval signature

DEQ Quality Assurance Director

Signature: (If Required – See QAPP instruction pages) _____
Name: Mark K. Clough, Quality Assurance Director, State Office Date _____

Program/Regional Manager

Signature: _____
Name: Staff Name, Position, Office/Region Date _____

Project Quality Assurance Officer

Signature: _____
Name: Staff Name, Position, Office/Region Date _____

Project Manager

Signature: _____
Name: Staff Name, Position, Office/Region Date _____

Project Technical Lead / Author

Signature: _____
Name: Staff Name, Position, Office/Region Date _____

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2. Table of Contents

The Table of Contents (Below) must be updated following the completion of the new QAPP.

This can easily be accomplished using Microsoft Word, through use of the following steps:

1. After the draft project QAPP has been completed, open the document in Microsoft Word 2010
2. Print this page so that you have these directions (if needed), then delete these shaded “table of contents directions” so that they will not be included in your newly created table of contents.
3. Using the mouse, single left click the table of contents, which will turn the table grey.
4. After a few seconds, a tab with the words “Update Table” on it will open at the top of the table of contents.
5. Click on the “Update Table” tab, and then select the “Update Entire Table” option.
6. Click “OK”, and the table of contents will immediately update.
7. Click anywhere in the document, outside the table of contents, and the table of contents update procedure will be completed.

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3. DISTRIBUTION LIST

The following personnel and analytical laboratory contacts, at a minimum, will receive either an electronic copy or a hard copy of the final signed QAPP:

Table 1: Project QAPP distribution list.

Name	Project Affiliation	Organization and address/location	Contact Number
Mark K. Clough	DEQ Quality Assurance Director	Idaho DEQ – Directors Office	208-373-0528
Name	Program Manager	Idaho DEQ	###
Name	Project Quality Assurance Officer	Idaho DEQ	###
Name	Project Manager	Idaho DEQ	###
Name	Project technical Lead	Idaho DEQ	###
Contact Name	Analytical Laboratory	Laboratory Name	###
Contact Name	Analytical Laboratory	Laboratory Name	###
Contact Name	Analytical Laboratory	Laboratory Name	###

4. PROJECT/TASK ORGANIZATION

Table 2: Key project personnel and associated responsibilities.

Name	Project Title/Responsibility
Name of assigned DEQ Staff	<p><u>Program Manager:</u> This person is the regional manager or state office program manager who will assist in the development, review, and approval of the project QAPP. Responsible for ensuring that the project QAPP is designed to meet the data needs of the program, and references current approved program procedures and policies. The Program Manager will also select a qualified Project Quality Assurance Officer, and after obtaining approval for this selection from the DEQ Quality Assurance Director, assign this individual to the project. This process is designed to enhance impartiality, and to ensure the accuracy of the authorized Project QA Officer list maintained by the DEQ Quality Assurance Director.</p>
Name of assigned DEQ Staff	<p><u>Project Quality Assurance Officer:</u> Each project is to have an assigned Project QA Officer (QAO). This person will assist in the development, review, and approval of the project QAPP, and project related documents such as Field Sampling Plans (FSPs). The Project QAO will perform periodic project reviews/audits in accordance with the DEQ QMP, and provide data verification and validation per the project QAPP and FSP. The Project QA Officer may also be part of the review team for project final reports. In matters of project quality assurance, this individual will have a direct line of communication to the DEQ Quality Assurance Director. Per EPA requirements, the Project QA Officer shall review the QAPP annually, to determine if revision is necessary. The Project QA Officer shall not be the Project Technical Lead, the Project Manager, the Program Manager, or be otherwise assigned to the project data generation efforts. Neither the Project Manager nor the Project Quality Assurance Officer may directly report to the other within the DEQ organizational structure, and both of these individuals may not be directly supervised by the same person. All assigned Project QA Officers shall, prior to signing for the approval of any project QAPP, contact the DEQ Quality Assurance Director to discuss the project. At that time, the DEQ QA Director shall also verify that the assigned Project QA Officer is on the authorized Project QA Officer list. This process is designed to ensure that all DEQ QAPPs are approved, and issued, in accordance with the DEQ Quality Management Plan.</p>

Name	Project Title/Responsibility
Name of assigned DEQ Staff	<p><u>Project Manager:</u> This person is responsible for overall project planning, document development and approval, sample planning and coordination, laboratory coordination, data review and verification, reporting functions, project report/summary development, and documentation of all project activities in the TRIM system and elsewhere as required by the project documents. Responsible for ensuring all project work is conducted in accordance with the DEQ QMP, and the approved project QAPP and associated FSPs. The Project Manager is responsible for ensuring that personnel assigned to this project are appropriately trained and qualified, with the corresponding training records on file in Human Resources. This individual will also perform periodic project reviews/audits in accordance with the DEQ QMP, and provide data verification and validation per the project QAPP and associated FSPs. The Project Manager may also be part of the review team for project final reports. The Project Manager shall review the project QAPP annually, and determine if revision is necessary. If the QAPP does require revision, the revised QAPP must be submitted for approval prior to implementation, per the DEQ QMP.</p>
Name of assigned DEQ Staff	<p><u>Project Technical Lead:</u> This individual is to be familiar with the technical aspects of the project, and is assigned by the Program / Project Manager to be the technical lead and to assist in the development of the project specific QAPP. This individual should have experience in the methods, procedures, and equipment to be employed in the conduct of the work described in the QAPP. Also responsible for Coordination with sample location contacts, management of day-to-day aspects of sampling; planning, data collection, sample handling, coordination with the labs for sample shipping and analysis, receipt of resulting data, and data review and verification per the approved project QAPP and associated FSPs. This individual should be familiar with the information contained in the EPA Guidance for Quality Assurance Project Plans, EPA QA/G-5 document.</p>
Name of assigned DEQ Staff	<p><u>Laboratory Contact/Manager:</u> Laboratory sample receipt, analysis, and laboratory data review.</p>

