

Risk-Based Decision Making for the Remediation of Contaminated Sites

Guidance includes:

Table of Generic Risk-Based Concentrations for Petroleum Constituents and Total Petroleum Hydrocarbons and Generic Remedy for Simple Risk-Based Sites

September 22, 2003

September 6, 2017 – Updated contact information and links

October 2, 2017 – Updated guidance name

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DISCLAIMER

This document is intended as guidance for employees of the Department of Environmental Quality (DEQ). DEQ guidance does not constitute rulemaking by the Environmental Quality Commission and may not be relied upon to create a right or benefit, substantive or procedural, enforceable at law on in equity, by any person. DEQ may take action at variance with this guidance.

i. Acknowledgments

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This document was updated September 6, 2017 to provide current links and contact information and on October 2, 2017 to remove the term “Petroleum” from the title of the guidance.

ii. Approval

This guidance document has been approved for use by the Department of Environmental Quality Land Quality Division.

[Original Signed by Dick Pedersen]
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9/24/03
Date

iii. Implementation Policy

This document replaces the Department of Environmental Quality's September 29, 1999 *Risk-Based Decision Making for the Remediation of Petroleum-Contaminated Sites Under OAR 340-122-0205 through 340-122-0360*. It is the intent of the Environmental Cleanup and Tank Program managers to implement this new guidance document in the following manner:

1. Sites that have been properly closed will remain closed unless previously unknown information is discovered that would require additional investigation.
2. Responsible parties with new sites or sites at which they have not yet finished the investigation or RI/FS stage and have not yet submitted a corrective action plan (CAP) or remedial action plan (RAP) must use the new guidance.
3. Responsible parties that have already completed a RI/FS or are implementing a CAP, RAP, or other remedy as of the date of this new guidance document have the option of:
 - a. Completing their site work under the 1999 RBDM guidance; or
 - b. Modifying their plans to adopt the new guidance.
4. Sites that have completed a ROD and are now under a RD/RA order will be reviewed under the new criteria at the specified or 5-year review cycle. Responsible parties in this category will be immediately notified of this approach, so that they have the opportunity to alter their remedy at this time, if they so choose.

Notwithstanding the above conditions, the DEQ reserves the authority to apply this updated guidance if it's necessary to adequately protect human health.

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The current version of this and other UST and cleanup program guidance documents can be found on the Department's website.

UST program documents are at: <http://www.oregon.gov/deq/tanks/Pages/Cleanup-Guidance.aspx>

Cleanup program documents are at: <http://www.oregon.gov/deq/Hazards-and-Cleanup/env-cleanup/Pages/Cleanup-Guidance-Docs.aspx>

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1. Introduction

1.1 DEQ Environmental Cleanup Programs

The Department of Environmental Quality (DEQ) has separate programs for the cleanup of petroleum releases from regulated underground storage tanks (USTs) and for the cleanup of contamination from other sources. The UST Program handles the former under the *Cleanup Rules for Leaking Petroleum UST Systems* (OAR 340-122-0205 through 340-122-0360)¹ and the Environmental Cleanup Program handles the latter under the *Hazardous Substance Remedial Action Rules* (OAR 340-122-0010 through 340-122-0115).

In September 2001, the DEQ merged the former Waste Prevention and Management Division and Environmental Cleanup Division into the Land Quality Division. The Land Quality Division is responsible for the agency's efforts in waste reduction and management, spill preparedness and response, environmental assessment and cleanup, and UST compliance and cleanup.

One of the goals of the Land Quality Division is to develop a consistent approach to the cleanup of releases from both regulated USTs and other sources. This document was prepared in accordance with that goal. It can be applied to petroleum hydrocarbon releases regardless of the source. However, because two separate cleanup programs and sets of rules still exist, there are some differences in the steps that you must take to meet the appropriate regulatory requirements. Therefore, even though the technical information is not program specific, *some of the requirements discussed in this document apply specifically to releases from USTs and some apply specifically to contamination from other sources.*

1.2 Purpose

The purpose of this document is to provide a consistent, streamlined decision-making process for evaluating the risk that petroleum hydrocarbon contamination poses to human health and the environment.² We have attempted to achieve this purpose by:

- Developing a process applicable to all petroleum contamination regardless of source;
- Including the evaluation of risk from exposure to petroleum hydrocarbon products as well as specific constituents found in those products;
- Allowing the use of site-specific risk calculations in addition to generic risk-based concentrations; and
- Providing several options for fulfilling the regulatory requirements associated with the cleanup of petroleum contamination.

¹ Contamination from residential heating oil tanks regulated under OAR 340-177-0001 through 340-177-0095 is also remediated using the options in OAR 340-122-0205 through 340-122-0360 (see OAR 340-177-0065). Therefore, the information in this document about regulated UST cleanups also applies to the cleanup of petroleum releases from residential heating oil tanks.

² Although this document focuses on petroleum contamination, the technical information and the decision-making process presented here can be applied to hazardous substances other than petroleum (see Appendix J). If you are considering such an application you should discuss your plans with the Department.

1.3 Summary of Contents

This document includes:

- An overview of the purpose, uses, and limitations of this guidance (Section 1);
- A review of basic risk concepts related to environmental cleanup sites (Section 2);
- A tiered process for evaluating risk and setting risk-based cleanup levels for petroleum contamination (Section 3.1);
- A summary of program-specific options and requirements for evaluating risk in the UST Program (Section 3.2) and the Environmental Cleanup Program (Section 3.3);
- A generic remedy for simple risk-based remedial actions (Section 4); and
- A table of generic risk-based concentrations (RBCs) for petroleum constituents as well as product-specific total petroleum hydrocarbons (TPH) (Appendix A).

In addition, the exposure equations, transport models, and related technical information used to develop the table of generic RBCs are contained in Appendices B-G. This information is provided to document the methods used by the Department to develop concentrations that meet the acceptable risk levels required by ORS 465.315. It may also be useful as a reference if you intend to develop site-specific risk-based concentrations. A glossary is provided in Appendix K to define acronyms, and technical and regulatory terms.

The basic concepts and general overall format of the 2003 edition of the risk-based decision making (RBDM) document are the same as in the original 1999 edition. The main differences are:

- Information about the *Hazardous Substance Remedial Action Rules* has been added to Section 3 to explain how the RBDM process can be applied to petroleum hydrocarbon releases from sources other than regulated USTs.
- The evaluation of risk from petroleum contamination has been expanded to include “whole product” risk in addition to the traditional approach of evaluating risk from a limited number of petroleum constituents. The role of TPH data in the overall risk evaluation process, the analytical methods for measuring various TPH fractions, and the methods for calculating RBCs for TPH products are discussed in Section 3 and Appendix B.
- The Generic Remedy for Simple Risk-Based Cleanups in Section 4 has been modified to broaden its scope to all petroleum releases.
- The Table of RBCs in Appendix A now includes TPH RBCs for gasoline, diesel/heating oil, and transformer mineral insulating oil.³ Site-specific TPH RBCs for these and other petroleum products can be evaluated using information discussed in Section 3 as well as technical information and equations added to Appendix B.

³ Transformer mineral insulating oil is the insulating oil used in the operation of a variety of electrical equipment used in the transmission and distribution of electricity. Do not use these TPH RBC values for regular mineral oil.

- Exposure scenarios for construction workers and urban residents were added based on numerous site-specific evaluations performed in the state in the last few years.
- The following exposure factors were modified, primarily to make them more consistent with EPA guidance:
 - Soil and groundwater ingestion rates were modified.
 - Skin surface areas for dermal contact were made consistent with body weight (according to EPA guidance).
 - The daily inhalation rate is now consistent with EPA, and avoids the potential confusion regarding the conversion of reference concentrations to reference doses, and unit risk factors to cancer slope factors.
 - The factor for evaluating workday exposure (8-hours) rather than a full day of exposure (24-hours) is now explicitly included in the RBC calculations.
- Toxicity data have been updated.
- Appendices have been added to discuss the toxicity of petroleum hydrocarbon fractions (Appendix G), the additional requirements of the Cleanup Program (Appendix H), and the evaluation of non-petroleum hydrocarbon compounds, particularly chlorinated solvents (Appendix J).
- The volatilization term has been revised to more appropriately address shorter-term exposure to non-carcinogens.

1.4 Relationship to Other Guidance Documents

This document replaces *Risk-Based Decision Making (RBDM) for the Remediation of Petroleum-Contaminated Sites under OAR 340-122-0205 through 340-122-0360* (DEQ, 1999).

A complete list of reference documents used to develop this guidance is provided in Appendix L. You may find it helpful to obtain copies of some of the documents. The main references used to derive the necessary equations and calculate the RBCs are mentioned below with comments about their relationship to this document. Additional discussions of any significant differences between DEQ, Environmental Protection Agency (EPA), and American Society for Testing and Materials (ASTM) documents are contained in Appendix B.

1.4.1 DEQ Guidance

The equations and exposure factors in this document are generally consistent with those discussed in *Guidance for Conduct of Deterministic Human Health Risk Assessments*, (DEQ, 2000b). That document was developed for risk assessments being carried out under the Department's *Hazardous Substance Remedial Action Rules* (OAR 340-122-0010 through 340-122-0115) and includes more exposure routes than you will find here. Note, however, that the equations in *Deterministic Human Health Risk Assessments* are written in a format that calculates average daily dose, whereas many of the equations included in this document are rearranged to calculate RBCs.

The following documents may also be useful for the RBDM process:

- *Guidance for Use of Institutional Controls*, DEQ (1998c);
- *Guidance for Conducting Beneficial Water Use Determinations at Environmental Cleanup Sites*, DEQ (1998e); and
- *Consideration of Land Use in Environmental Remedial Actions*, DEQ (1998f).

These references, along with other useful guidance documents and policies, can be found on the DEQ's Environmental Cleanup Program Website at:

<http://www.oregon.gov/deq/Hazards-and-Cleanup/env-cleanup/Pages/default.aspx>

1.4.2 EPA Guidance

All of the DEQ's human health risk guidance documents are designed to be consistent with EPA guidance. The two principal EPA documents used to develop this guidance document are

- *Soil Screening Guidance: Technical Background Document* (EPA, 1996b); and
- *Risk Assessment Guidance for Superfund: Volume I - Human Health Evaluation Manual (Part B, Development of Risk-Based Preliminary Remediation Goals)* (EPA, 1991a).

The *Soil Screening Guidance* provides an excellent review of many of the concepts associated with contaminant fate and transport. It also includes chemical and toxicological data for 110 common contaminants. Note, however, that in the *Soil Screening Guidance* EPA defines "volatilization factors" differently than either DEQ or ASTM (see Appendix B).

Risk Assessment Guidance for Superfund is the source for many of the RBC equations. Some modifications have been made to the equations to provide a consistent format. Adjusted exposure factors and the combined drinking-water-ingestion and vapor-inhalation pathway ("tap water" pathway) are based on information adapted from EPA Region 9's *Preliminary Remediation Goals (PRGs)* (EPA, 2002a).

1.4.3 ASTM Guidance

The DEQ RBDM guidance incorporates many of the concepts covered in the *Standard Guide for Risk-Based Corrective Action at Petroleum Release Sites* published by the American Society for Testing and Materials (ASTM, 1995b). There are, however, some important differences. The DEQ process includes:

- Exposure to children in the residential scenario;
- Exposure to inhalation of volatiles in the drinking water pathway; and
- Urban residential, construction worker, or excavation worker scenarios.

Therefore, the ASTM guidance should not be applied without taking these differences into account. Note, however, that the “volatilization factor” format used by ASTM for transport equations is used in this document (see Appendix B).

1.4.4 TPHCWG Publications

The method for evaluating risk from exposure to petroleum contamination described in this document is based in part on work done by the Total Petroleum Hydrocarbon Criteria Working Group (TPHCWG, 1999). The TPHCWG was a national workgroup made up of representatives from industry, government, and academia to develop scientifically defensible information that could be used to establish cleanup levels that are protective of human health at petroleum contaminated sites. This guidance document explains how to use the recommendations of the TPHCWG within the context of the DEQ’s existing environmental cleanup rules.

1.5 *Limitations*

This document has been developed for the remediation of petroleum contamination from regulated USTs under OAR 340-122-0205 through 340-122-0360, residential heating oil tank releases governed by OAR 340-177-0001 through 340-177-0095, or other sources of contamination under OAR 340-122-0010 through 340-122-0115. Its use for cleanup projects under other authorities or for contaminants other than petroleum hydrocarbons should be discussed with the Department. Additional limitations and possible options for addressing them are discussed below.

1.5.1 Default Site Conditions

In developing the Table of RBCs in Appendix A, we used reasonable exposure parameters that are conservative enough to cover most typical UST and simple cleanup sites. The default parameters may not, however, be appropriate for sites with widespread contamination, large amounts of free product, or other conditions not taken into account by the process documented in Appendix B. **Therefore, the Department reserves the right to disallow the use of generic RBCs at sites that may not fit the default conditions.**

This guidance applies to sites, or to well-defined units within a site, for which petroleum hydrocarbons are the primary contaminants of interest. Other contaminants, such as polychlorinated biphenyls and/or metals, may be present only if it can be clearly demonstrated that they are not significant contributors to the risk at the site (or cleanup unit).

The Table of RBCs includes the most commonly encountered petroleum constituents that may present a risk (either carcinogenic or noncarcinogenic) to human health. It also includes three petroleum products: gasoline, diesel, and mineral insulating oil. Risk-based concentrations are provided for each of the constituents and the three products by the exposure scenarios and pathways typically associated with leaking underground petroleum storage tanks and simple cleanup sites. Depending on site-specific conditions, however, the Department may require that additional constituents, scenarios, or pathways be evaluated. In that case the Department will provide relevant default exposure and transport equations, exposure factors, and generic risk-based concentrations for the additional constituents, scenarios or pathways.

1.5.2 Cumulative Risks

It has been our experience at UST and simple cleanup sites that most of the constituent risk is usually caused by only one or two components, such as benzene or naphthalene. In other words, even though a large number of petroleum constituents may be detected in soil or groundwater, only one or two of those constituents actually approach or exceed risk-based concentrations. Therefore, most risk-based decisions related to petroleum constituents will be based on a direct comparison of the site data to either the numbers listed in Appendix A or specific RBCs that you calculate for your site. However, in cases where several constituents are detected at levels close to or above the risk-based concentrations, the Department may require a determination of cumulative risk to ensure that the overall site risk does not exceed acceptable levels.⁴ For sites covered under the Cleanup Program, a screening step for multiple chemicals of interest should be performed. Screening of chemicals is discussed later in Section 3.1.6.3. Methods that you can use to estimate cumulative site risk are summarized in Appendix H. Appendix I has an example of how to perform a screening evaluation with multiple chemicals of interest.

As described in Section 3 and Appendix B, the process used for calculating generic or site-specific whole product TPH RBCs takes into account the cumulative noncarcinogenic risk from all of the pertinent TPH components. Cumulative risk considerations would only apply for TPH if sources of noncarcinogenic risk are present that are not already accounted for in the TPH RBC calculation or if two or more products are present.

1.5.3 Ecological Risks

The information in this document and the RBCs in Appendix A are strictly for the evaluation of human health risks. Risk-based site closures may also require an evaluation of ecological risk (see OAR 340-122-0244(3) and OAR 340-122-0084). However, unless the Department determines that screening is required for threatened and endangered species, screening for potential ecological affects will generally not be required if the site is obviously devoid of ecologically important species and habitat, or you can demonstrate that:

- Contaminated soils are only present at a depth greater than three feet below the ground surface, or, if present at a shallower depth, such soils cover an area no greater than 0.125 acre;
- Surface water has not been affected, nor is it likely to be affected in the future as a result of the release;
- Contaminated groundwater does not and is not reasonably likely to discharge to surface waters or otherwise reach the surface in a manner that might result in contact with ecological receptors; and
- Contaminated groundwater does not and is not reasonably likely to come into contact with aquatic sediments.

⁴ Reports submitted for cleanups carried out under UST program rules will usually not have to include an explicit calculation of cumulative risk. It will be considered on a case-by-case basis. However, reports submitted for cleanups under the Environmental Cleanup rules are required to include a calculation of cumulative risk (see Section 3.3).

Your report should discuss your evaluation of ecological risks. Reports submitted for non-UST cleanups should document this evaluation by including the checklist from *Guidance for Ecological Risk Assessment, Level 1 - Scoping* (DEQ, 1998b). Depending on their complexity, UST Program sites requiring ecological risk assessments may be referred to the Environmental Cleanup Program for oversight.

If petroleum-contaminated groundwater at your site discharges into surface water and the surface water is a point of exposure for ecological receptors, then, unless site-specific testing establishes an alternative level, the Department requires the groundwater at the point where it discharges to the surface water to be less than 1 mg/L TPH. This is not a risk-based concentration, but is consistent with NPDES general discharge permit requirements.

1.5.4 Implementation Risks

The potential exposures and risks discussed in this document are limited to those resulting from people contacting petroleum constituents directly (*e.g.*, dermal contact or soil ingestion) or indirectly as a result of the transport of the contaminants by normal physical and chemical means (*e.g.*, diffusion resulting in volatile inhalation exposures or dissolution resulting in tap water ingestion exposures). When you are evaluating the methods that you will use to remediate a site you must also consider the exposures and risks that might result while implementing the remedy. For example, the models or generic RBCs presented here do not apply to employees or nearby residents who are exposed to vapors discharged from an air stripper. Implementation risks like this, however, must be addressed when you remediate the site. Questions about implementation risks should be discussed with the Department.

1.5.5 Technical Background Requirements

Although this document includes a summary of some basic risk concepts, and describes how risk-based concentrations are incorporated into the UST and Environmental Cleanup Program rules, it is not intended to be a training manual on risk assessment, or to provide a complete description of all UST and Environmental Cleanup Program rules and cleanup options. To effectively apply the information in this document, therefore, you should have adequate knowledge of:

- Site assessment and remediation methods;
- Toxicology and risk assessment principles and procedures;
- Contaminant fate and transport processes;
- UST Program rules (OAR 340-122-0205 through 340-122-0360);
- Heating Oil Tank Program rules (OAR 340-177-0001 through 340-177-0095); and
- Environmental Cleanup Program rules (OAR 340-122-0010 through 340-122-0115).

The Department believes that risk-based decision making can be beneficial at petroleum release sites. However, it also recognizes that proper implementation requires adequate technical knowledge and experience. Therefore, the Department strongly recommends that people with

limited backgrounds in these areas seek additional training or consultation before applying this guidance document.

The Department intends to review the Table of RBCs periodically and revise it based on changes in toxicity data, modeling approaches, and other factors that may affect the RBCs. Therefore, you should make sure that you have the most recent version of the table before applying it. Copies will be available at the Internet addresses listed on page ii of this document.

2. How Does Risk Affect Your Site Investigation?

Risk-based decision making involves evaluating current and reasonably likely future risks to human health and the environment associated with contamination at a site, and using that information to develop the best combination of cleanup and site management to reduce risks to acceptable levels. To apply this process you need to have a clear understanding of the factors that contribute to site risk so you can carefully evaluate them during the investigation and effectively deal with them when implementing the remedy.

This section introduces some basic risk concepts. The degree to which they are applied at any given site will depend on the cleanup goals for that site. For example, projects being evaluated with a site-specific risk assessment will require a different level of information than projects using generic RBCs. They both, however, rely on the same underlying risk concepts.

The information in this section is intended to help you view site investigations from the perspective of risk, and is not meant to be a complete survey of risk assessment principles and practices. How this information is specifically applied to the various UST and Environmental Cleanup Program options is discussed in Section 3. More in-depth information about risk assessments can be found in some of the references listed in Appendix L. Methods for calculating risk-based concentrations are described in Appendix B.

2.1 What is Risk?

Risk from exposure to chemicals is generally defined as the product of a chemical's toxicity and the degree of exposure to that chemical.

$$\boxed{\text{RISK}} = \boxed{\text{TOXICITY}} \times \boxed{\text{EXPOSURE}}$$

To assess risk at a contaminated site you must have information about the following:

- The nature of the release (*what kinds of contaminants are there?*);
- The magnitude of the release (*what are the contaminant concentrations?*);
- The extent of contamination (*soil, groundwater, on-site, off-site?*);
- The toxicity of the identified contaminants (*carcinogens, non-carcinogens?*); and
- The possible ways that exposure might occur (*inhalation, ingestion?*).

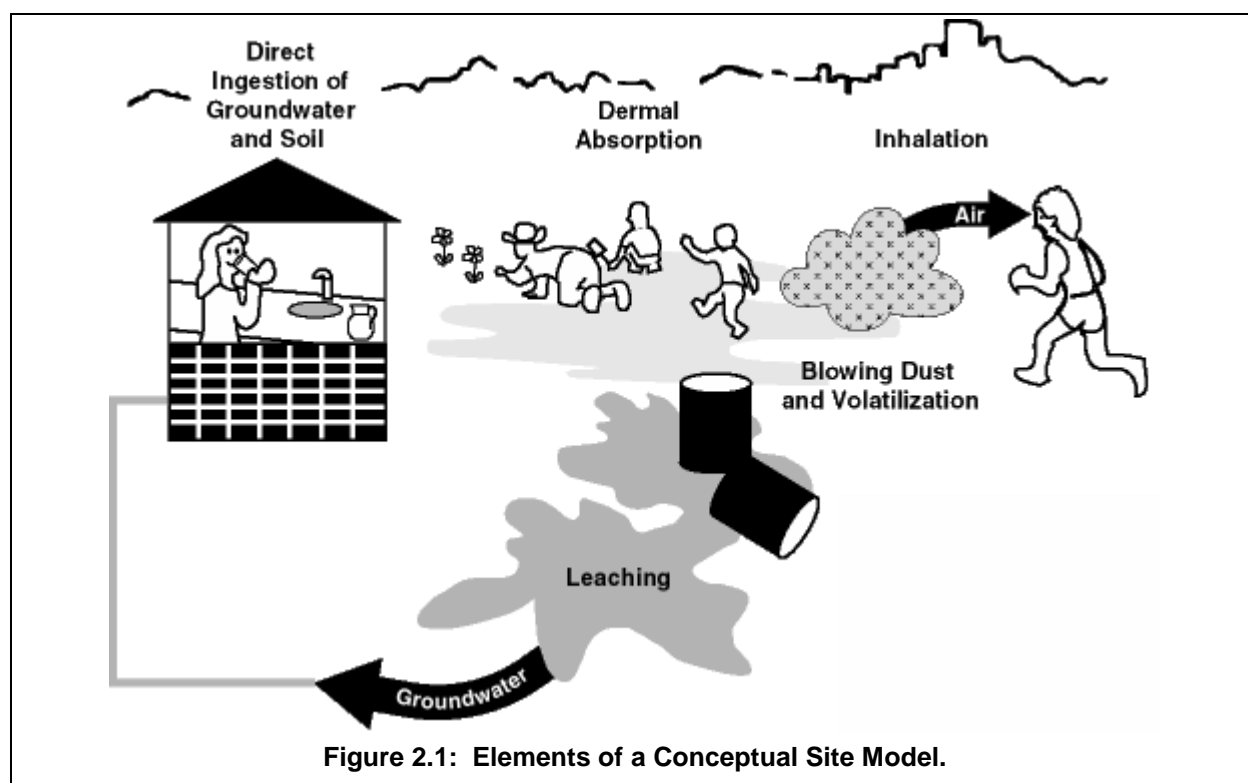
When you perform a site investigation your initial goal is to gather information about the first three items listed above. The fourth item, toxicity information, is generally available for the petroleum constituents and product fractions included in this document (see Appendix E). Your ultimate goal is to use that information along with other site-specific factors such as land and water use to evaluate all current and reasonably likely future exposures at your site, establish appropriate cleanup levels, and implement a protective remedy.

2.2 What is a Conceptual Site Model?

A conceptual site model (CSM) is a summary that:

- Describes all of the known or suspected **sources** of contamination,
- Considers how and where the contaminants are likely to move (**pathways**), and
- Identifies who is likely to be affected by them (**receptors**).

At its most basic level, the CSM can be thought of as a “picture” of your site⁵ that shows the relationships between all of the sources, exposure pathways, and receptors (Figure 2.1). As discussed later in this section, however, this picture must represent not only the conditions at the site today, but also the conditions as they are reasonably likely to be in the future.



In order to have risk, all three components of the CSM must be present.

- **Sources:** The term “source” often refers to the initial source of the release, such as a leaking tank or broken fuel line (sometimes referred to as “primary” sources). When evaluating risk, however, this term usually means the contaminants that are present (e.g., gasoline, benzene, or naphthalene) and the environmental media in which they are contained (e.g., soil or groundwater). These are the potential sources of risk (sometimes referred to as “secondary” sources) discussed in this document.

⁵ “Site” refers to the areas defined by the current and anticipated extent of contamination (absent any remedies). The “Site” is not necessarily restricted to the property and may include one or more parcels of land.”

- **Pathways:** Pathway evaluation means taking the sources that you find at the site and considering all of the reasonably likely ways that people might come into contact with them. This includes not only the ways that someone might contact the contaminants where they were originally released, but also the ways by which the contaminants can be transported to new locations. For example, vapors might migrate from contaminated soils into the air (indoor or outdoor) where they could be inhaled, or contaminants could leach into a source of drinking water and be ingested.
- **Receptors:** Identification of potential receptors should be based on current and reasonably likely future land and water uses. People living or working on the site or on adjacent properties may become exposed to vapors and contaminated shallow soils. Excavation workers may be exposed to deeper contaminated soils. People with nearby wells may drink water contaminated by the on-site source.

The CSM can help you design your site investigation to collect the type of information that you will need to make risk-based decisions later in the process. You should start this effort by considering a broad range of potential sources, pathways, and receptors. As your investigation proceeds, the data being collected can be used to narrow your focus to the combinations that are reasonably likely to result in risk at your site.

2.2.1 Sources

Source information is the first element of the CSM for you to consider. Incomplete source information may require you to go back out to the site to collect additional samples, which is both costly and time-consuming. Therefore, it is important to make sure that the initial sampling of your site is planned to provide the information necessary to complete both a site investigation and a risk-based approach. *Note that the Department does not consider a site investigation to be complete until the full vertical and horizontal magnitude and extent of site-related contamination has been determined.* In many cases this determination will not be confined to the property boundaries of your site. If potentially significant levels of site-related contamination have moved beyond your property line,⁶ you may be required to collect sufficient samples from adjacent properties in order to complete the investigation. Failure to collect off-site samples, where warranted, is one of the most common omissions in site investigations.

To complete the assessment of sources at your site you should determine:

- The type of products that were released and where the release(s) occurred;
- The media that are contaminated;
- The constituents of interest (COIs) present in each medium; and
- The distribution and concentrations of contaminants in each medium.

⁶ Potentially significant levels of contamination means soil or groundwater concentrations that exceed soil matrix TPH levels or generic RBCs for reasonably likely pathways, and which may require remedial action. Lower concentrations will usually not require any additional cleanup or risk management.

Obtaining this information as efficiently as possible requires careful planning during the sampling and analysis phase of the investigation.

To determine the types of petroleum products that were released at your site, you should analyze representative samples of obviously-contaminated soil by the Northwest Total Petroleum Hydrocarbon Identification Method (NWTPH-HCID). Sufficient samples should be tested by NWTPH-HCID in order to identify the product or products in each distinct area of release. After the type of product or products has been confirmed in each location, you should analyze subsequent soil and groundwater samples for:

- TPH using the appropriate method or methods (NWTPH-Gx and NWTPH-Dx); and
- Relevant COIs listed in Table 2.1 using the analytical methods listed in Table 2.2.

A site-specific list of COIs can then be developed from the initial sample results. Enough samples should be collected and analyzed to allow you to estimate the full magnitude and extent of the contamination in soil and groundwater.

Table 2.1: Constituents of Interest in Petroleum Products¹

Products	Gasoline	Kerosene, Jet Fuel, Diesel, Light Fuel Oil & Heating Oil	Heavy Fuel Oil	Transformer Mineral Insulating Oil ⁸	Used or Waste Oil
Constituents					
Total Petroleum Hydrocarbons (TPH)	X	X	X	X	X
Benzene, toluene, ethylbenzene, and xylenes (BTEX)	X	X	X ²		X
Polynuclear aromatic hydrocarbons (PAHs)	X ³	X	X		X
Methyl t-butyl ether (MTBE ⁴)	X				X
iso-propylbenzene, n-propylbenzene, 1,2,4-trimethylbenzene, and 1,3,5-trimethylbenzene	X				X
EDC and EDB	X ⁵				
Lead	X ⁵				X ⁶
Cadmium and Chromium					X ⁶
Chlorinated Solvents					X
Polychlorinated biphenyls (PCBs)				X	X ⁷

¹ An "X" denotes the COIs most likely to be present in a given petroleum product. Depending on site-specific conditions, the Department may require that additional constituents be analyzed. For constituents not listed in Appendix A, please refer to the Region 9 Preliminary Remediation Goals (EPA 2002a)

² Test in groundwater if heavy fuel oil contamination is suspected.

³ If only gasoline contamination is present, the PAH test can be limited to naphthalene. The Department has approved a BTEX+N analytical method for such situations.

⁴ MTBE should be considered at sites where gasoline might have been released after 1975. Other oxygenated additives may also be included if suspected.

⁵ Test if leaded gasoline releases are suspected. For regulated UST releases, collect field-filtered samples and test for dissolved metals. For all other releases, collect unfiltered samples and test for total recoverable metals.

⁶ Leachable Cd, Cr and Pb are required for waste oils.

⁷ PCB tests required for commercial waste oil tanks only.

⁸ Insulating oil used in the operation of electrical equipment used for transmission and distribution of electricity.

Table 2.2: Required Analytical Methods⁷

Constituents	Analytical Methods
BTEX	8021B Aromatic and Halogenated Volatiles by GC/PID/Hall 8260B Volatile Organic Compounds by GC/MS
BTEX + Naphthalene	8021B Aromatic and Halogenated Volatiles by GC/PID/Hall 8260B Volatile Organic Compounds by GC/MS
iso-propylbenzene n-propylbenzene 1,2,4-trimethylbenzene 1,3,5-trimethylbenzene	8021B Aromatic and Halogenated Volatiles by GC/PID/Hall 8260B Volatile Organic Compounds by GC/MS
Chlorinated Solvents	8021B Aromatic and Halogenated Volatiles by GC/PID/Hall 8260B Volatile Organic Compounds by GC/MS
EDB	8021B Aromatic and Halogenated Volatiles by GC/PID/Hall 8260B Volatile Organic Compounds by GC/MS 8011 EDB and DBCP by microextraction and GC/ECD
EDC	8021B Aromatic and Halogenated Volatiles by GC/PID/Hall 8260B Volatile Organic Compounds by GC/MS
MTBE	8260B Volatile Organic Compounds by GC/MS
PAHs	8270C Semivolatile Organic Compounds by GC/MS 8270C Modified PAHs by GC/MS/SIM (ODEQ Method) 8310 Polynuclear Aromatic Hydrocarbons by HPLC
PCBs	8082 Polychlorinated Biphenyls by GC/ECD
Hydrocarbon Identification	Northwest Total Petroleum Hydrocarbon Identification (NWTPH-HCID)
⁸ TPH (Gasoline)	NWTPH-Gx
⁸ TPH (Diesel and heavier hydrocarbons)	NWTPH-Dx
TPH Fractions	Method for the Determination of Volatile Petroleum Hydrocarbons (VPH) Method for the Determination of Extractable Petroleum Hydrocarbons (EPH) Washington State Department of Ecology (1997)
Cadmium	Sample digestion by 3010A, 3020A, 3015, 3050B, or 3051 followed by: 6020 or 6010B Inductively Coupled Plasma 7130 or 7131A Trace Metals by Flame or Graphite Furnace AA
Chromium	Sample digestion by 3010A, 3020A, 3015, 3050B, or 3051 followed by: 6020 or 6010B Inductively Coupled Plasma 7190 or 7191 Trace Metals by Flame or Graphite Furnace AA
Lead	Sample digestion by 3010A, 3020A, 3015, 3050B, or 3051 followed by: 6020 or 6010B Inductively Coupled Plasma 7420 or 7421 Trace Metals by Flame or Graphite Furnace AA

⁷ When there is a choice of analytical methods, you should consider the method detection limit and the target RBC to decide which method to use. To demonstrate regulatory compliance, the analytical method used for quantifying the concentration of a specific contaminant must have a detection limit that is equal to or less than its corresponding RBC. In some instances, however, achieving detection limits at or below the applicable risk-based screening level will not be possible. This should be noted and discussed in reports to the DEQ.

⁸ If your samples are likely to contain plant material or other non-petroleum organic matter, you should talk to your laboratory about using a cleanup step before carrying out the TPH analyses.

After completing the investigation, you should summarize your findings on a site map that shows the location of all samples, lists representative analytical results, and illustrates with concentration contours or simple boundaries the estimated extent of soil and groundwater contamination.

2.2.2 Receptors

The Department believes that potential receptors at most petroleum-contaminated sites will generally fit one or more of the following five scenarios:

- Adults and children in a residential scenario (single-family housing);
- Adults and children in an urban residential scenario (apartment, condominium, *etc.*);
- Adults in an occupational scenario;
- Adults in a construction worker scenario; and
- Adults in an excavation worker scenario.

When deciding what receptors are reasonably likely you should consider your site and the adjacent properties. This is especially true if contamination has migrated beyond the property line. You must consider the current and reasonably likely future uses of these properties. For assistance with identifying land use issues, the Department recommends that you contact the local city or county land use planning agency. Cities and counties are required to prepare and adopt comprehensive land use and zoning maps. For additional help on land use issues please refer to *Consideration of Land Use in Environmental Remedial Actions* (DEQ, 1998f).

When collecting land use information, be sure to inquire about conditional uses, if any, that local governments might allow in established zones. If you plan to propose an industrial scenario it is important that you submit sufficient evidence to show that the property is likely to remain industrial. Sufficient evidence would be a record of current property use and comprehensive land use and zoning maps or other documentation from the appropriate city or county land-planning agency demonstrating commercial or industrial use. In the absence of evidence to the contrary, you must default to the residential scenario.

If you plan to propose an industrial scenario for your site, the Department may require that a deed restriction or other type of property use limitation (<i>i.e.</i> , institutional control) be placed on the site.
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In former urban industrial areas, residential development will often consist of apartments or condominiums. We expect that residents in these urban settings will be exposed to contaminated soil less frequently and will live in the same location for a shorter duration than residents in typical single-family housing. Therefore, the type of residential scenario that you apply will also depend on land-use considerations. If appropriate, you should evaluate an urban residential scenario rather than a residential scenario.

Since many commercial or industrial areas are being remediated in preparation for redevelopment, you may need to evaluate exposures to construction workers who will be working on that property in the future. Also, most properties are bounded on at least one side by road and/or utility rights-of-way where utilities such as sanitary and storm sewers, and telephone, power and cable TV lines

may be located. As a result, excavation workers could also be exposed to contaminated soil and groundwater. The main difference between these two scenarios is the frequency of the exposure in a given year. The excavation worker scenario is for very short-term exposures (9 days), whereas the construction worker could be on-site up to 250 days. As a conservative default assumption, construction workers are assumed to be in contact with soil during work lasting one year at a large development site. This is consistent with current EPA guidance on soil exposure at construction sites (EPA 2002c). For potential exposure to groundwater, far more limited contact is expected, assumed to be consistent with that of an excavation worker. Regardless of whether you have selected a residential or occupational scenario for your site, you may also have to consider the construction and excavation worker scenarios.

2.2.3 Pathways

To determine the pathways that might allow contaminants from the known sources to reach the potential receptors, you should consider how someone might become exposed to the contaminants in their present locations, and how the contaminants might move, resulting in future exposures. Human exposure to toxic substances may result from:

- **Inhalation:** Inhalation exposure can occur by breathing the vapors of volatile constituents such as benzene, or by breathing fine dust particles that have hazardous constituents sorbed onto them. If petroleum products have been spilled on the surface of the ground, vapors can directly enter the surrounding air. However, vapors from volatile substances can also be slowly released from underground spills as the volatile constituents move upward through the pores in the soil, or when the soil is exposed during excavation. Vapors can also be released in a similar fashion from contaminated groundwater, or, for example, when water is used for showering.
- **Ingestion:** Exposure by ingestion can occur when drinking contaminated surface or groundwater or from incidental ingestion of contaminated soil that becomes airborne, or is picked up on your hands. Dust is principally a consideration when there has been a surface spill or when subsurface soil is brought to the surface through excavation or erosion.
- **Dermal Contact:** Dermal exposure can occur when contaminants come into contact with the skin. Certain hazardous substances can cause dermal effects merely by contacting the skin surface. Other hazardous substances can actually be absorbed through the skin and cause health effects after they are transported throughout the body by the bloodstream. Although you are most likely to come into contact with shallow soils, excavation of deeper soils during construction or utility work may also result in dermal exposures.