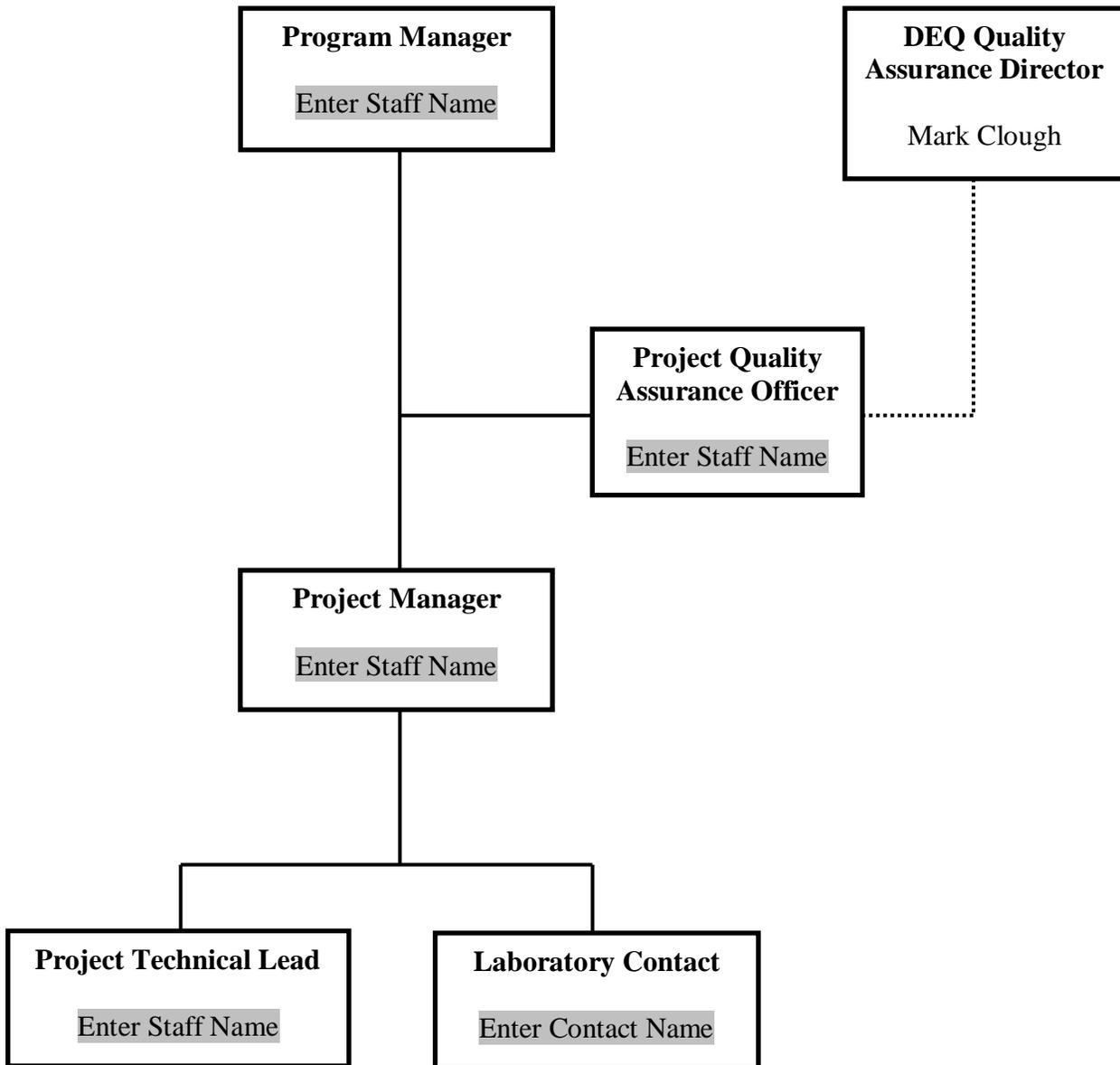


Figure 1: Project organizational chart

5. PROBLEM DEFINITION/BACKGROUND

A. Problem Statement

The Idaho Department of Environmental Quality (DEQ) is responsible for conducting regional ground water monitoring activities, per the Idaho Ground Water Quality Plan. The DEQ Idaho Falls Regional Office (IFRO) develops monitoring projects to investigate regional ground water quality issues. These issues can be the result of local public concern, regional office priority, or State-wide Departmental emphasis. Regional projects may include nitrate source or trend-related investigations focusing on Nitrate Priority Areas (NPAs), and sampling to address specific local concerns such as arsenic. The DEQ regional office is also charged with facilitating drinking water source protection. Projects may include sampling to support protection implementation strategies.

The overall rationale for regional nitrate monitoring activities is to address DEQ's responsibilities under the Ground Water Quality Plan, summed up as to provide ground water monitoring data that will aid in:

- identifying areas of high vulnerability
- assess concentration trends in areas of degraded ground water quality
- identify, delineate, and explain sources of variability and degradation at regional and local levels,
- informing, directing, and prioritizing ground water protection programs and efforts, and
- Providing a means of evaluating effectiveness of best management practices, improving these best management practices, and to support regulatory decisions.

This Quality Assurance Project Plan (QAPP) provides a framework for data collection to identify potential sources of impact to ground water within the region. More specifically, this QAPP includes elements consistent for ground water monitoring events focusing on identifying potential sources of nitrate impacts to drinking water sources, primarily ground water. Nitrate-related sampling campaigns shall reference this QAPP, and include a Field Sampling Plan (FSP) detailing specific objectives, analytes, sampling strategies, pertinent background and sample locations.

B. Intended Usage of Data

The data collected for the Regional NPA Monitoring will be used to determine the nature and extent of ground water contamination due to nitrate. The sample results will be shared with Idaho State Department of Agriculture (ISDA) or other agencies, as necessary, to determine appropriate response activities. All sample results will be entered into the DEQ Ground Water Quality Database and be available through the online mapping application.

Sample results for NPA monitoring will be presented in either an annual DEQ ground water monitoring report or a campaign/project-specific report that will be included in the DEQ Ground Water Technical Report Series. Nitrate data may also be used in the NPA ranking process.

Private well owners will receive a report of analytical data from samples collected from their well. Appropriate data interpretation and recommendations may also be included.

6. PROJECT/TASK DESCRIPTION

A. General Overview of Project

Sampling projects will assess regional and local ground water quality impacts to the public due to the nitrates in ground water. The framework for monitoring to assess regional and local water quality and impacts will be described in a regional nitrate monitoring design document to be developed. A project/campaign-specific description, including network design/site selection will be included in the FSP for each monitoring campaign. Sites will be selected based on a combination of criteria, as pertinent to the specific project, including; well completion depth, location, accessibility, and historic sample results. Random or stratified random selection processes may be employed. Preference may be given to wells representative of sensitive populations and wells screened in the upper-most aquifer or portion of the aquifer. Priority may also be given to previously sampled wells to allow development/evaluation of trends.

Samples may be collected at each location for analysis of one or more of the following, as required for the specific sampling campaign:

- Major cations (e.g. calcium, magnesium, sodium, potassium)
- anions (e.g., nitrate, nitrite, sulfate, chloride, bromide, fluoride and o-phosphate)
- ammonia
- bacteria: total coliform bacteria , E. coli

- nitrogen isotope ($\delta^{15}\text{N}$)
- oxygen/deuterium isotopic ($\delta^2\text{H}$ - $\delta^{18}\text{O}$)
- nitrogen and oxygen isotopic for nitrate anion ($\delta^{15}\text{N}_{\text{NO}_3}$, $\delta^{18}\text{O}_{\text{NO}_3}$)
- tritium
- Pharmaceuticals and Personal Care Products (PPCPs)

Sample submission may follow a staged approach to maximize cost vs. diagnostic benefits; for example while samples collected for less costly analyses such as $\delta^{15}\text{N}$, and $\delta^{18}\text{O}$ may be collected and submitted for all sites, samples for more expensive analyses such as $\delta^{15}\text{N}_{\text{NO}_3}$ and $\delta^{18}\text{O}_{\text{NO}_3}$ or PPCPs may be collected at all sites, but not submitted for analysis unless initial results indicate that such information may confirm contamination sources or geochemical processes are occurring. These tiered analyses may aid in correctly identifying the primary factors to explain contaminant conditions observed. Holding times and sample preservation requirements would allow for this staged approach.

B. Project Timetable

The specific project timetable will be designated for each monitoring project in the FSP.

7. QUALITY OBJECTIVES AND CRITERIA

The objective of quality assurance and quality control (QA/QC) is to assure that analytical results obtained by sample analyses are representative of actual chemical and physical compositions of the ground water. Field QA/QC will consist of following a standard protocol for sample collection and by collecting and analyzing sample duplicates and field blanks. The duplicates will be used to determine both field and laboratory precision. The field blank will be used to check the integrity of the sample collection and handling process. Both the duplicate and field blank samples are stored and handled with the normal sample load for shipment to the laboratory. Project goals and sampling conditions may require additional field QC samples, including equipment blanks or spiked samples. Field QC samples will be submitted “blind”. Ideally, at least one set of field quality assurance samples will accompany each sample shipment or analysis batch.

Field QC samples will comprise at least 10% of all samples with a goal of 20% QC samples.

Field screening data (e.g., field parameters of pH, temperature, specific conductivity, and dissolved oxygen) are at data quality Level I (field parameter/ screening level data). Laboratory analytical data (i.e., data from samples submitted to a laboratory for analysis) are at data quality Level III (standard laboratory procedures and data reviewed by standard Quality Assurance protocols). Specific data quality objectives or requirements will be included in the FSP if not included in the project QAPP.

A. Data Precision, Accuracy, Measurement Range

Accuracy is a measure of the closeness of the agreement between a “true” or reference value and the associated measured value. A sampling campaign may include spiked samples with a known matrix submitted blind to the laboratory or may rely on reported recoveries for Laboratory Control Samples (LCS). The recoveries of laboratory control samples (LCS), matrix spikes, and surrogate spikes will be used to evaluate the accuracy of the measurements. These recoveries are typically calculated as “percent recovery” represented by the following equations:

Spiked sample or LCS Percent Recovery:

$$\%R = C_M / C_T * 100$$

Where: C_M = Measured spike/LCS concentration

C_T = True spike/LCS concentration

Matrix Spike and Surrogate Recoveries:

$$\%R = (C_S - C_{US}) / C_T * 100$$

Where : C_S = Measured concentration of Spiked Sample

C_{US} = Measured concentration of Un-Spiked Sample

C_T = True Concentration of Spike Added

Laboratory accuracy for each analysis is set by a statistical analysis of the laboratory equipment and the acceptable accuracy range for the laboratory equipment will be indicated in the laboratory sheets. Any outliers from the acceptable range in % Recovery, as determined by the laboratory, will be flagged by the laboratory. **Typical accuracy goals will be $\pm 20\%$.** Accuracy goals will be specified in the FSP if not specified in the QAPP.

Precision is a measure of agreement between two measurements of the same property under prescribed conditions. Sampling campaigns may include duplicate samples (field replicates or split samples) or may rely on LCS split sample results. The Relative Percent Difference (RPD) of duplicate samples will be used to assess data precision. For laboratory duplicates, field duplicates and matrix spike duplicates, the following equation will be used to calculate Relative Percent Difference (RPD):

$$RPD = \frac{(C_1 - C_2)}{(C_1 + C_2) / 2} * 100$$

Where: C_1 = Concentration in first sample

C_2 = Concentration in the second/duplicate sample

Where both C_1 and $C_2 > 5$ times the laboratory Method Detection Limit (MDL).

Where one or both C_1 and C_2 are less than 5 times the MDL, the results will be considered within control limits where C_1 and C_2 are \pm MDL.

For radiological samples, such as tritium, precision will be assessed by RPD where both results exceed 5 times the MDL, otherwise results will be considered within control limits when within 3 times Pooled Standard Error (PSE):

$$PSE = |R_1 - R_2| \leq 3(S_1^2 + S_2^2)^{1/2}$$

Where:

R_1 = concentration in first sample

R_2 = concentration in second/duplicate sample

S_1 = analytical uncertainty (counting error associated with laboratory measurement of the first sample)

S_2 = analytical uncertainty (counting error associated with laboratory measurement of the duplicate sample)

The goal for precision and what that precision will be based on for each sampling campaign will be included in the FSP if not included in the QAPP. In general, precision will be based on field duplicates with a goal of $\pm 20\%$.

Appropriate **Measurement Range** is determined by reviewing results with comparison to the laboratory reporting levels/MDL. Reporting requirements are determined prior to sampling through review of historical data for the analytes and region of interest, and reflected in choice of analytical laboratories, analysis methods and requested reporting levels/MDL. Assessment criteria and goals will be described in the FSP if not included in the QAPP.