For exposure to occur a receptor needs both an exposure point (*e.g.*, contaminated soils located at a residence) and an exposure route (*e.g.*, incidental ingestion of those soils). Depending on the nature and extent of the release, there may be more than one exposure point for any given receptor (*e.g.*, nearby residents may be exposed to contaminated soil and groundwater), and there may be more than one exposure route for any given exposure point (contaminated soils may produce both dermal and ingestion exposures).

The most likely pathways at petroleum-contaminated sites are listed in Table 2.3. This list is based on the assumption that soil and groundwater are contaminated, and on the transport properties of constituents commonly found in petroleum products. You should consider the pathways on this list for possible inclusion in your conceptual site model. The pathways that you actually include will depend on the sources and receptors that you identify at your site. Table 2.4 includes a list of conditions that describe when certain pathways should be included. Depending on the conditions at your site, the Department may request that you also consider other exposure pathways not listed in Table 2.3.

Table 2.3: Typical Exposure Pathways for Contaminated Media

Medium	Exposure Pathway
Air	Air samples are not routinely required at cleanup sites. The air inhalation pathway is usually taken into account indirectly by considering volatilization from contaminated soil or groundwater. Air monitoring may be applied when soil or groundwater screening levels are exceeded for the indoor air pathway and additional tests are needed to assess the exposure. Under these circumstances the air concentrations must not exceed the air RBCs in Table A, <u>not</u> OSHA standards. We suggest that you discuss such sampling with the Department before implementation.
Soil	Ingestion, inhalation of particulates or vapors, and dermal absorption ¹
	Volatilization to outdoor air with subsequent inhalation
	Volatilization to indoor air with subsequent inhalation
	Leaching to groundwater with subsequent ingestion and inhalation of volatiles
Groundwater	Ingestion and inhalation of volatiles
	Volatilization to outdoor air with subsequent inhalation
	Volatilization to indoor air with subsequent inhalation
	Dermal absorption

¹ These three pathways -- ingestion, inhalation of particulates or vapors, and dermal absorption -- are usually combined when considering "direct contact" exposures to contaminated soils.

You should provide adequate site-specific information to support the inclusion or exclusion of any of these pathways. For example, if there is no potable aquifer under the site, then you can eliminate leaching-to-groundwater as an exposure pathway. Likewise, groundwater data or soil gas data may support an argument that the drinking-water-ingestion pathway and the vapor-intrusion-into-building pathway are not applicable to your site. In the absence of such data for a given pathway, however, you should include it in your analysis.

Since the Department considers groundwater to be a vital state resource, a review of both current and reasonably likely future uses of groundwater in the vicinity of your site must be included if you are proposing to eliminate the groundwater pathway on the basis that it will not be used. Suitability of the aquifer as a resource, both in terms of adequate yield and water quality, should also be considered. Where public water supply systems are present, you should not only determine the location of the public water supply wells, but also investigate possible private use of groundwater for drinking, irrigation, or industrial processes.

Information on surface or groundwater uses may be obtained from local public water supply agencies, county water masters, or the State of Oregon Water Resources Department. Local environmental health or health departments may also be a good source of information since they usually administer public water supply systems. You may also want to contact the U.S. Geological Survey, especially for regional aquifer information. This information should be used along with relevant site-specific hydrogeological data to evaluate groundwater-related pathways at your site. For more information please refer to *Guidance for Conducting Beneficial Water Use Determinations at Environmental Cleanup Sites* (DEQ, 1998e).

Table 2.4: Exposure Pathway Applicability

Medium	Exposure Pathway ¹	Applicability
Air	Volatile inhalation (RBC _a)	As needed. Discuss with the Department.
Soil	Ingestion, inhalation of particulates or vapors, and dermal absorption (RBC _{ss})	Include this pathway any time someone is likely to come into contact with contaminated soils. For residential, urban residential and occupational scenarios, exposure to contaminated soils should be considered a potential exposure pathway for all contaminants found in the top three feet of soil. For the construction worker and excavation worker scenarios, the depth is site-specific and should be based on current or reasonably likely maximum depths of building excavations onsite or utility trenches in the vicinity of the site. It could be as deep as 10 - 15 feet, or greater in some cases.
	Volatilization to outdoor air (RBC _{so})	Include this pathway whenever vadose zone soils are contaminated with volatile compounds.
	Volatilization to indoor air (RBC _{si})	Include this pathway whenever vadose zone soils contaminated with volatile compounds are located beneath or within 10 feet of a commercial building or beneath or within 50 feet of a residential building.
	Leaching to groundwater (RBC _{sw})	Include this pathway whenever vadose zone contamination is found overlying an aquifer that is currently used or is reasonably likely to be used in the future.
Groundwater	Ingestion and inhalation of volatiles (RBC _{tw})	Include this pathway whenever groundwater contamination is found in an aquifer that is currently used or is reasonably likely to be used for drinking water.
	Volatilization to outdoor air (RBC _{wo})	Include this pathway whenever the groundwater is contaminated with volatile compounds.
	Volatilization to indoor air (RBC _{wi})	Include this pathway whenever volatile compounds in groundwater are located beneath or within 10 feet of a commercial building, or beneath or within 50 feet of a residential building, or may be in such a location in the future
	Dermal absorption and inhalation of volatiles (RBC _{we})	Include this pathway in cases where construction or excavation workers may come into contact with contaminated groundwater in a semi-enclosed space such as an excavation.

¹ The RBC terms in this column (RBC_{ss}, etc.) refer to the terms used in Appendix A to identify the different exposure pathways. Additional information about each pathway can be found in Appendix B.

2.3 Putting the Conceptual Site Model Pieces Together

After completing your site investigation, use the results to reduce the list of potential sources, pathways and receptors discussed in Section 2.2 down to a site-specific list of those combinations that warrant further attention. The level of detail that is needed for this effort will depend on the complexity of your site. Simple sites can be covered with a table or list of pathways. More complex sites may require a flowchart such as the one shown in Figure 2.2 to illustrate all of the pathways.

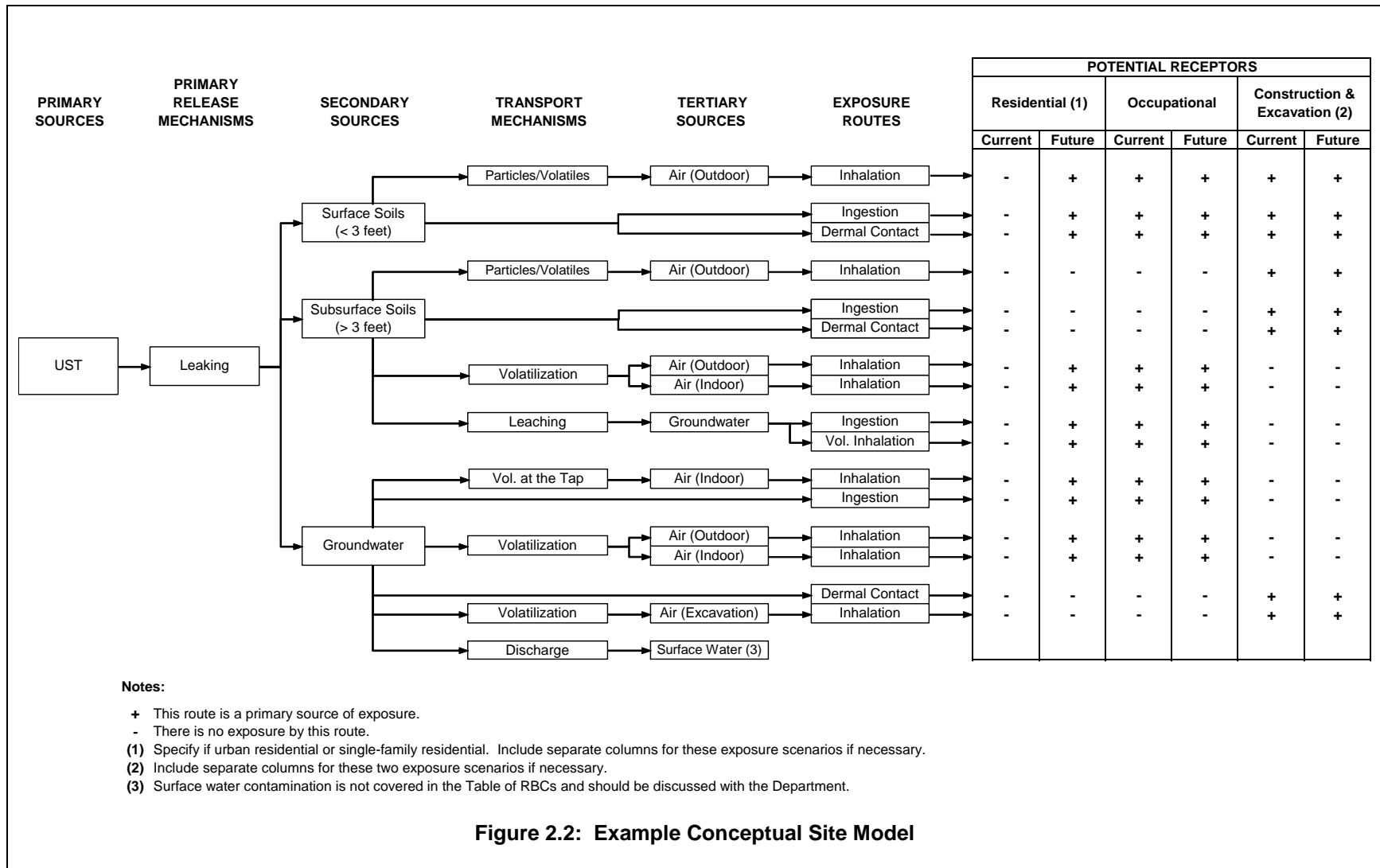
When you develop your proposal or report, you should include a section that describes your CSM and specifically identifies the sources, pathways, and receptors. In addition to a discussion of these pathway considerations, we suggest that you include a table that summarizes your evaluation of exposure pathways such as the example in Table 2.5. Make sure that you include both *current and reasonably likely future scenarios* in the CSM.

Table 2.5: Example Summary of Conceptual Site Model¹

Potentially Exposed Population	Exposure Route, Medium and Exposure Point	Was This Pathway Selected?	Reason for Selection or Exclusion
CURRENT LAND USE: INDUSTRIAL			
Employees Excavation Workers Construction Workers	Direct contact with chemicals in on-site soil	Yes	Contaminated soil is in area accessible to workers
Employees	Inhalation of chemicals volatilized into buildings	No	No volatile contaminants found in soil or GW beneath or near buildings
Residents (Single-Family)	Leaching to GW followed by ingestion from nearby downgradient wells	Yes	Local groundwater sometimes used for drinking water
Residents (Single-Family)	Ingestion of contaminated GW from nearby downgradient wells	Yes	Local groundwater sometimes used for drinking water
FUTURE LAND USE: INDUSTRIAL OR RESIDENTIAL			
Residents (Single-Family)	Direct contact with chemicals in on-site soil	Yes	Area could be developed for residential use

¹ This limited example does not include all of the pathways summarized in Table 2.3. Your CSM should discuss all pathways and explain why they were either selected or rejected.

Regardless of the cleanup option you eventually select, using basic risk concepts to help guide your site investigation should help ensure that you have the information you need later to make appropriate risk-based decisions.



3. Applying Risk-Based Decision Making to Site Cleanups

This section describes how you can use risk-based decision making to remediate petroleum contaminated soil and groundwater. The same risk concepts and goals apply whether the contamination is from regulated underground storage tanks remediated under the *Cleanup Rules for Leaking Petroleum Underground Storage Tank (UST) Systems* (OAR 340-122-0205 through 340-122-0360),⁹ or from sources other than regulated USTs remediated under the *Hazardous Substance Remedial Action Rules* (OAR 340-122-0010 through 340-122-0115). There are, however, important differences in the requirements of these two sets of rules. This section:

- Describes the basic process for evaluating risk from petroleum contamination regardless of the source or what regulatory program is overseeing the remediation (Section 3.1);
- Summarizes regulatory requirements and options under the rules implemented by the UST Program (Section 3.2); and
- Summarizes regulatory requirements and options under the rules implemented by the Environmental Cleanup Program (Section 3.3).

We assume that you will be completing the site investigation and developing a conceptual site model prior to or along with your evaluation of risk.

3.1 Evaluating Risk from Petroleum Contamination

When evaluating risk from exposure to chemicals in soil and groundwater, you must consider both carcinogens and noncarcinogens. This is done for petroleum by assessing:

- Carcinogenic risk from exposure to specific petroleum constituents, and
- Noncarcinogenic risk from exposure to the overall product (*i.e.*, TPH).

This document provides you with several options for demonstrating that the risk from petroleum contamination at your site is acceptable (see Figure 3.1). Two of the options – generic remedies and soil matrix rules – require a relatively limited evaluation of risk. These options are probably best applied to sites with low to moderate levels of contamination. More complex sites may benefit from a more formal risk-based approach. The risk-based approach that we recommend is a tiered process where you have the option of basing your target cleanup levels on:

- Generic RBCs provided by the Department (see Appendix A), or
- Site-specific RBCs that you calculate¹⁰ using information gathered during the site investigation.

If contamination at your site exceeds your target cleanup levels you will probably need to take action to mitigate the risk that contamination poses to human health and/or the environment. Such action may include risk reduction strategies (*e.g.*, excavation and off-site removal of soil

⁹ Contamination from residential heating oil tanks regulated under OAR 340-177-0001 through 340-177-0095 is also remediated using the options in OAR 340-122-0205 through 340-122-0360 (see OAR 340-177-0065).

¹⁰ Spreadsheets are available from the Department of Environmental Quality for this purpose.

contamination, soil vapor extraction, groundwater pump and treat, *etc.*) and/or risk management strategies (*e.g.*, use of engineering and/or institutional controls to assure protection of human health and the environment).

The options listed above are described in Sections 3.1.1 through 3.1.6 and illustrated in Figure 3.1. You should keep the following points in mind when reviewing this information and employing risk-based decision making at your site:

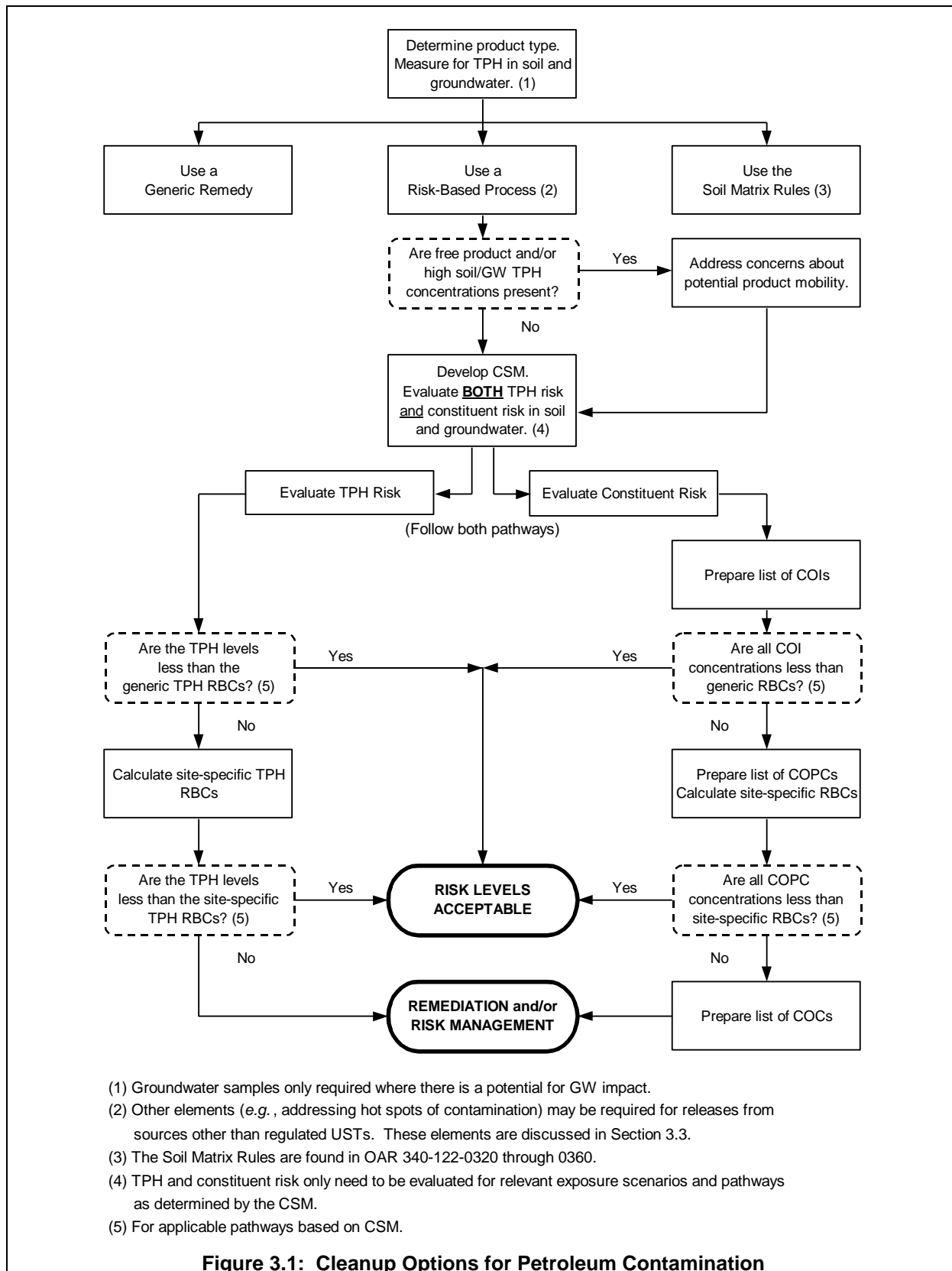
- You must complete the investigation – that is, determine the full nature, magnitude, and extent of soil and groundwater contamination both on and off-site – before you can evaluate the potential risk from exposure to the contaminants.
- You are not required to go through each of the steps illustrated in Figure 3.1. In some cases you can readily determine, based on experience and information gathered during the investigation, the method that is likely to work best for your site. Complete those steps that are appropriate for your site.
- If you elect to use the more detailed risk-based option you must develop a conceptual site model and use that to evaluate risk from exposure to petroleum constituents and petroleum product (TPH) in all appropriate media. This generally means that you will test both soil and groundwater for TPH and constituents. Air samples are not generally required.
- If you can document that a scenario or pathway does not currently exist at your site and is unlikely to be there in the future, the RBCs for that scenario or pathway can be disregarded. You will not have to collect additional samples to demonstrate compliance for that scenario or pathway. For example, if the tap water pathway has been eliminated from consideration, groundwater will not have to be sampled for compliance with RBCs for tap water. Groundwater samples may still be required, however, for compliance with RBCs for volatilization to indoor or outdoor air.
- Be sure to consider the appropriate use of an analytical method before sending samples to the lab for analysis. The purpose of the HCID method is to identify the type of product – gasoline, diesel, heavy oil, *etc.* You should test sufficient samples to identify different sources of contamination at the site but it is not necessary to test all samples by HCID. Likewise, the VPH and EPH methods used to test for TPH fractions are only used to determine the site-specific composition of a product, which is then used to calculate a set of site-specific TPH RBCs. These methods are not required for routine TPH testing.

3.1.1 Identify and Quantify TPH Contamination

Whenever petroleum products are a contaminant of interest, you should collect one or more obviously contaminated samples¹¹ to identify the type of product or products present. The Northwest Total Petroleum Hydrocarbon Identification Method (NWTPH-HCID) should be used for this purpose.¹² The NWTPH-HCID test is only used at the beginning of your investigation to identify the type of contamination present and should never be used for confirmatory testing. The number of samples you collect for identification will depend on the number of sources or contaminated areas being investigated.

¹¹ Samples of contaminated soil will usually be adequate for this purpose. There may be cases where samples of free product or contaminated water are more easily obtained and appropriate to use at a given site.

¹² If only a single product is present and its identity is clearly known, such as the case of a residential heating oil tank, then the HCID is not required.



Based on the results of the NWTPH-HCID tests, you should use appropriate tests to measure the amount of contamination at your site. NWTPH-Gx should be used to measure automotive and aviation gasoline and mineral spirits and NWTPH-Dx should be used for diesel, jet fuels, kerosene, hydraulic fluids, mineral oils, lubricating oils and fuel oils. You should test enough samples to determine the lateral extent as well as the depth of the petroleum contamination. If groundwater is contaminated, you may also have to test for TPH levels in water samples.

3.1.2 Use a Generic Remedy

If your site meets the requirements of one of the DEQ's generic remedies, that may be the easiest method for you to complete the remediation and close the site. The option to use generic remedies is available in both the *Cleanup Rules for Leaking Petroleum UST Systems* (see OAR 340-122-0252) and the *Hazardous Substance Remedial Action Rules* (see OAR 340-122-0047). Therefore, if a generic remedy is appropriate for petroleum contamination and your site meets all of the requirements of the remedy, you can apply the remedy regardless of the source of contamination.

3.1.2.1 What is a Generic Remedy?

A generic remedy is a set of procedures that you can use on a specific type of site to bring it into compliance with the existing cleanup rules. The idea behind the generic remedy is that if there are many sites with common characteristics, then if you can determine how to clean up one of those sites, the same procedures should be applicable to similar sites. A generic remedy, therefore, is not designed for all cleanup sites. Such a remedy can only be applied to the specific category of sites defined in the remedy.

It is important to note that the generic remedies developed by the Department must be in compliance with all existing rules. In other words, the generic remedy authority does not allow the Department to develop cleanup levels or procedures that could not already be applied to any individual site under the current rules. A generic remedy simply defines a set of procedures or standards which, if applied to the specified type of site, will ensure that the site meets existing regulations.

3.1.2.2 What Generic Remedies Are Available?

Generic remedies are developed on an as-needed basis. The DEQ currently has the following generic remedies that are related to petroleum contamination:

- *Heating Oil Tank Generic Remedy Guidance Document* (DEQ, 2000a), for contamination due to releases from residential heating oil tanks; and
- “Generic Remedy for Simple Risk-Based Cleanups” (Section 4), which applies to all petroleum contamination regardless of source.

When additional generic remedies are developed, the DEQ will post information on the Land Quality Division Web site (see address on page ii).

If your site does not qualify for a generic remedy, then you should proceed with one of the other options outlined in Sections 3.1.3 through 3.1.6.

3.1.3 Compare Soil TPH Levels to the Soil Matrix Cleanup Levels

If your site meets all of the requirements of OAR 340-122-0320 through 340-122-0355, then it is assumed to meet acceptable risk levels.¹³ A more formal evaluation of risk will not be required. In some cases where only contaminated soil is present, you may be able to demonstrate that your site meets these requirements using only TPH-HCID, TPH-Gx and TPH-Dx measurements. In many cases, however, such as when contamination reaches groundwater, is located under a building, or comes from a waste oil tank, you will be required to test soil and water samples for constituents. Refer to the rules for the specific requirements and the *UST Cleanup Manual* (DEQ, 2000c) for additional assistance in interpreting and applying them.

If contaminated groundwater is found at your site, but the contaminated soil meets the requirements of OAR 340-122-0320 through 340-122-0355, then the soil is assumed to meet acceptable risk levels. Additional evaluation of the risk from exposure to the contaminated groundwater would be required using one of the other options.

If your site does not meet the soil matrix cleanup level requirements, you should consider whether it is feasible to clean up the site to meet those requirements. If it is not, you can demonstrate that your site meets acceptable risk levels by:

- Showing that the TPH concentrations meet acceptable risk levels as described in Section 3.1.5; and
- Showing that the concentrations of constituents meet acceptable risk levels as described in Section 3.1.6.

If free product is found at your site or there are large volumes of heavily contaminated soil present from which product may be continuing to migrate, then you will also have to address concerns about potential product mobility as discussed in Section 3.1.4.

3.1.4 Address Free Product and Potential Product Mobility

Evaluating risk from exposure to contaminants involves estimating both direct exposures, such as ingesting contaminated soil or groundwater, and indirect exposures, such as inhaling vapors that originate in a layer of contaminated subsurface soil. Methods commonly used for estimating indirect exposures employ models that simulate the movement of individual contaminants such as benzene and naphthalene as vapors or dissolved in groundwater. These transport models do not, however, simulate the movement of the petroleum product itself. Furthermore, the exposure models and assumptions used to calculate constituent RBCs may not apply to direct exposures to free product.¹⁴ Therefore, in some cases you will have to address concerns about potential product mobility and exposure to free product in addition to completing a traditional risk evaluation.

¹³ Although these requirements are part of the UST Cleanup Rules, the soil matrix numbers are considered adequately protective for petroleum contamination regardless of source. Therefore, they may also be used as cleanup levels for sites being remediated under the Hazardous Substance Remedial Action Rules.

¹⁴ The DEQ assumes that direct exposure to free product is an unacceptable risk unless otherwise determined.

Free product mobility and exposure is potentially a concern when:

- Free product is found floating on groundwater in excavations or wells at your site; or
- Soils with relatively high concentrations of petroleum hydrocarbons are present.

You should consider the following actions to evaluate and address these situations.

3.1.4.1 Remove Free Product

We recommend that you start removing free product as soon as possible. Cleanups carried out under the UST Cleanup Rules are required to remove free product “to the maximum extent practicable.”¹⁵ For information on techniques, see *How to Effectively Recover Free Product at Leaking Underground Storage Tanks Sites* (EPA, 1996c). If you have questions about product removal at your site you should contact your DEQ project manager.

3.1.4.2 Evaluate Potential Mobility of Product in Soil

Even if you do not encounter free product floating on groundwater, high concentrations of TPH in the soil indicate the product is potentially mobile and could eventually reach groundwater or seep out onto surface water bodies. This can happen when concentrations exceed a product’s residual saturation in the soil.

Residual saturation should not be confused with the saturation concentration (C_{sat}), which is discussed elsewhere in this document. C_{sat} is a theoretical concentration above which free product can start to appear in the soil. Residual saturation is the point above which the free product can start to flow through the soil. Residual saturation concentrations are usually several orders of magnitude higher than C_{sat} concentrations.

Residual saturations vary widely depending on the combination of product and soil type (Brost and DeVaul, 2000). The DEQ recommends that you consider potential product mobility when you are proposing to leave soils contaminated with:

- Gasoline in concentrations exceeding 1,000 mg/kg TPH-Gx, or
- Diesel, mineral insulating oil, or other similar non-gasoline petroleum products in concentrations exceeding 10,000 mg/kg TPH-Dx.

These values are **not** cleanup levels. You should use them as guidelines for when you might be asked to provide additional assurances that product mobility is not a concern at your site. In most cases mobility from contaminated soil will only be a problem when there are relatively large volumes of highly contaminated soil in the vicinity of groundwater, surface water, or other receptors that might be affected if the product continues to move.

The cleanup action may also need to consider elements unrelated to risk such as aesthetics and odor.

¹⁵ See OAR 340-122-0235 for the free product removal requirements for releases from regulated USTs.

3.1.5 Evaluate TPH for Noncarcinogenic Risk

3.1.5.1 Compare TPH Levels to the Generic TPH RBCs

If the contamination at your site has been identified as gasoline, diesel, or transformer mineral insulating oil, you can use the generic TPH RBCs in Appendix A to evaluate noncarcinogenic risk. The risk is acceptable if TPH concentrations do not exceed the generic TPH RBCs for all relevant exposure scenarios and pathways at your site.

TPH-HCID results must confirm the presence of one or more of the products listed in the Table of RBCs (Appendix A), namely gasoline, diesel/heating oil or transformer mineral insulating oil.¹⁶ Or, HCID results must indicate that the petroleum product is similar in composition to one or more of these products before the generic TPH RBCs can be used to evaluate TPH risk. The Department may disallow the use of the generic TPH RBCs at sites where the TPH-HCID results indicate that the generic values may not be adequately protective.

The TPH concentration of any individual product must not exceed any of the TPH RBCs for that product for all relevant exposure scenarios and pathways at your site. For example, if the product is identified as gasoline, then the TPH-Gx levels must meet all of the relevant TPH RBCs for gasoline. If the product is identified as transformer mineral insulating oil, then the TPH-Dx levels must meet all of the relevant TPH RBCs for transformer mineral insulating oil. If the product is identified as diesel, heating oil, or other similar petroleum products, then the TPH-Dx levels must meet all of the relevant TPH RBCs for diesel.

If two or more types of petroleum contamination have been identified at the site, then the combined exposure to all of the products cannot exceed a hazard index of one as demonstrated by equation H-4 in Appendix H. For example, if gasoline and diesel contamination are present, then the TPH-Gx and TPH-Dx concentrations would be used to calculate the hazard index for each relevant pathway using the equation below.

$$\text{Hazard Index} = \left(\frac{\text{TPH-Gx (mg/kg)}}{\text{RBC for Gasoline (mg/kg)}} \right) + \left(\frac{\text{TPH-Dx (mg/kg)}}{\text{RBC for Diesel (mg/kg)}} \right) \quad [3-1]$$

If the TPH concentrations at your site meet these requirements you must also show that the concentrations of carcinogenic petroleum constituents do not exceed acceptable risk levels before you can conclude that the site meets acceptable risk levels. This is discussed in Section 3.1.6. If the concentrations of all of the carcinogenic constituents and TPH are less than their respective generic RBCs, the Generic Remedy for Simple Risk-Based Closures (Section 4) might be the easiest way for you to close the site.

If the TPH concentrations at your site do not meet the requirements discussed above, you should consider whether it is feasible to clean up the site to meet those requirements. If it is not, you can also demonstrate that the TPH levels meet acceptable risk levels by showing that the TPH concentrations meet site-specific TPH RBCs as described in Section 3.1.5.2.

¹⁶ Transformer mineral insulating oil is insulating oil used in the operation of a variety of electrical equipment for the transmission and distribution of electricity. The numbers in Table A are for this product only, not for regular mineral oil or mineral spirits.

3.1.5.2 Compare TPH Levels to Site-Specific TPH RBCs

The generic TPH RBCs listed in Appendix A were calculated assuming:

- The products – gasoline, diesel, and transformer mineral insulating oil – are relatively fresh and have the compositions listed in Appendix F; and
- The exposure factors and physical conditions at the site are described by the parameters listed in Appendix C.

If the petroleum composition or conditions at your site differ from those used for the generic RBCs, then you should consider calculating site-specific TPH RBCs. This can be done by using information about site-specific product composition, site-specific exposure parameters, or both.

Use Site-Specific Product Composition

In general, the older the release and the more degraded the product, the more likely you are to benefit from using site-specific TPH RBCs based on site-specific TPH fractions. This is especially true for gasoline and diesel, but not as important for mineral insulating oil.

As illustrated in the equation below, TPH RBCs are a function of the composition of the product and represent a weighted-average toxicity of all of the components in a given product.

$$RBC_{TPH} = \frac{1}{\left(\frac{\text{Wt. Fraction}_1}{RBC_1}\right) + \left(\frac{\text{Wt. Fraction}_2}{RBC_2}\right) + \dots + \left(\frac{\text{Wt. Fraction}_n}{RBC_n}\right)} \quad [3-2]$$

Since petroleum components have a wide range of toxicities, site-specific RBCs for a particular product will change as the composition of that product changes. The change in composition may be due to remedial measures like vapor extraction or to degradation from aging. Because some of the more toxic petroleum constituents also tend to be the more volatile, soluble, and degradable constituents, aged products are often less toxic than fresh products (this is particularly true for gasoline). Therefore, site-specific TPH RBCs are often less stringent than generic TPH RBCs.

Before you can calculate site-specific TPH RBCs you need to know the composition of the product at your site. In this document we refer to the composition of a petroleum product by dividing it up into specific “TPH fractions”¹⁷ developed by the TPHCWG and selected constituents like BTEX. The fractions and constituents used in this document are shown in Table 3.1.

There are two methods to obtain TPH fraction data to calculate site-specific TPH RBCs. The first method requires you to estimate the fractions based on available constituent and TPH data. The second method requires you to test samples using analytical methods developed for the purpose of measuring these fractions. This first method may result in TPH RBCs that are more conservative than the second method. Since it generally does not require additional tests, however, the first method may be less costly to implement. The methods are summarized below.

¹⁷ A “TPH fraction” is just a portion of the whole product. For example, if a particular petroleum product consists of hydrocarbons ranging from C6 to C12, then the hydrocarbons ranging from C6 - C8 are only a fraction of the product.

Method 1: Calculating Site-Specific TPH RBCs using TPH and Constituent Data

This method can only be used on products that have been identified as gasoline or diesel. To estimate TPH fractions you need to have the following data:

- TPH data measured by method NWTPH-Gx or NWTPH-Dx, as appropriate; and
- Corresponding data for benzene, toluene, ethylbenzene, total xylenes, 1,2,4-trimethylbenzene (1,2,4-TMB), 1,3,5-trimethylbenzene (1,3,5-TMB), and naphthalene.

The data must be from the same sample. The constituent data (BTEX, etc.) must represent the concentration of constituents in the sample having the reported TPH concentration.

Table 3.1: TPH Fractions and Constituents Used for Calculating TPH RBCs

Aliphatic Hydrocarbons	TPH Fractions	C5-C6
		>C6-C8
		>C8-C10
		>C10-C12
		>C12-C16
		>C16-C21
		>C21-C34
		Constituents
Aromatic Hydrocarbons	TPH Fractions	>C8-C10
		>C10-C12
		>C12-C16
		>C16-C21
		>C21-C34
	Constituents	Benzene (2)
		Toluene
		Ethylbenzene (3)
		Total xylenes (3)
		1,2,4-trimethylbenzene (3)
	1,3,5-trimethylbenzene (3)	
	Naphthalene (4)	

(1) Refer to Appendix G for an explanation of why n-hexane and other constituents are included along with the TPH fractions in the calculation of TPH RBCs. Although you will need site-specific data for all of the other constituents listed in this table, you are not required to test for n-hexane. For the purpose of calculating TPH RBCs, the Department assumes the concentration of n-hexane in gasoline is up to 2.4% by weight, but not greater than the aliphatic C5-6 fraction. The estimated n-hexane concentration is subtracted from the aliphatic C5-6 fraction before calculating the RBCs.

(2) Benzene is both a carcinogen and a noncarcinogen. Its contribution to noncarcinogenic risk must be included when calculating TPH RBCs.

(3) The concentrations of ethylbenzene, total xylenes, and the TMBs are subtracted from the Aromatic >C8-C10 fraction before calculating TPH RBCs.

(4) The concentration of naphthalene is subtracted from the Aromatic >C10-12 fraction before calculating TPH RBCs.

Calculate the TPH fractions as follows:

1. Calculate the “Reduced TPH Concentration” by subtracting the sum of all of the required constituents (benzene, toluene, ethylbenzene, total xylenes, 1,2,4-TMB, 1,3,5-TMB, and naphthalene) from the corresponding TPH concentration.
2. Calculate the concentration of each TPH fraction by multiplying the reduced TPH concentration by the appropriate multiplier from the table below.
3. Subtract the sum of the estimated TPH fractions from the Reduced TPH to obtain the estimated n-hexane concentration.

Table 3.2: Multipliers for Calculating TPH Fractions

Required TPH Fractions		Use the following multipliers IF the product is gasoline	Use the following multipliers IF the product is diesel
Aliphatic Fractions	C5-C6	0.302	0
	>C6-C8	0.322	0
	>C8-C10	0.132	0.020
	>C10-C12	0.044	0.071
	>C12-C16	0	0.354
	>C16-C21	0	0.343
	>C21-C34	0	0
Aromatic Fractions	>C8-C10	0.132	0.0025
	>C10-C12	0.033	0.0075
	>C12-C16	0	0.081
	>C16-C21	0	0.121
	>C21-C34	0	0

Use the calculated TPH fractions and site-specific constituent data to calculate the TPH RBCs as described in Appendix B. The Department has a Microsoft Excel® spreadsheet that you can use for this purpose (DEQ, 2003a).¹⁸ You should calculate a set of RBCs for each area of the site that has a different type of contamination.