B. Data Representativeness

Representativeness is defined as the degree to which the sample data accurately and precisely represent site conditions. The representativeness criterion is best satisfied by confirming that sampling locations are properly selected, sample collection procedures are appropriate and consistently followed, a sufficient number of samples are collected, and analytical results meet data quality objectives. All sampling procedures will follow the sampling procedures in the sampling protocol in Appendix A. Representativeness is evaluated by comparing the combination of data accuracy, precision, appropriate measurement range and methods, and assessing other potential sources of bias; including sample holding times, blank samples, and laboratory quality assurance review. Any additional specific assessment criteria and goals will be described in the FSP if not included in the QAPP.

C. Data Comparability

Comparability is defined as the confidence with which one data set can be compared to another data set. Using standard sampling and analytical procedures will maximize

comparability. In an effort to ensure data comparability, sample collection protocols (included in Appendix A) will be consistently followed, the same analytical procedures will be used, and the same laboratory will be used to analyze the samples throughout each project. The FSP for each project will include the laboratory to be used for each analyte.

D. Data Completeness

Completeness is defined as the percentage of valid data relative to the total possible data points. For data to be considered valid, it must meet all of the acceptance criteria, including accuracy and precision, as well as any other criteria specified by the analytical method used. The overall data quality objective for completeness for the sampling events conducted under this QAPP is 80%. Any required departure from this goal will be justified and explained in the FSP.

8. SPECIAL TRAINING/CERTIFICATION

The Project Manager and/or Program Manager is responsible for ensuring that personnel assigned to this project are appropriately trained and qualified, with the appropriate training records on file in DEQ Human Resources.

All work performed by DEQ personnel will be conducted in accordance with the State of Idaho Worker Health and Safety Plan.

No special training for ground water sample collection is required; staff will have previous ground water sampling experience and on-the-job training.

9. DOCUMENTATION AND RECORDS

Project documents will be filed electronically in TRIM, in accordance with applicable program filing procedures. The Project Manager is responsible for ensuring that the most current approved revision of the project QAPP, with related FSPs and SOPs, is available in the DEQ TRIM electronic records management system.

Field personnel will document each day's activities in field notes. Information is to be recorded as follows:

- Project data must be recorded directly, promptly, and legibly.
- Field logbook or field sheet entries must be made in black or blue permanent ink and must be signed/initialed and dated by the person making the entry.
- Changes or corrections to data must be indicated with a single line through the original entry.
- Changes must be initialed, dated, and explained.

In addition to field notes (as identified in Appendix B at a minimum), documentation is to include all data used to develop the monitoring network, well sampling permission documentation, a sampling procedures document, the reports summarizing the sampling events and results.

10. SAMPLING PROCESS DESIGN

A. Rationale for Selection of Sampling Sites

The nitrate priority area monitoring network will consist of existing private domestic, irrigation or public water system wells that are selected following the protocol (to be developed) for the IFRO Regional Ground Water Monitoring Network Design. Sampling frequency, where not described in the regional ground water monitoring design document, will be described in the associated FSP. The specific FSP will identify the number of sample locations and specify analytes, collection and analysis requirements, special handling or follow-up criteria and reporting requirements. Permission from the well owner will be obtained prior to sampling each well.

B. Sample Design Logistics

Sampling logistics will be identified in the specific monitoring campaign FSP if not identified in this QAPP.

11. SAMPLING METHODS

QA/QC procedures as specified for sample collection will be followed by sampling personnel. The QA/QC procedures will be fulfilled by adhering to all requirements detailed in this QAPP and the ground water sampling procedure located in Appendix A of this QAPP. Such adherence will be demonstrated through appropriate documentation of sampling procedures within the field logbook or field sheets as described herein. Field audits by the Project QA Officer may also be part of QA/QC procedures.

Samples collected from private domestic wells, irrigation or public supply wells will utilize the existing pump and distribution system. Water samples will be collected from a faucet or sample port nearest the well and before any treatment system. Samples collected from monitoring wells will utilize a submersible pump, peristaltic pump, or disposable bailer. If a pump is used, dedicated or disposable tubing will also be used. Equipment blanks may be included with the complement of quality assurance samples.

A portable meter will be used to measure pH, specific conductance, dissolved oxygen, and temperature at each sample location. A GPS will be used to determine the longitude and latitude of the well/sampling point.

Field work quality will be controlled by following standard sampling protocols (Appendix A) during each sampling event, using consistent sampling containers and laboratories, and collecting sample duplicates and blanks. Protocols for items such as equipment decontamination, chain of custody forms, sample blanks, etc, are found in Appendix A, and further detailed in the project FSP. Detailed field notes will be taken for quality control and proper sample identification.

Analytes, laboratories, shipping addresses, and current contract numbers as appropriate are included in Table 3. Analytical methods, sample container, preservation and holding times are identified in Section 13 and Table 4.

Table 3: Analytes, laboratories, and contract numbers.

Analytes	Preferred analyzing Laboratory	Shipping address	DEQ Contract number
Major anions, Major cations, nutrients	State of Idaho Bureau of Laboratories	2220 Old Penitentiary Rd Boise ID 83712	MOA
Bacteria: Total Coliforms, E. Coli	IAS-EnviroChem	3314 Pole Line Road Pocatello, ID 83201	Vendor
Stable isotopes: ^{15}N , ^{18}O , ^2H	University of Arizona Environmental Isotope Geosciences Laboratory	Department of Geosciences Gould-Simpson Building Tucson, AZ 85721-0077	C515
tritium	Idaho State University Environmental Monitoring Laboratory	Department of Physics 785 Sth 8th Bldg3 RmB107A Pocatello, ID 83209	research partner
Stable isotopes: $^{15}\text{N}_{\text{NO}_3}$, $^{18}\text{O}_{\text{NO}_3}$	University of Waterloo Environmental Isotope Laboratory	UwEILAB C/O Chemistry Stores University of Waterloo 200 University Ave. W. Waterloo, ON Canada N2L 3G1	(Update)
Stable isotopes: ^{15}N , ^{18}O , ^2H , $^{15}\text{N}_{\text{NO}_3}$, $^{18}\text{O}_{\text{NO}_3}$	Northern Arizona University Colorado Plateau Stable Isotope Laboratory	Northern Arizona University CPSIL/CPAL Room 108 115 W Dupont Ave Building 88 Flagstaff, AZ 86011 Tel: 928-853-1983	Vendor

Analytes	Preferred analyzing Laboratory	Shipping address	DEQ Contract number
Pharmaceuticals and Personal Care Products (PPCPs)	(Appropriate Laboratories and contacts will be developed as needed)	(Update)	(Update)

12. SAMPLE HANDLING AND CUSTODY

Samples will be collected by DEQ personnel into laboratory-supplied sampling containers, labeled, placed in an ice-chilled cooler and transported directly to the laboratory or shipment location. Samples collected for $^{15}\text{N}_{\text{NO}_3}$ and $^{18}\text{O}_{\text{NO}_3}$ analysis will be frozen at DEQ until the chemistry and other stable isotope results from the sample location are received and reviewed.