Example: You are working on a site where TPH-HCID test results show that you are dealing with gasoline contamination. Tests on a soil sample gave the following results: 5700 ppm TPH-Gx; 8.2 ppm benzene; 65 ppm toluene; 18 ppm ethylbenzene; 72 ppm total xylenes; 84 ppm 1,2,4-TMB; 16 ppm 1,3,5-TMB; and 5.8 ppm naphthalene.

The sum of all seven constituent concentrations is 269 ppm. Therefore, the reduced TPH concentration is 5700 - 269 = 5431 ppm. Using the gasoline multipliers, the calculated TPH fractions for this product are: 1640 ppm C5-C6 aliphatics; 1749 ppm >C6-C8 aliphatics; 717 ppm >C8-C10 aliphatics; 239 ppm >C10-C12 aliphatics; 717 >C8-C10 aromatics; and 179 ppm >C10-C12 aromatics. Subtract the sum of these values (5241 ppm) from 5431 to obtain an estimated n-hexane concentration = 190 ppm. These calculated fractions and the site-specific constituents can be used to calculate site-specific TPH RBCs.

Note: The Department’s spreadsheet will perform these calculations for you.

¹⁸ The Department’s spreadsheet, *Calculating RBCs for Total Petroleum Hydrocarbons*, includes an option that will estimate the TPH fractions for you using the process described in this section.

The easiest way to handle mixtures of gasoline and diesel may be to treat them as a single site-specific product and use Method 2 (next section) to test for the TPH fractions. However, if that is not cost-effective you can use the method described in Appendix F to estimate what portion of each constituent can be attributed to each product and then apply the method described above to gasoline and diesel separately. For products other than gasoline and diesel you will have to use Method 2 to obtain site-specific information.

Method 2: Calculating Site-Specific TPH RBCs using TPH Fraction Data

To test for site-specific TPH fractions you will have to collect additional samples and have them analyzed with one or both of the following methods developed by the State of Washington Department of Ecology (Washington DOE, 1997):

- *Method for the Determination of Volatile Petroleum Hydrocarbon (VPH) Fractions*

The VPH method is for gasoline and other light petroleum products. It gives results for *aliphatic* hydrocarbons in the ranges of C5-C6, >C6-C8, >C8-C10, and >C10-C12; *aromatic* hydrocarbons in the ranges of C8-C10, >C10-C12, and >C12-C13; as well as benzene, toluene, ethylbenzene, xylenes, and methyl t-butyl ether (MTBE). If the results of your earlier HCID tests show that there is a significant amount of product heavier than C10, then you must also test the sample using the EPH method.

- *Method for the Determination of Extractable Petroleum Hydrocarbon (EPH) Fractions*

The EPH method is for diesel and heavier petroleum products. It gives results for *aliphatic* hydrocarbons in the ranges of C8-C10, >C10-C12, >C12-C16, >C16-C21, and >C21-C34; and *aromatic* hydrocarbons in the ranges of C8-C10, >C10-C12, >C12-C16, >C16-C21, and >C21-C34. If the results of your earlier HCID tests show a significant amount of product lighter than C10, then you must also test the sample using the VPH method.

You do not have to test all samples with methods VPH and EPH. The purpose of the test is to determine the composition of the product or mixture of products¹⁹ at your site. You should, however, test samples that represent all of the different sources found at your site. After you know the composition of the product(s) at your site and have calculated site-specific RBCs, TPH-Gx and/or TPH-Dx can be used to test for compliance with the RBCs.

If you are required to test a particular sample with both methods (*i.e.*, the sample is contaminated with light products like gasoline and heavier products like diesel), then the VPH and EPH results for that sample must be combined as described in Table 3.3 to obtain the overall product composition. The overall composition must be used to calculate the RBCs. Otherwise use the individual VPH or EPH results to calculate the RBCs.

Use the site-specific TPH fractions and constituent data to calculate the TPH RBCs as described in Appendix B. The Department has a Microsoft Excel® spreadsheet that you can use for this purpose (DEQ, 2003a). You should calculate a set of RBCs for each area of the site that has a different type of contamination.

¹⁹ If several products are commingled in a given location, you could use VPH and/or EPH results to develop a single set of site-specific TPH RBCs for that mixture.

Table 3.3: How to Combine Test Results For a Sample Analyzed by VPH and EPH

VPH Test Results	EPH Test Results	Overall Product Composition
-- ALIPHATIC HYDROCARBONS --		
C5-C6 Aliphatics		Use the VPH result.
>C6-C8 Aliphatics		Use the VPH result.
>C8-C10 Aliphatics	C8-C10 Aliphatics	Use the higher of the VPH or EPH result.
>C10-C12 Aliphatics	>C10-C12 Aliphatics	Use the higher of the VPH or EPH result.
	>C12-C16 Aliphatics	Use the EPH result.
	>C16-C21 Aliphatics	Use the EPH result.
	>C21-C34 Aliphatics	Use the EPH result.
-- AROMATIC HYDROCARBONS --		
Benzene		Use the VPH result.
Toluene		Use the VPH result.
Ethylbenzene		Use the VPH result.
Total Xylenes		Use the VPH result.
C8-C10 Aromatics	C8-C10 Aromatics	Use the higher of the VPH or EPH result. ²⁰
>C10-C12 Aromatics	>C10-C12 Aromatics	Use the higher of the VPH or EPH result.
>C12-C13 Aromatics	>C12-C16 Aromatics	Use the higher of the VPH or EPH result.
	>C16-C21 Aromatics	Use the EPH result.
	>C21-C34 Aromatics	Use the EPH result.

Use Site-Specific Parameters

TPH RBCs can also be modified by replacing some of the default physical parameters like depth to groundwater with site-specific parameters in the models used for the RBC calculations. This is the same process that is used for calculating site-specific RBCs for petroleum constituents. Please see Section 3.1.6.4 for more information. Information on modifying these parameters is also included under each of the exposure pathways discussed in Appendix B. The Department has a Microsoft Excel® spreadsheet that you can use for this purpose (DEQ, 2003b).

The risk from exposure to TPH at your site is acceptable if the TPH concentrations do not exceed the site-specific TPH RBCs described in this section for all relevant exposure scenarios and pathways at your site.

If the TPH concentrations at your site meet these requirements, you must also show that the concentrations of carcinogenic petroleum constituents do not exceed acceptable risk levels before you can conclude that the site meets acceptable risk levels. This is discussed in Section 3.1.6.

²⁰ Because ethylbenzene and the xylenes are also detected in the C8-C10 aromatic range, the DEQ spreadsheet subtracts their concentrations from the C8-C10 aromatic concentration before calculating site-specific TPH RBCs. You should not adjust any of the reported concentrations before using the TPH RBC spreadsheet.

If the TPH concentrations at your site do not meet the requirements discussed above, you should consider whether it is feasible to clean up the site to meet those requirements. If it is not, you will have to develop appropriate engineering and/or institutional controls to reduce risks from exposure to TPH to acceptable levels (see Section 3.1.8).

You can combine both methods discussed in this section to calculate TPH RBCs taking into account changes in product composition (TPH fractions) and site parameters.

3.1.6 Evaluate Petroleum Constituents for Carcinogenic Risk

3.1.6.1 Develop a List of Contaminants of Interest

Before you can evaluate risk from constituents you have to develop a complete list of petroleum constituents found at your site. These are the contaminants of interest (COIs). Refer to Table 2.1 for the COIs you should look for based on the type of petroleum contamination found at your site. Include both carcinogens and noncarcinogens on this list.

Table 3.4 is an example of such a list for a site where only four contaminants were detected in soil and groundwater — benzene, benzo[a]pyrene, toluene, and naphthalene. Because soils at different depths or groundwater in different aquifers may result in different exposures, it can also be helpful to list the depths or aquifers from which samples were collected.

Table 3.4: Example List of Contaminants of Interest

Contaminant (Risk Type)	Soil		Groundwater Maximum Concentration µg/L (ppb)
	Maximum Concentration mg/kg (ppm)	Depth (ft)	
Benzene (c)	105	0-5	230
	11	5-10	
	27	10-20	
Benzo[a]pyrene (c)	1.2	0-5	<0.5
	0.4	5-10	
	<0.01	10-20	
Toluene (nc)	15	0-5	750
	<0.01	5-10	
	4.2	10-20	
Naphthalene (nc)	6.2	0-5	3.4
	55	5-10	
	12	10-20	

3.1.6.2 Compare COI Concentrations to the Generic Constituent RBCs

Based on the relevant exposure pathways and scenarios in the CSM, and the constituents in the list of COIs, you should develop a list of generic RBCs from Appendix A that apply to your site. For example, Table 3.5 is the list you would obtain from the four COIs in Table 3.4 and the six pathway/receptor combinations from the example CSM in Table 2.5.

Table 3.5: Example List of Generic RBCs from Appendix A

Medium →	Soil mg/kg (ppm)								GW µg/L (ppb)			
Pathway →	Ingestion, Dermal, and Inhalation								Leaching to GW		Ingestion and Vapor Inhal'n	
Scenario →	Residential		Occupational		Construction		Excavation		Residential		Residential	
Contaminant		Note		Note		Note		Note		Note		Note
Benzene (c)	6.9		34		340		9,400	>Csat	0.0084		0.35	
Benzo[a]pyrene (c)	0.062		0.27		2.1		59	>Csat	2.4		0.0078	
Toluene (nc)	2600	>Csat	68,000	>Csat	39,000	>Csat	-	>MAX	44		720	
Naphthalene (nc)	34		770	>Csat	710		20,000	>Csat	3.8		6.2	

Compare the concentrations of each carcinogen on your list of COIs to the RBCs. Take into account the location of the contamination (*e.g.*, for residential and occupational settings, current exposures to the combined ingestion/dermal/inhalation pathway typically apply to only contamination in the top three feet of soil). The risk from exposure to carcinogenic constituents at your site is acceptable if none of the carcinogenic COI concentrations exceed their respective RBCs for the relevant exposure scenarios and pathways at your site and if the combined exposure for all carcinogens (the cumulative risk) meets acceptable risk levels when evaluated as shown in Appendix H.

If the concentrations of the carcinogenic COIs at your site meet these requirements you must also show that the noncarcinogenic risk from TPH concentrations does not exceed the acceptable risk level before you can conclude that the site meets all acceptable risk levels. This is discussed in Section 3.1.5.

If the concentrations of the carcinogenic COIs and TPH are all less than their respective generic RBCs, the “Generic Remedy for Simple Risk-Based Closures” (Section 4) might be the easiest way for you to close the site.

If the concentrations of the carcinogenic COIs at your site do not meet the requirements discussed above, you should consider whether it is feasible to clean up the site to meet those requirements. If it is not, you can also demonstrate that these constituents meet acceptable risk levels by showing that their concentrations meet site-specific RBCs.

3.1.6.3 Develop a List of Contaminants of Potential Concern

If your site does not meet the requirements of the previous section, it is typically not the case that all of the COIs exceed the generic RBCs. Therefore, before calculating site-specific RBCs, you should screen the list of COIs and eliminate any that are not contributing significantly to the overall risk. In the Tank Program this is usually carried out by comparing the COI concentrations to their respective RBCs. COIs that have concentrations less than their RBCs can be screened out.²¹ The Environmental Cleanup Program carries out screening as illustrated in Appendix I. Constituents that remain after the screening step are the contaminants of potential concern (COPCs). For example, Table 3.6 lists the COPCs that remain after the COI data in Table 3.4 are screened for the tank program against the CSM-derived RBCs in Table 3.5.

²¹ The Tank Program reserves the right to ask for a formal Appendix I screening on a site-specific basis.

Table 3.6: Example List of Contaminants of Potential Concern

COPC	Medium	Pathway	Receptor
Benzene (c)	Soil	Leaching to GW	Current residential exposures offsite Future residential exposures onsite and offsite
	Groundwater	Ingestion/ vapor inhalation	Current residential exposures offsite Future residential exposures onsite and offsite
Benzo[a]pyrene (c)	Soil	Soil contact	Current residential exposures offsite Future res. and occ. exposures onsite and offsite
Toluene (nc)	Soil	Leaching to GW	Current residential exposures offsite Future residential exposures onsite and offsite
	Groundwater	Ingestion/ vapor inhalation	Current residential exposures offsite Future residential exposures onsite and offsite
Naphthalene (nc)	Soil	Leaching to GW	Current residential exposures offsite Future residential exposures onsite and offsite
	Groundwater	Ingestion/ vapor inhalation	Current residential exposures offsite Future residential exposures onsite and offsite

In this example, benzene concentrations in soil exceed the RBCs for residential and occupational ingestion/dermal/inhalation soil exposures as well as for leaching to groundwater. Benzene was detected at the soil surface, which indicates that current residential exposure may be occurring. Benzene is also present at depth (greater than 3 feet) at concentrations exceeding RBCs. Although not a current exposure, contamination at moderate depths is a concern for future exposures. This is particularly true for residential sites where subsurface soils could be placed at the surface (by landscaping, installing a swimming pool, *etc.*). So, there is a potentially unacceptable future residential exposure to chemicals in subsurface soils. The benzene concentrations in groundwater exceed the RBC for the residential tap water ingestion/vapor inhalation pathway, so benzene is also a COPC for that pathway.

Concentrations of toluene in soil are acceptable for all scenarios, but the groundwater concentration exceeds the residential RBC. Benzo[a]pyrene (BaP) was detected in soil at concentrations that exceed the RBCs for the residential, urban, and occupational ingestion/dermal/inhalation pathway. BaP does not exceed RBCs for construction and excavation workers, who could be exposed at depth.

Although benzo[a]pyrene was not detected in groundwater, the detection limit is greater than the RBC. In such cases the Department will generally consider the contaminant not present in that medium as long as the appropriate analytical method was applied, an acceptable limit of detection has been attained, and there is no reason to question the quality of the data.

Screening should also consider cumulative effects of carcinogenic chemicals of interest, in addition to the comparison of concentrations with individual chemical RBCs. A method for screening is provided in Appendix H (see equation [H-3]). Chemicals of interest exceeding the cumulative criteria should be screened in (*i.e.*, retained) as chemicals of potential concern for additional evaluation.

Toluene and naphthalene are *noncarcinogens* and risk from exposure to all noncarcinogens will generally be covered by the TPH RBCs. However, there are still important reasons to continue to analyze and list the data for the noncarcinogenic constituents. If you decide to estimate site-specific TPH RBCs or your product is not one of the three listed in Appendix A you will need the data (see Section 3.1.5.2). Also, if there is some question about the product at your site – is it gasoline, diesel, or some other product – the constituent data might help resolve the matter. The data could also be useful when you are selecting a remedy – high concentrations of volatiles might be handled differently than high concentration of nonvolatiles.

After compiling the list of COPCs, determine if any of the constituents are designated as “>C_{sat}” or “>S” in the note columns for the pathways that you have identified in your CSM. Concentrations with this designation are RBCs that exceed certain “saturation” limits. These designations are used only for pathways that do not require contaminant transport (*e.g.*, soil direct contact, RBC_{ss}). If you have concentrations that exceed an RBC designated as “>C_{sat}” in soil or “>S” in water, not only is the risk unacceptable, but it means that you may have free product at your site. The presence of free product could result in concentrations that are much higher than the saturation limits and produce additional risks. You should indicate which of the COPCs found at your site fit these categories and address concerns about potential product mobility as discussed in Section 3.1.4. Refer to Section B.2.1.4 for more information about the meaning of these notes. Contaminant-specific values of C_{sat} and S can be found in Appendix D.

3.1.6.4 Calculate Site-Specific Constituent RBCs

The only RBCs that are reasonable to consider for site-specific calculations are those for indirect pathways, such as leaching to groundwater and volatilization from soil or groundwater to indoor or outdoor air. This is because the direct pathways, such as groundwater or soil ingestion, are calculated from exposure models that only contain factors that are not reasonable to measure on a site-specific basis, and which may not vary much from site to site anyway (*e.g.*, the volume of water consumed per day by adults or children). Indirect pathway calculations, however, include transport factors that are amenable to site-specific measurement and likely to exhibit variation (*e.g.*, depth to groundwater, and the depth and size of the contaminated zone).

Unlike site-specific TPH RBCs (see Section 3.1.5.2), the method for calculating site-specific constituent RBCs used in this document does not require data on TPH composition. Therefore, this can be done without additional analytical tests. Before calculating site-specific constituent RBCs, however, you should try to determine if the calculations are likely to produce values that are different than the generic RBCs. To determine this you need to know:

- The equations or models that were used to calculate the generic RBCs, and
- The default parameters that were used in the calculations.

Site-specific calculations can be beneficial when conditions at your site are significantly different than the default conditions used by the DEQ to calculate the generic RBCs in Appendix A. For example, Table 3.6 indicates that benzene leaching to groundwater may be a problem as a result of residential groundwater ingestion. If your site has a much greater depth to groundwater than

the 3-meter (about 10-foot) depth used by the Department for the generic value, it may be worth your while to calculate a site-specific RBC for benzene leaching to groundwater.²²

You can use site-specific data in the same basic spreadsheet models that were used by the DEQ, or you can use more sophisticated computer models to evaluate exposure and generate site-specific RBCs. If you are considering site-specific calculations, you should refer to Appendix B for a detailed discussion of the models used to develop the generic RBCs. Also included in that appendix are suggestions for making site-specific calculations. These suggestions cover not only what parameters may be worth adjusting in the existing models, but also what other models may be useful for specific pathways. Appendix C lists the default exposure factors.

All site-specific calculations should be described in detail in your report to the Department. Include information about the models used and site-specific data that substantiate the parameters that were changed from the defaults.

3.1.6.5 Compare COPC Concentrations to the Site-Specific Constituent RBCs

Risk from exposure to carcinogenic COPCs at your site is acceptable if none of the COPC concentrations exceed site-specific RBCs for the relevant exposure scenarios and pathways at your site and if the cumulative risk for all carcinogens meets acceptable risk levels when evaluated as shown in Appendix H. If the concentrations at your site meet these requirements, you must also show that the TPH concentrations do not exceed acceptable risk levels before you can conclude that the site meets acceptable risk levels. This is discussed in Section 3.1.5.

If all of the COPCs at your site do not meet the requirements discussed above, screen out the ones that do and retain the rest as contaminants of concern (COCs). You should consider whether it is feasible to clean up the COCs to meet the site-specific RBCs. Information about various technologies applicable to petroleum remediation can be found in quite a few documents including *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites* (EPA, 1994a). If cleanup is not feasible, you will have to develop appropriate engineering and/or institutional controls to reduce exposure to the COCs to acceptable levels (see Section 3.1.8).

3.1.7 Analyze Site-Specific Data

You do not have to perform statistical tests on the data before you can compare them to RBCs. Individual sample results can be compared directly to applicable RBCs to determine compliance. When larger numbers of samples are collected to estimate an average exposure, however, statistical evaluation of the data is often appropriate for demonstrating compliance.²³ This is particularly useful when sample variation over a broad area of soil contamination may make it difficult to attain the cleanup level at every sampling location. One of the more common statistical methods used to test compliance is to show that a particular upper confidence limit (UCL) of the mean is at or below the cleanup level. EPA suggests using the 95% UCL for compliance. The DEQ, however, generally accepts the 90% UCL for this purpose. Therefore, the 90% UCL can be compared to applicable RBCs to determine compliance with acceptable risk levels.

²² As mentioned in Section 1.5.1, the Department may also require you to use site-specific RBCs at sites where conditions are more sensitive than those used to develop the generic RBCs (*i.e.*, sites for which the generic RBCs may not be protective).

²³ EPA recommends a minimum of 10-20 samples for this type of statistical evaluation (EPA, 1992b).

Data can only be averaged if they represent a reasonable average exposure. For example, it might be reasonable to assume that a person could come into contact with soil from any location across a given site. Therefore, if there are an adequate number of samples that represent the soil, the UCL of the arithmetic mean could be calculated and used to determine compliance for a direct contact exposure. However, samples from depths that do not represent direct contact exposures should not be included. On the other hand, at a very large site it is unlikely that a typical exposure to soil would be from an average across the entire site. A smaller exposure unit may have to be used in that case. Exposure from ingestion of contaminated groundwater also is not likely to be an average from across a site since normal use would be from a single well located somewhere on the site. Therefore, individual monitoring wells may be a better representation of potential exposure than the UCL of all monitoring wells.

When using statistical tests you must be able to determine what kind of distribution fits your data set in order to figure out what equation to use to calculate the 90% UCL. Since most environmental data tend to be either normally or lognormally distributed, selecting the distribution is often a matter of applying some simple tests to see which of the two distributions provides a better fit. For more information about normal and lognormal distributions and how to perform these calculations please refer to *Calculating Upper Confidence Limits for Exposure Point Concentrations at Hazardous Waste Sites* (EPA, 2002d) and *Statistical Methods for Environmental Pollution Monitoring* (Gilbert, 1987). The DEQ has developed a spreadsheet that you can use to calculate the 90% UCL (DEQ, 2001).

3.1.8 Use Engineering and Institutional Controls

When it is not feasible to clean up a site to meet the generic or site-specific RBCs discussed in Sections 3.1.5 and 3.1.6 you will be required to manage areas with unacceptable risk. You should use the RBCs discussed above to define the areas where risk exceeds acceptable levels and where some type of risk management will be required.

If you propose some form of risk management, you should clearly identify those areas of your site where risk management will be employed. Provide sufficient information to show that the proposed remedy is appropriate for the conditions at your site and is reasonable in light of the sources, pathways, and receptors identified in your CSM. Some methods to consider for risk management are discussed below.

3.1.8.1 Alternative Compliance Points

Compliance points are the locations where you will demonstrate, upon completion of your proposed remedy, that cleanup levels have been attained. In the simplest cases, compliance “points” are generally defined as the entire contaminated zone. For example, you might specify that you plan to cleanup *all* soil contamination down to a specified concentration, or treat groundwater until samples from *all* monitoring wells meet a specified standard.

Multiple compliance points may be reasonable based on your CSM. For example, using the suggestions found in Table 2.4, you may have noted that even though you have both shallow and deep soil contamination, only the shallow contamination is subject to dermal contact, ingestion, and inhalation by people who frequent the site. Therefore, you may propose one soil cleanup

level for the upper three feet of soil, and a different cleanup level for deeper soils. In this case different depths define your compliance “points”.

Another common situation where compliance points may be useful is groundwater remediation. In cases where it can be documented that the groundwater in the vicinity of the site is not being used, and there are no other immediate affects from the groundwater contamination, it might be reasonable to propose source removal coupled with groundwater monitoring to demonstrate that the plume can be stabilized to the point where groundwater *leaving the site* meets acceptable risk levels. Groundwater contamination remaining on site may need to be dealt with by other means, such as institutional controls. The compliance point(s) in this case may be one or more wells downgradient from the source. The preferred location for compliance points is on your property, as close to the source as is reasonable. Compliance points on adjacent properties will require permission of the adjacent property owner and should be discussed with the Department.

If you are proposing compliance points (*i.e.*, not site-wide attainment), then you must explain in your report to the Department why the proposed compliance points are reasonable and protective within the context of your CSM. Note, however, that institutional controls may be required before the Department gives final approval to the use of the compliance points in your remedy.

3.1.8.2 Engineering Controls

Specific engineering controls will not be discussed in this document. If you are planning to include controls like vapor barriers, hydraulic barriers, or capping as part of your remedy, however, you must not only provide information about how they will be designed and constructed, but you must also be able to explain, in the context of your CSM, how such controls will reduce risk to acceptable levels.

Another important aspect of engineering controls that must be discussed is how you intend to *maintain their protectiveness*. If you are installing a cap to reduce leaching to groundwater, for example, what kind of maintenance will be required to retain the needed low permeability? Will some type of monitoring be required to ensure its effectiveness? How will you prevent someone from digging up the cap in the future? These issues must be discussed and addressed in your proposed remedy.

3.1.8.3 Institutional Controls

Institutional controls can be effective in situations where exposures can be prevented by legal or administrative means. In other words, if curtailment of certain activities can prevent exposure, then a restriction on those activities may provide adequate protection. For example, if contaminated soils under a site are likely to create an unacceptable risk only if they were to be dug up and exposed, then prohibiting excavation by means of a deed restriction may be an acceptable control.

As with engineering controls, if you intend to propose institutional controls, you must not only provide information about how they will be implemented and maintained, but also explain, in the context of your CSM, how such controls will reduce risks to acceptable levels. For more information on this topic see *Guidance for Use of Institutional Controls* (DEQ, 1998c).

3.2 Petroleum Releases from Regulated USTs

This section summarizes options for using the risk evaluation methods of Section 3.1 on releases from regulated USTs. For additional information see the *UST Cleanup Manual* (DEQ, 2000c).

DEQ's *Cleanup Rules for Leaking Petroleum Underground Storage Tank (UST) Systems* (OAR 340-122-0205 through 340-122-0360) are designed to provide several options for cleaning up soil and groundwater contaminated by releases from regulated USTs (see Figure 3.2). After carrying out all appropriate reporting, abatement, and investigation requirements, you can complete an UST cleanup by demonstrating that your site meets:

- Low-impact site (LIS) requirements (OAR 340-122-0243);
- Soil matrix cleanup levels (OAR 340-122-0320 through OAR 340-122-0360);
- Risk-based concentrations (OAR 340-122-0244); or
- Generic remedy requirements developed by the Department (OAR 340-122-0252).

The option you select will depend on site-specific factors including the magnitude and extent of contamination, age of the release, constituents found at the site, and land and water use. The purpose of this section is to provide guidance on applying the risk-related aspects of these options.

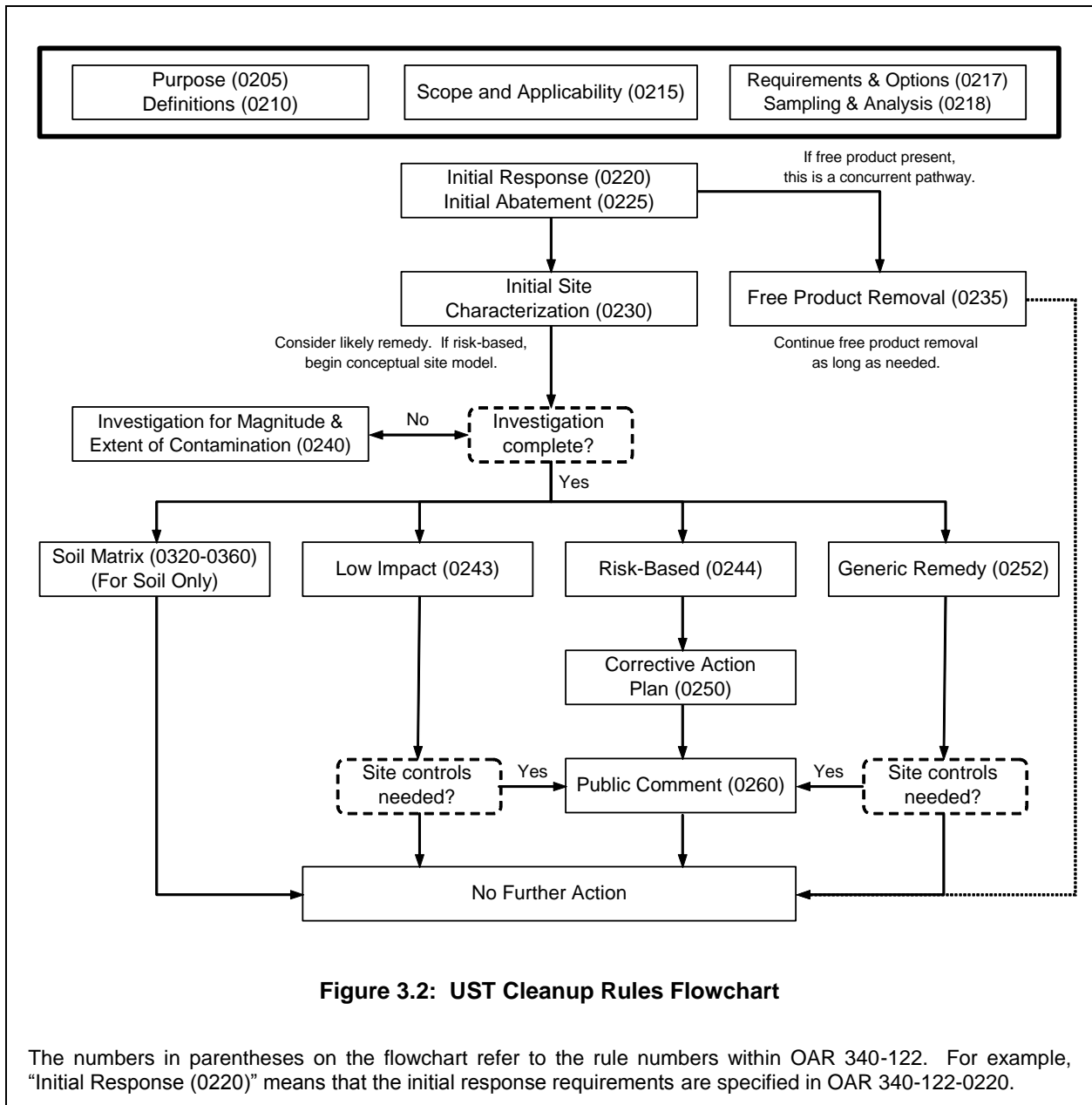
*This document only addresses risk-related aspects of the UST cleanup rules. The initial response, reporting, abatement, and site investigation requirements of the rules (OAR 340-122-0205 through 340-122-0240) are not covered. You should refer to the rules themselves and to the *UST Cleanup Manual* (DEQ, 2000c) for additional information on all of the rule requirements.*

3.2.1 Low-Impact Sites (OAR 340-122-0243)

Sites being handled under the LIS option will not require the formal evaluation of TPH and constituent risk described in Sections 3.1.5 and 3.1.6. With respect to the process illustrated in Figure 3.1, treat the LIS rule as a generic remedy.

The purpose of the low-impact site (LIS) rule is to provide a streamlined process for use at gas stations or other industrial or commercial properties that allows these facilities to remain in operation while you manage any potential risk from contamination remaining at these sites. The LIS rule is structured to directly address risk concerns by including a list of pathway-specific compliance options similar to the following:

- There is no pathway for exposure (*e.g.*, there is no building over or close to the soil or groundwater contamination so the indoor air pathway is not a problem); or
- There is a pathway for exposure but the risk is acceptable (*e.g.*, there is a building over some soil contamination but the contaminant concentrations in that soil are below the generic standards for that exposure pathway); or
- There is a pathway for exposure and concentrations exceed generic standards, but actions have been taken to prevent exposure (*e.g.*, the crawl space is being ventilated to prevent vapors from entering the building).



If your site meets the first option, there is no need to consider the remaining options. If not, you should then consider the second option, *etc.* In order to apply any of the options you need to know what the sources, pathways, and receptors are at your site. Therefore, it will be helpful for you to have a CSM in mind during the site investigation.

Table 3.7 lists the rule sections in OAR 340-122-0243 where the five RBC-related LIS requirements can be found and states what pathway or scenario the RBC must protect.

For each of these five requirements you should:

- Determine if the pathway is reasonable for your site. If not, no action is necessary.
- If the pathway is reasonable, determine if the likely receptors are one or more of the following: residents (either single-family or urban), occupational workers, construction workers, or excavation workers. This will depend on the location of the contamination and the land uses of the adjacent properties.
- For each contaminant detected at your site, compare the highest concentration found in any source area to the number in the Table of RBCs for the pathway and receptor being tested.
- If the number from your site is less than or equal to the appropriate number in the Table of RBCs, then your site meets the requirement and it is not necessary to go on to the next option for that particular requirement.
- If the number exceeds the appropriate number in the Table of RBCs, then you need to take some action to reduce risk to acceptable levels. This may mean cleaning the contaminated area until the levels that remain are below the number in the table, or employing some type of engineering or institutional control to provide protection. (For additional information on engineering and institutional controls see Section 3.1.8.)

Table 3.7: RBC Requirements for Low-Impact Sites

Rule Section 243(1)	Pathway to be Protected by RBC¹
(e)(A)	Soil contaminant concentrations within three feet of the surface must not exceed generic risk-based concentrations for direct contact. ²
(f)(B)	Soil contaminant concentrations in utility corridors must not exceed generic risk-based concentrations for the excavation worker scenario. ³
(g)(A)	Soil contaminant concentrations beneath or within 10 lateral feet of nonresidential buildings, or beneath or within 50 lateral feet of residences must not exceed generic risk-based concentrations for volatilization from soils into buildings. ⁴
(h)(D)	The groundwater plume must not leave the source property at concentrations exceeding generic risk-based concentrations. ⁵
(h)(E)(i)	Groundwater contaminant concentrations beneath or within 10 lateral feet of nonresidential buildings, or beneath or within 50 lateral feet of residences must not exceed generic risk-based concentrations for volatilization from groundwater into buildings. ⁶

¹ The notes below refer to the columns in the Table of RBCs (Appendix A) where the specified RBCs are listed.

² See "SOIL, Soil Ingestion, Dermal Contact, and Inhalation, RBC_{ss}."

³ See "SOIL, Soil Ingestion, Dermal Contact, and Inhalation, RBC_{ss}."

⁴ See "SOIL, Vapor Intrusion into Buildings, RBC_{si}."

⁵ See "GROUNDWATER, Groundwater Ingestion/Vapor Inhalation, RBC_{tw}."

⁶ See "GROUNDWATER, Vapor Intrusion into Buildings, RBC_{wi}."

For complete coverage of the LIS requirements, please refer to *Guidance for Applying the Low-Impact Site Rule to UST Cleanup Sites* (DEQ, 1998a).

3.2.2 Soil Matrix Cleanup Rules (OAR 340-122-0320 through 0360)

The soil matrix cleanup rules were originally developed prior to Oregon's adoption in 1995 of acceptable risk levels as the remedial goal at hazardous substance cleanup sites. Although the TPH cleanup levels in these rules were specifically exempted from the risk requirements of the statute (ORS 465.315(6)), the Department believes they are generally conservative enough to provide adequate protection. Therefore, during the 1998 revisions to the UST cleanup rules the soil matrix portion of the rules (OAR 340-122-0320 through 0360) was left largely intact.

The one aspect of the soil matrix rules that specifically requires an evaluation of risk comes into play in cases where the soil matrix levels can NOT be met. In situations where a pocket of contamination exceeding the required soil matrix cleanup level remains in a location from which removal is not feasible, the Department has the authority to decide whether such contamination can remain without threatening public health, safety, and welfare or the environment (OAR 340-122-0355(4)). In other words, a site can be closed under the soil matrix rules even if all of the soil is not cleaned up to the appropriate soil matrix standards as long as the soil exceeding those standards (the "pocket") meets all of the following conditions:

- The pocket is located under a building or other structure where further removal would endanger the structure, or be prohibitively expensive; and
- Sufficient samples have been collected from the pocket to estimate the extent, volume, and level of contamination; and
- The remaining contamination does not result in unacceptable risk.

In order to demonstrate that the pocket does not result in unacceptable risk levels, you will have to:

- Analyze samples from the pocket for specific constituents and TPH as appropriate; and
- Show that the contaminant levels you are proposing to leave are less than either the generic RBCs for the appropriate soil pathway in the Table of RBCs in Appendix A, or site-specific RBCs.

At most sites where contamination remains under a building, the only current pathway of concern will be from vapor intrusion into the building.²⁴ However, if other pathways are likely, they should also be evaluated. In cases where the RBCs are not met, the Department may require additional cleanup or implementation of risk management controls to provide adequate protection from risk for both current and future uses of the property. This may require site closure as a risk-based cleanup site instead of a soil matrix cleanup site.

²⁴ In the case of vapor intrusion into buildings, equation [B-134] or a similar equation could be used to calculate the maximum average indoor air concentration that would result if all of the mass of a given contaminant entered the building. If the result does not exceed the RBC_{air} for the contaminant of concern, then the vapor intrusion pathway could be eliminated for that contaminant.

If you are using the soil matrix cleanup levels as risk-based concentrations for petroleum contamination not associated with a regulated UST, check with the DEQ project manager about what type of report to submit for your site. For soil matrix cleanups carried out under the UST program rules, submit a report as specified in OAR 340-122-0360.