Where analytical results for a sample location exceed 5 mg/L, and/or supporting results suggest chemical evolution of nitrogen in groundwater samples collected for $^{15}\text{N}_{\text{NO}_3}$ and $^{18}\text{O}_{\text{NO}_3}$ analysis may be sent to University of Waterloo EIL or Northern Arizona University CPSIL for analysis. DEQ personnel will oversee proper storage and handling of all samples collected until transferred into the care of others. Properly filled out chain of custody forms will be used and maintained at all times. Protocols for chain of custody forms, sample handling, etc, are found in Appendix A, and further detailed in the project FSP. Chain of custody forms will accompany the samples from the time of sample collection throughout the duration of the shipping process.

13. ANALYTICAL METHODS

All sample containers, labels, and preservatives will be obtained from the analytical laboratory. Samples must be preserved and analyzed within the holding times. The laboratory will be notified prior to sample shipment to ensure the holding time is not exceeded. All other instructions provided by the analytical laboratory will be followed throughout the duration of each project.

Table 3 lists analytical laboratories for the NPA monitoring projects, including the potential parameters to be analyzed by that laboratory and the location of the laboratory. Samples may be sent to other laboratories as needed to achieve specific sample campaign objectives. In general, samples for major ion/common ion chemistry and nutrients will be sent to Idaho Bureau of Laboratories, Boise; bacteria to IAS-Envirochem, Pocatello; and environmental-level tritium to Idaho State University EML. Stable isotope analysis may be sent to one or more laboratories based on factors including proven quality of results, timeliness of result

receipt, cost, and convenience. Inter laboratory comparisons may be conducted to determine long-term laboratory choices. Initially, the University of Arizona Environmental Isotope Laboratory will be used for ^{15}N , ^{18}O , ^2H analysis. A selection of samples for $^{15}\text{N}_{\text{NO}_3}$, $^{18}\text{O}_{\text{NO}_3}$ will be sent to University of Waterloo EIL, with comparison samples sent to Northern Arizona University CPSIL for analysis and method comparison. Future analysis result comparisons for ^{15}N , ^{18}O , and ^2H may also be made between University of Arizona and Northern Arizona University.

Table 4: Analytical method, container, preservation and sampling holding times.

Sample	Parameter	Analytical Method	Sample container	Preservative	Holding Time
Major cations	Ca, Mg, Na, K,	EPA 200.7	1 L LDPE	HNO ₃ , 4 ⁰ C	6 months
Major anions	Cl, F, SO ₄ ,	EPA 300.0	1 L LDPE	4 ⁰ C	28 days
	Alkalinity (as CaCO ₃)	SM2320B		4 ⁰ C	14 days
	Total Dissolved Solids	SM2540C		4 ⁰ C	7 days
Nutrients	NO ₂ +NO ₃ -N	EPA 353.2	1 L LDPE	H ₂ SO ₄ , 4 ⁰ C	28 Days
	Ammonia	EPA 350.1		H ₂ SO ₄ , 4 ⁰ C	28 Days
	Ortho-phosphorus	SM 4500P-E		H ₂ SO ₄ , 4 ⁰ C	28 Days
Tritium	Low-level tritium	HASL 300	1 L HDPE	None	180 days
bacteria	Total Coli form, E. Coli bacteria	9223B	120 ml polystyrene	4 ⁰ C	30 hours
Stable isotopes	¹⁵ N	TP11	1 L LDPE	Freeze samples	Unlimited if frozen
	¹⁵ N _{NO₃} , ¹⁸ O _{NO₃}	Carlo Erba ² 1500 EA, VG PRISM, Denitrifying ² bacteria	2L LDPE ² , 60 ml x2 HDPE ²	Freeze samples ² , Filter and freeze ²	56 days ¹ , Unlimited ²
	¹⁸ O	TP13	250 ml HDPE	None	None
	Deuterium	TP04		None	None
PPCPs	(Specific parameter, analysis methods and sampling requirements will be identified as needed)				

¹ Waterloo EIL

²Northern Arizona University CPSIL

14. QUALITY CONTROL

A. Field QC Checks

Field QC samples, typically duplicates and blanks, will be submitted blind (not identified as a QC sample) for analysis. The overall field QC frequency will be at least 10% of the sample load. Submission of QC samples will be scheduled to ensure that at least one QC sample set will be included with each batch of samples submitted to the laboratory. Field QC checks are to be as evenly distributed as project conditions allow between duplicates, blanks, and spikes.

Duplicates

Duplicate samples are two samples collected from the same location and representing the same sampling event and are carried through all assessment and analytical procedures in an identical manner. Duplicate can be “replicates” (samples taken one immediately after the other, separated only by the actual time required to fill the sample container), or “splits” (subsamples drawn from the same initial volume of matrix). The FSP will describe the method for obtaining duplicate samples. Field sampling procedures outlined in Appendix A will also be followed for each of the sampling events to ensure consistency in sample collection. All relevant information will be recorded for the duplicates in the field logbook or field sheet. The duplicates will allow assessment of repeatability and accuracy of the sampling procedures and will also be used to assist in assessment of any cross-contamination issues. Results from the field duplicate analysis will be presented in the analytical report.

Field and Equipment Blanks

A blank is a sample of known matrix where the specific constituents requested for analysis are known to not be present, or are present at concentrations less than the laboratory lower limit of detection.