3.2.3 Risk-Based Cleanups (OAR 340-122-0244 and 340-122-0250)

The remedial option in the UST program that offers the greatest amount of flexibility and adaptability to site-specific conditions is the risk-based cleanup. However, it is also the option that might require you to collect more site-specific data and evaluate more alternatives than the other three options. Under this option you are required to develop a CSM and determine RBCs according to OAR 340-122-0244 and incorporate them into a corrective action plan (CAP) developed and implemented according to OAR 340-122-0250.

3.2.3.1 Develop CSM and Determine RBCs According to OAR 340-122-0244

The information needed to complete the requirements of OAR 340-122-0244 is covered in other sections of this guidance document. The principal risk-based steps are:

- Develop a CSM as described in Section 2 and use it to identify all current and reasonably likely future pathways and receptors at the site;
- Use the process described in Sections 3.1.5 and 3.1.6 to determine what generic or site-specific RBCs you intend to apply to the TPH and petroleum constituents identified during the site investigation; and
- Screen your site as described in Section 1.5.3 to ensure that contamination does not pose a risk to ecological receptors, and for all sites, complete a Level I scoping ecological risk assessment using the checklist forms provided in DEQ ecological risk assessment guidance (DEQ, 1998b). If the potential for adverse ecological effects is identified, a Level II screening evaluation will be required.

3.2.3.2 Develop and Submit a Corrective Action Plan According to OAR 340-122-0250

Submit a corrective action plan (CAP) to the Department that describes what you are proposing to do to bring your site into compliance with acceptable risk levels. The CAP must address all contaminants that exceed acceptable risk levels, taking into account the need for engineering and institutional controls if your remedy does not reduce contaminants to acceptable levels. Include the following basic types of information in your CAP:

- **Summary of Site Activities**

In most cases you will already have submitted several reports describing past site activities and containing sampling results. Include a summary of these activities in the CAP to put your proposal into perspective for reviewers who may not be familiar with the site. Also include appropriate site maps.
- **Determination of Risk-Based Concentrations**

Starting with a summary of the magnitude and extent of contamination and other relevant data collected during the site investigation, you should develop a list of

contaminants and their associated RBCs as described in Sections 3.1.5 and 3.1.6. The RBCs may be generic or site-specific. Be sure to identify any RBCs that may also indicate the presence of free product.

- Proposal for Remedial Activities

You must propose a remedy for all contaminants or products that exceed acceptable risk levels. Remedies can include cleanup activities (*e.g.*, soil removal, bioremediation, vapor extraction), engineering controls (*e.g.*, capping, fencing), or institutional controls (*e.g.*, deed restrictions). Include information about how you plan to deal with implementation risks, such as air discharges of toxic chemicals from remediation systems.

- References and Supporting Documentation

Include a list of references to previous site reports and other reports, journal articles or materials mentioned in the text or used to develop the CAP. Supporting documentation, such as engineering specifications, construction diagrams, and well logs should also be provided.

You might need to address more than just the attainment of human health-based acceptable risk levels in the CAP. In your effort to identify potential pathways and receptors, you should document any special environments that may be at risk from contaminants released at your site. You can obtain information on sensitive habitats from local land use planning agencies or state and federal fish and wildlife agencies. Include in your CAP a statement about whether or not your site meets all four of the conditions in Section 1.5.3.

You should also discuss any problems related to petroleum vapors or odors at the site. Concerns about imminent hazards (*e.g.*, possible explosive levels) should have been addressed during the initial response phase. However, vapors in buildings or other locations that create a public nuisance must also be dealt with, even if measurements show that they are not explosive and do not present an unacceptable risk. If nuisance conditions have been identified as a concern at your site, discuss them in the CAP and describe the actions that you took to remedy them. You must also address vapors that will be discharged during the course of your proposed remedy.

A DEQ project manager will review your proposal and may ask for additional information or clarification. If the CAP is satisfactory, the Department is required to notify any affected property owners and the public (OAR 340-122-0260). Based on comments received, modifications or additional information may be required before the CAP is approved. Following approval the remedy must be implemented until such time as you can confirm that post-remedial conditions at the site meet acceptable risk levels. This, of course, will depend on the RBCs, compliance points, and engineering and institutional controls originally specified in the approved CAP. When all of the requirements of the CAP have been met to the Department's satisfaction, the Department will issue a no further action (NFA) letter.

3.2.4 Generic Remedies (OAR 340-122-0252)

OAR 340-122-0252 differs from all other sections of the UST cleanup rules in that it defines a process that the Department can use to develop remedies for special categories of UST cleanup sites.²⁵ There is actually nothing in this rule that defines how you can clean up a petroleum-contaminated site. The rule does, however, provide the following for the public and the regulated community:

- An opportunity to be involved when the Department develops a generic remedy (usually either as a member of a workgroup, or during a public comment period before approval of the remedy); and
- The authority to use any generic remedy developed by the Department if the remedy is appropriate for the site.

Generic remedies are developed by the Department for your use. You are not, however, required to use them.

For more information about generic remedies, see Section 3.1.2. For the requirements of the Generic Remedy for Simple Risk-Based Sites, see Section 4.

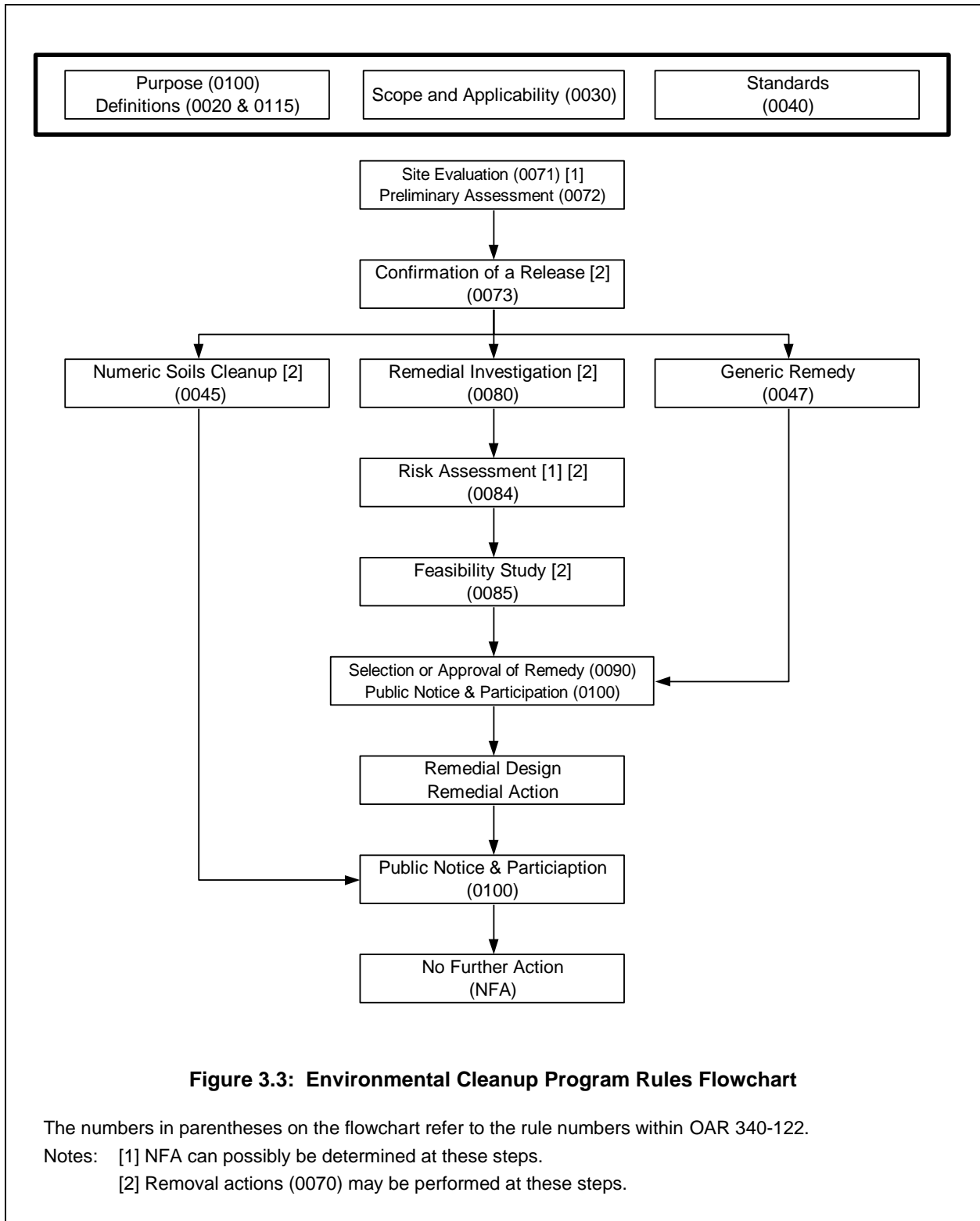
3.3 Other Petroleum Releases

DEQ's *Hazardous Substance Remedial Action Rules* (OAR 340-0010 through 0115) are also designed to provide several options for cleaning up releases of hazardous substances into the environment. Figure 3.3 illustrates the cleanup options for hazardous substance releases in the Environmental Cleanup Program. After carrying out all appropriate reporting, abatement, and investigation requirements, you can complete a cleanup by demonstrating that your sites meets any of the following standards (OAR 340-122-0040):

- Acceptable risk levels as defined in OAR 340-122-0115 and as demonstrated by a residual risk assessment;
- Numeric cleanup standards developed as part of an approved generic remedy identified or developed by the Department under OAR 340-122-0047, if applicable;
- Numeric soil cleanup levels specified in OAR 340-122-0045, if applicable; or
- For areas where hazardous substances occur naturally, the background level of the hazardous substances, if higher than those levels specified above.

Although none of the preceding standards are specifically for petroleum hydrocarbons, the *Hazardous Substance Remedial Action Rules* require the same acceptable risk levels as are required by the *UST Cleanup Rules* (OAR 340-122-0205 through 340-122-0360). In practice Voluntary Cleanup Program and Site Response Program staff often use the *UST Cleanup Rules* and UST Program guidance to close sites impacted by petroleum hydrocarbon releases.

²⁵ The authority to develop generic remedies is provided in ORS 465.315(1)(f).



Since the numeric soil cleanup levels (OAR 340-122-0045) do not have standards for TPH, and petroleum contamination is not considered natural background, you only have the first two options listed above to evaluate the threat to human health and the environment posed by releases of petroleum hydrocarbons from sources other than regulated USTs. The option that you select will depend on a number of site-specific factors including the magnitude and extent of contamination, age of the release, constituents found at the site, and land and water use. The purpose of this section is to provide you with guidance on applying risk-based decision making for petroleum contamination in the Environmental Cleanup Program by applying either (1) acceptable risk levels as defined by OAR 340-122-0115; or (2) numeric cleanup standards developed as part of an approved generic remedy.

This document and process may be used for sites contaminated with petroleum hydrocarbons that are participating in the following subprograms of the Environmental Cleanup Program:

- Voluntary Cleanup Program (including the Independent Cleanup Pathway), and
- Site Response Program.

3.3.1 Site Closure Using Acceptable Risk Levels

The option in either the Voluntary Cleanup Program (VCP) or the Site Response Program (SRP) that offers the greatest flexibility and adaptability to site-specific conditions is to clean up to acceptable risk levels as defined in OAR 340-122-0115. However, as with the requirements in the UST Program (see Section 3.2.3), this option might require you to collect more site-specific data and evaluate more alternatives than the Generic Remedy option (Section 3.3.2).

The investigation and cleanup of hazardous substance releases in Oregon under the VCP or SRP typically takes place in three phases:

- Gathering information;
- Determining appropriate cleanup actions; and
- Cleaning up the site.

3.3.1.1 Gathering Information

You should obtain and evaluate facts about the characteristics of the facility; the sources, nature, and extent of contamination; possible hot spots of contamination; and the risk that contamination poses to human health and the environment. In most cases you also will need information about the current and reasonably likely future uses of water and land affected by the release.

Once the facility has been adequately characterized and the sources, nature, and extent of contamination adequately defined, you can follow a risk screening or risk assessment path described in OAR 340-122-0084 and DEQ's published guidance on human health (DEQ, 2000b) and ecological risk assessments (DEQ, 1998b). For human health, you can use the process described in Sections 3.1.5 and 3.1.6 to determine what generic or site-specific RBCs you intend to apply to the TPH and petroleum constituents identified during the site investigation or remedial investigation (RI).

For TPH and other chemicals, the risk assessment will be similar to the evaluation shown in Sections 3.1.5 and 3.1.6. However, four additional steps are necessary to comply with cleanup program requirements that are not typically required for cleanups under the UST program rules.

1. Central tendency exposure should be considered in addition to reasonable maximum exposure;²⁶
2. Excess lifetime cancer risks and non-carcinogenic hazards need to be explicitly presented, and not just inferred from a comparison with a table of RBCs developed using acceptable risk levels;
3. Cumulative risk must be explicitly presented; and
4. Uncertainty should be evaluated.

These four additional steps are discussed in Appendix H.

If the risks posed by contaminants released at the facility exceed acceptable risk levels (as defined in OAR 340-122-0115), then you are required to perform a remedial action to either reduce or manage the risk to protect present and future human health and the environment.

3.3.1.2 Determining Appropriate Cleanup Actions

This phase requires a more detailed analysis of site information. Once you have adequately characterized the facility, defined the sources, nature, and extent of contamination, and evaluated the risk posed to human health and the environment, you must choose a removal or cleanup action (*i.e.*, remedial action).

If you plan to cleanup petroleum contamination from a source other than a regulated UST and you are participating in the DEQ's VCP or SRP, you will probably have to complete a feasibility study (FS). The DEQ will then select the remedy for the site using the FS as described in OAR 340-122-0090. You will then need to comply with public notice and participation requirements described in OAR 340-122-0100. Once the public notice and participation requirements have been satisfied, you move into the Remedial Design/Remedial Action (RD/RA) portion of the project. In the RD/RA, at a minimum, you will need to prepare a work plan for DEQ's review and approval describing how the selected remedy will be implemented.

If you plan to perform a petroleum hydrocarbon cleanup resulting from a release from a source other than a regulated UST and you are not participating in DEQ's VCP or SRP, then you can select and complete the remedy without review by the DEQ. However, the remedy must protect human health and the environment to the extent required by statute. Always document and retain information regarding your removal or remedial actions. DEQ may ask for the documentation at a later date to determine if site conditions are protective or you may ask for DEQ's approval and sign-off on the cleanup sometime in the future.

²⁶ The Department's RBC spreadsheets include an option to calculate RBCs on the basis of either central tendency or reasonable maximum exposure.

The approved cleanup action must protect present and future human health and the environment as demonstrated through a residual risk assessment. It also must consider treating hot spots of contamination to the extent feasible, and may need to consider preventing or minimizing future releases and the migration of hazardous substances in the environment. The cleanup action may also need to consider elements unrelated to risk such as aesthetics, odor, *etc.*

3.3.1.3 Cleaning Up the Site

In the final phase you must implement appropriate removal or remedial actions. A removal is generally a time-critical action taken to remove or reduce a release or threat of release of a hazardous substance to the environment. A remedial action is a permanent remedy designed to reduce or manage the risk the hazardous substance release poses to a level protective of human health and the environment.

The general process of closing sites impacted by contaminant sources other than regulated USTs using acceptable risk levels (as defined in OAR 340-122-0115) mirrors the Environmental Cleanup Program Rules Flowchart presented in Figure 3.3.

3.3.2 Generic Remedies (OAR 340-122-0047)

OAR 340-122-0047 differs from all other sections of the Hazardous Substance Remedial Action Rules in that it defines a process that the Department can use to develop remedies for use at eligible facilities. Similar to the UST rule regarding generic remedies, there is nothing in OAR 340-122-0047 that defines how you can clean up a petroleum-contaminated site. The rule does, however, provide the following for the public and the regulated community:

- An opportunity to be involved when the Department develops a generic remedy (usually either as a member of a workgroup, or during a public comment period before approval of the remedy); and
- The authority to use any generic remedy developed by the Department if the remedy is appropriate for the site.

Generic remedies are developed by the Department for your use. You are not, however, required to use them. For more information about generic remedies, see Section 3.1.2. For the requirements of the Generic Remedy for Simple Risk-Based Sites, see Section 4.

DEQ developed *Generic Remedies for Soils Contaminated with Polychlorinated Biphenyls (PCBs)* in December 1997, available on the Internet at <http://www.oregon.gov/deq/FilterDocs/GenericRemediesSoilsContPCBs.pdf>, and the *Heating Oil Tank Generic Remedy Guidance and Cleanup Options* in February 2000, available on the Internet at www.oregon.gov/deq/FilterDocs/HOTGenericRemedyGuidance.pdf.

4. Generic Remedy for Simple Risk-Based Cleanups

The risk-based cleanup option provides the greatest amount of flexibility and adaptability to site-specific conditions. However, it is also the most rigorous option because each risk-based decision that you make requires you to collect sufficient site-specific data to prove that it is appropriate for that particular site. For complex sites the trade-off is that this additional effort can lead to more cost-effective remedial measures. For simple sites, however, the potential savings in the final cleanup may be rather limited and not worth the additional effort and cost of developing a site-specific risk-based cleanup proposal. The Department believes, therefore, that a more straightforward risk-based process may result in a more efficient and less costly way to deal with relatively simple petroleum-contaminated sites.

The purpose of this generic remedy²⁷ is to provide a streamlined risk-based process that can be applied to simple petroleum-contaminated sites. Sites that are cleaned up to meet all applicable generic RBCs in Appendix A, and which have no complicating factors such as ecological risks, can be closed under the requirements of this remedy.

Although this generic remedy is a simplified risk-based process, its use still requires an understanding of many of the risk concepts discussed in Section 2 of this guidance document.

4.1 Applicability

This generic remedy has been developed in accordance with OAR 340-122-0047 and 340-122-0252 and may only be used at sites that meet all of the following conditions:

- Contamination at the site must be limited to petroleum, motor fuels, and heating oils as defined in OAR 340-122-0210(22), 340-122-0210(19), and 340-122-0210(16) respectively, and the constituents (*e.g.*, BTEX and PAHs) released into the environment as a result of the release of those products.
- All hazardous constituents found at the site must be listed in the Table of RBCs in Appendix A. Other contaminants may be present only if it can be clearly demonstrated that they are not significant contributors to the risk at the site (or cleanup unit).
- There can be no potentially unacceptable ecological risks (see Section 1.5.3), nuisance conditions such as product odors entering nearby buildings, or other conditions at the site that cannot be adequately addressed by the application of the generic RBCs developed for the protection of human health.

²⁷ As used in this section, the term “generic remedy” means the specific requirements contained in Section 4 of this guidance document. Section 4 is a specific application of the generic remedy authority discussed in Section 3.1.2.

4.2 General Requirements

4.2.1 Contamination from Regulated USTs

Before you can submit a proposal to close a site under the *Generic Remedy for Simple Risk-Based Cleanups* you must complete all of the applicable requirements of OAR 340-122-0205 through 0240.

- The initial response, site abatement, and site characterization phases of your project must be completed;
- The magnitude and extent of soil and groundwater contamination must be fully delineated;
- Free product must be removed to the maximum extent practicable; and
- All of the required documentation (20-day, 45-day and other reports as appropriate) must be submitted to the Department.

Proposals for site closure under this generic remedy must include sufficient data and documentation to demonstrate compliance with Sections 4.1 through 4.4. Unless specifically provided as an option in this generic remedy, site-specific modifications are not allowed.

4.2.2 Other Sources of Petroleum Contamination

Before you can submit a proposal to close a site impacted by a release from other than a regulated UST under the *Generic Remedy for Simple Risk-Based Cleanups*, you must adequately characterize the facility and define the source, nature, and extent of contamination as described in OAR 340-122-0080 and Section 3.3.1 of this RBDM guidance.

Proposals for site closure under this generic remedy must include sufficient data and documentation to demonstrate compliance with Section 4.1 through 4.4. Unless specifically provided as an option in this generic remedy, site-specific modifications are not allowed.

4.3 Cleanup Requirements

To be closed under this generic remedy, your site must meet all of the following requirements:

- The concentrations of TPH and constituents that you are proposing to leave in soil and groundwater upon completion of this generic remedy must be no greater than the most stringent applicable concentrations listed in the Table of RBCs in Appendix A of this guidance document. This can be demonstrated in one of the following ways:
 - (1) If you do not develop a conceptual site model (Section 2), then the concentrations of all contaminants remaining at the site must be less than or equal to the most stringent concentration listed in the Table of RBCs for that contaminant in the specified medium. For example, the *highest* benzene

concentration found in all of the confirmatory soil samples can not exceed the *lowest* benzene RBC listed for all of the soil pathways in the Appendix A table.²⁸

(2) If you develop a CSM, all contaminant concentrations remaining at the site must be less than or equal to the most stringent concentration for the applicable pathways listed in the Table of RBCs. For example, if your CSM shows that the benzene-contaminated soil is only likely to result in exposure due to leaching to groundwater, then the highest benzene concentration found in the soil only has to meet the benzene concentration for the leaching-to-groundwater pathway. All other benzene soil concentrations listed in the Table of RBCs are not applicable at this site.

- Remediation must be completed without institutional or engineering controls. Therefore, you can only eliminate pathways from your CSM if they are not reasonably likely due to the location of the contaminants, or the current and reasonably likely future uses for the land and groundwater. For example, if contamination remains in shallow soils at the site in concentrations exceeding acceptable levels for direct contact, you cannot remediate the site *under this generic remedy* by proposing engineering controls such as capping the site to prevent exposure to the shallow soils. The soil would have to be treated to reduce the concentrations or removed. However, if that contamination remains in soils at sufficient depth that direct contact can be ruled out as a reasonably likely pathway, then the site could be closed under this generic remedy (assuming, of course, that all other applicable conditions are met).
- Soil remaining at the site can not contain excessively high levels of TPH such that continuing product mobility is possible (see Section 3.1.4). For purposes of this generic remedy, gasoline-contaminated soils exceeding 1000 ppm TPH, and diesel or other non-gasoline contaminated soils exceeding 10,000 ppm TPH are not allowed.

4.4 Reporting Requirements

You must submit a *Proposal for Site Closure Under the Generic Remedy for Simple Risk-Based Cleanups* which contains all of the following information:

4.4.1 Statement of Applicability

The report must contain a brief introductory section that confirms that your site meets all of the applicability requirements listed in Section 4.1 of this generic remedy. You must specifically attest to the following:

- Contamination is only from petroleum hydrocarbons;
- There are no unacceptable ecological risks at the site; and

²⁸ If enough data are available, the 90% upper confidence limit of the mean can be used in place of the highest concentration for determining compliance with this generic remedy. For more information please see Section 3.1.7.

- There are no odors or other nuisance conditions that cannot be adequately addressed by the application of risk-based concentrations.

This section should be as concise as possible while still covering the required information. Therefore, if some or all of the information related to these requirements is detailed in other reports, then simply state that the requirement is met and give a specific reference to where it is documented. If that requirement is covered elsewhere in your report, then reference that location and include the details there. Keep this section brief and to the point.

4.4.2 Summary of Site Activities

In many cases you will already have submitted to the Department one or more reports describing past site activities and containing sampling results. If that's the case, you should still include a brief chronological summary of these activities to put your proposal into perspective for reviewers who may not be familiar with the site. Include references where appropriate. If new information is being submitted, be sure to provide adequate detail. Your summary should include sufficient information to answer the following questions:

- Have all of the sources of the release been identified?
- Was any free product found on the site?
- Have the magnitude and extent of the release, both horizontal and vertical, been determined? Provide a site map that shows the approximate area of contaminated soil and the approximate area of the groundwater plume with representative data points. Include data showing how contaminant levels vary with depth at representative locations.
- Have tests been made for all potential contaminants of concern based on the types of products that were released? Provide a list of all contaminants found at the site.
- If there is a groundwater plume, are there sufficient data to estimate the direction of groundwater flow and confirm that the plume has stabilized or is receding?
- If contamination has migrated off-site, have adjacent property owners been made aware of the contamination and of what is being proposed?
- Did you exclude ecological concerns by demonstrating that your site meets the requirements of Section 1.5.3 of this guidance document? Reports submitted for non-UST cleanups must document this evaluation by including the checklist from *Guidance for Ecological Risk Assessment, Level 1 - Scoping* (DEQ, 1998b).

4.4.3 Conceptual Site Model and List of Applicable Cleanup Levels

As stated in Section 4.3, the cleanup levels for any site applying this generic remedy are either (1) the most stringent concentrations listed in the Table of RBCs for the contaminants of concern in the specified media, or (2) the most stringent concentrations for the applicable pathways listed in the Table of RBCs *based on a site-specific CSM*.

If you develop a CSM, describe it in this report and include information about:

- Current and reasonably likely future land uses;
- Current and reasonably likely future uses of the groundwater; and
- Each of the pathways in Table 2.3 and Table 2.4.

Include a list of the cleanup levels that apply to your site.

4.4.4 Cleanup Activities and Confirmation

Provide a summary of all cleanup activities.

- If contaminated soil was removed, how much was excavated and where was it disposed? Have all heavily contaminated soils (>10,000 ppm TPH-D or >1000 ppm TPH-G) been removed? If not, approximately how much remains?
- If free product was found at the site, how much was removed, where was it disposed, and does any still remain?
- What other remedial activities were carried out (*e.g.*, vapor extraction, pump-and-treat) and what were their outcomes?

Include sufficient data from confirmatory samples to show that all remaining soil and groundwater contamination at the site meet the cleanup levels listed in the previous section of your report.

4.4.5 References and Supporting Documentation

Include a listing of all previous reports as well as relevant supporting documentation such as well logs, lab data sheets, site maps and other items not included in previous reports.

4.5 Department Review and Public Notice

Upon receipt and review of your proposal, the Department may:

1. Approve the proposal and issue a letter for no further action if the site meets all of the requirements of this remedy as documented in the proposal for closure; or
2. Request that additional information be submitted, or additional actions be taken to bring the site into compliance with the requirements of this generic remedy; or
3. Reject the generic remedy proposal and require that action be taken under one of the other remedial action options if the site does not meet the applicable requirements of Sections 4.1 through 4.4, or if site conditions differ significantly from those used to develop the generic RBCs.

The Department will not require routine public notice for approval and implementation of cleanups under this generic remedy. However, you are required to notify²⁹ neighbors and other affected parties when contamination has spread or is likely to spread onto adjacent properties. The Department may require public notice in cases where significant local concerns surface during the site investigation. The public may request that the Department conduct a meeting at or near the site for purpose of receiving comment about proposed remedial activities under this generic remedy.

²⁹ Notification may include but is not limited to personal contacts, letters to individual households or businesses, notice in local newspapers or state registers, or block advertisements.

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Appendix A: Table of Risk-Based Concentrations (RBCs)

See Table 2.4 for a description of the pathways. Refer to page A-5 for an explanation of the notes.

Contaminated Medium		SOIL mg/Kg (ppm)										SOIL mg/Kg (ppm)					
Exposure Pathway		Soil Ingestion, Dermal Contact, and Inhalation RBC _{SS}										Volatilization to Outdoor Air RBC _{SO}					
Receptor Scenario		Residential		Urban Residential		Occupational		Construction Worker		Excavation Worker		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note		Note		Note
Benzene	c, v	6.9		21		34		340		9,400	>Csat	8.5		18		48	
Toluene	nc, v	2,600	>Csat	5,300	>Csat	68,000	>Csat	39,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
Ethylbenzene	nc, v	4,000	>Csat	8,100	>Csat	74,000	>Csat	28,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
Xylenes	nc, v	790	>Csat	1,600	>Csat	24,000	>Csat	19,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
iso-propylbenzene	nc, v	2,300	>Csat	4,500	>Csat	51,000	>Csat	24,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
n-propylbenzene	nc, v	840	>Csat	1,700	>Csat	19,000	>Csat	9,300	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
1,2,4-trimethylbenzene	nc, v	48		97		1,500	>Csat	1,400	>Csat	40,000	>Csat	200		200		790	
1,3,5-trimethylbenzene	nc, v	48		97		1,500	>Csat	1,400	>Csat	40,000	>Csat	200		200		-	>Csat
Acenaphthene	nc, v	2,900	>Csat	5,900	>Csat	41,000	>Csat	16,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
Anthracene	nc, v	21,000	>Csat	41,000	>Csat	-	>MAX	90,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
Benz[a]anthracene	c, nv	0.62		1.7		2.7		21	>Csat	590	>Csat	-	>Csat	-	>Csat	-	>Csat
Benzo[b]fluoranthene	c, nv	0.62		1.7		2.7		21	>Csat	590	>Csat	-	>Csat	-	>Csat	-	>Csat
Benzo[k]fluoranthene	c, nv	6.2	>Csat	17	>Csat	27	>Csat	210	>Csat	5,900	>Csat	-	>Csat	-	>Csat	-	>Csat
Benzo[a]pyrene	c, nv	0.062		0.17		0.27		2.1		59	>Csat	-	>Csat	-	>Csat	-	>Csat
Chrysene	c, nv	62	>Csat	170	>Csat	270	>Csat	2,100	>Csat	59,000	>Csat	-	>Csat	-	>Csat	-	>Csat
Dibenz[a,h]anthracene	c, nv	0.062		0.17		0.27		2.1		59	>Csat	-	>Csat	-	>Csat	-	>Csat
Fluoranthene	nc, nv	2,300	>Csat	4,600	>Csat	29,000	>Csat	8,900	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
Fluorene	nc, v	2,600	>Csat	5,200	>Csat	35,000	>Csat	12,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
Indeno[1,2,3-cd]pyrene	c, nv	0.62	>Csat	1.7	>Csat	2.7	>Csat	21	>Csat	590	>Csat	-	>Csat	-	>Csat	-	>Csat
Naphthalene	nc, v	34		67		770	>Csat	710	>Csat	20,000	>Csat	240		240		-	>Csat
Pyrene	nc, nv	1,700	>Csat	3,400	>Csat	21,000	>Csat	6,700	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
MTBE	c, v	150		500		760		9,000	>Csat	-	>MAX	130		270		720	
EDB (1,2-dibromoethane)	c, v	0.0074		0.020		0.033		0.25		7.1		0.30		0.64		1.7	
EDC (1,2-dichloroethane)	c, v	2.9		9.9		15		180		5,000	>Csat	2.5		5.4		14	
Lead	NA, NA	400	L	400	L	750	L	750	L	750	L		NA		NA		NA
Generic Gasoline	nc, v	720		1,500		22,000		13,000		-	>MAX	4,500		4,500		80,000	
Generic Diesel	nc, nv	3,900		8,300		70,000		23,000		-	>MAX	-	>MAX	-	>MAX	-	>MAX
Generic Mineral Insulating Oil	nc, nv	9,800		20,000		-	>MAX	40,000		-	>MAX	-	>MAX	-	>MAX	-	>MAX

Appendix A: Table of RBCs (continued)

See Table 2.4 for a description of the pathways. Refer to page A-5 for an explanation of the notes.

Contaminated Medium		SOIL mg/Kg (ppm)						SOIL mg/Kg (ppm)					
Exposure Pathway		Vapor Intrusion into Buildings RBC _{si}						Leaching to Groundwater RBC _{sw}					
Receptor Scenario		Residential		Urban Residential		Occupational		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note
Benzene	c, v	0.068		0.15		1.2		0.0084		0.017		0.052	
Toluene	nc, v	180		180		-	>Csat	44		44		180	
Ethylbenzene	nc, v	-	>Csat	-	>Csat	-	>Csat	160		160		-	>Csat
Xylenes	nc, v	110		110		-	>Csat	25		25		100	
iso-propylbenzene	nc, v	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
n-propylbenzene	nc, v	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
1,2,4-trimethylbenzene	nc, v	70		70		840		14		14		55	
1,3,5-trimethylbenzene	nc, v	12		12		140		3.1		3.1		12	
Acenaphthene	nc, v	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Anthracene	nc, v	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Benz[a]anthracene	c, nv	-	>Csat	-	>Csat	-	>Csat	9.3		16		-	>Csat
Benzo[b]fluoranthene	c, nv	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Benzo[k]fluoranthene	c, nv	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Benzo[a]pyrene	c, nv	-	>Csat	-	>Csat	-	>Csat	2.4		4.1		-	>Csat
Chrysene	c, nv	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Dibenz[a,h]anthracene	c, nv	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Fluoranthene	nc, nv	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Fluorene	nc, v	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Indeno[1,2,3-cd]pyrene	c, nv	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
Naphthalene	nc, v	290		290		-	>Csat	3.8		3.8		15	
Pyrene	nc, nv	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat	-	>Csat
MTBE	c, v	2.1		4.4		35		0.050		0.10		0.30	
EDB (1,2-dibromoethane)	c, v	0.022		0.047		0.37		8.2E-06		0.000014		0.000059	
EDC (1,2-dichloroethane)	c, v	0.033		0.071		0.56		0.0012		0.0025		0.0074	
Lead	NA, NA		NA		NA		NA	30	L	30	L	30	L
Generic Gasoline	nc, v	140		140		-	>MAX	26		26		110	
Generic Diesel	nc, nv	-	>MAX	-	>MAX	-	>MAX	2,800		2,800		-	>MAX
Generic Mineral Insulating Oil	nc, nv	-	>MAX	-	>MAX	-	>MAX	-	>MAX	-	>MAX	-	>MAX

Appendix A: Table of RBCs (continued)

See Table 2.4 for a description of the pathways. Refer to page A-5 for an explanation of the notes.

Contaminated Medium		GROUNDWATER µg/L (ppb)						GROUNDWATER µg/L (ppb)					
Exposure Pathway		Ingestion & Inhalation from Tap Water RBC _{tw}						Volatilization to Outdoor Air RBC _{wo}					
Receptor Scenario		Residential		Urban Residential		Occupational		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note
Benzene	c, v	0.35		0.70		2.2		2,400		5,100		13,000	
Toluene	nc, v	720		720		2,900		-	>S	-	>S	-	>S
Ethylbenzene	nc, v	1,300		1,300		5,400		-	>S	-	>S	-	>S
Xylenes	nc, v	210		210		820		-	>S	-	>S	-	>S
iso-propylbenzene	nc, v	660		660		2,600		-	>S	-	>S	-	>S
n-propylbenzene	nc, v	240		240		970		-	>S	-	>S	-	>S
1,2,4-trimethylbenzene	nc, v	12		12		49		-	>S	-	>S	-	>S
1,3,5-trimethylbenzene	nc, v	12		12		49		-	>S	-	>S	-	>S
Acenaphthene	nc, v	370		370		1,500		-	>S	-	>S	-	>S
Anthracene	nc, v	1,800	>S	1,800	>S	7,300	>S	-	>S	-	>S	-	>S
Benz[a]anthracene	c, nv	0.078		0.13		0.56		-	>S	-	>S	-	>S
Benzo[b]fluoranthene	c, nv	0.078		0.13		0.56		-	>S	-	>S	-	>S
Benzo[k]fluoranthene	c, nv	0.78		1.3	>S	5.6	>S	-	>S	-	>S	-	>S
Benzo[a]pyrene	c, nv	0.0078		0.013		0.056		-	>S	-	>S	-	>S
Chrysene	c, nv	7.8	>S	13	>S	56	>S	-	>S	-	>S	-	>S
Dibenz[a,h]anthracene	c, nv	0.0078		0.013		0.056		-	>S	-	>S	-	>S
Fluoranthene	nc, nv	1,500	>S	1,500	>S	5,800	>S	-	>S	-	>S	-	>S
Fluorene	nc, v	240		240		970		-	>S	-	>S	-	>S
Indeno[1,2,3-cd]pyrene	c, nv	0.078	>S	0.13	>S	0.56	>S	-	>S	-	>S	-	>S
Naphthalene	nc, v	6.2		6.2		25		-	>S	-	>S	-	>S
Pyrene	nc, nv	1,100	>S	1,100	>S	4,400	>S	-	>S	-	>S	-	>S
MTBE	c, v	6.4		13		38		96,000		210,000		550,000	
EDB (1,2-dibromoethane)	c, v	0.00064		0.0011		0.0046		440		940		2,500	
EDC (1,2-dichloroethane)	c, v	0.13		0.26		0.75		1,600		3,400		9,000	
Lead	NA, NA	15	L	15	L	15	L		NA		NA		NA
Generic Gasoline	nc, v	100		100		400		-	>S	-	>S	-	>S
Generic Diesel	nc, nv	88		88		350		-	>S	-	>S	-	>S
Generic Mineral Insulating Oil	nc, nv	290		290		1,100		-	>S	-	>S	-	>S

Appendix A: Table of RBCs (continued)

See Table 2.4 for a description of the pathways. Refer to page A-5 for an explanation of the notes.

Contaminated Medium		GROUNDWATER µg/L (ppb)						GROUNDWATER µg/L (ppb)		AIR (see notes) µg/m ³					
Exposure Pathway		Vapor Intrusion into Buildings RBC _{wi}						GW in Excavation RBC _{we}		Inhalation RBC _{air}					
Receptor Scenario		Residential		Urban Residential		Occupational		Construction and Excavation Worker		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note		Note
Benzene	c, v	160		340		2,700		1,700		0.27		0.57		1.5	
Toluene	nc, v	210,000		210,000		-	>S	78,000		400		400		1,600	
Ethylbenzene	nc, v	-	>S	-	>S	-	>S	110,000		1,100		1,100		4,200	
Xylenes	nc, v	59,000		59,000		-	>S	22,000		110		110		420	
iso-propylbenzene	nc, v	-	>S	-	>S	-	>S	-	>S	400		400		1,600	
n-propylbenzene	nc, v	-	>S	-	>S	-	>S	-	>S	150		150		580	
1,2,4-trimethylbenzene	nc, v	4,300		4,300		51,000		1,300		6.2		6.2		25	
1,3,5-trimethylbenzene	nc, v	3,200		3,200		38,000		1,400		6.2		6.2		25	
Acenaphthene	nc, v	-	>S	-	>S	-	>S	-	>S	220		220		880	
Anthracene	nc, v	-	>S	-	>S	-	>S	-	>S	1,100	>Pv	1,100	>Pv	4,400	>Pv
Benz[a]anthracene	c, nv	-	>S	-	>S	-	>S	9.1		0.0098		0.021		0.056	
Benzo[b]fluoranthene	c, nv	-	>S	-	>S	-	>S	-	>S	0.0098		0.021		0.056	
Benzo[k]fluoranthene	c, nv	-	>S	-	>S	-	>S	-	>S	0.098	>Pv	0.21	>Pv	0.56	>Pv
Benzo[a]pyrene	c, nv	-	>S	-	>S	-	>S	0.53		0.00098		0.0021		0.0056	
Chrysene	c, nv	-	>S	-	>S	-	>S	-	>S	0.98		2.1		5.6	
Dibenz[a,h]anthracene	c, nv	-	>S	-	>S	-	>S	0.21		0.00098	>Pv	0.0021	>Pv	0.0056	>Pv
Fluoranthene	nc, nv	-	>S	-	>S	-	>S	-	>S	150	>Pv	150	>Pv	580	>Pv
Fluorene	nc, v	-	>S	-	>S	-	>S	-	>S	150		150		580	
Indeno[1,2,3-cd]pyrene	c, nv	-	>S	-	>S	-	>S	-	>S	0.0098	>Pv	0.021	>Pv	0.056	>Pv
Naphthalene	nc, v	29,000		29,000		-	>S	680		3.1		3.1		13	
Pyrene	nc, nv	-	>S	-	>S	-	>S	-	>S	110	>Pv	110	>Pv	440	>Pv
MTBE	c, v	17,000		36,000		280,000		31,000		4.0		8.5		23	
EDB (1,2-dibromoethane)	c, v	110		230		1,800		20		0.0093		0.020		0.053	
EDC (1,2-dichloroethane)	c, v	210		460		3,600		600		0.079		0.17		0.45	
Lead	NA, NA		NA		NA		NA		NA		NA		NA		NA
Generic Gasoline	nc, v	-	>S	-	>S	-	>S	12,000		650		650		2,600	
Generic Diesel / Heating Oil	nc, nv	-	>S	-	>S	-	>S	-	>S	120		120		490	
Generic Mineral Insulating Oil	nc, nv	-	>S	-	>S	-	>S	-	>S	490		490		2,000	

Notes and References for Table of RBCs:

The numbers in this table will be updated as new information becomes available. The current version of this guidance document can be found on the Department's UST program web site at <http://www.oregon.gov/deg/tanks/Pages/Risk-Based-Decision-Making.aspx> or the Environmental Cleanup web site at <http://www.oregon.gov/deg/Hazards-and-Cleanup/env-cleanup/Pages/Cleanup-Guidance-Docs.aspx>.

Although RBC values for air are included in this table, air samples are not routinely required at cleanup sites due to the great temporal and spatial variability in air concentrations that makes it difficult to collect representative samples. The air inhalation pathway is usually taken into account indirectly by considering volatilization from contaminated soils or groundwater. Air monitoring may be applied when soil or groundwater screening levels are exceeded for the indoor air pathway and additional tests are needed to assess exposure. Under these circumstances the air concentrations must meet the air RBCs in Table A, not OSHA or other air standards. We suggest that you discuss such sampling with the Department before implementation.

The symbols in the "Note" columns have the following meanings:

- c This chemical is a known or suspected carcinogen. The RBCs in this row were calculated using equations for carcinogens described in Appendix B.
- >C_{sat} This soil RBC exceeds the limit of three-phase equilibrium partitioning. Refer to Appendix D for the corresponding value of C_{sat}. Soil concentrations in excess of C_{sat} indicate that free product might be present. See Section B.2.1.4 for additional information.
- L The values for lead reported in this table are not derived from the equations developed in Appendix B. See Section B.3.4 for the source of the lead numbers and information on applying them.
- >MAX The constituent RBC for this pathway is greater than 100,000 mg/kg. The TPH RBC is greater than the maximum amount that would be present if all of the initial air space is filled with petroleum product. The Department believes it is highly unlikely that such concentrations will ever be encountered.
- NA This pathway is not applicable to the chemical of interest.
- nc This chemical has non-carcinogenic toxic effects. The RBCs in this row were calculated using equations for noncarcinogens described in Appendix B.
- nv This chemical is classified as "nonvolatile" for purposes of the exposure calculations in this document.
- >P The air concentration reported for the RBC exceeds the vapor pressure of the pure chemical. It can be assumed that this constituent can not create an unacceptable risk by this pathway. See Section B.2.1.4 for additional information.
- >S This groundwater RBC exceeds the solubility limit. Refer to Appendix D for the corresponding value of S. Groundwater concentrations in excess of S indicate that free product may be present. See Section B.2.1.4 for additional information.
- v This chemical is classified as "volatile" for purposes of the exposure calculations in this document.
- The RBC for this indirect pathway is not printed since it is assumed that it is not physically possible to exceed the unacceptable risk level by this pathway. See Section B.2.1.4 for additional information.

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Appendix B: Calculation of Generic RBCs

B.1 Introduction

This appendix explains the equations and procedures used to calculate the generic risk-based concentrations (RBCs) listed in Appendix A. Some technical background information is included to explain why the Department made certain assumptions or used particular models to calculate the RBCs. Additional information can be found in the references listed in Appendix L. The default exposure factors, chemical data, toxicological data, and product data used to calculate the RBCs are provided in Appendix C, Appendix D, Appendix E, and Appendix F, respectively. The discussions in this Appendix are limited to deterministic methods of risk assessment. If you are interested in probabilistic risk assessments, please refer to *Guidance for Use of Probabilistic Analysis in Human Health Risk Assessments* (DEQ, 1998d).

The exposure and three-phase transport equations used in this document are taken primarily from *Guidance for Conduct of Deterministic Human Health Risk Assessments* (DEQ, 2000b), *Soil Screening Guidance: Technical Background Document* (EPA, 1996b), and *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites* (ASTM, 1995b). The four-phase equations are based on work by Mott (1995), Mariner *et al.* (1997), and Park and San Juan (2000). Modifications have been made where needed to maintain a consistent format throughout the document. Though generally consistent, some terms, symbols, and units used in this document may differ from those found in the reference documents. For clarity, most of the key equations are followed by a set of defined terms, symbols and units. Where necessary, unit conversion factors are included to ensure that results will be in the correct units *if* you use data with the specified units.

Derivation of some of the equations in Section B.3 will be easier to follow if you are familiar with common relationships within the systems that we are modeling. A summary of common porous media properties and relationships as they relate to the three-phase system calculations used for constituent RBCs is provided in Section B.2.1. Modifications to these relationships required for the four-phase system calculations used for TPH RBCs are described in Section B.2.2. More information on these types of physical and chemical properties can be found in EPA (1996b) or in many environmental chemistry and hydrogeology texts (*e.g.*, Fetter (1993) or Schwarzenbach *et al.* (1993)) or in the references mentioned above.

The models described in this document can be used to calculate site-specific RBCs. Some suggestions are included in this appendix to help you think about what changes might be worth considering when calculating site-specific numbers. Note, however, that the models used here are relatively simple and conservative. Although they are very useful for calculating screening levels, other models may be more appropriate for site-specific work. For information about additional models, please refer to Section B.4.

If you are not already experienced with the types of calculations summarized in this appendix, the Department recommends that you consult with a toxicologist or hydrogeologist, or take appropriate training in these subjects before attempting your own site-specific calculations.

B.2 Equations and Terminology

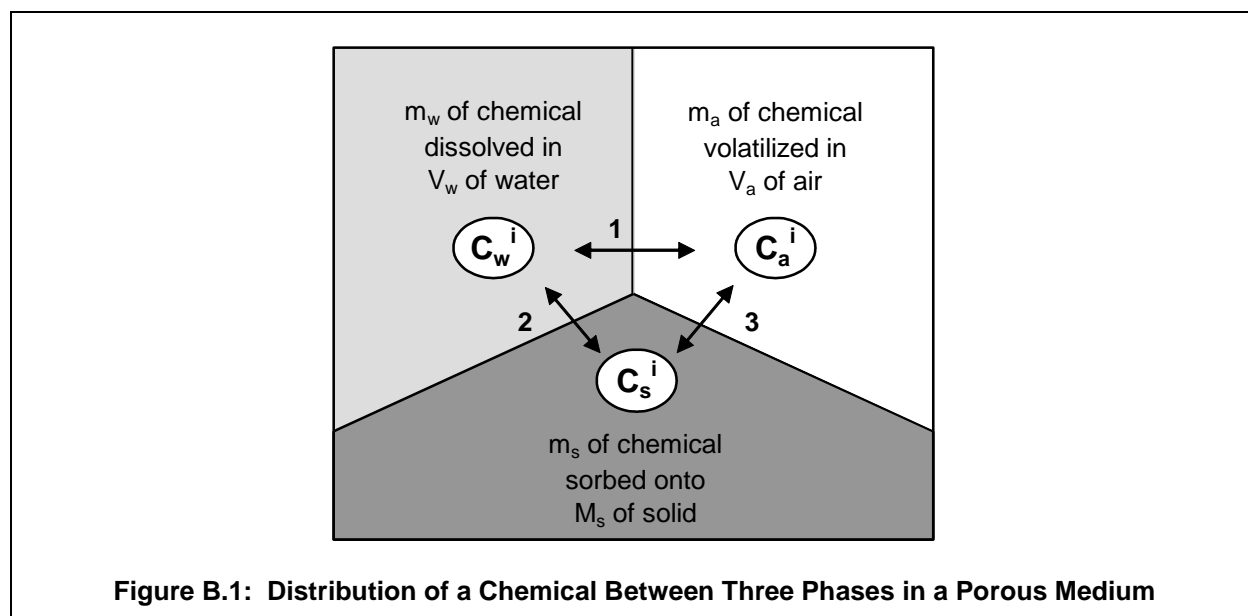
Transport of a chemical constituent in a multiphase system can take place *within* a given phase and *between* different phases. The former (intrapphase transport) often relates to long-range transport, such as the movement of a polluted air mass or a plume of contaminated groundwater. The latter (interphase transport) relates to short-range transport such as dissolution of benzene from gasoline into the pore water of petroleum-contaminated soil. Although it is a short-range phenomenon, transport between phases is critical since it controls the strength of a contaminant source for exposures that require transport. For example, if a contaminant with a very low solubility is spilled on the ground, even if it leaches to the groundwater the resulting concentration will be very low. The focus of the discussion in this section is on transport between phases and the equations that predict the distribution of chemicals between them. This information is subsequently used in the RBC calculations discussed in Section B.3.

B.2.1 Three-Phase Systems

The system used for modeling the distribution of petroleum constituents and calculating constituent RBCs in this document consists of a porous medium with three phases:

- A solid phase (the sand, silt, clay, *etc.*);
- A liquid phase (the pore water); and
- A gas phase (the pore air).

In this system all of the released petroleum dissolves in the pore water, volatilizes into the pore air, and sorbs onto the available solid (*i.e.*, no petroleum remains as free product). This three-phase system and the relationships between the phases are represented by Figure B.1, where C_a , C_w , and C_s represent the concentrations of a given constituent in the three phases at equilibrium.



B.2.1.1 Summary of Basic Relationships and Concentration Terms³⁰

The total mass of a sample collected from a three-phase system (M_T) is the mass of the solid phase (M_s), the mass of the pore water (M_w), and the mass of the pore air (M_a).

$$M_T = M_s + M_w + M_a \quad [B-1]$$

Likewise, the total volume of a sample (V_T) is simply the volume of the solid phase (V_s), the volume of the pore water (V_w), and the volume of the pore air (V_a).

$$V_T = V_s + V_w + V_a \quad [B-2]$$

When a chemical is added to the system it will dissolve, volatilize and sorb as determined by its chemical properties until it is distributed between the phases. The total mass of chemical (m_T), therefore, is the mass sorbed onto the solid phase (m_s), the mass dissolved in the pore water (m_w), and the mass volatilized in the pore air (m_a).

$$m_T = m_s + m_w + m_a \quad [B-3]$$

Because this system is a porous medium, relationships for porosity – the fraction of sample volume not occupied by the solid – also apply. The total porosity (n) is simply the sum of the water-filled porosity (n_w) and the air-filled porosity (n_a).

$$n = n_w + n_a \quad [B-4]$$

Porosity is also the factor that relates the density of the solid phase (ρ_s , the mass of solid per volume of solid) to the bulk density of the porous medium (ρ_b , the mass of solid per volume of sample).

$$n = 1 - \frac{\rho_b}{\rho_s} \quad [B-5]$$

When a soil sample is collected and analyzed for a particular chemical, the sample preparation method captures the chemical from all three phases (*i.e.*, m_T). The analytical results, however, are generally reported on the basis of dry-weight. Therefore, the concentration of the chemical in soil (C_{soil}) is the total mass of the chemical from all three phases divided by the mass of the soil (*i.e.*, the solid phase):

$$C_{soil} = \frac{m_T}{M_s} \quad [B-6]$$

Relationships between masses, volumes, porosity and other concentration terms in a three-phase system are summarized in Table B.1.

³⁰ Most of the equations used to develop the 3-phase and 4-phase relationships in Section B.2 are expressed in a basic format without the use of units or unit conversion factors. Important intermediate or final relationships, however, will include these terms.

Table B.1: Mass, Volume and Concentration Relationships in a Three-Phase Porous Medium

Symbol	Name and Definition	Equation
n	Total porosity (unitless) The fraction of sample volume not occupied by the solid phase	$n = (V_w + V_a)/V_T$ $n = n_w + n_a$
n_w	Water-filled porosity (unitless) The fraction of the sample volume occupied by the pore water	$n_w = V_w/V_T$
n_a	Air-filled porosity (unitless) The fraction of the sample volume occupied by the pore air	$n_a = V_a/V_T$
ρ_b	Bulk density of the soil (typical units = g/cm ³) The mass of the solid divided by the total volume of the sample	$\rho_b = M_s/V_T$
C_{soil}	Concentration of a constituent in a soil sample (all phases) (typical units = mg/kg)	$C_{soil} = m_T/M_s$
C_s	Concentration of a constituent in the sorbed phase (soil particles) (typical units = mg/kg)	$C_s = m_s/M_s$
C_a	Concentration of a constituent in the vapor phase (soil gas) (typical units = $\mu\text{g}/\text{m}^3$)	$C_a = m_a/V_a$
C_w	Concentration of a constituent in the dissolved phase (pore water) (typical units = mg/L or $\mu\text{g}/\text{L}$)	$C_w = m_w/V_w$

B.2.1.2 Distribution Between Phases

Important relationships with respect to transport modeling are those that describe how the concentration of a contaminant in one phase is related to its concentration in another phase at equilibrium. Since there are three phases in this system, two distribution coefficients are required in order to uniquely describe how a given chemical will be distributed between the phases. The distribution coefficients used for this purpose are the sorption partition coefficient and the Henry's Law constant.

Sorption Partition Coefficient

The sorption partition coefficient, K_d , represents the distribution of a contaminant between the solid and liquid phases (arrow 2 in Figure B.1). Typical units for K_d are L/kg or cm³/g.

$$K_d = \frac{C_s}{C_w} \quad [\text{B-7}]$$

Because different soils have different sorption capacities, which are generally controlled by the fraction of organic carbon (f_{oc}) present in the soil, sorption coefficients are usually expressed in a normalized format known as the organic-carbon partition coefficient, K_{oc} . In order to convert K_{oc} to a soil-specific K_d value you need to know the fraction of organic carbon in the soil (f_{oc}).

$$K_d = f_{oc} \cdot K_{oc} \quad [\text{B-8}]$$

The fraction of organic carbon can be determined through a simple lab test on a representative uncontaminated sample.

Henry's Law Constant

The Henry's Law constant, H, represents the distribution of a contaminant between the air and water phases (arrow 1 in Figure B.1). Since Henry's constants are often used in two different formats – one with dimensions (units) and one without – care must be taken to ensure that the correct format is used. This document distinguishes between the two formats by using K_H for Henry's constant in units of $\text{m}^3\text{-atm/mol}$, and H for the unitless Henry's constant. Most transport models incorporate the unitless form of the Henry's constant:

$$H = \frac{C_a}{C_w} \quad [\text{B-9}]$$

The following equation derived from the Ideal Gas Law can be used to convert from the dimensional form of the Henry's constant to the unitless form:

$$H = \frac{K_H}{R \cdot T} \quad [\text{B-10}]$$

where:

H	=	Henry's constant (unitless)
K_H	=	Henry's constant ($\text{m}^3\text{-atm/mol}$)
R	=	Ideal Gas Law Constant ($\text{m}^3\text{-atm/K-mol}$)
T	=	Temperature (K)

Using a temperature of 298 K along with $R = 8.21 \times 10^{-5} \text{ m}^3\text{-atm/K-mol}$ results in the relationship given in EPA (1996b):

$$H = K_H \cdot 41 \quad [\text{B-11}]$$

Theoretical and experimental values for K_{oc} and H can be found for most common organic compounds in many references (*e.g.*, EPA, 1996b). When data are not available for a particular compound, theoretical and empirical methods can be used to estimate values for K_{oc} and H (Lyman *et al.*, 1990; and Reinhard and Drefahl, 1999). Henry's constants, for example, can be estimated from a compound's vapor pressure (P), solubility (S), and molecular weight (MW).

$$K_H = \frac{P \cdot MW}{S} \quad [\text{B-12}]$$

Although partition coefficients vary with temperature (especially Henry's constant), data are often available only for laboratory temperatures, typically 20 °C or 25 °C.

B.2.1.3 Concentration Relationships

Mass and volume relationships for the three-phase system can be used along with the partition coefficients to develop equations to derive the equilibrium concentration of a chemical in any of the three phases from its concentration in a soil sample (C_{soil}). These equations are the basis for the models that are used to derive generic risk-based concentrations for petroleum constituents.

By using a process similar to that of Feenstra *et al.* (1991), we can start with the mass balance equation for a three-phase system (equation [B-3]) and substitute relationships from Table B.1 along with the definitions of Henry's constant and the sorption partition coefficient as follows:

$$m_T = V_w \cdot C_w + M_s \cdot C_s + V_a \cdot C_a \quad [B-13]$$

Replacing C_s and C_a with the equations for K_{oc} and H yields:

$$m_T = V_w \cdot C_w + M_s \cdot f_{oc} \cdot K_{oc} \cdot C_w + V_a \cdot H \cdot C_w \quad [B-14]$$

Since C_w is common to all three summed terms it can be put outside the summation.

$$m_T = C_w \cdot (V_w + M_s \cdot f_{oc} \cdot K_{oc} + V_a \cdot H) \quad [B-15]$$

Using equation [B-6] for C_{soil} to replace m_T and normalizing to a 1 cm³ sample³¹ gives:

$$\frac{C_{soil}}{C_w} = \frac{n_w + f_{oc} \cdot K_{oc} \cdot \rho_b + n_a \cdot H}{\rho_b} \quad [B-16]$$

This is a particularly useful relationship for modeling transport in three-phase systems and is sometimes referred to as K_{sw} (L/kg).

$$K_{sw} \text{ (L/kg)} = \frac{C_{soil}}{C_w} = \frac{n_w + f_{oc} \cdot K_{oc} \cdot \rho_b + n_a \cdot H}{\rho_b} \quad [B-17]$$

K_{sw} depends on chemical properties (K_{oc} and H) and site conditions (n_a , n_w , f_{oc} and ρ_b). Since all of these terms are constant for a specified chemical and system, K_{sw} is also a constant. After you determine its value you can use it along with the soil concentration for that chemical to estimate the concentration in each of the three phases.

$$C_w \text{ (mg/L)} = \frac{C_{soil}}{K_{sw}} \quad [B-18]$$

$$C_a \text{ (}\mu\text{g/m}^3\text{)} = \frac{H \cdot C_{soil}}{K_{sw}} \cdot 10^6 \frac{\mu\text{g} \cdot \text{L}}{\text{mg} \cdot \text{m}^3} \quad [B-19]$$

$$C_s \text{ (mg/kg)} = \frac{f_{oc} \cdot K_{oc} \cdot C_{soil}}{K_{sw}} \quad [B-20]$$

These equations relate the concentration of a chemical in a soil sample to its sorbed-phase concentration, pore water concentration, and pore air concentration. Such relationships are needed to develop the transport equations used to calculate RBCs for constituents.

³¹ By normalizing to a volume of 1 cm³, the volume of the air phase equals the air-filled porosity (n_a), the volume of the liquid phase equals the water-filled porosity (n_w), and the mass of the solid phase equals the bulk density (ρ_b).

B.2.1.4 Limitations of a Three-Phase System

A three-phase system works well for simulating the partitioning of moderate amounts of petroleum contamination. However, as the amount of contamination is increased, a point is finally reached where the three phases become saturated and the additional contamination can no longer dissolve into the pore water, evaporate into the pore gas, or sorb onto the solid phase. At that point product will remain in the system as a fourth phase (see Section B.2.2). Because the transport models used to calculate the constituent RBCs are based on three-phase equilibrium partitioning, it is important to define the limit of that partitioning. This limit is usually referred to as the saturation concentration, C_{sat} . The equation for C_{sat} can be readily obtained by recognizing that C_{soil} becomes C_{sat} when the pore water concentration (C_w) reaches its solubility limit (S). Substituting these terms into equation [B-17] and rearranging gives:

$$C_{\text{sat}} = S \cdot K_{\text{sw}} = S \cdot \left(\frac{n_w + f_{\text{oc}} \cdot K_{\text{oc}} \cdot \rho_b + n_a \cdot H}{\rho_b} \right) \quad [\text{B-21}]$$

Feenstra *et al.* (1991) use the C_{sat} limitation to test soil data for the likelihood of a fourth phase.

If this is a limitation of the model, then how are we to interpret or apply an RBC that *exceeds* the C_{sat} concentration? That will depend on the pathway that is involved. The important physical concepts to keep in mind are:

- The soil sample concentration can continue to increase past C_{sat} as the sample accumulates free product (the fourth phase);
- The pore-water concentration can not increase past the solubility (*i.e.*, when the soil concentration is at C_{sat} or higher, the pore-water concentration remains at the solubility limit (S)); and
- The soil-gas concentration can not increase past the vapor pressure (*i.e.*, when the soil concentration is at C_{sat} or higher, the soil-gas concentration remains at the vapor pressure (P)).

Therefore, for pathways that involve direct contact with the soil, such as soil ingestion and dermal contact, RBCs that exceed C_{sat} are still applicable. The fact that they exceed C_{sat} simply means that some of the contamination may be present as a nonaqueous, or "oily" phase. For indirect pathways (*i.e.*, those that require contaminant transport in the vapor phase or dissolved phase), RBCs exceeding C_{sat} means that it is not theoretically possible for vapor levels in the soil to be high enough to result in unacceptable risk levels from exposures to air. Nor is it theoretically possible for pore-water concentrations to be high enough to result in unacceptable risk levels from exposures to groundwater.

Constituent RBCs for all of the *soil* pathways in Appendix A were compared to the corresponding values of C_{sat} . RBCs associated with direct contact (RBC_{ss}) are listed in the table regardless of whether they do or do not exceed this limit. Those that exceed the saturation limit are identified by the note "> C_{sat} ." If they exceed 100,000 mg/kg, however, they are not listed in the table since such extreme concentrations are very unlikely. These are identified by the note ">MAX." RBCs for the indirect soil pathways (RBC_{so} , RBC_{si} , and RBC_{sw}) are not listed in the

table if they exceed C_{sat} . You can assume that these constituents can not create an unacceptable risk by these indirect pathways. You can find values of C_{sat} for these constituents in Appendix D. If soil contaminant concentrations measured at your site exceed C_{sat} values, it could mean that you have free product present at your site.

RBCs for *groundwater* also have a theoretical limit – solubility (S). As with soil, exceeding this limit indicates the possible presence of free product, and the effect on exposure depends on whether the pathway involves contact with groundwater or transport to another medium. The constituent RBCs for all of the *groundwater* pathways in Appendix A were compared to the corresponding values of S. RBCs associated with ingestion (RBC_{tw}) are listed in the table regardless of whether they do or do not exceed this limit. Those that exceed the solubility limit are identified by the note “>S.” However, groundwater RBCs for the indirect pathways (RBC_{wo} , RBC_{wi} , and RBC_{we}) are not listed in the table if they exceed S. You can assume that these constituents can not create an unacceptable risk by these indirect pathways. The solubilities of the constituents are listed in Appendix D. If groundwater contaminant concentrations measured at your site exceed the solubilities, it could mean that you have free product present at your site.

Finally, RBCs for *air* are limited by vapor pressures (P). If a constituent RBC for air exceeds the P of that compound, then it is not possible to exceed the acceptable risk level as long as the only exposure is from breathing the vapor phase (*i.e.*, no incidental ingestion or dermal exposure to free product). The RBCs for the *air* pathway in Appendix A were compared to the corresponding values of P. If the RBC exceeds the value of P, then “>P” appears in the note column. RBC_{air} values that exceed P will also show up as soil RBCs that exceed C_{sat} or water RBCs that exceed S, so RBC_{air} values are generally not needed unless air monitoring is implemented.³² They are included in the table primarily for reference.

Since petroleum products are mixtures of many different constituents, the solubilities and vapor pressures of the constituents in the product are actually less than the values listed for the pure compounds in Appendix D. However, product composition is highly variable and is not normally taken into account in screening applications of the type used for constituent RBCs in three-phase systems. Composition is taken into account, however, in four-phase TPH RBCs.

B.2.2 Four-Phase Systems

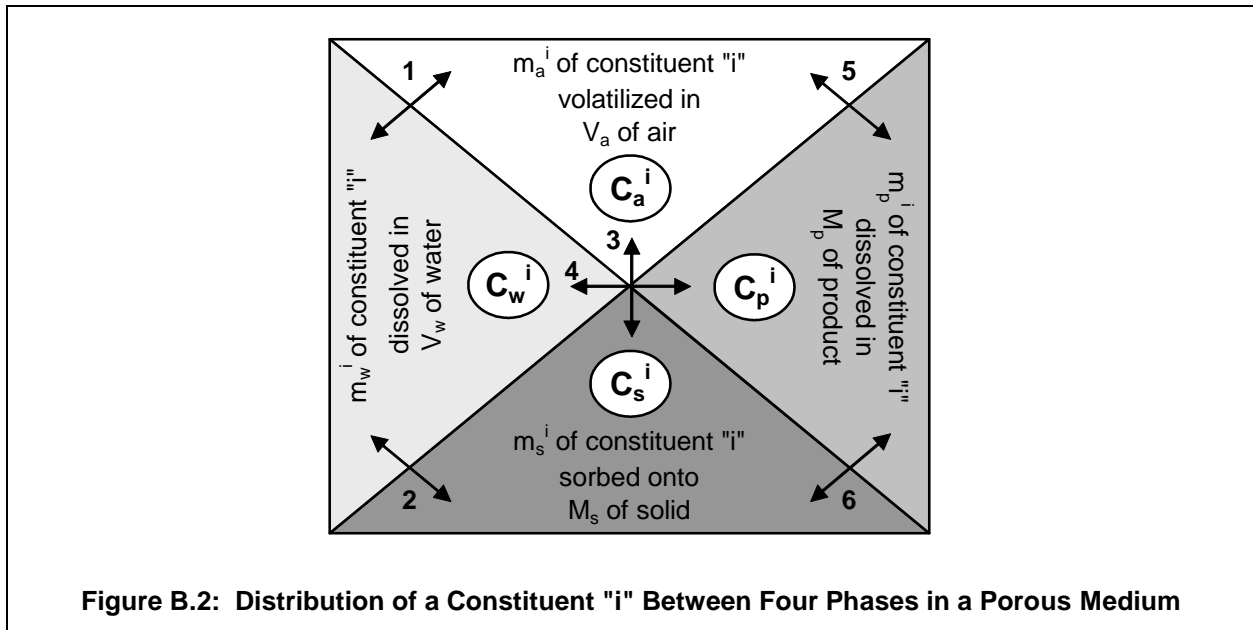
To avoid the limitations of three-phase systems, Mott (1995) expanded the work of Feenstra *et al.* (1991) to develop a four-phase partitioning model where the fourth phase is a multi-component nonaqueous phase liquid (NAPL). The advantage of such a model is that you can use it to estimate the distribution of petroleum constituents in the presence of a fourth phase. The disadvantage is that you need to have fairly complete information about the composition of the petroleum product. Park and San Juan (2000), as part of their work for the State of Washington’s revised Model Toxics Control Act (Washington DOE, 2001), use a four-phase system to assess leaching potential for petroleum hydrocarbon constituents and fractions.

³² As noted in Section B.3.1, the Department does not usually require you to collect air samples.

The system used for modeling the distribution of petroleum products and calculating petroleum product (*i.e.*, TPH) RBCs in this document consists of a porous medium with four phases:

- A porous-medium solid phase (sand, silt, clay, *etc.*);
- An aqueous phase (pore water);
- A gas phase (pore air); and
- An immiscible nonaqueous liquid phase (petroleum product).

This system is produced when sufficient petroleum is available so that after product dissolves into the pore water, volatilizes into the pore air, and sorbs onto the porous medium, some remains as a separate petroleum phase (*i.e.*, NAPL is present). This four-phase system and the relationships between the phases can be represented by Figure B.2, where C_a^i , C_w^i , C_p^i , and C_s^i represent the concentration of a specific constituent of interest "i" in each of the four phases at equilibrium.³³



B.2.2.1 Summary of Basic Relationships and Concentration Terms

Mass, Volume and Porosity

The relationships for four-phase systems are analogous to those presented for three-phase systems. The total mass of a sample (M_T) is equal to the mass of the solid (M_s), the mass of the pore water (M_w), the mass of the pore air (M_a), and the mass of the petroleum product (M_p).

³³ In a three-phase system each constituent acts independently (*i.e.*, the distribution of one constituent does not affect the distribution of another constituent). The three-phase equations can be solved for a single constituent like benzene without knowing anything about the other constituents or the product as a whole. In a four-phase system, however, the composition of the product affects the ultimate distribution of constituents in each of the phases. Therefore, we need to keep track of all components and carry out calculations for all of them simultaneously. The superscript "i" represents any of the constituents and is a reminder that all must be considered at the same time.

$$M_T = M_s + M_w + M_a + M_p \quad [B-22]$$

The total volume (V_T) is the volume of the solid phase (V_s), the volume of the pore water (V_w), the volume of the pore air (V_a), and the volume of the product (V_p).

$$V_T = V_s + V_w + V_a + V_p \quad [B-23]$$

The total mass of a particular petroleum constituent "i" (m_T^i) is the mass of "i" sorbed onto the solid phase (m_s^i), the mass dissolved in the pore water (m_w^i), the mass volatilized in the pore air (m_a^i), and the mass remaining in the immiscible petroleum phase (m_p^i).³⁴

$$m_T^i = m_s^i + m_w^i + m_a^i + m_p^i \quad [B-24]$$

Since a fourth phase is present, the total porosity (n) now consists of the water-filled porosity (n_w), the air-filled porosity (n_a), and the product-filled porosity (n_p).³⁵

$$n = n_w + n_a + n_p \quad [B-25]$$

Concentration Terms

As the name implies, the concentration term "total petroleum hydrocarbons" (TPH) is a measure of the total mass of petroleum in a sample. With the results reported on the basis of dry-weight, the TPH concentration (C_{TPH}) is the mass of the petroleum divided by the mass of the solid phase — not the mass of the *sample* — typically reported in units of mg/kg (ppm). The mass of petroleum consists of the mass of the petroleum phase (M_p) as well as the mass of all petroleum constituents in the other three phases.

$$C_{TPH} = \frac{M_p + \sum (m_s^i + m_w^i + m_a^i)}{M_s} \quad [B-26]$$

When we talk about "petroleum" dissolving into pore water or evaporating into pore air, we really mean that constituents like benzene are dissolving or evaporating. The degree to which that occurs depends on the chemical properties of the constituent as well as the composition of the petroleum. The concentration of a constituent in the petroleum (C_p^i) can be expressed as the mass of the constituent in the product (m_p^i) divided by the mass of the product (M_p).

$$C_p^i = \frac{m_p^i}{M_p} \quad [B-27]$$

³⁴ The total mass of all of the constituents "i" (*i.e.*, $\sum m_T^i$) is assumed to have originated in the NAPL phase.

³⁵ The fourth phase (petroleum product) is assumed to occupy part of the volume that was formerly occupied only by air. In other words, $n_a + n_p$ for the four-phase system are assumed to equal n_a for the corresponding three-phase system. The water-filled porosity, n_w , remains unchanged.

Another way to express the concentration of a petroleum constituent "i" is mole fraction (X_i).³⁶ This is the number of moles of "i" divided by the total number of moles of all of the constituents in the petroleum product.

$$X_i = \frac{\text{moles "i"}}{\text{moles "a" + moles "b" + ... + moles "i" + ... + moles "n"}} \quad [\text{B-28}]$$

where:

"i" = the constituent for which you are calculating the mole fraction
 "a" ... "n" = all of the constituents in the petroleum product

The sum of all of the mole fractions in a given product is always equal to one.

$$\sum X_i = 1 \quad [\text{B-29}]$$

The number of moles of a compound is calculated by dividing the mass of that compound by its molecular weight (MW). Therefore, equation [B-28] can be rewritten as:

$$X_i = \frac{m_p^i / MW_i}{m_p^a / MW_a + m_p^b / MW_b + \dots + m_p^i / MW_i + \dots + m_p^n / MW_n} \quad [\text{B-30}]$$

A simplified form of this equation is typically used:

$$X_i = \frac{m_p^i / MW_i}{M_p / MW_p} \quad [\text{B-31}]$$

where:

m_p^i = the mass of constituent "i" in the petroleum product (g)
 MW_i = the molecular weight of constituent "i" (g/mol)
 M_p = the mass of petroleum product (g)
 MW_p = the molecular weight of the petroleum product (g/mol)

The mole fraction is an important concentration term in four-phase system calculations since, as we will see in the next section, it controls the amount of any given constituent that dissolves, volatilizes, or sorbs from the petroleum product into the other three phases.

Since petroleum is a mixture, we have to define some of its properties in terms of the properties of its constituents. The molecular weight, MW_p , is calculated as the weighted average of the molecular weights of all of the constituents.

$$MW_p = \sum X_i \cdot MW_i \quad [\text{B-32}]$$

The density of the petroleum product, ρ_p , can be estimated from the molecular weight of the product along with the molecular weights, mole fractions and densities of its constituents.

$$\rho_p = \frac{MW_p}{\sum (X_i \cdot MW_i / \rho_i)} \quad [\text{B-33}]$$

³⁶ For more information on "mole" and "mole fraction" please refer to any introductory chemistry text.