Field blanks are samples of blank matrix, typically deionized water, prepared in the field under similar conditions, processed the same as and included for analysis as a regular sample. Field blanks are a quality control check to identify potential problems with the sample collection, handling and analysis process. Equipment blanks are blank sample matrix passed through or over non-dedicated sampling equipment to check the decontamination process between samples or sample sites.

Equipment blanks may be collected when sampling equipment requiring decontamination (portable pumps, sampling manifolds, ect.) are carried from well to well. Equipment

blanks when collected, will also be submitted blind for analysis and may be included in the overall 10% QC sample calculation.

Field spikes

Samples from a third party vendor that include a known concentration of analytes of concern may be submitted blind to the analyzing laboratory. These “spiked” samples may be included in the sample load to allow for an independent accuracy assessment or for inter laboratory comparisons. Due to the added cost of procuring or preparing field spike samples these may not be included with all sampling campaigns. Use of spiked samples will be described in the FSP.

B. Laboratory QC Checks

Laboratory quality control checks are routinely performed as part of the analysis process. Frequency and type of QC samples are often analysis method-dependent and include reagent blanks, matrix spikes, and internal laboratory splits. Analyzing laboratories will report any variance from QC control limits impacting quality of sample results and may report details of internal laboratory QC if requested. The analytical laboratory may provide appropriate sample containers, chain of custody forms, sample labels, and any necessary container seals. Laboratory QA/QC and data reports will be filed in TRIM following applicable filing protocols.

Quality control checks include internal checks for sampling analysis activities, duplicate samples and blanks. Quality Control procedures for the laboratories have been certified through the U.S. Environmental Protection Agency. The following list documents key components of the laboratory QA/QC program for this project.

Laboratory Blanks

A laboratory blank is a sample of an uncontaminated reference matrix. The laboratory blank is analyzed to evaluate the accuracy of the analysis.

Laboratory Quality Control Samples

Laboratory control samples (LCSs) are samples that contain a known concentration of analytes and are analyzed to assess the overall method performance. They undergo the same preparatory and determinative procedures as the project environmental samples and are the primary indicator of laboratory performance. LCS recoveries are used to measure accuracy. The relative percent difference (RPD) for duplicate LCS recoveries is used to measure precision.

Laboratory Duplicate Sample

A laboratory duplicate sample is a sample that is split by the laboratory into two separate and identical samples. The two samples are analyzed and a comparison of the results (RPD) is used to assess laboratory precision.

Matrix Spike and Matrix Spike Duplicate (MS/MSD) Samples

A matrix spike (MS) is a sample with known amount of the target analyte added to project matrix before analysis to assess possible matrix interferences on the analysis. Percent recoveries (%R) on MS samples should be compared to %R of LCS samples. A MS, matrix spike duplicate (MSD) pair can be used to assess precision.

C. Data Analysis QC Checks

The QC check data may be checked/reviewed for quality by the Project Technical Lead, the Project Manager, or the Project QA Officer at any time during the project, and must be checked once all of the data is collected. Corrective actions, as needed, will be documented in the event that control limits are exceeded. Data qualifiers will be assigned following appropriate data verification/validation procedures. Any qualifiers added will be defined in the project summary/technical report and will be consistent with appropriate EPA guidance, EPA QA/G-8.

15. INSTRUMENT/EQUIPMENT TESTING, INSPECTION, AND MAINTENANCE

Laboratory instrument/equipment testing, inspection, and maintenance are performed by and documented by the laboratory as required by or consistent with the State of Idaho laboratory certification process. Procedures and schedules for preventive maintenance of sampling equipment are the responsibility of the laboratory. Each instrument or item of laboratory equipment will be maintained periodically to ensure accuracy. These procedures and frequency of performance are designated in the individual instrument manuals.

Project field instrument/equipment testing, inspection, and maintenance will be performed in accordance with the individual instrument/equipment manual.

16. INSTRUMENT/EQUIPMENT CALIBRATION AND FREQUENCY

Laboratory instrument calibration is conducted, and documented by the laboratories laboratory as required by or consistent with the State of Idaho certification process.

All field monitoring equipment for the measurement of field parameters (temperature, pH, specific conductance, dissolved oxygen) will be calibrated and maintained as recommended by the manufacturer, or as found in individual instrument/equipment manuals, to ensure accuracy within specified limits. Field equipment used to collect samples will be calibrated according to manufacturers' procedures or internal guidelines at the start of each field day (at a minimum) and/or at intervals recommended by the manufacturer or found in individual instrument/equipment manuals. Calibration details will be recorded in the field logbook or field sheet.

17. INSPECTION/ACCEPTANCE OF SUPPLIES AND CONSUMABLES

The equipment and supplies required for monitoring campaigns will be consistent with the included ground water sampling procedure (Appendix A). Sampling equipment and personal protective equipment beyond that listed in the ground water sampling procedure will be documented in the FSP (i.e. if antibiotics or steroids are collected, a face mask will be used). All sample containers may be obtained from the analytical laboratory. All gloves, face masks, and sample containers will be new, and will be used once during each sample collection. Each instrument or item will be calibrated per the individual instrument/equipment manuals, and also visually inspected by field sampling personnel for damage and operability.

18. NON-DIRECT MEASUREMENTS & DATA ACQUISITION

This section addresses data obtained from existing data sources, not directly measured or generated in the scope of this project.

The laboratories shall provide DEQ with a data package that includes the analytical results of the submitted samples, the QA/QC report for the analyses, and a copy of the chain-of-custody record. Laboratories may be requested to provide results and reports in an electronic format.

No other non-direct data is expected to be acquired.

19. DATA MANAGEMENT

Hard copies of field notes and laboratory data reports will be kept at least until data review and reporting is complete. Electronic copies of all field notes and laboratory reports will be kept in TRIM. The analytical results will be uploaded to the DEQ Ground Water Quality

database after review by the Project QA officer and will be available to the public through the DEQ online mapping application.

20. ASSESSMENT AND RESPONSE ACTIONS

Assessment of the project quality control plan will be performed by reviewing field notes and laboratory reports and by conducting field audits where possible. This assessment will be completed or directed by the Project QA Officer. Any errors or inconsistencies identified in the field notes will be investigated and corrected to ensure the integrity of the data and conformation to the QAPP and FSP. Review of internal laboratory quality assurance, audits, and surveillances or other types of laboratory assessments will also be taken into account. If unexpected analytical results are reported for any reason, the laboratory will be contacted to perform an additional quality review of the data in question. The Project QA Officer will perform additional assessment of the plan independently of the Project Manager and sampling lead.