We usually don't have information about all of the constituents in products as complex as petroleum. However, the molecular weight and density can be estimated from the above equations using data for the TPH fractions discussed in Section 3.1.5.

Using equation [B-27] to replace m_p^i/M_p in equation [B-31] and rearranging to solve for C_p^i we obtain a relationship for the concentration of a constituent in the product to the concentration expressed as a mole fraction.

$$C_p^i = X_i \cdot \frac{MW_i}{MW_p} \quad [B-34]$$

As in a three-phase system, the concentration of a constituent in a soil sample (C_{soil}^i) is the total mass of the constituent from all of the phases divided by the mass of the solid phase.

$$C_{soil}^i = \frac{m_T^i}{M_s} \quad [B-35]$$

Relationships between masses, volumes, porosity and other concentration terms in a four-phase system are summarized in Table B.2.

B.2.2.2 Distribution Between Phases

As mentioned in the discussion of three-phase systems, the equilibrium distribution of a constituent between the vapor phase and the aqueous phase is represented by Henry's constant (arrow 1 in Figure B.2), and the distribution between the aqueous phase and sorption onto the solid phase is represented by the sorption partition coefficient (arrow 2 in Figure B.2). Although these relationships still hold in four-phase systems, we need an additional relationship to account for the presence of the NAPL (product) phase.³⁷ The impact of the fourth phase on the volatilization, dissolution, and sorption of petroleum constituents is discussed below.

Volatilization

The tendency for a constituent to volatilize is measured by its vapor pressure (P), commonly expressed in atmospheres (atm). Since petroleum products are not pure liquids, the tendency for a petroleum constituent "i" to volatilize is based not only on the vapor pressure of that constituent if it were a pure liquid (P_i^0), but also on the mole fraction of that constituent in the petroleum product. This is known as Raoult's Law.

$$P_i = X_i \cdot P_i^0 \quad [B-36]$$

This is the relationship between the vapor phase and the petroleum product phase at equilibrium represented by arrow 5 in Figure B.2.

³⁷ Although Figure B.2 shows that there are 6 possible two-phase interactions in a four-phase system, only three two-phase relationships are needed to uniquely describe all four phases. The three used in this discussion are represented by arrows 1, 2, and 5.

Table B.2: Mass, Volume, and Concentration Relationships in a Four-Phase Porous Medium

Symbol	Name (Units)	Relationship
C_a^i	Concentration of constituent "i" in the vapor phase (soil gas) (typical units = $\mu\text{g}/\text{m}^3$)	$C_a^i = m_a^i/V_a$
C_w^i	Concentration of constituent "i" in the dissolved phase (pore water) (typical units = mg/L or $\mu\text{g}/\text{L}$)	$C_w^i = m_w^i/V_w$
C_s^i	Concentration of constituent "i" in the sorbed phase (soil particles) (typical units = mg/kg)	$C_s^i = m_s^i/M_s$
C_p^i	Concentration of constituent "i" in the immiscible product (petroleum) (typical units = mg/kg)	$C_p^i = m_p^i/M_p$
C_{soil}^i	Concentration of constituent "i" in a soil sample (typical units = mg/kg)	$C_{\text{soil}}^i = m_T^i/M_s$
C_{TPH}	Total petroleum hydrocarbon concentration (typical units = mg/kg)	$C_{\text{TPH}} = \frac{M_p + \sum (m_a^i + m_w^i + m_s^i)}{M_s}$
n	Total porosity (unitless) The fraction of sample volume not occupied by the solid phase	$n = (V_w + V_a + V_p)/V_T$ $n = n_w + n_a + n_p$
n_a	Air-filled porosity (unitless) The fraction of the sample volume occupied by the pore air	$n_a = V_a/V_T$
n_p	Product-filled porosity (unitless) The fraction of the sample volume occupied by the petroleum	$n_p = V_p/V_T$
n_w	Water-filled porosity (unitless) The fraction of the sample volume occupied by the pore water	$n_w = V_w/V_T$
ρ_b	Bulk density of the soil (typical units = g/cm^3) The mass of the solid divided by the total volume of the sample	$\rho_b = M_s/V_T$
X_i	Mole fraction of constituent "i" in the petroleum (unitless)	$X_i = \frac{\text{moles "i"}}{\text{moles product}}$

The vapor pressure in equation [B-36] can be converted into more traditional air-phase concentration units of mass/volume (C_a) by multiplying by MW_i/RT .³⁸

$$C_a^i = \frac{X_i \cdot P_i^0 \cdot MW_i}{R \cdot T} \cdot 10^6 \frac{\mu\text{g}}{\text{g}} \quad [\text{B-37}]$$

where:

- C_a^i = the concentration of "i" in the air phase ($\mu\text{g}/\text{m}^3$)
- MW_i = the molecular weight of constituent "i" (g/mol)
- P_i^0 = the vapor pressure of constituent "i" (atm)
- R = the Ideal Gas Law constant ($\text{m}^3\text{-atm}/\text{K}\text{-mol}$)
- T = the temperature (K)
- X_i = the mole fraction of constituent "i" in the product (unitless)

³⁸ This relationship is derived from the Ideal Gas Law, $PV = nRT$.

Using equations for Henry's constant (K_H in $m^3\text{-atm/mol}$; equation [B-12]) and its relationship to the dimensionless Henry's constant (equation [B-10]), this can be further simplified.

$$C_a^i = \frac{X_i \cdot K_H^i \cdot S_i^o}{R \cdot T} \quad [B-38]$$

$$C_a^i = X_i \cdot H_i \cdot S_i^o \quad [B-39]$$

where:

- H_i = the Henry's constant for "i" (unitless)
 S_i^o = the solubility of pure constituent "i" in water (mg/L)

This is the equation that relates the concentration of constituent "i" in the air phase to the mole fraction of that constituent in the petroleum product phase at equilibrium (arrow 5 in Figure B.2).

Dissolution

Since the Henry's constant is the ratio of the concentration of a constituent in air to its concentration in water at equilibrium (arrow 1 in Figure B.2), we can use that definition along with equation [B-39] to derive an equation for the aqueous-phase concentration in this system.

$$H_i = C_a^i / C_w^i \quad [B-40]$$

$$H_i = X_i \cdot H_i \cdot S_i^o / C_w^i \quad [B-41]$$

Therefore, the relationship between the aqueous phase and the petroleum product phase represented by arrow 4 in Figure B.2 is simply

$$C_w^i = X_i \cdot S_i^o \quad [B-42]$$

Sorption

There is no standard chemical property like vapor pressure, or equilibrium relationship like Henry's constant that defines the distribution of a constituent between a solid phase and a NAPL phase (arrow 6 in Figure B.2). When the system reaches equilibrium, however, all four phases will be in equilibrium with each other. Since there is a relationship between the dissolved phase and the sorbed phase (arrow 2 in Figure B.2), we can use that to derive the relationship that we need.

As noted earlier, the sorption partition coefficient (K_d) and the organic carbon partition coefficient (K_{oc}) relate the concentrations in the sorbed and dissolved phases.

$$K_d^i = f_{oc} \cdot K_{oc}^i = \frac{C_s^i}{C_w^i} \quad [B-43]$$

Combining this with equation [B-42] generates an expression for the distribution of a constituent between the dissolved phase and the sorbed phase in a four-phase system.

$$C_s^i = f_{oc} \cdot K_{oc}^i \cdot X_i \cdot S_i^o \quad [B-44]$$

This is the relationship represented by arrow 2 in Figure B.2.

B.2.2.3 Concentration Relationships

Now that we have relationships for all of the phases, we can again use mass balance to develop a set of equations that describe the entire system at equilibrium in terms of concentrations measured in a soil sample (C_{soil}^i). Starting with equation [B-24], we can substitute expressions for the mass of constituent in each phase by using the first four equations in Table B.2.

$$m_T^i = (C_s^i \cdot M_s) + (C_w^i \cdot V_w) + (C_a^i \cdot M_a) + (C_p^i \cdot V_p) \quad [B-45]$$

The concentration terms C_s^i , C_w^i , C_a^i , and C_p^i can be replaced with expressions that we derived in equations [B-44], [B-42], [B-39], and [B-34] respectively.

$$m_T^i = \left(f_{oc} \cdot K_{oc}^i \cdot X_i \cdot S_i^o \cdot M_s \right) + \left(X_i \cdot S_i^o \cdot V_w \right) + \left(X_i \cdot H_i \cdot S_i^o \cdot V_a \right) + \left(\frac{X_i \cdot MW_i \cdot M_p}{MW_p} \right) \quad [B-46]$$

Since X_i , the mole fraction, is common to all four summed terms, it can be put outside the summation.

$$m_T^i = X_i \cdot \left[\left(f_{oc} \cdot K_{oc}^i \cdot S_i^o \cdot M_s \right) + \left(S_i^o \cdot V_w \right) + \left(H_i \cdot S_i^o \cdot V_a \right) + \left(\frac{MW_i \cdot M_p}{MW_p} \right) \right] \quad [B-47]$$

We can use equation [B-35] to replace m_T^i and normalize the result on a per cm^3 basis by replacing mass and volume terms by density and porosity terms.³⁹ This produces an expression for the soil concentration of any constituent in terms of the mole fraction, and the basic chemical and physical properties of the constituent and the four-phase system.

$$C_{soil}^i = \frac{X_i}{\rho_b} \cdot \left[\left(f_{oc} \cdot K_{oc}^i \cdot S_i^o \cdot \rho_b \right) + \left(S_i^o \cdot n_w \right) + \left(H_i \cdot S_i^o \cdot n_a \right) + \left(\frac{MW_i \cdot \rho_p \cdot n_p}{MW_p} \right) \right] \quad [B-48]$$

In the three-phase system we found that the K_{sw} , the ratio between the soil concentration and the water concentration (see equation [B-17]), was a useful relationship for calculating equilibrium concentrations. We can derive a comparable relationship for four-phase systems from equations [B-48] and [B-42], which we define in this document as R_{sw}^i (L/kg).⁴⁰

³⁹ When normalized on a per cm^3 basis, the mass of solid is the bulk density (ρ_b), the volume of water is the water-filled porosity (n_w), and the volume of air is the air-filled porosity (n_a). The mass of petroleum (M_p) is the density of the petroleum (ρ_p) times the volume, which is the petroleum-filled porosity (n_p).

⁴⁰ Note in equation [B-49] that when there is no product present (*i.e.*, $n_p = 0$) the last parenthetical term becomes zero and the four-phase equation for R_{sw}^i reduces to the three-phase equation for K_{sw} .

$$R_{sw}^i \text{ (L/kg)} = \frac{C_{soil}^i}{C_w^i} = \frac{1}{\rho_b} \cdot \left((f_{oc} \cdot K_{oc}^i \cdot \rho_b) + (n_w) + (H_i \cdot n_a) + \left(\frac{MW_i \cdot \rho_p \cdot n_p}{MW_p \cdot S_i^o} \cdot 10^6 \frac{\text{mg} \cdot \text{cm}^3}{\text{g} \cdot \text{L}} \right) \right) \quad [\text{B-49}]$$

The relationship for R_{sw}^i can be inserted back into equation [B-48] to give a relationship for calculating the mole fraction of a constituent from its measured soil concentration.

$$X_i = \frac{C_{soil}^i}{R_{sw}^i \cdot S_i^o} \quad [\text{B-50}]$$

We can now use these relationships to develop a final set of equations for the concentration of a constituent "i" in each phase in terms of the measured soil concentration (C_{soil}^i) and R_{sw}^i .

Rearranging [B-49] gives:

$$C_w^i \text{ (mg/L)} = \frac{C_{soil}^i}{R_{sw}^i} \quad [\text{B-51}]$$

Relating the water concentration above to the air concentration via Henry's constant (equation [B-40]) yields:

$$C_a^i \text{ (}\mu\text{g/m}^3\text{)} = H_i \cdot \frac{C_{soil}^i}{R_{sw}^i} \cdot 10^6 \frac{\mu\text{g} \cdot \text{L}}{\text{mg} \cdot \text{m}^3} \quad [\text{B-52}]$$

Relating the water concentration to the sorbed concentration via the K_{oc} (equation [B-43]) yields:

$$C_s^i \text{ (mg/kg)} = \frac{f_{oc} \cdot K_{oc}^i \cdot C_{soil}^i}{R_{sw}^i} \quad [\text{B-53}]$$

Substituting equation [B-50] into equation [B-34] gives:

$$C_p^i \text{ (mg/kg)} = \frac{MW_i}{MW_p} \cdot \frac{C_{soil}^i}{R_{sw}^i \cdot S_i^o} \cdot 10^6 \frac{\text{mg} \cdot \text{cm}^3}{\text{g} \cdot \text{L}} \quad [\text{B-54}]$$

Note that the first three of the four equations above are the same as the equations derived for a three-phase system (see equations [B-18], [B-19], and [B-20]) except that K_{sw} has been replaced by R_{sw}^i . The fourth equation represents the fourth phase.

In the earlier discussion of three-phase systems we noted that the K_{sw} for each constituent is constant in a given system because it only depends on other constant terms (see Section B.2.1.3). Therefore, the calculation of K_{sw} for each constituent can be carried out independently. In other words, the behavior of any one constituent does not affect the behavior of any of the other constituents in a three-phase system. In a four-phase system, however, R_{sw}^i is not a constant. It changes because neither the amount of product (n_p) nor the composition of product remains

constant. As a four-phase system moves towards equilibrium, volatilization and dissolution of the product reduce n_p , increase n_a and change the mole fractions of the constituents that remain in the product.

The fact that R_{sw}^i is not a constant for a given system means that the distribution of each constituent cannot be calculated independently as it can be in a three-phase system. Results must be obtained from the simultaneous solution of equations for all constituents. Mott (1995), Mariner *et al.* (1997), and Park and San Juan (2000) describe computer programs that can be used for this purpose.

The Department's TPH RBC spreadsheet uses a four-phase system of equations to calculate generic RBCs for gasoline, diesel, and mineral insulating oil. It also can be used to estimate site-specific TPH RBCs from TPH and constituent data and calculate site-specific TPH RBCs using data obtained from the VPH and EPH analytical methods (see Section 3.1.5.2).

B.2.3 Transport and Exposure Models

Now that we have equations for estimating chemical concentrations in three-phase and four-phase systems, we need equations that we can use to relate concentrations to risk. Risk-based concentrations are calculated with mathematical equations (models) that estimate:

- How contaminants move from where they were released, through various media (air, soil, water), to where receptors are located (transport models); and
- How much of each contaminant is taken in by various uptake mechanisms (ingestion, inhalation, dermal absorption, *etc.*) after the contaminants reach the receptors (exposure models).

Many of the references listed in Appendix L provide information about transport and exposure models (*e.g.*, EPA, 1996b), so they will not be discussed at length in this document. The purposes of this section are to offer some general remarks about how the Department applied these types of models, and to give a brief overview of how various transport factors such as "Volatilization Factors" are used to link the two model outcomes together to calculate RBCs. Information on modeling resources is provided in Section B.4.

B.2.3.1 Transport Models

If a receptor is exposed to a chemical at the source of a release, you can use the equations from Sections B.2.1 or B.2.2 to estimate the concentrations needed to calculate risk. If the receptor is not at the source, however, you will need a transport model to estimate the concentration to which the receptor might be exposed. The risk can then be calculated from that concentration. Consider some gasoline-contaminated soil, for example. You can use the previous equations to estimate the concentration of benzene that can volatilize into the pore air. Then, a transport model can be used to estimate the concentration of benzene in the air in a house above the contaminated soil. Finally, you can use an exposure model to estimate risk from breathing the benzene-contaminated air in that house.

For convenience, transport model results are often expressed in terms of a *transport factor*. A transport factor is nothing more than the ratio of the concentration in a given medium or location (e.g., at the receptor) that the model predicts will result from a known concentration in another medium or location (e.g., at the source). Transport factors are commonly referred to by a specific name that reflects the mode of transport. For example, “volatilization factor” is used in the case of soil or water contamination volatilizing into air, and “leaching factor” is used for soil contamination leaching into underlying groundwater. If a transport model were used to predict the average air concentration that might result at a site due to volatilization from soils with a known contaminant concentration, the volatilization factor (VF) would be:

$$VF(\text{kg/m}^3) = \frac{\text{Predicted Concentration in Air}(\text{mg/m}^3)}{\text{Known Concentration in Soil}(\text{mg/kg})} \quad [\text{B-55}]$$

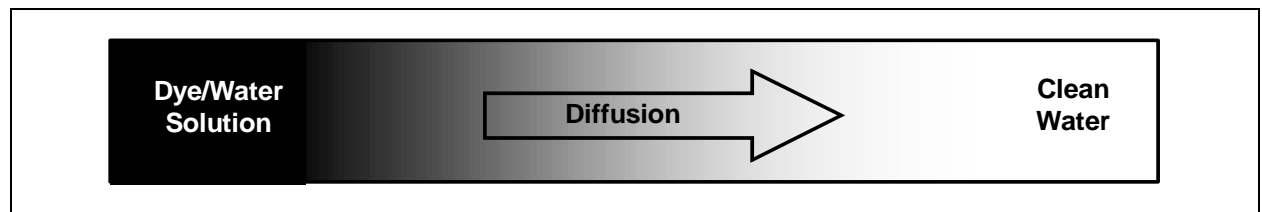
Transport factors are usually chemical-specific and pathway-specific. There are some special cases, however, where a single factor can be applied to numerous chemicals by a given pathway.

The specific transport models used for the Table of RBCs in Appendix A are discussed in Section B.3 along with comments about transport factors.

Important Note About Transport Factors: Although volatilization factors are used by both ASTM (1995b) and by EPA (1996b), please note that they are *NOT defined in the same way* by both organizations. The VF format presented above in equation [B-55] (predicted air concentration divided by known soil concentration) is the format used by ASTM. EPA, however, uses a VF format that is the inverse of ASTM's (i.e., known soil concentration divided by predicted air concentration). The same is true of the particulate emission factor (PEF, see Section B.3.2.1). Therefore, you should use caution when comparing these documents or in applying transport factors from other sources. The Department decided to be consistent with ASTM's format since we believe that more users of the Department's original UST program guidance document were familiar with ASTM's methods than with EPA's methods.

B.2.3.2 Diffusion

Since diffusion coefficients in various formats appear in many of the transport equations, it may be useful to provide a brief background. Diffusion is the movement of matter resulting from random molecular motion (sometimes referred to as Brownian motion). In the simplest case we can consider a system where only two compounds are present, for example, dye in water. If dye is added to water, even if the water is not stirred the color will eventually disperse throughout the water. Although it is not possible to predict the movement of any given dye molecule at any given time, the movement of the diffusing substance on the average will be away from zones of higher concentration to zones of lower concentration.



The rate of movement of the diffusing substance through a unit area perpendicular to the direction of flow is proportional to the concentration gradient and is described by Fick's first law of diffusion (Crank, 1975). The one-dimensional form of Fick's first law is shown below. The minus sign simply indicates that diffusion occurs in a direction opposite to that of increasing concentration.

$$J = -D \cdot \frac{\partial C}{\partial L} \quad [B-56]$$

where:

- J = Flux: the quantity of substance diffusing through a unit area per unit time
- C = Chemical concentration
- D = Diffusion coefficient
- L = Distance
- $\frac{\partial C}{\partial L}$ = Chemical concentration gradient

Diffusion is affected by a number of factors including the size and mass of the diffusing substance, the viscosity of the medium through which diffusion occurs, and the temperature. Table B.3 lists diffusion coefficients in air and water for several representative petroleum constituents. For the types of organic compounds addressed in this document diffusion coefficients generally range from 10^{-2} to 10^{-1} cm²/s in air (D_{air}) and 10^{-6} to 10^{-5} cm²/s in water (D_w) at 25 °C. A temperature decrease from 25 °C to 5 °C would reduce these numbers by about half (Fetter, 1993).

Table B.3: Diffusion Coefficient Examples (EPA, 1996b)

Compound	Molecular Weight (grams/mole)	Diffusion Coefficient at 25 °C (cm ² /s)	
		In Air (D_{air})	In Water (D_w)
Benzene	76	8.8×10^{-2}	9.8×10^{-6}
Naphthalene	128	5.9×10^{-2}	7.5×10^{-6}
Chrysene	228	2.5×10^{-2}	6.2×10^{-6}

In cases where a diffusion coefficient cannot be found, an estimate can be obtained by multiplying a known diffusion coefficient for a similar compound by the square-root of the ratio of the molecular weights for the two compounds (Schwarzenbach *et al.*, 1993).

$$D_2 = D_1 \cdot \sqrt{\frac{MW_1}{MW_2}} \quad [B-57]$$

where:

- D_1 = Known diffusion coefficient for compound 1
- D_2 = Diffusion coefficient to be estimated for compound 2
- MW_1 = Molecular weight for compound 1
- MW_2 = Molecular weight for compound 2

Because the transport equations in this document deal with diffusion through porous media rather than through air or water, the diffusion coefficients must be modified to account for the fact that contaminant movement is now restricted to the pore space. Also, the pore space (at least in the vadose zone) contains both air and water through which diffusion can occur. Under these circumstances diffusion is usually characterized by an *effective* diffusion coefficient (Johnson and Ettinger, 1991).

$$D_{veff} = \frac{D_{air} \cdot n_a^{10/3} \cdot H + D_w \cdot n_w^{10/3}}{H \cdot n^2} \quad [B-58]$$

where:

D_{veff}	=	Effective diffusion coefficient in the vadose zone soil (cm ² /s)
D_{air}	=	Diffusion coefficient in air (cm ² /s)
D_w	=	Diffusion coefficient in water (cm ² /s)
H	=	Henry's constant (unitless)
n	=	Total soil porosity (unitless)
n_a	=	Air-filled porosity in the vadose zone (unitless)
n_w	=	Water-filled porosity in the vadose zone (unitless)

A single effective diffusion coefficient is adequate as long as the region being modeled is relatively homogeneous. However, if the zone being modeled contains two or more layers with different porosities or moisture contents, then the effective diffusion coefficient must take all of the layers into account.

The relationship generally used for estimating overall effective diffusion coefficients in a system containing multiple layers perpendicular to the direction of flow is based on uni-directional diffusion through a series (Crank, 1975).

$$\frac{L_T}{D_T} = \left(\frac{L_1}{D_1} \right) + \left(\frac{L_2}{D_2} \right) + \dots + \left(\frac{L_n}{D_n} \right) \quad [B-59]$$

where:

L_1, L_2, \dots	=	the thickness of layers 1, 2, ... in a system with multiple layers
L_T	=	the total thickness of the system (<i>i.e.</i> , $L_1 + L_2 + \dots + L_n$)
D_1, D_2, \dots	=	diffusion coefficients within layers 1, 2, ... in a system with multiple layers
D_T	=	the total diffusion coefficient for the system

As noted earlier, since we are dealing with porous media, the diffusion coefficient for a given layer must be expressed as an effective diffusion coefficient (equation [B-58]) which depends on the diffusive properties of the contaminant, and on the porosity and saturation of the media. Rearranging equation [B-59] and writing it in terms of effective diffusion coefficients yields an equation for calculating the *total* effective diffusion coefficient in a multi-layer system.

$$D_{T\text{eff}} = \frac{L_1 + L_2 + \dots + L_n}{\left(\frac{L_1}{D_{1\text{eff}}}\right) + \left(\frac{L_2}{D_{2\text{eff}}}\right) + \dots + \left(\frac{L_n}{D_{n\text{eff}}}\right)} \quad [\text{B-60}]$$

Even in the very simple models used in this document, a two-layer system is applied when simulating diffusion from the water table to the ground surface. One layer represents average conditions in the vadose zone and has an effective diffusion coefficient calculated with equation [B-58]. The other layer represents conditions in the capillary fringe where the water content is much higher. Capillary fringe diffusion can be represented by the analogous equation below.

$$D_{\text{cap}\text{eff}} = \frac{D_{\text{air}} \cdot n_{\text{acap}}^{10/3} \cdot H + D_{\text{w}} \cdot n_{\text{wcap}}^{10/3}}{H \cdot n^2} \quad [\text{B-61}]$$

where:

$D_{\text{cap}\text{eff}}$	=	Effective diffusion coefficient in the capillary fringe (cm^2/s)
D_{air}	=	Diffusion coefficient in air (cm^2/s)
D_{w}	=	Diffusion coefficient in water (cm^2/s)
H	=	Henry's constant (unitless)
n	=	Total soil porosity (unitless)
n_{acap}	=	Air-filled porosity in the capillary fringe (unitless)
n_{wcap}	=	Water-filled porosity in the capillary fringe (unitless)

The total effective diffusion coefficient for this two-layer system is, therefore:

$$D_{T\text{eff}} = \frac{L_{\text{w}}}{\left(\frac{L_{\text{v}}}{D_{\text{v}\text{eff}}}\right) + \left(\frac{L_{\text{cap}}}{D_{\text{cap}\text{eff}}}\right)} \quad [\text{B-62}]$$

where:

$D_{T\text{eff}}$	=	Total effective diffusion coefficient (cm^2/s)
$D_{\text{v}\text{eff}}$	=	Effective diffusion coefficient in vadose zone soil (cm^2/s)
$D_{\text{cap}\text{eff}}$	=	Effective diffusion coefficient in the capillary fringe (cm^2/s)
L_{cap}	=	Thickness of the capillary fringe (cm)
L_{v}	=	Thickness of the vadose zone soils (cm)
L_{w}	=	Total distance from groundwater to surface (cm) ($L_{\text{w}} = L_{\text{cap}} + L_{\text{v}}$)

The specific applications of these diffusion coefficients are discussed in relevant portions of Section B.3.

B.2.3.3 Exposure Models

Exposure models for common pathways like the ones included in the Table of RBCs in Appendix A are fairly standard. A summary of such models can be found in the Department's *Guidance for Conduct of Deterministic Human Health Risk Assessments* (DEQ, 2000b). As applied in risk assessments, exposure models are used with site-specific concentration data, scenario-specific intake data, and chemical-specific toxicity data to yield estimates of risk that could result from exposure to the chemical(s) of concern.

$$\text{Risk} = \text{Concentration} \times \text{ExposureFactors} \times \text{Toxicity} \quad [\text{B-63}]$$

For example, the two equations below are models for estimating risk from exposure due to the inhalation of toxic constituents in air. The first equation estimates noncarcinogenic risk and the second equation estimates carcinogenic risk.

$$\text{HazardQuotient} = C_{\text{air}} \cdot \left[\frac{\text{ED} \cdot \text{EF} \cdot \text{IRA}}{\text{AT} \cdot \text{BW}} \right] \cdot \frac{1}{\text{RfD}} \quad [\text{B-64}]$$

$$\text{Risk} = C_{\text{air}} \cdot \left[\frac{\text{ED} \cdot \text{EF} \cdot \text{IRA}}{\text{AT} \cdot \text{BW}} \right] \cdot \text{SlopeFactor} \quad [\text{B-65}]$$

where:

C_{air}	=	Air concentration
AT	=	Averaging time
BW	=	Body weight
ED	=	Exposure duration
EF	=	Exposure frequency
IRA	=	Inhalation rate
RfD	=	Noncancer reference dose
Slope Factor	=	Cancer slope factor

The exposure factor components of these models (the terms in square brackets) represent the mechanism of exposure – in this example, the volume of air inhaled per day (IRA), how many days/year the receptor is exposed to the air (EF), how many years the receptor is exposed to the air (ED), *etc.* The values for these parameters are standardized and vary depending on the exposure scenario (residential, occupational, *etc.*). Default exposure factors for the calculations carried out in this document are listed in Appendix C.

B.2.4 Calculating RBCs from Exposure and Transport Models

The method that you have to use to calculate a given RBC depends on:

- The number of phases in the system; and
- Whether the exposure is direct or indirect.

All constituent RBCs will be based on three-phase partitioning. All TPH RBCs will be based on four-phase partitioning where appropriate.⁴¹

For purposes of this document, the term “direct pathway” refers to one that requires no transport before exposure takes place. In other words, it is one where we are establishing a risk-based concentration for the medium in which the exposure takes place. For example, the RBC for air is an air concentration that results in an acceptable level of risk to those who are breathing the air. This is a direct exposure pathway.

⁴¹ The four-phase equations will reduce to three-phase equations when the TPH level is too low to generate a fourth phase. See footnote 40 in Section B.2.2.3.

An “indirect pathway” is one that requires transport to move the toxic chemical from the medium where it is currently located to another medium where exposure takes place. In other words, it is one where we are establishing a risk-based concentration for a medium other than the one in which exposure takes place. For example, RBC_{so} (see Section B.3.2.2) is a soil concentration in the vadose zone that results in an acceptable level of risk to those who breathe the air that is contaminated as a result of chemicals volatilizing from the soil into the air. So, even though the RBC is for soil, the goal of the RBC is to protect people from inhalation exposures. This is an indirect exposure pathway

B.2.4.1 RBCs for Constituents (Three-Phase Systems)

Constituent RBCs for Direct Exposure Pathways

To calculate constituent RBCs for direct exposures you must rearrange the exposure equation to solve for the concentration term rather than risk. For example, the risk equations introduced in the previous section can be used to calculate RBC_{air} as follows:

$$RBC_{air} = \left[\frac{AT \cdot BW}{ED \cdot EF \cdot IRA} \right] \cdot \frac{\text{HazardQuotient}}{(1/RfD)} \quad [B-66]$$

$$RBC_{air} = \left[\frac{AT \cdot BW}{ED \cdot EF \cdot IRA} \right] \cdot \frac{\text{Risk}}{(\text{SlopeFactor})} \quad [B-67]$$

In order to solve these you must have an “acceptable risk level” that you can use for “Hazard Quotient” and “Risk” in the above equations. In Oregon, acceptable risk levels (ARLs) for protection of human health are defined in statute⁴² as a lifetime excess cancer risk of one per one million people exposed, or exposure to noncarcinogens resulting in a hazard index⁴³ of less than or equal to one. Therefore, all calculations in this document are based on an acceptable risk level for carcinogens (ARL_c , “Risk”) = 1×10^{-6} , or an acceptable risk level for noncarcinogens (ARL_n , “Hazard Quotient”) = 1.

Constituent RBCs for Indirect Exposure Pathways

Constituent RBCs for indirect exposures can be calculated by combining the RBCs for direct exposure pathways with transport factors that represent the movement of the chemicals of concern from the medium where the source is located to the medium where the exposure takes place (see Section B.2.3.1). For example, if you have RBC_{air} from the previous equation you can calculate the RBC for vadose zone soils that will protect outdoor air (RBC_{so}) by using a factor that accounts for volatilization from soil to air.

$$RBC_{so} (\text{Soil Volatilizing to Air}) = \frac{RBC_{air}}{\text{Volatilization Factor from Soil to Outdoor Air}} \quad [B-68]$$

All necessary direct and indirect three-phase RBC equations are provided in Section B.3.

⁴² Oregon Revised Statute (ORS) 465.315(1)(b)(A)

⁴³ The “Hazard Index” is the sum of hazard quotients for multiple noncarcinogens.

B.2.4.2 RBCs for Total Petroleum Hydrocarbons (Four-Phase Systems)

Four-phase TPH RBCs are derived from the same exposure models used for three-phase constituent RBCs. Since the TPH RBCs represent only noncarcinogenic risk, however, we only need the noncarcinogenic exposure equations. The procedures for using these equations must be modified to:

- Combine exposures for a number of different TPH fractions into a single RBC for the product of interest; and
- Account for the presence of a four-phase system.

As with the three-phase models, the method used to calculate the RBCs depends on whether you are dealing with a direct exposure or an indirect exposure.

TPH RBCs for Direct Exposure Pathways

For direct exposure pathways, you must first calculate an RBC for each petroleum fraction using the equation developed for the three-phase constituent RBCs. After obtaining an RBC for each of the fractions, use equation [B-69] to calculate the overall product RBC on the basis of the product composition.

$$RBC_{TPH} = \frac{1}{\left(\frac{\text{Wt. Fraction}_1}{RBC_1}\right) + \left(\frac{\text{Wt. Fraction}_2}{RBC_2}\right) + \dots + \left(\frac{\text{Wt. Fraction}_n}{RBC_n}\right)} \quad [B-69]$$

The weight fraction that you must use in this equation depends on the medium of exposure. For exposure to soil containing the product, use the TPH weight fractions in the product.⁴⁴ For exposure to air, use the weight fractions in the air after volatilization from the product takes place. For exposure to water, use the weight fractions in the water after dissolution from the product takes place. You can calculate the air and water fractions using the following equations derived from four-phase relationships introduced in Section B.2.2.2:

$$WtFraction_{air}^i = \frac{X_i \cdot H_i \cdot S_i^o}{\sum (X_i \cdot H_i \cdot S_i^o)} \quad [B-70]$$

$$WtFraction_{water}^i = \frac{X_i \cdot S_i^o}{\sum (X_i \cdot S_i^o)} \quad [B-71]$$

where:

- | | | |
|-------|---|---|
| X_i | = | the mole fraction of TPH fraction or constituent "i" in the product |
| H_i | = | Henry's constant of TPH fraction or constituent "i" |
| S_i | = | Solubility of TPH fraction or constituent "i" |

⁴⁴ The weight fractions for the generic gasoline, diesel/heating oil, and mineral insulating oil that appear in the Table of RBCs are given in Appendix F.

TPH RBCs for Indirect Exposure Pathways

As described earlier, RBCs for indirect exposure pathways require transport factors (*i.e.*, volatilization factors, leaching factors, *etc.*) that represent the ratio of the concentration at the receptor to the concentration at the source. Some transport factors have been determined empirically or are calculated from parameters that do not depend on the chemical or the composition of the system. TPH RBCs for this type of indirect exposure pathway are calculated using the same process as is used for direct exposure pathways. That is, you calculate the RBC for each fraction or constituent using the three-phase equation and then combine the results into an RBC for the product using equation [B-69].

If the transport factors are based on the composition of the system, the TPH RBC calculations are more complex because the composition of the system will change as constituents in the petroleum phase dissolve into pore water, volatilize into pore air, and sorb onto the solid. You have to solve for the equilibrium composition of all of the components in all four phases simultaneously. Mott (1995), Mariner *et al.* (1997), and Park and San Juan (2000) all describe methods and programs for performing this calculation. Because we cannot calculate the composition of a four-phase system without knowing the total amount of product present (*i.e.*, without knowing the RBC when we start the calculation), TPH RBCs for these indirect pathways must be solved iteratively. The basic steps are:

1. Select a value for the TPH RBC.
2. Calculate the composition of a four-phase system with this TPH concentration.
3. Use the resulting concentrations from the composition to calculate noncarcinogenic risk (*i.e.*, use a risk equation such as the one in equation [B-64]).
4. If the risk is not 1, try again. If the risk =1, then the selected value is the RBC.

Transport factors are derived and discussed in Section B.3. Those that depend on the composition of the system are identified. The Department provides a spreadsheet that you can use to perform these calculations (DEQ, 2003b). A more detailed description of the iterative process used in the Department's spreadsheet is provided in Section B.3.5.

B.2.5 Scenario Variations

Risk-based concentrations are provided in Appendix A for residential, urban residential, occupational, construction, and excavation worker scenarios. In the occupational, construction, and excavation worker scenarios the assumption is made that only *adults* are exposed to the contaminants of concern found at the site. The residential and urban residential scenarios, however, consider exposure to *children and adults*. Because ingestion rates, inhalation rates and other factors are different for children and adults, these differences must be taken into account when calculating residential RBCs. Since the exposure calculations for carcinogens and noncarcinogens have different underlying assumptions, the method used to account for these adult/child differences will depend on whether the contaminant is classified as a carcinogen or a noncarcinogen.

B.2.5.1 Carcinogens

Risk from exposure to carcinogens is evaluated on the basis of long-term average exposures. In a residential scenario, such exposures are typically calculated for the first 30 years of life. This dose is then averaged over a 70-year lifetime. To account for differences in exposures to children and adults over the 30-year period, weighted averages are calculated for the exposure factors assuming 6 years of exposure at a childhood exposure rate and 24 years of exposure at an adult exposure rate. These “age-adjusted” parameters, therefore, approximate an integrated exposure from birth through age 30 by combining contact rates, body weights, and exposure durations for the two age groups.

DEQ also evaluates risk for an urban residential scenario. This scenario has an exposure duration of 11 years. Therefore, a second set of adjusted factors is needed to provide integrated exposures over this time period. The equations for the 30-year age-adjusted factors were obtained from *Risk Assessment Guidance for Superfund, Part B* (EPA, 1989) and *Region 9 Preliminary Remediation Goals* (EPA, 2002a). The equations for the 11-year age-adjusted factors have the same format but are adjusted to account for exposure parameters that are specific to the urban residential exposure scenario.

Age-Adjusted Inhalation Factor (Air)		
Residential	$\text{IFAadj}_r = \frac{\text{ED}_{\text{cr}} \cdot \text{IRA}_{\text{c}}}{\text{BW}_{\text{c}}} + \frac{(\text{ED}_{\text{r}} - \text{ED}_{\text{cr}}) \cdot \text{IRA}_{\text{r}}}{\text{BW}_{\text{a}}}$	[B-72]
Urban Residential	$\text{IFAadj}_u = \frac{\text{ED}_{\text{cu}} \cdot \text{IRA}_{\text{c}}}{\text{BW}_{\text{c}}} + \frac{(\text{ED}_{\text{u}} - \text{ED}_{\text{cu}}) \cdot \text{IRA}_{\text{u}}}{\text{BW}_{\text{a}}}$	[B-73]
Age-Adjusted Ingestion Factor (Soil)		
Residential	$\text{IFSadj}_r = \frac{\text{ED}_{\text{cr}} \cdot \text{IRS}_{\text{cr}}}{\text{BW}_{\text{c}}} + \frac{(\text{ED}_{\text{r}} - \text{ED}_{\text{cr}}) \cdot \text{IRS}_{\text{r}}}{\text{BW}_{\text{a}}}$	[B-74]
Urban Residential	$\text{IFSadj}_u = \frac{\text{ED}_{\text{cu}} \cdot \text{IRS}_{\text{cu}}}{\text{BW}_{\text{c}}} + \frac{(\text{ED}_{\text{u}} - \text{ED}_{\text{cu}}) \cdot \text{IRS}_{\text{u}}}{\text{BW}_{\text{a}}}$	[B-75]
Age-Adjusted Ingestion Factor (Water)		
Residential	$\text{IFWadj}_r = \frac{\text{ED}_{\text{cr}} \cdot \text{IRW}_{\text{c}}}{\text{BW}_{\text{c}}} + \frac{(\text{ED}_{\text{r}} - \text{ED}_{\text{cr}}) \cdot \text{IRW}_{\text{r}}}{\text{BW}_{\text{a}}}$	[B-76]
Urban Residential	$\text{IFWadj}_u = \frac{\text{ED}_{\text{cu}} \cdot \text{IRW}_{\text{c}}}{\text{BW}_{\text{c}}} + \frac{(\text{ED}_{\text{u}} - \text{ED}_{\text{cu}}) \cdot \text{IRW}_{\text{u}}}{\text{BW}_{\text{a}}}$	[B-77]

Age-Adjusted Skin Surface Area Factor (Soil)

$$\text{Residential} \quad \text{SFSadj}_r = \frac{\text{ED}_{\text{cr}} \cdot \text{AF}_c \cdot \text{SA}_c}{\text{BW}_c} + \frac{(\text{ED}_r - \text{ED}_{\text{cr}}) \cdot \text{AF}_r \cdot \text{SA}_r}{\text{BW}_a} \quad [\text{B-78}]$$

$$\text{Urban Residential} \quad \text{SFSadj}_u = \frac{\text{ED}_{\text{cu}} \cdot \text{AF}_c \cdot \text{SA}_c}{\text{BW}_c} + \frac{(\text{ED}_u - \text{ED}_{\text{cu}}) \cdot \text{AF}_u \cdot \text{SA}_u}{\text{BW}_a} \quad [\text{B-79}]$$

where:

- *IFAadj = Age-adjusted inhalation factor for air ([m³-yr]/[kg-d])
- *IFSadj = Age-adjusted ingestion factor for soils ([mg-yr]/[kg-d])
- *IFWadj = Age-adjusted ingestion factor for water ([L-yr]/[kg-d])
- *SFSadj = Age-adjusted skin contact factor for soils ([mg-yr]/[kg-d])
- *AF = Adherence factor (mg/cm²-d)
- *BW = Body weight (kg)
- *ED = Exposure duration (yr)
- *IRA = Inhalation rate (m³/d)
- *IRS = Soil ingestion rate (mg/d)
- *IRW = Water ingestion rate (L/d)
- *SA = Skin surface contact area (cm²)

* The subscripts on these parameters in the equations refer to the following: a = adult; c = child; cr = residential child; cu = urban residential child; r = residential; and u = urban residential.

B.2.5.2 Noncarcinogens

The potential for health effects from exposure to a noncarcinogen is evaluated by determining if the dose of contaminant taken in by a receptor exceeds a “safe” reference dose. Although reference doses are meant to represent chronic exposures, which are considered to be a minimum of 7 years (10% of a 70-year lifetime), exposures to noncarcinogens are not averaged over a lifetime. Rather, they are simply averaged over the specified exposure duration. As a result, the exposure duration (ED) has no effect on the calculated noncarcinogenic risk since it always equals the noncarcinogenic averaging time (AT_n) and the two terms cancel out of the overall equation. (For example, consider the affect of setting AT_{nr} equal to ED_r in equation [B-81].)

Since noncarcinogenic doses are averaged only over the exposure duration and not over a lifetime, the age-adjusted factors discussed in the previous section are not used in any of the equations for noncarcinogenic RBCs. Instead, adult/child differences for exposures to residential noncarcinogens are taken into account simply by evaluating the exposure to whichever group is considered to be more vulnerable.

Based on EPA’s recommendations (EPA, 2002a), exposures to noncarcinogenic contaminants in residential soils should be evaluated for children only. The higher daily soil ingestion rates combined with lower body weights results in significantly greater childhood doses. Note that since the RBCs for the soil contact pathway are based on a combined exposure from three routes

(soil ingestion, dermal contact, and either vapor or particulate inhalation), the dermal and inhalation factors used in the combined equation also incorporate childhood rates.

Conversely, for residential groundwater consumption and air inhalation, exposures to noncarcinogens are evaluated for adults only. This is considered protective because adults have higher daily intake rates and a much longer exposure duration. Note again that the longer exposure duration does not affect the actual calculation, but it does reflect an exposure that is more likely to represent a chronic condition and thus suggests that the adult population may be more vulnerable to these exposure pathways.

Table B.4 summarizes the discussion in this section, listing which set of exposure factors – age-adjusted (*i.e.*, “Children + Adults”), adult-only, or child-only – were used for each exposure scenario included in the Table of RBCs in Appendix A.

Table B.4: Exposure Factor Usage Summary

Contaminated Medium	Risk Type ¹	Exposure Scenario	
		Residential and Urban Residential	Occupational, Construction Worker and Excavation Worker
Air	c	Children + Adults ²	Adults
	nc	Adults	Adults
Soil	c	Children + Adults	Adults
	nc	Children	Adults
Groundwater	c	Children + Adults	Adults
	nc	Adults	Adults

1. “c” = exposure to carcinogens; “nc” = exposure to noncarcinogens
2. Age-adjusted factors are used to evaluate residential exposure to children and adults from carcinogens

B.3 Calculation of Risk-Based Concentrations

This section lists all of the exposure and transport equations, and associated transport factors used to calculate the RBCs listed in Appendix A. Transport calculations are based on the three-phase and four-phase relationships discussed in Sections B.2.1 and B.2.2.

Equations are presented first by medium and then by exposure pathways associated with that medium. Each equation is identified by the risk type (carcinogen, or noncarcinogen) and scenario (residential, urban residential, occupational, construction worker, or excavation worker) to which it applies. Information about the sites to which these equations apply is included. Derivations of key transport factors are also presented as well as information on how three-phase and four-phase transport factors differ. This information is provided as technical background as well as to serve as a basis for potential site-specific modifications of the equations.

B.3.1 Air

Due to the great temporal and spatial variability in air concentrations, which makes it difficult to collect representative samples, the Department does not routinely require that air (indoor or outdoor) be tested at UST cleanup sites. However, in cases where soil gas or air samples are collected because of vapor problems, or to better assess site-specific risk from breathing airborne volatiles, the RBCs for air should be used as the acceptable air concentrations, not OSHA or other air standards.

RBCs for air are required primarily so that acceptable soil and groundwater concentrations can be calculated for the volatilization-to-air pathways.

Three-Phase Calculations

Air RBCs for petroleum constituents are calculated directly from exposure equations [B-80] through [B-85].

Residential - Carcinogens

$$RBC_{air} (\mu\text{g}/\text{m}^3) = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot 10^3 \mu\text{g}/\text{mg}}{EF_r \cdot IFAadj_r \cdot SF_i} \quad [B-80]$$

Residential - Noncarcinogens

$$RBC_{air} (\mu\text{g}/\text{m}^3) = \frac{ARL_n \cdot AT_{nr} \cdot 365 \text{ d/yr} \cdot BW_a \cdot 10^3 \mu\text{g}/\text{mg}}{ED_r \cdot EF_r \cdot IRA_r \cdot (1/RfD_i)} \quad [B-81]$$

Urban Residential - Carcinogens

$$RBC_{air} (\mu\text{g}/\text{m}^3) = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot 10^3 \mu\text{g}/\text{mg}}{EF_r \cdot IFAadj_u \cdot SF_i} \quad [B-82]$$

Urban Residential – Noncarcinogens

$$RBC_{air} (\mu\text{g}/\text{m}^3) = \frac{ARL_n \cdot AT_{nu} \cdot 365 \text{ d/yr} \cdot BW_a \cdot 10^3 \mu\text{g}/\text{mg}}{ED_u \cdot EF_r \cdot IRA_u \cdot (1/RfD_i)} \quad [\text{B-83}]$$

Occupational - Carcinogens

$$RBC_{air} (\mu\text{g}/\text{m}^3) = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot BW_a \cdot 10^3 \mu\text{g}/\text{mg}}{SF_i \cdot IRA_o \cdot ED_o \cdot EF_o} \quad [\text{B-84}]$$

Occupational - Noncarcinogens

$$RBC_{air} (\mu\text{g}/\text{m}^3) = \frac{ARL_n \cdot AT_{no} \cdot 365 \text{ d/yr} \cdot BW_a \cdot 10^3 \mu\text{g}/\text{mg}}{ED_o \cdot EF_o \cdot IRA_o \cdot (1/RfD_i)} \quad [\text{B-85}]$$

where:

RBC _{air}	=	Risk-based air concentration (μg/m ³)
ARL _c	=	Acceptable Risk Level for Carcinogens (unitless)
ARL _n	=	Acceptable Risk Level for Noncarcinogens (unitless)
AT _c	=	Averaging time – carcinogens (yr)
*AT _n	=	Averaging time – noncarcinogens (yr)
*BW	=	Body weight (kg)
*ED	=	Exposure duration (yr)
*EF	=	Exposure frequency (d/yr)
*IFAadj	=	Age-adjusted inhalation factor for air ([m ³ -yr]/[kg-d])
*IRA	=	Inhalation rate (m ³ /d)
RfD _i	=	Noncancer reference dose – inhaled (mg/kg-d)
SF _i	=	Cancer slope factor – inhaled (mg/kg-d) ⁻¹

* The subscripts on these parameters in the equations refer to the following: a = adult; c = child; cr = residential child; cu = urban residential child; o = occupational; r = residential; and u = urban residential.

Note that the urban residential equations for RBC_{air} use the same exposure frequency as the residential equations (EF_r). The exposure frequency for urban residents (EF_u) is only used to represent a more limited contact with soil for the soil pathway (RBC_{ss}) (see Section B.3.2.1).

RBC_{air} equations are not needed for the excavation and construction worker scenarios since those results are not needed for subsequent calculations such as volatilization to outdoor air (RBC_{so} and RBC_{wo}) or volatilization to indoor air (RBC_{si} and RBC_{wi}).

Four-Phase Calculations

This is a direct exposure pathway. Therefore, calculate RBCs for each TPH fraction using the appropriate equation for noncarcinogens above. Then, use weight fractions for the TPH fractions in air along with equation [B-69] to calculate the overall TPH RBC.

Summary - Calculating RBCs for Exposure from Inhalation of Contaminated Air

RBCs for petroleum constituents in air are calculated directly from equations [B-80] through [B-85].

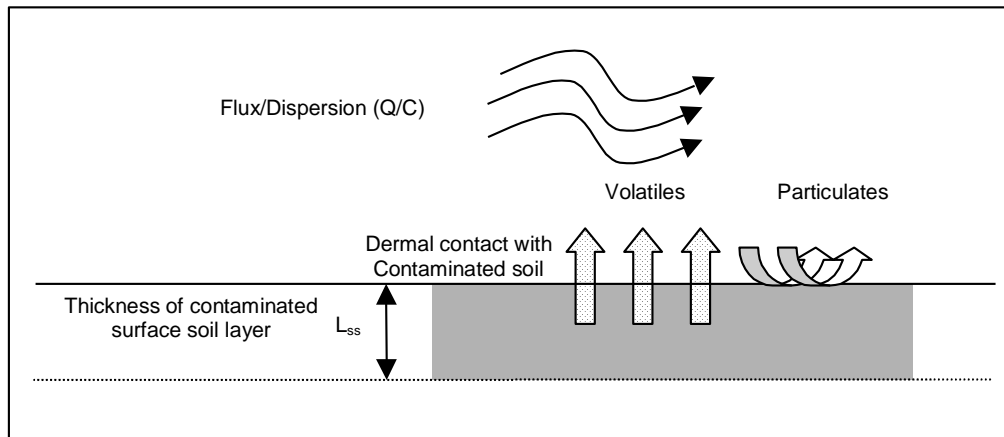
RBCs for petroleum fractions in air are calculated with the same equations and then combined using equation [B-69] to obtain the TPH RBC for the product.

Suggestions for Site-Specific Calculations for RBC_{air}

Since the RBC values for air are based on exposure factors such as inhalation rates that would be difficult to develop on a site-specific basis, the Department does not recommend that you attempt to calculate site-specific values for RBC_{air} .

B.3.2 Soil

B.3.2.1 Exposure to Contaminated Surface Soils



For residential, urban residential, and occupational scenarios, exposure to chemicals in surface soils should be considered a potential exposure pathway for all chemicals found in the top 100 cm (~3 feet) of soil. For construction and excavation worker scenarios the depth is site-specific and should be based on current or reasonably likely maximum depths of construction excavations or utility trenches in the vicinity of the site. It could be as deep as 10 - 15 feet, or greater in some cases.

RBCs for surface soils are based on ingestion, dermal contact, and inhalation exposures. For convenience, all three routes are combined into one exposure equation. The ingestion and dermal contact pathway contributions are calculated directly from exposure equations. The inhalation pathway, however, requires a transport model to estimate either (1) how much chemical volatilizes from the soil into the air, or (2) how much soil containing a given chemical enters the air as dust. The factor that is used is based on whether the chemical is considered volatile or nonvolatile. For the purpose of these calculations a “volatile” chemical has a Henry’s constant $> 10^{-5} \text{ m}^3\text{-atm/mol}$ and a molecular weight $< 200 \text{ g/mol}$ (EPA, 1991a). All other chemicals are considered nonvolatile.

Volatilization Factor

For *volatile* contaminants, the inhalation exposure component results from breathing air containing compounds that have evaporated from the contaminated surface soil. Therefore, the transport factor – in this case a volatilization factor (VF) – represents the concentration of contaminated vapor dispersed in the air above a given area of contaminated soil. This transport factor is actually made up of two components: (1) a flux component that represents how fast the contaminant is volatilizing out of the soil, and (2) a dispersion component that represents how the contaminant mixes into the air above the site.

EPA (1996b) performed a modeling study using meteorological data from 29 locations across the United States to estimate how these two factors (flux and dispersion) interact at sites ranging in size from 0.5 to 30 acres. The results of this study have been tabulated as Q/C values where:

$$Q/C = \frac{\text{Average Flux from Contaminated Surface Soil}}{\text{Air Concentration at the Center of the Site}} \quad [\text{B-86}]$$

To represent a conservative value that will account for meteorological conditions at most sites, EPA suggests using the 90th percentile Q/C value from their study, which is 68.81 (g/m²-s)/(kg/m³) for a 0.5 acre site. This dispersion component is not a function of the number of phases.

For the purposes of calculating screening concentrations, we can assume that our goal is to have “air concentrations at the center of the site” that do not exceed the RBC_{air} values calculated in Section B.3.1. Therefore, equation [B-86] can be combined with a model that calculates the flux from contaminated soil to generate volatilization factors for this pathway.

One of the simplest models for calculating average flux from surface soils is the Jury infinite source model, which is derived from work by Mayer *et al.* (1974). As described by EPA (1996b), this model calculates the average flux over time as:

$$J_{ss\text{ave}} = 2 \cdot C_{\text{soil}} \cdot \rho_b \cdot \sqrt{\frac{D_A}{\pi \cdot t_{\text{vol}} \cdot 3.16 \cdot 10^7 \text{ s/yr}}} \quad [\text{B-87}]$$

where:

- $J_{ss\text{ave}}$ = Average flux from surface soil (μg/cm²-s)
- C_{soil} ⁴⁵ = Surface soil concentration (mg/kg)
- ρ_b = Soil bulk density (g/cm³)
- π = 3.14... (unitless)
- t_{vol} = Time over which volatilization flux is being averaged (yr)

and

$$D_A = \frac{(D_{\text{air}} \cdot n_a^{10/3} \cdot H + D_w \cdot n_w^{10/3})}{n^2 \cdot (n_a \cdot H + n_w + \rho_b \cdot f_{\text{oc}} \cdot K_{\text{oc}})} \quad [\text{B-88}]$$

where:

- D_A = Apparent diffusion coefficient (cm²/s)
- D_{air} = Diffusion coefficient in air (cm²/s)
- D_w = Diffusion coefficient in water (cm²/s)
- f_{oc} = Fraction of organic carbon in soil (unitless)
- H = Henry's constant (unitless)
- K_{oc} = Organic carbon partition coefficient (cm³/g)
- n = Total soil porosity (unitless)
- n_a = Air-filled porosity (unitless)
- n_w = Water-filled porosity (unitless)
- ρ_b = Soil bulk density (g/cm³)

⁴⁵ As described in EPA (1996b), Jury's equation uses μg/cm³ as the units for the contaminant concentration (C_o). In this modification, C_{soil} * ρ_b has been substituted for C_o in order to use the more common units of mg/kg (ppm) for C_{soil}.

By examining Jury's expression for D_A we see that it can be written in terms of other factors that we have previously defined:

$$D_A = \frac{(D_{\text{air}} \cdot n_a^{10/3} \cdot H + D_w \cdot n_w^{10/3})}{H \cdot n^2} \cdot \frac{H}{(n_a \cdot H + n_w + \rho_b \cdot f_{\text{oc}} \cdot K_{\text{oc}})} \quad [\text{B-89}]$$

$$D_A = D_{\text{veff}} \cdot \left(\frac{H}{K_{\text{sw}} \cdot \rho_b} \right) \quad (3 \text{ phases}) \quad [\text{B-90}]$$

The $(H/K_{\text{sw}} \cdot \rho_b)$ term represents the ratio of a constituent's concentration in air to its concentration in soil. In other words, Jury's *apparent* diffusion coefficient is just the porous media *effective* diffusion coefficient written in a format that can be used with soil concentration as the source term instead of soil *gas* concentration.

We have seen that K_{sw} is associated with partitioning in three-phase systems. Therefore, this version of D_A can only be used for calculating VF_{ss} for three-phase systems. For four-phase systems the value must be adjusted by using R_{sw} in place of K_{sw} .

$$D_A^i = D_{\text{veff}}^i \cdot \left(\frac{H_i}{R_{\text{sw}}^i \cdot \rho_b} \right) \quad (4 \text{ phases}) \quad [\text{B-91}]$$

Substituting equation [B-87] for the flux term in [B-86] yields:

$$Q/C = \frac{2 \cdot C_{\text{soil}} \cdot \rho_b}{C_{\text{air}}} \cdot \sqrt{\frac{D_A}{\pi \cdot t_{\text{vol}} \cdot 3.16 \cdot 10^7 \text{ s/yr}}} \quad [\text{B-92}]$$

To estimate exposures the volatilization time (t_{vol}) is sometimes set to the exposure duration (ED).⁴⁶ However, this can result in very high rates of flux and overly conservative RBCs when short exposure durations, such as 1 year for construction and excavation workers, are used. Because chemicals that remain after a remedial action are not fresh spills (*i.e.*, we are not dealing with the early stages of volatilization), the Department suggests that the volatilization time be set to 6 years for exposures to children and 25 years for exposures to adults (see Appendix C).

Since the volatilization factor is simply $C_{\text{air}}/C_{\text{soil}}$, the equation above can be rearranged and appropriate unit conversion factors introduced to give an equation for estimating VF_{ss} – the volatilization factor for surface soils – from the Jury infinite source flux model:

$$\text{VF}_{\text{ss}} (\text{kg/m}^3) = \frac{2 \cdot \rho_b}{Q/C} \cdot \sqrt{\frac{D_A}{\pi \cdot t_{\text{vol}} \cdot 3.16 \cdot 10^7 \text{ s/yr}}} \cdot 10^4 \text{ cm}^2 / \text{m}^2 \quad [\text{B-93}]$$

Note that VF_{ss} is both contaminant-specific, since it depends on diffusion (D_A), and scenario-specific, since it depends on the volatilization time (t_{vol}).

⁴⁶ EPA (2002a) refers to this at the "exposure interval" and uses a constant value equal to 30 years (9.5×10^8 seconds). ASTM (1995b) defines this as the "averaging time for vapor flux" and uses a constant value equal to 25 years (7.88×10^8 seconds). The DEQ used the variable ED for this purpose in the 1999 edition of the RBDM guidance, but now employs the constant values described in the text above.

Although the Jury infinite source model is easy to use, it can overestimate the average contaminant flux, especially for very volatile contaminants, long exposure durations, or thin layers of surface contamination. This is because the model does not account for depletion of the source due to the volatilization. To prevent significant errors from using this model, the values of VF_{ss} calculated above should always be compared to the maximum volatilization factor ($VF_{ss,max}$) that would result if all of the contaminant volatilized over the designated time. In this case the maximum flux averaged over the entire site is:

$$J_{ss \text{ max}} = \frac{\text{total contaminant mass}}{\text{site area} \times \text{volatilization time}} \quad [\text{B-94}]$$

$$J_{ss \text{ max}} = \frac{A_{soil} \cdot L_{ss} \cdot \rho_b \cdot C_{soil}}{A_{site} \cdot t_{vol} \cdot 3.16 \cdot 10^7 \text{ s/yr}} \quad [\text{B-95}]$$

where:

$J_{ss,max}$	=	Maximum average site flux from surface soil ($\mu\text{g}/\text{cm}^2\text{-s}$)
A_{site}	=	Area of site that is open (<i>i.e.</i> , not covered with buildings) (cm^2)
A_{soil}	=	Area of contaminated surface soils (cm^2)
C_{soil}	=	Surface soil concentration (mg/kg)
L_{ss}	=	Thickness of contaminated surface soils (cm)
ρ_b	=	Soil bulk density (g/cm^3)
t_{vol}	=	Time over which volatilization flux is being averaged (yr)

Substituting this into equation [B-86], rearranging, and inserting a unit conversion factor yields:

$$VF_{ss \text{ max}} (\text{kg}/\text{m}^3) = \frac{f_{ss} \cdot L_{ss} \cdot \rho_b \cdot 10^4 \text{ cm}^2 / \text{m}^2}{(Q/C) \cdot t_{vol} \cdot 3.16 \cdot 10^7 \text{ s/yr}} \quad [\text{B-96}]$$

where f_{ss} is the fraction of the site's open area that has surface soil contamination ($f_{ss} = A_{soil}/A_{site}$ ⁴⁷). Note that $VF_{ss,max}$, unlike VF_{ss} , is not contaminant-specific, but is scenario-specific because it depends on the volatilization time (t_{vol}). Therefore, separate $VF_{ss,max}$ values are required for adult and child exposure scenarios. $VF_{ss,max}$, however, does not depend on the number of phases.

Depending on whether the attenuating capacity of the soil or the total contaminant present in the soil is the limiting factor, either VF_{ss} or $VF_{ss,max}$ will better represent the average flux over the exposure duration. Therefore, the smaller of the two VF values (VF_{ss} or $VF_{ss,max}$) is used for TF_{ss} in equations [B-100] through [B-109] to calculate the RBC_{ss} values for surface soils containing volatile contaminants.

Particulate Emission Factor

For *nonvolatile* contaminants, inhalation exposure results from breathing air that contains contaminated dust particles, the source of which is the contaminated surface soil. Therefore, the transport factor – in this case a particulate emission factor (PEF) – represents the amount of

⁴⁷ The default f_{ss} is 0.5. The Department may require a larger value for sites with wide-spread contamination.

contaminated dust that becomes entrained in the air above a given area of contaminated soil. This depends on many conditions including the type of soil, amount of ground cover, wind velocity, *etc.* EPA (1996b) incorporated the results of their previously-discussed 29-site modeling study into a particulate emission model developed by Cowherd *et al.* (1985) to develop an equation for calculating values of PEF.

$$\text{PEF} = \text{Q/C} \cdot \frac{3600 \text{ s/hr}}{0.036 \cdot (1-V) \cdot (U_m/U_t)^3 \cdot F(x)} \quad [\text{B-97}]$$

$$U_t = U_f \cdot 2.5 \cdot \ln(700/Z_o) \quad [\text{B-98}]$$

$$F(x) = 0.886 \cdot (U_t/U_m) \quad [\text{B-99}]$$

where:

PEF	=	Particulate emission factor (m ³ /kg)*
Q/C	=	Flux/mean concentration at center of source area ((g/m ² ·s)/(kg/m ³))
V	=	Fraction of vegetative cover (unitless)
U _m	=	Mean annual wind speed (m/s)
U _t	=	Equivalent threshold value of wind speed at 7 m (m/s)
U _f	=	Threshold friction velocity (m/s)
Z _o	=	Surface roughness height (cm)
F(x)	=	Function dependent of U _t /U _m (unitless)

*Note that the PEF that results from equations [B-97] through [B-99] is the reciprocal (m³/kg instead of kg/m³) of that needed for the nonvolatile transport in equations [B-100] through [B-109]. See *Important Note About Transport Factors* on page B-18.

To represent a conservative value that will account for most site conditions, EPA suggests using the 90th percentile value from their study. *In the format used in this guidance document*, the 90th percentile PEF value for a 0.5 acre site is 7.58 x 10⁻¹⁰ kg/m³. Therefore, for all nonvolatile contaminants, the Department used this value of PEF as the default TF in equations [B-100] through [B-109]. PEF does not depend on the number of phases in a system.

Three-Phase Calculations

RBCs for petroleum constituents in surface soils (RBC_{ss}) are calculated from equations [B-100] through [B-109]. Use the three-phase version of D_A for calculating TF_{ss}.

Residential - Carcinogens

$$\text{RBC}_{\text{ss}} \text{ (mg/kg)} = \frac{\text{ARL}_c \cdot \text{AT}_c \cdot 365 \text{ d/yr}}{\text{EF}_r \cdot \left[\left(\frac{\text{IFSadj}_i \cdot \text{SF}_o}{10^6 \text{ mg/kg}} \right) + \left(\frac{\text{SFSadj}_i \cdot \text{RAF}_d \cdot \text{SF}_o}{10^6 \text{ mg/kg}} \right) + (\text{IFAadj}_i \cdot \text{SF}_i \cdot \text{TF}_{\text{ss}}) \right]} \quad [\text{B-100}]$$

Residential - Noncarcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_n \cdot AT_{nc} \cdot 365 \text{ d/yr} \cdot BW_c}{ED_{Cr} \cdot EF_r \cdot \left[\left(\frac{IRSc_r}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_c \cdot AF_c \cdot RAF_d}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_c \cdot TF_{ss}}{RfD_i} \right) \right]} \quad [B-101]$$

Urban Residential – Carcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr}}{EF_u \cdot \left[\left(\frac{IFSadj_u \cdot SF_o}{10^6 \text{ mg/kg}} \right) + \left(\frac{SFSadj_u \cdot RAF_d \cdot SF_o}{10^6 \text{ mg/kg}} \right) + (IFAadj_u \cdot SF_i \cdot TF_{ss}) \right]} \quad [B-102]$$

Urban Residential – Noncarcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_n \cdot AT_{nc} \cdot 365 \text{ d/yr} \cdot BW_c}{ED_{cu} \cdot EF_u \cdot \left[\left(\frac{IRSc_u}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_c \cdot AF_c \cdot RAF_d}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_c \cdot TF_{ss}}{RfD_i} \right) \right]} \quad [B-103]$$

Occupational - Carcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot BW_a}{ED_o \cdot EF_o \cdot \left[\left(\frac{IRSo \cdot SF_o}{10^6 \text{ mg/kg}} \right) + \left(\frac{SA_o \cdot AF_o \cdot RAF_d \cdot SF_o}{10^6 \text{ mg/kg}} \right) + (IRA_o \cdot SF_i \cdot TF_{ss}) \right]} \quad [B-104]$$

Occupational - Noncarcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_n \cdot AT_{no} \cdot 365 \text{ d/yr} \cdot BW_a}{ED_o \cdot EF_o \cdot \left[\left(\frac{IRSo}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_o \cdot AF_o \cdot RAF_d}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_o \cdot TF_{ss}}{RfD_i} \right) \right]} \quad [B-105]$$

Construction Worker – Carcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot BW_a}{ED_k \cdot EF_k \cdot \left[\left(\frac{IRSk \cdot SF_o}{10^6 \text{ mg/kg}} \right) + \left(\frac{SA_k \cdot AF_k \cdot RAF_d \cdot SF_o}{10^6 \text{ mg/kg}} \right) + (IRA_k \cdot SF_i \cdot TF_{ss}) \right]} \quad [B-106]$$

Construction Worker – Noncarcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_n \cdot AT_{nk} \cdot 365 \text{ d/yr} \cdot BW_a}{ED_k \cdot EF_k \cdot \left[\left(\frac{IRSk}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_k \cdot AF_k \cdot RAF_d}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_k \cdot TF_{ss}}{RfD_i} \right) \right]} \quad [B-107]$$

Excavation Worker - Carcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot BW_a}{ED_e \cdot EF_e \cdot \left[\left(\frac{IRSe \cdot SF_o}{10^6 \text{ mg/kg}} \right) + \left(\frac{SA_e \cdot AF_e \cdot RAF_d \cdot SF_o}{10^6 \text{ mg/kg}} \right) + (IRA_e \cdot SF_i \cdot TF_{ss}) \right]} \quad [B-108]$$

Excavation Worker - Noncarcinogens

$$RBC_{ss} \text{ (mg/kg)} = \frac{ARL_n \cdot AT_{ne} \cdot 365 \text{ d/yr} \cdot BW_a}{ED_e \cdot EF_e \cdot \left[\left(\frac{IRS_e}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_e \cdot AF_e \cdot RAF_d}{RfD_o \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_e \cdot TF_{ss}}{RfD_i} \right) \right]} \quad [B-109]$$

where:

RBC _{ss}	=	Risk-based concentration for soils (mg/kg)
*AF	=	Adherence factor (mg/cm ² -d)
ARL _c	=	Acceptable Risk Level for Carcinogens (unitless)
ARL _n	=	Acceptable Risk Level for Noncarcinogens (unitless)
*AT _n	=	Averaging time – noncarcinogens (yr)
AT _c	=	Averaging time – carcinogens (yr)
*BW	=	Body weight (kg)
*ED	=	Exposure duration (yr)
*EF	=	Exposure frequency (d/yr)
*IFAadj	=	Age-adjusted inhalation factor for air ([m ³ -yr]/[kg-d])
*IFSadj	=	Age-adjusted ingestion factor for soils ([mg-yr]/[kg-d])
*IRA	=	Inhalation rate (m ³ /d)
*IRS	=	Ingestion rate for soils (mg/d)
*SFSadj	=	Age-adjusted dermal contact factor for soils ([mg-yr]/[kg])
RAF _d	=	Relative dermal absorption factor (unitless)
RfD _i	=	Reference dose – inhaled (mg/kg-d)
RfD _o	=	Reference dose – oral (mg/kg-d)
*SA	=	Skin surface contact area (cm ²)
SF _i	=	Cancer slope factor – inhaled (mg/kg-d) ⁻¹
SF _o	=	Cancer slope factor – oral (mg/kg-d) ⁻¹
TF _{ss}	=	Transport factor for surface soil, which is either a volatilization factor (VF _{ss} , kg/m ³), or a particulate emission factor (PEF, kg/m ³)

* The subscripts on these parameters in the equations refer to the following: a = adult; c = child; cr = residential child; cu = urban residential child; e = excavation worker; k = construction worker; o = occupational; r = residential; and u = urban residential.

Four-Phase Calculations

One of the three exposure pathways (the inhalation pathway) in this combined equation is an indirect exposure with a transport factor that depends on the composition of the system. Therefore, use the hazard quotient equations below along with the method for indirect pathways in Section B.2.3.3 to calculate TPH RBCs for surface soil exposures. Use the four-phase version of D_A for calculating TF_{ss}.

Residential - Noncarcinogens

$$HQ_{ss}^i = \frac{C_{soil}^i \cdot ED_{cr} \cdot EF_r}{AT_{nc} \cdot 365 \text{ d/yr} \cdot BW_c} \cdot \left[\left(\frac{IRS_{cr}}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_c \cdot AF_c \cdot RAF_d}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_c \cdot TF_{ss}^i}{RfD_i^i} \right) \right] \quad [B-110]$$

Urban Residential – Noncarcinogens

$$HQ_{ss}^i = \frac{C_{soil}^i \cdot ED_{cu} \cdot EF_u}{AT_{nc} \cdot 365 \text{ d/yr} \cdot BW_c} \cdot \left[\left(\frac{IRS_{cu}}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_c \cdot AF_c \cdot RAF_d}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_c \cdot TF_{ss}^i}{RfD_i^i} \right) \right] \quad [B-111]$$

Occupational - Noncarcinogens

$$HQ_{ss}^i = \frac{C_{soil}^i \cdot ED_o \cdot EF_o}{AT_{no} \cdot 365 \text{ d/yr} \cdot BW_a} \cdot \left[\left(\frac{IRS_o}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_o \cdot AF_o \cdot RAF_d}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_o \cdot TF_{ss}^i}{RfD_i^i} \right) \right] \quad [B-112]$$

Construction Worker – Noncarcinogens

$$HQ_{ss}^i = \frac{C_{soil}^i \cdot ED_k \cdot EF_k}{AT_{nk} \cdot 365 \text{ d/yr} \cdot BW_a} \cdot \left[\left(\frac{IRS_k}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_k \cdot AF_k \cdot RAF_d}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_k \cdot TF_{ss}^i}{RfD_i^i} \right) \right] \quad [B-113]$$

Excavation Worker - Noncarcinogens

$$HQ_{ss}^i = \frac{C_{soil}^i \cdot ED_e \cdot EF_e}{AT_{ne} \cdot 365 \text{ d/yr} \cdot BW_a} \cdot \left[\left(\frac{IRS_e}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{SA_e \cdot AF_e \cdot RAF_d}{RfD_o^i \cdot 10^6 \text{ mg/kg}} \right) + \left(\frac{IRA_e \cdot TF_{ss}^i}{RfD_i^i} \right) \right] \quad [B-114]$$

where:

- HQ_{ss}^i = Hazard quotient for TPH fraction "i" – surface soils (unitless)
- C_{soil}^i = The concentration of TPH fraction "i" in surface soil (mg/kg)

All other terms are as previously defined.

Some uncertainty still surrounds the determination of risk associated with dermal contact (Zartarian and Leckie, 1998). One important data gap is the lack of verified toxicity values for the dermal route. For screening purposes we often assume that oral toxicity values can be substituted for missing dermal toxicity values since that is usually a conservative estimate. However, when conducting site-specific risk assessments (outside of the generic lookup numbers) this may not always be an appropriate assumption and should be checked by a qualified toxicologist.