A note to the file will be included with the field notes and laboratory reports if any follow up quality assurance activities regarding field notes or laboratory reports are conducted.

The Project QA Officer shall review the QAPP annually, to determine if revision is necessary. The Project Manager should also review the project QAPP on an annual basis to ensure that the project QAPP continues to meet the needs of the data users. If the project QAPP does require revision, the revised QAPP must be submitted for approval, prior to implementation, per the DEQ QMP.

21. REPORTS TO MANAGEMENT

Sample results for NPA-related monitoring will be presented in either an annual DEQ ground water monitoring report or a site-specific report that will be included in the DEQ Ground Water Technical Report Series.

22. DATA REVIEW, VERIFICATION, AND VALIDATION

Data collected under this QAPP will be reviewed by the Project Manager, Project Technical Lead, and the Project QA Officer to ensure the data has been recorded, transmitted, and processed correctly. RPDs will be calculated for all field duplicates and the laboratory %R and RPDs will be reviewed. Review by the Project QA Officer shall include a minimum of 10 percent of all project data with a goal of 20 percent. This review will include verification/validation to the original laboratory data reports.

Data verification and validation efforts will be recorded in project documentation.

23. VERIFICATION AND VALIDATION METHODS

DEQ personnel performing data verification and validation are encouraged to review the EPA guidance on methods for this task, found in EPA Guidance on environmental Data Verification and Data Validation, EPA QA/G-8.

Data verification will be performed by the Project Manager and/or Project Technical Lead by reviewing all chain-of-custody sheets, surrogate recoveries, method blanks and LCS and MS sample/sample duplicates to assess %R and range of RPDs. The %R and RPDs will be compared to project goals as described in the QAPP and FSP and an assessment of completeness will be made.

Data validation will be performed by the Project Manager and/or Project Technical Lead, and the Project QA Officer, extending the data evaluation beyond method and procedural compliance, to determine the analytical quality of the data set. Assignment of data validation qualifiers will be completed by the Project Manager and/or Project Technical Lead consistent with appropriate EPA guidance. Validation by the Project QA Officer will include review of data qualifiers. The intent of data validation is to determine if the data are adequate to support the objectives of the project. Items to be considered include: Does the data meet the needs of the project, does the data meet the quality objectives of the project, and are the conclusions drawn from the gathered data supportable. Data validation will also include a determination, where possible of the reasons for any failure to meet method, procedural, or contractual requirements, and an evaluation of the impact of such failure on the overall data set.

Any discrepancies from requirements of the QAPP, with respect to the data, will be noted during the verification and validation process. As determined by the Project Manager, the Project Technical Lead, or the Project QA Officer, if the data do not meet the needs of the project, or the quality objectives of the QAPP, and/or if the conclusions drawn from the data do not appear to be reasonable, the Project Manager and the Project QA Officer shall immediately report such findings to the appropriate Regional Manager and State Office Program Manager for determination of the necessary corrective actions.

24. RECONCILIATION WITH USER REQUIREMENTS

Data quality objectives (DQOs) will be discussed with the analytical laboratory as needed by the Project Manager or Project Technical Lead when DQOs are not met to insure that the laboratory is taking appropriate corrective action. Corrective actions may be initiated to suggest updates to internal laboratory QA procedures in order to rectify QA issues. If no

corrective actions are being implemented and no plan can be developed to address QA issues, the Project Manager will consider changing laboratories for future sampling events.

Data Quality Assessment (DQA) will be performed in accordance with the DEQ QMP. Additional guidance can also be found in EPA Data Quality Assessment: A Reviewer's Guide, EPA QA/G-9R, or in EPA, 2006, Data Quality Assessment: Statistical Methods for Practitioners, EPA QA/G-9S, EPA/240/B-06/003.

The DQA, performed by the Project Manager and the Project QA Officer, addresses the determination of if a data set is of the right type, quality, and quantity to achieve the objectives of the project and can confidently be used to make an informed decision.

As previously stated in Section 23, if the Project Manager, the Project Technical Lead, or the Project QA Officer, reach the conclusion that the project data do not meet the needs of the project, or the quality objectives of the QAPP, and/or if the conclusions drawn from the data do not appear to be reasonable, the Project Manager and the Project QA Officer shall immediately report such findings to the appropriate Regional Manager and State Office Program Manager for determination of the necessary corrective actions

If sampling activities require revision, the project QAPP and/or the project FSP will be revised as necessary. Following revision, and prior to implementation, the revised project QAPP and/or FSP must be re-approved in accordance with the Idaho DEQ QMP.

25. REFERENCES

DEQ, 2007, Quality Management Plan, Revision 2

DEQ, 20XX. Idaho Falls Regional Office Regional Ground Water Monitoring Network Design, (in process).

EPA, 2006, Data Quality Assessment: A Reviewer's Guide, EPA QA/G-9R, EPA/240/B-06/002

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EPA, 2002, Guidance for Quality Assurance Project Plans, EPA QA/G-5, EPA/240/R-02/009

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EPA, 2004. USEPA Contract Laboratory Program National Functional Guidelines for Inorganic Data Review, OSWER 9240.1-45, EPA 540-R-04-004, October 2004

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APPENDIX A - GROUND WATER SAMPLING PROCEDURES, IFRO SAMPLING PROJECTS

Note: In this example, a standard procedure for water sampling was incorporated into the project QAPP as an appendix. Not all project QAPP's will require this, but this example illustrates how this can be done. Another way to accomplish this is to reference an approved DEQ Standard Operating Procedure (SOP).

It must be noted and understood that this "Appendix A" is NOT the Field Sampling Plan (FSP) referenced in this example QAPP. A FSP is a stand-alone document that gives project specific information and direction with respect to project sampling. This example QAPP assumes that a FSP will be written to accompany the QAPP. If the project for which a QAPP is being written (using this example/template) will not have a specific FSP written for it, then all the information that this example/template QAPP defers to the FSP will need to be included within the new project QAPP itself.

Equipment required: field log book with collection data sheets, sample labels, water-proof pens and markers, cell phone, GPS, instruments for field parameter measurement, sample collection equipment (may include hose bib, sample collection port and associated tubing, peristaltic pump, bucket, submersible pump and generator), sample containers, preservatives, sample cooler and ice, powder-free nitrile or vinyl gloves, safety glasses or face shield, paper towels, first-aid equipment, bag for trash.

1.0 Well Purging Procedures

Each well/sample point will be purged until the field parameters stabilize as defined in Section 2 of this Appendix. The volume of water and amount of time required to properly purge each well will be dependent on the size and yielding characteristics of each well.

2.0 Field Parameter Measuring Procedures

Field measurements of pH, temperature, and specific conductance will be measured throughout the purging sequence and recorded on the field data sheet or logbook. Field parameters will be recorded at least once for every five minutes while the well is purged. Stabilization of these parameters is considered successful when three successive readings (a minimum of five minutes apart) meet the following criteria:

pH : ± 0.1 standard unit
Specific Conductance: $\pm 10\mu\text{mhos/cm}$ or ten percent of the preceding reading

Temperature: $\pm 0.5^{\circ}\text{C}$

Measurements of field parameters will be taken using a field parameter meter that is calibrated prior to each day of sampling. Water used in field parameter measurements will be collected into a dedicated bucket or flow-through from the sampling hose connected to a faucet nearest to the wellhead. All measurements collected will be recorded in the field sheets and field logbook with appropriate times and well identification information. When possible, static water level measurements will be recorded.

3.0 Sample Collection Procedures

Once the field parameters have stabilized, collect the sample from the faucet or sample port. If a hose must be used for sample collection, a dedicated hose supplied by DEQ will be used. Samples should be collected as quickly as possible following stabilization of the field parameters. Collect the sample directly into the appropriate container. If a filtered sample is required, use an in-line filter connected with tubing at the faucet or sample port. If the sample point or conditions do not allow use of an inline filter, a peristaltic pump can be used. Collect water from the sample point in a bucket that has been triple rinsed in the sample matrix. Purge the pump line by running at least 500 ml of the water through the pump and proceed to collect samples. Samplers will wear a new pair of vinyl/nitrile gloves at each location, and will keep gloves on until samples are collected and required preservatives added. Samples should be collected and handled in a way that reduces the potential for losing the analyte from the sample matrix; for a VOC samples, reduce the discharge to a low, laminar flow, leaving a positive meniscus but not allowing the container to overflow and thereby losing preservative from the container. Typically, sample containers that are not pre-preserved should be triple rinsed with the sample matrix prior to collection.

The samples will be labeled with durable labels and water-resistant ink to provide proper identification. Labels will have the following information: unique sample identification number, date and time of collection, parameters requested, and project name/number.

Preservation of the collected samples will follow laboratory instructions. Samples to be chilled will be placed on ice in an ice chest at less than 4°C from the time of sampling until the analysis is complete. All samples will be transported in ice chests with ice packs and chain of custody forms.

4.0 Decontamination Procedures

The sample collection equipment carried from one location to another will be rinsed with deionized water or sample matrix prior to collecting measurements at the new site. Equipment that cannot be sufficiently purged with the sample matrix prior to sample collection will be rinsed with deionized water. Decontamination between sites may

require a stronger solution, depending on the nature of the contaminant. Special decontamination procedures will be detailed in the FSP.

5.0 Field sampling sheets

Field sampling sheets within a bound logbook will be completed for each well at each site visit. An example field sample sheet is included in Appendix B. At a minimum, the following information, as available, will be documented for each site visited during each sampling event:

- Identification of the well
- Total well depth
- Approximate purge volume and rate
- Date and time of sample collection
- Sample identification numbers and parameters requested
- Field parameter measurements and methods
- Field observations and remarks
- Name of collectors
- Weather conditions

6.0 Chain of Custody Forms

Once the samples have been collected, they will be placed in an ice chest (with ice) while in the field, and stored in a designated sample refrigerator until delivered or shipped to the lab. A chain of custody form will accommodate each ice chest during shipment to the lab. The chain of custody form will include the following information:

- Project name/code
- Laboratory name and address
- Sample identification number
- Date and time of collection
- Type of sample, number of containers, and analysis requested
- Sample preservation methods
- Signature of sample collector(s)/shipper
- Date and time of release to shipper/common carrier

The following procedures will be followed to ensure proper chain of custody:

- The chain of custody record will be checked for a signature
- The sample will be stored in a secure area until it is analyzed.

7.0 Quality Assurance/Quality Control

The objective of quality assurance and quality control is to make certain that the ground water analytical results represent the actual chemical and physical composition of the ground water at the site. DEQ will be responsible for the QA/QC activities of the samples and analytical laboratories. Components of the QA/QC program are as follows:

Laboratory: The analytical laboratory will provide or assist in the sampling containers, preservatives, chain of custody, labels and seals. A laboratory QA/QC report with continuing calibration checks will accompany each data report and will be kept on file by DEQ.

Sample Collection: QA/QC procedures for sample collection will be accomplished by the sampling personnel. A standardized field logbook or field sheet will be kept for each sampling event following the format described above. It will include all label and seal numbers and documentation of QA/QC procedures related to sample collection.

Trip Blank: Trip blanks may be included if samples for VOA analysis are included with the project.

Field Blank: Field blanks will be collected at the rate of at least 5 percent.

Duplicate Samples: Duplicate samples will be collected at the rate of at least 5 percent.

Field Spike: Spikes prepared by an independent source and submitted blind to the lab may be included with field QC samples.

Field QC Sample Goals: Field QC samples (duplicates, blanks, and spikes) will constitute at least 10%-20% of samples submitted to the analyzing laboratory.

APPENDIX B - GROUND WATER SAMPLING FIELD SHEET - IFRO

In this example, this appendix was used to supply an approved field sheet to the staff engaged in sampling efforts. Not all project QAPP's will require this appendix, but this illustrates how this type of information is included in a QAPP.

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APPENDIX C - GROUND WATER SAMPLING PERMISSION FORM

In this example, this appendix was used to supply an approved access permission form to the staff engaged in sampling efforts. Not all project QAPP's will require this appendix, but this illustrates how this type of information is included in a QAPP.

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