Summary – Calculating RBCs for the Exposure to Contaminated Surface Soils

For each contaminant:

1. Determine if the contaminant is a volatile or a nonvolatile compound.
2. If volatile,
 - a. Use equation [B-93] with either the 3-phase or 4-phase D_A to calculate VF_{ss} .
 - b. Use equation [B-96] to calculate VF_{ssmax} for the appropriate scenario.
 - c. Let TF_{ss} = the smaller of VF_{ss} or VF_{ssmax} .
3. If nonvolatile, let TF_{ss} = PEF (7.58×10^{-10} kg/m³).
4. For petroleum constituents, use TF_{ss} along with the default exposure factors, contaminant toxicity data, and the appropriate exposure-specific equation from [B-100] through [B-109] to calculate RBC_{ss} .
5. For petroleum products, use TF_{ss} along with the default exposure factors, contaminant toxicity data, and the appropriate hazard quotient equation to calculate TPH RBC_{ss} using the method for indirect exposure pathways described in Section B.2.4.2.

Suggestions for Site-Specific Calculations Related to Exposure to Contaminated Surface Soils

One or both of the following approaches may be useful if you want to evaluate site-specific exposure to contaminated surface soils.

1. Calculate RBC_{ss} from site-specific transport factors.

If the contaminant of concern is volatile, one of the following methods can be used to calculate site-specific values for VF :

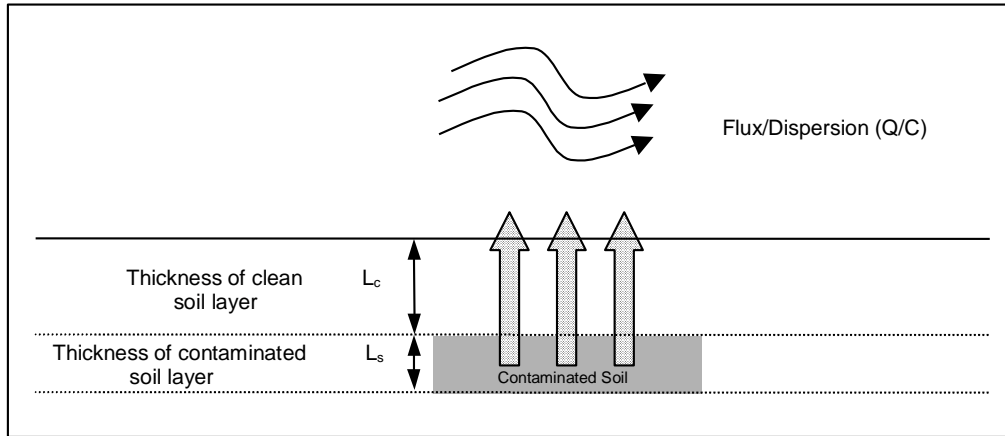
- a. Calculate a site-specific value for VF_{ss} by substituting your own data for ρ_b and D_A into equation [B-93]. Note that rates of diffusion can be very sensitive to soil moisture content.
- b. Calculate a site-specific value for VF_{ssmax} by substituting your own data for L_{ss} and f_{ss} into equation [B-96]; or
- c. Select a less conservative flux model (e.g., a finite-source model; see Section B.4) to estimate a site-specific average flux. Use the model results with equation [B-55] to calculate VF_{ss} .

If the contaminant of concern is nonvolatile and you are considering estimating a site-specific PEF, refer to Section 2.4.5 and Table 3 in EPA (1996b). Note, however, that many of the terms in the PEF equation are difficult to evaluate. Changing only the Q/C term by choosing a more appropriate one from EPA's Table 3 is not likely to change the PEF by more than 10 or 20%. The change in RBC will be even less than this since it is based on exposures from three pathways and PEF only affects one of the three.

2. Use statistical methods to evaluate the soil data.

When used for screening purposes, RBCs are usually compared to the highest concentrations remaining at the site. For exposure to surface soils it may be useful to collect and analyze enough samples so that the RBCs (either generic or site-specific) can be compared to the 90% upper confidence limit of the mean soil concentration rather than the maximum soil concentration. Note, however, that for large sites such statistical averaging may have to be done over a number of smaller exposure units rather than the entire site (see Section 3.1.7).

B.3.2.2 Volatilization from Subsurface Soils to Outdoor Air



Volatilization from subsurface soils to outdoor air should be considered a potential exposure pathway for all residential, urban residential and occupational scenarios.

For the purposes of this document, subsurface soils are considered to be those located at depths greater than 100 cm (~3 ft). Because contamination is at depth, it is assumed that there will be no current direct exposure to the contaminated soils. Therefore, dermal contact and soil ingestion are not expected to contribute to the overall risk, and exposure is limited to inhalation. Furthermore, the inhalation pathway is limited to inhalation of volatiles, since contaminated dust and particulates are not likely to result from an undisturbed subsurface source. Note, however, that if this subsurface soil is disturbed or brought to the surface during excavation, then exposure should be evaluated by treating this as *surface* soil (Section B.3.2.1).⁴⁸

Since the potential exposure is from an indirect pathway, a transport model is needed to estimate the outdoor air concentration that may result as contaminants volatilize from the subsurface soils and migrate into the air. Although the transport equation is different than that used for the volatilization component of the surface soil pathway, much of the logic is the same as that used in Section B.3.2.1. Basically, the goal will be to estimate the contaminant flux at the surface and combine that with EPA's modeled flux/concentration relationship (Q/C, EPA (1996b)) to derive a volatilization factor. The VF will then be used along with the previously calculated RBC_{air} values to calculate the corresponding RBC values for the subsurface soil to outdoor air pathway (RBC_{so}).

Assuming that the main transport mechanism for volatile contaminants in the subsurface to reach the surface is diffusion, then flux at the surface can be estimated with Fick's first law of diffusion (see Section B.2.3.2).

$$J = -D \cdot \frac{\partial C}{\partial L} \quad [B-115]$$

⁴⁸ For this reason, contaminated subsurface soil could be a potential *future* risk via direct contact.

In our situation D is the effective diffusion coefficient (D_{eff}) for the contaminant in a porous medium (equation [B-58]) and L is the distance to the subsurface contamination. Therefore, to complete the model we need a value for C , the vapor phase concentration at the source (*i.e.*, the soil gas concentration within the contaminated soil zone). This can be estimated from a combination of equilibrium partition coefficients (see Section B.2.1.3). For a three-phase system:

$$C_{\text{source}} = C_{\text{soil}} \cdot \frac{H}{K_{\text{sw}}} \quad [\text{B-116}]$$

where:

C_{source}	=	The vapor-phase contaminant concentration in the subsurface soil ($\mu\text{g}/\text{cm}^3$)
C_{soil}	=	The total contaminant concentration in the subsurface soil (mg/kg)
H	=	Henry's constant (unitless)
K_{sw}	=	Total soil sample/pore water concentration ratio for 3-phase systems (cm^3/g)

Using the results of equation [B-116] for C , the concentration gradient can be written as:

$$\frac{\partial C}{\partial L} = \frac{C_{\text{soil}} \cdot H}{K_{\text{sw}} \cdot L_c} \quad [\text{B-117}]$$

where L_c (cm) is the thickness of the clean soil layer overlying the contaminated zone. Inserting this into Fick's first law (equation [B-115]) yields the model for diffusive flux from subsurface contamination (J_s)⁴⁹:

$$J_s = D_{\text{v,eff}} \cdot \left(\frac{H \cdot C_{\text{soil}}}{K_{\text{sw}} \cdot L_c} \right) \quad [\text{B-118}]$$

As was done in Section B.3.2.1, this flux model can be substituted into equation [B-86] to give:

$$Q/C = \frac{D_{\text{v,eff}} \cdot H \cdot C_{\text{soil}}}{K_{\text{sw}} \cdot L_c \cdot C_{\text{air}}} \quad [\text{B-119}]$$

This equation can then be rearranged and appropriate unit conversion factors added to derive the volatilization factor for the subsurface soil to outdoor air pathway (VF_{so}):

$$\text{VF}_{\text{so}} (\text{kg} / \text{m}^3) = \frac{D_{\text{v,eff}} \cdot H \cdot 10^4 \text{cm}^2 / \text{m}^2}{(Q/C) \cdot K_{\text{sw}} \cdot L_c} \quad (3 \text{ phases}) \quad [\text{B-120}]$$

VF_{so} is contaminant-specific and, therefore, must be calculated for each compound. VF_{so} also depends on the composition of the system. The equation above is for a three-phase system since we used a three-phase relationship for the source term in equation [B-116]. By starting with

⁴⁹ Note that the minus sign has been omitted from equation [B-118] (compare to [B-115]) since in our application we know the flux direction and are only concerned with calculating the mass.

equation [B-52] as the four-phase relationship for the source term and following the same derivation we obtain the following four-phase version of VF_{so} .

$$VF_{so}^i (\text{kg} / \text{m}^3) = \frac{D_{veff}^i \cdot H_i \cdot 10^4 \text{ cm}^2 / \text{m}^2}{(Q/C) \cdot R_{sw}^i \cdot L_c} \quad (4 \text{ phases}) \quad [\text{B-121}]$$

Like the Jury infinite source model discussed in Section B.3.2.1, the diffusion flux model is also prone to overestimation of the average contaminant flux when applied to very volatile contaminants. To prevent significant errors from using this model, the values of VF_{so} calculated above should always be compared to the maximum volatilization factor ($VF_{so\max}$) that would result if all of the contaminant volatilized over the designated time. In this case the maximum flux averaged over the entire site and over the volatilization time is simply:

$$J_{so \max} = \frac{A_{soil} \cdot L_s \cdot \rho_b \cdot C_{soil}}{A_{site} \cdot t_{vol} \cdot 3.16 \cdot 10^7 \text{ s/yr}} \quad [\text{B-122}]$$

where:

$J_{so\max}$	=	Maximum average flux from subsurface soil to outdoor air ($\mu\text{g}/\text{cm}^2\text{-s}$)
A_{site}	=	Area of site that is open (<i>i.e.</i> , not covered with buildings) (cm^2)
A_{soil}	=	Area of contaminated subsurface soils (cm^2)
C_{soil}	=	Contaminant concentration in subsurface soil (mg/kg)
L_s	=	Thickness of contaminated subsurface soils (cm)
ρ_b	=	Soil bulk density (g/cm^3)
t_{vol}	=	Time over which volatilization flux is being averaged (yr)

Substituting this into equation [B-86], rearranging, and inserting a unit conversion factor yields:

$$VF_{so \max} (\text{kg}/\text{m}^3) = \frac{f_{so} \cdot L_s \cdot \rho_b \cdot 10^4 \text{ cm}^2 / \text{m}^2}{(Q/C) \cdot t_{vol} \cdot 3.16 \cdot 10^7 \text{ s/yr}} \quad [\text{B-123}]$$

where f_{so} is the fraction of site's open area underlain with contaminated subsurface soils ($f_{so} = A_{soil}/A_{site}$ ⁵⁰). Note that $VF_{so\max}$ is not contaminant-specific or scenario-specific. $VF_{so\max}$ also does not depend on the number of phases.

The smaller of the two VF values (VF_{so} or $VF_{so\max}$) is used as the transport factor (TF_{so}) to calculate RBC_{so} values for subsurface soil.

Three-Phase Calculations

RBCs for petroleum constituents in subsurface soils (RBC_{so}) are calculated using the following equation. Use the three-phase version of VF_{so} along with $VF_{so\max}$ for determining TF_{so} .

⁵⁰ The default f_{so} is 0.5. The Department may require a larger value for sites with wide-spread contamination.

$$RBC_{so}(mg/kg) = \frac{RBC_{air}(\mu g/m^3) \cdot 10^{-3} mg/\mu g}{TF_{so}(kg/m^3)} \quad [B-124]$$

Four-Phase Calculations

Since the volatilization factor from subsurface soil to outdoor air (VF_{so}) depends on the composition of the system, use the hazard quotient equation below along with the method for indirect pathways in Section B.2.4.2 to calculate TPH RBCs for exposures due to volatilization from subsurface soil to outdoor air. Use the four-phase version of VF_{so} along with $VF_{so,max}$ for determining TF_{so} . The concentrations of the TPH fractions in the soil (C_{soil}^i) are calculated by multiplying the estimated value of TPH RBC by the weight fractions from the product of interest given in Appendix F.

$$HQ_{so}^i = \frac{C_{soil}^i \cdot TF_{so}^i \cdot 1000 \mu g/mg}{RBC_{air}} \quad [B-125]$$

where:

C_{soil}^i	=	The concentration of TPH fraction "i" in subsurface soil (mg/kg)
HQ_{so}^i	=	Hazard quotient for TPH fraction "i" – subsurface soils to outdoor air (unitless)
RBC_{air}^i	=	Risk-based air concentration for TPH fraction "i" ($\mu g/m^3$)
TF_{so}^i	=	Transport factor for TPH fraction "i" from subsurface soils to outdoor air

Summary - Calculating RBCs for Subsurface Soil Volatilization to Outdoor Air

For each contaminant:

1. Use equation [B-120] or [B-121] to calculate the three-phase or four-phase VF_{so} .
2. Use equation [B-123] to calculate $VF_{so,max}$ for the appropriate scenario.
3. Let TF_{so} = the smaller of VF_{so} or $VF_{so,max}$.
4. For petroleum constituents, use TF_{so} along with the appropriate RBC_{air} and equation [B-124] to calculate RBC_{so} .
5. For petroleum products, use TF_{so} along with the hazard quotient equation to calculate the TPH RBC_{so} using the method for indirect exposure pathways described in Section B.2.4.2.

Suggestions for Site-Specific Calculations for the Soil-to-Outdoor-Air Pathway

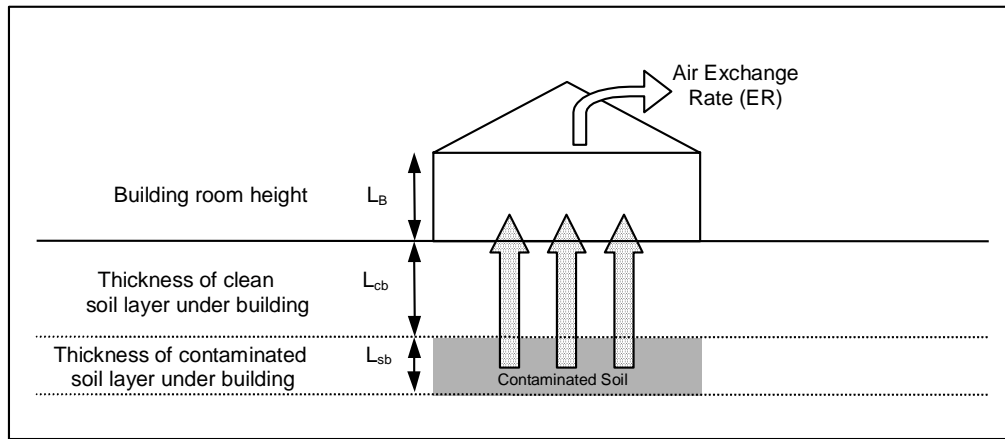
Since this is entirely an indirect pathway, site-specific efforts should be directed at modifying the generic transport factors (in this case, the volatilization factors), which in turn will change the RBCs. One of the following methods may be useful for this purpose:

1. Calculate a site-specific value for VF_{so} by substituting your own data for L_c into equation [B-120]. Site-specific information could also be used to modify the value of D_{veff} in this equation. Note that rates of diffusion can be very sensitive to soil moisture content.
2. Calculate a site-specific value for $VF_{so,max}$ by substituting your own data for L_s , f_{so} , and ρ_b into equation [B-123].
3. Select a less conservative flux model (e.g., a finite source model; see Section B.5) to estimate a site-specific average flux. Use the model results with equation [B-55] to calculate VF_{so} .

Use the site-specific volatilization factors with appropriate values for RBC_{air} and equation [B-124] to calculate site-specific values for RBC_{so} .

Compare your RBC_{so} value to C_{sat} to determine if exposure via this pathway is reasonable (see Section B.2.1.4).

B.3.2.3 Volatilization from Subsurface Soils to Indoor Air



If contaminated soils are located under or very close to existing buildings, or in locations where buildings are likely to be located in the future, exposures for volatilization to indoor air should be evaluated.

Johnson and Ettinger (1991) developed a model for volatilization from subsurface soils to indoor air that takes into account both diffusive flux like that used for the outdoor air pathway, and the convective flux that results when lower air pressures inside buildings draw contamination inside through cracks in the floor. Their model derives values for α , which they define as:

$$\alpha = \frac{C_{\text{building}}}{C_{\text{source}}} \quad [\text{B-126}]$$

where:

- α = Source attenuation coefficient (unitless)
- C_{building} = Contaminant concentration in air inside the building (g/cm^3)
- C_{source} = The vapor-phase contaminant concentration in the subsurface soil (g/cm^3)

Substituting equation [B-116] for C_{source} yields an expression that relates the air concentration in the building to the soil concentration in a three-phase system.

$$\alpha = \frac{C_{\text{building}} \cdot K_{\text{sw}}}{C_{\text{soil}} \cdot H} \quad [\text{B-127}]$$

Since we have defined soil-to-air volatilization factors as $\text{VF} = C_{\text{air}}/C_{\text{soil}}$, and since C_{building} is the air concentration in the building that must not exceed acceptable risk levels, this equation can be rearranged to arrive at a relationship that uses α to derive the volatilization factor for the subsurface-soil-to-indoor-air pathway, VF_{si} .

$$\text{VF}_{\text{si}} = \frac{\alpha \cdot H}{K_{\text{sw}}} \quad [\text{B-128}]$$

Johnson and Ettinger (1991) derive expressions for a steady-state α resulting from an infinite source, and a time-averaged α resulting from a finite source. They also derive alternative expressions for infinite-source α terms under certain limiting conditions, such as when transport is dominated by either convection or diffusion. When the source is directly underneath a building foundation (*i.e.*, contaminated soils are in contact with the foundation), convection is expected to dominate. However, when the source is distant from the foundation, then diffusion is expected to dominate. The infinite-source diffusion-limited equation for α is:

$$\alpha = \frac{\left(\frac{D_{T\text{eff}} \cdot A_B}{Q_B \cdot L_{cb}} \right)}{1 + \left(\frac{D_{T\text{eff}} \cdot A_B}{Q_B \cdot L_{cb}} \right) + \left(\frac{D_{T\text{eff}} \cdot A_B \cdot L_{crk}}{D_{crk\text{eff}} \cdot A_{crk} \cdot L_{cb}} \right)} \quad [\text{B-129}]$$

where:

A_B	=	Cross-sectional area of building (cm^2)
A_{crk}	=	Area of cracks available for transport into the building (cm^2)
$D_{crk\text{eff}}$	=	Effective diffusion coefficient in building cracks (cm^2/s)
$D_{T\text{eff}}$	=	Total effective diffusion coefficient between source and building (cm^2/s)
L_{cb}	=	Thickness of clean soil layer between contaminated soil and building (cm)
L_{crk}	=	Thickness of crack (building slab) (cm)
Q_B	=	Building ventilation rate (cm^3/s)

The building ventilation rate (Q_B) can be expressed in terms of the building dimensions and an exchange rate (ER) which is the frequency at which one building volume of air is replaced.

$$Q_B = \frac{A_B \cdot L_B \cdot ER}{86,400 \text{ s/day}} \quad [\text{B-130}]$$

where:

A_B	=	Cross-sectional area of building (cm^2)
L_B	=	Height of rooms in building (cm)
ER	=	Building air exchange rate (day^{-1})

A_{crk}/A_B can be expressed as the fraction of the building slab that is available for transport (f_{crk}). Making these substitutions in [B-129] and using the resulting term for α in [B-128] produces the following equation for VF_{si} :

$$VF_{si} (\text{kg}/\text{m}^3) = \frac{\left(\frac{H}{K_{sw}} \right) \cdot \left(\frac{D_{v\text{eff}} \cdot 86,400\text{s/day}}{L_B \cdot ER \cdot L_{cb}} \right)}{1 + \left(\frac{D_{v\text{eff}} \cdot 86,400\text{s/day}}{L_B \cdot ER \cdot L_{cb}} \right) + \left(\frac{D_{T\text{eff}} \cdot L_{crk}}{f_{crk} \cdot D_{crk\text{eff}} \cdot L_{cb}} \right)} \cdot 10^3 \frac{\text{kg} \cdot \text{cm}^3}{\text{g} \cdot \text{m}^3} \quad [\text{B-131}]$$

In the case of a vadose zone source where the soil is relatively homogeneous, $D_{T\text{eff}}$ is simply $D_{v\text{eff}}$ defined in equation [B-58]. Assuming that the cracks around the foundation and in the slab are likely to be filled with the same porous medium over which the building sits, $D_{v\text{eff}}$ can also be substituted for $D_{crk\text{eff}}$. In this case the equation for VF_{si} simplifies to:

$$VF_{si} \text{ (kg/m}^3\text{)} = \frac{\left(\frac{H}{K_{sw}}\right) \cdot \left(\frac{D_{veff} \cdot 86,400\text{s/day}}{L_B \cdot ER \cdot L_{cb}}\right)}{1 + \left(\frac{D_{veff} \cdot 86,400\text{s/day}}{L_B \cdot ER \cdot L_{cb}}\right) + \left(\frac{L_{crk}}{f_{crk} \cdot L_{cb}}\right)} \cdot 10^3 \frac{\text{kg} \cdot \text{cm}^3}{\text{g} \cdot \text{m}^3} \text{ (3 phases)} \quad [\text{B-132}]$$

VF_{si} is contaminant-specific and, therefore, must be calculated for each compound. VF_{si} also depends on the composition of the system. The equation above is for a three-phase system since we used a three-phase relationship for the source term in equation [B-116]. By starting with equation [B-52] as the four-phase relationship for the source term and following the same derivation we obtain the following four-phase version of VF_{si} .

$$VF_{si}^i \text{ (kg/m}^3\text{)} = \frac{\left(\frac{H_i}{R_{sw}^i}\right) \cdot \left(\frac{D_{veff}^i \cdot 86,400\text{s/day}}{L_B \cdot ER \cdot L_{cb}}\right)}{1 + \left(\frac{D_{veff}^i \cdot 86,400\text{s/day}}{L_B \cdot ER \cdot L_{cb}}\right) + \left(\frac{L_{crk}}{f_{crk} \cdot L_{cb}}\right)} \cdot 10^3 \frac{\text{kg} \cdot \text{cm}^3}{\text{g} \cdot \text{m}^3} \text{ (4 phases)} \quad [\text{B-133}]$$

Since this equation is based on an infinite source model, it is likely to overestimate volatilization into buildings in cases where the contaminants are very volatile. To prevent significant errors from using this model, the values of VF_{si} calculated using the above equation should always be compared to the maximum volatilization factor ($VF_{si,max}$) that would result if all of the contaminant volatilized into the building over the designated time. $VF_{si,max}$ can be derived by assuming that the maximum average air concentration in the building will be the total contaminant mass in the soil divided by the total air volume in the building over the volatilization time:

$$C_{air} = \frac{A_{soil} \cdot L_{sb} \cdot \rho_b \cdot C_{soil} \cdot 10^6 \text{ cm}^3/\text{m}^3}{A_B \cdot L_B \cdot ER \cdot t_{vol} \cdot 365 \text{ day/yr}} \quad [\text{B-134}]$$

where:

A_B	=	Cross-sectional area of building (cm ²)
A_{soil}	=	Area of contaminated subsurface soils (cm ²) ⁵¹
C_{air}	=	Contaminant concentration in building air (µg/m ³)
C_{soil}	=	Contaminant concentration in subsurface soil (mg/kg)
ER	=	Building air exchange rate (day ⁻¹)
L_B	=	Height of building (cm)
L_{sb}	=	Thickness of contaminated subsurface soils under building (cm)
ρ_b	=	Soil bulk density (g/cm ³)
t_{vol}	=	Time over which volatilization flux is being averaged (yr)

Rearranging to fit the definition of a volatilization factor ($VF = C_{air}/C_{soil}$), substituting $f_{sb} = A_{soil}/A_B$ ⁵², and inserting appropriate unit conversion factors yields:

⁵¹ A_{soil} should include not only the area of contaminated soil under the building, but also the area of contaminated soil within 10 feet of a commercial building or within 50 feet of a residential building (see Table 2.4).

$$VF_{si,max}(kg/m^3) = \frac{f_{sb} \cdot L_{sb} \cdot \rho_b}{L_B \cdot ER \cdot t_{vol} \cdot 365 \text{ day/yr}} \cdot 10^3 \frac{kg \cdot cm^3}{g \cdot m^3} \quad [B-135]$$

$VF_{si,max}$ is not contaminant-specific or scenario-specific. $VF_{si,max}$ also does not depend on the number of phases.

The smaller of the two VF values (VF_{si} or $VF_{si,max}$) is used as the transport factor (TF_{si}) to calculate RBC_{si} values for subsurface soil.

Three-Phase Calculations

RBCs for volatilization of petroleum constituents from subsurface soils to indoor air (RBC_{si}) are calculated using the following equation. Use the three-phase version of VF_{si} along with $VF_{si,max}$ for determining TF_{si} .

$$RBC_{si}(mg/kg) = \frac{RBC_{air}(\mu g / m^3) \cdot 10^{-3} mg / \mu g}{TF_{si}(kg / m^3)} \quad [B-136]$$

Four-Phase Calculations

Since the volatilization factor from subsurface soil to indoor air (VF_{si}) depends on the composition of the system, use the hazard quotient equation below along with the method for indirect pathways in Section B.2.4.2 to calculate TPH RBCs for exposures due to volatilization from subsurface soil to indoor air. Use the four-phase version of VF_{si} along with $VF_{si,max}$ for determining TF_{si} . The concentrations of the TPH fractions in the soil (C_{soil}^i) are calculated by multiplying the estimated value of TPH RBC by the weight fractions from the product of interest given in Appendix F.

$$HQ_{si}^i = \frac{C_{soil}^i \cdot TF_{si}^i \cdot 1000 \mu g / mg}{RBC_{air}^i} \quad [B-137]$$

where:

- C_{soil}^i = The concentration of TPH fraction "i" in subsurface soil (mg/kg)
- HQ_{si}^i = Hazard quotient for TPH fraction "i" – subsurface soils to indoor air (unitless)
- RBC_{air}^i = Risk-based air concentration for TPH fraction "i" ($\mu g/m^3$)
- TF_{si}^i = Transport factor for TPH fraction "i" from subsurface soils to indoor air

⁵² The default f_{sb} is 0.5. The Department may require a larger value for sites with widespread contamination.

Note that the method described in this section is based on the assumption that the contaminated soils under the building are not directly in contact with, or close to, the concrete slab.⁵³ In other words, there is a layer of clean soil over the contaminated zone that limits the movement of contaminants resulting in a system that is diffusion limited. If contamination is near the slab it may be necessary to use a model to estimate exposure that takes advection into account. Also, the RBCs derived in this section are not to be applied to buildings with dirt floors or other substandard flooring that does not provide a barrier to underlying vapors.

Summary - Calculating RBCs for Soil-to-Indoor-Air Pathway

For each contaminant:

1. Use equation [B-132] or [B-133] to calculate the three-phase or four-phase VF_{si} .
2. Use equation [B-135] to calculate $VF_{si\max}$ for the appropriate scenario.
3. Let TF_{si} = the smaller of VF_{si} or $VF_{si\max}$.
4. For petroleum constituents, use TF_{si} along with the appropriate RBC_{air} and equation [B-136] to calculate RBC_{si} .
5. For petroleum products, use TF_{si} along with the hazard quotient equation to calculate TPH RBC_{si} using the method for indirect exposure pathways described in Section B.2.4.2.

Suggestions for Site-Specific Calculations for the Soil-to-Indoor-Air Pathway

Since this is an indirect pathway, you can use site-specific data to modify the generic transport factors (in this case, the volatilization factors). One of the following methods may be useful for this purpose:

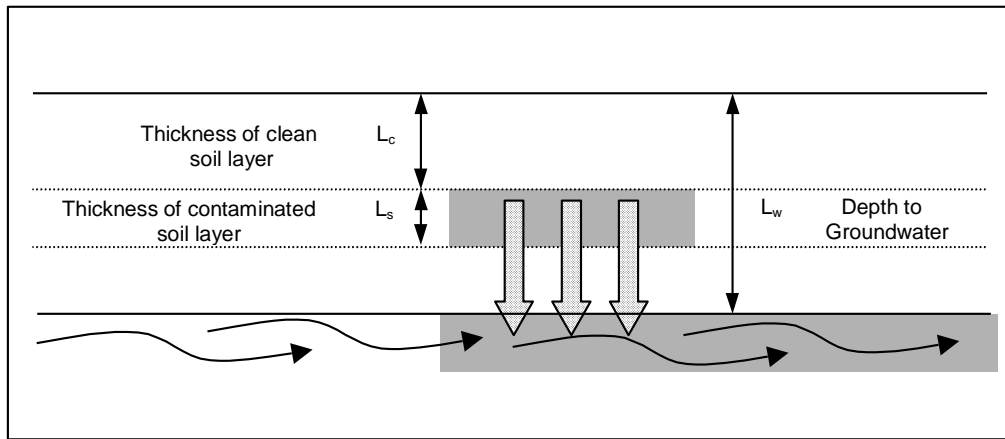
1. Calculate a site-specific value for VF_{si} by substituting site-specific data for L_B , L_{cb} , L_{crk} , f_{crk} and ER into equation [B-132]. Site-specific information could also be used to modify the value of D_{veff} in this equation. Note that rates of diffusion can be very sensitive to soil moisture content. See EPA (2002b) for soil-dependent properties for the Johnson and Ettinger model.
2. Calculate a site-specific value for $VF_{si\max}$ by substituting site-specific data for f_{sb} , L_{sb} , and L_B into equation [B-135].
3. Select a less conservative flux model (e.g., a finite source model; see Section B.5) to estimate a site-specific value of α . Use the model results with equation [B-132] to calculate VF_{si} .

Use the site-specific volatilization factors with appropriate values for RBC_{air} and equation [B-136] to calculate site-specific values for RBC_{si} .

Compare RBC_{si} to C_{sat} to determine if exposure via this pathway is reasonable (see Section B.2.1.4).

⁵³ Studies reported in EPA (2002b) indicate that the zone of advective influence from a building is likely limited to a zone within 1 to 2 meters of the building foundation. Therefore, contamination closer than about 6 feet below a building may require site-specific modeling to assess potential exposures.

B.3.2.4 Leaching to Groundwater



Leaching to groundwater should be considered a potential pathway at any site where vadose zone contamination has been detected and the underlying groundwater is reasonably likely to be used as a source of drinking water or other use where exposure may occur.

The generic RBCs for the leaching-to-groundwater pathway (RBC_{sw}) are based on protecting the groundwater for use as drinking water (*i.e.*, tap water in a building). Therefore, this is an indirect pathway which requires a transport model to estimate the concentration of a given contaminant in groundwater (C_{gw}) that might result from a specified concentration of that contaminant in the vadose zone soil (C_{soil}). The ratio of the resulting groundwater concentration to the initial soil concentration is the transport factor. In this case the transport factor is usually referred to as the leaching factor (LF).

$$LF (kg/L) = \frac{C_{gw} (\mu g/L)}{C_{soil} (mg/kg)} \cdot 10^{-3} mg/\mu g \quad [B-138]$$

Leaching factors for the soil-to-groundwater pathway are made up of two components: (1) a term that represents how a contaminant partitions into the pore water from the contaminated soil (the partitioning factor, PF), and (2) a term that represents how that pore water concentration subsequently becomes attenuated due to factors like sorption, volatilization, and dilution as the contaminant makes its way from the vadose zone to the groundwater (the dilution-attenuation factor, DAF). Since K_{sw} is the ratio of the soil concentration to the equilibrium pore-water concentration in a three-phase system (see Section B.2.1.3), $1/K_{sw}$ can be used for PF, the pore-water-to-soil partitioning factor.

$$LF (kg/L) = \frac{PF (kg/L)}{DAF} = \frac{1}{K_{sw} \cdot DAF} \quad (3 \text{ phases}) \quad [B-139]$$

Similarly, $1/R_{sw}$ can be used for PF in the leaching factor for four-phase systems.

$$LF_{sw}^i \text{ (kg/L)} = \frac{1}{R_{sw}^i \cdot DAF} \quad (4 \text{ phases}) \quad [B-140]$$

There are a number of different ways to estimate the DAF term that are adequate for screening models. EPA (1996b) contains an excellent summary. Also discussed in EPA (1996b) is a more sophisticated modeling study that EPA carried out to develop a default DAF term for use with the *Soil Screening Guidance* (EPA, 1996a). For this study EPA used their Composite Model for Leaching Migration with Transformation Products (EPACMTP) to derive probabilistic estimates of DAF for source areas ranging from 0.02 acres up to 69 acres with varying chemical and site parameters.

The results of the EPA study indicate that a DAF of about 170 would be protective at the 90th percentile for a 0.5 acre site. The DAF drops to about 7.0 when coverage is extended to the 95th percentile. The DAF increases as the size of the site decreases. Values for a 0.23 acre site are 644 at the 90th percentile, and 15 at the 95th percentile. (See Table 5 on page 49 of EPA (1996b) for the variation of DAF with source size.) EPA suggests using a value of 20 for the Soil Screening Guidance DAF.

To determine what DAF would be appropriate for the types of sites covered by this guidance (*i.e.*, relatively small sites with groundwater no more than 3 meters from the surface), the Department compared results for the generic model shown in equation [B-139] with those obtained in a modeling study undertaken for the development of the numerical soil cleanup levels found in OAR 340-122-0045 (Anderson, 1997). A DAF of 60 results in generic model results that fall within about 0.5 to 2 times the comparable values in OAR 340-122-0045. Therefore, DAF = 60 was used to generate the generic RBCs in Appendix A. These generic values may not be appropriate for sites with contamination covering more than 1/4 acre. If the contaminated area is close to 1/2 acre, the Department recommends that DAF = 20 be used for screening. Larger contaminated zones will require site-specific modeling. The value of DAF does not depend on the number of phases.

Since we want to protect the groundwater for drinking water, the contaminant concentrations in the groundwater must not exceed the acceptable RBCs for tap water (RBC_{tw}).

Three-Phase Calculations

RBCs for the leaching of petroleum constituents from subsurface soils to groundwater (RBC_{sw}) are calculated using the following equation. Use the three-phase version of LF for the calculation.

$$RBC_{sw} \text{ (mg/kg)} = \frac{RBC_{tw} \text{ (}\mu\text{g/L)}}{LF \text{ (kg/L)}} \cdot 10^{-3} \text{ mg/}\mu\text{g} \quad [B-141]$$

Four-Phase Calculations

Since the leaching factor depends on the composition of the system, use the hazard quotient equation below along with the method for indirect pathways in Section B.2.4.2 to calculate TPH RBCs for exposures due to leaching to groundwater with subsequent use as tap water. Use the four-phase version of LF for the calculations. The concentrations of the TPH fractions in the soil (C_{soil}^i) are calculated by multiplying the estimated value of TPH RBC by the weight fractions from the product of interest given in Appendix F.

$$HQ_{sw}^i = \frac{C_{soil}^i \cdot LF_{sw}^i \cdot 1000 \mu\text{g}/\text{mg}}{RBC_{tw}^i} \quad [\text{B-142}]$$

where:

C_{soil}^i	=	The concentration of TPH fraction "i" in subsurface soil (mg/kg)
HQ_{sw}^i	=	Hazard quotient for TPH fraction "i" – leaching to groundwater (unitless)
RBC_{tw}^i	=	Risk-based water ingestion concentration for TPH fraction "i" ($\mu\text{g}/\text{L}$)
LF_{sw}^i	=	Leaching factor for TPH fraction "i" from subsurface soils to groundwater (kg/L)

Summary - Calculating RBCs for the Leaching-to-Groundwater Pathway

For each contaminant:

1. Use the appropriate LF equation and DAF=60 to calculate the contaminant-specific LF_{sw} .
2. For petroleum constituents, use equation [B-141] with the three-phase LF_{sw} and the contaminant-specific value for RBC_{tw} from the Table of RBCs to calculate RBC_{sw} .
3. For petroleum products, use the four-phase LF_{sw}^i along with the hazard quotient equation to calculate the TPH RBC_{sw} using the method for indirect exposure pathways described in Section B.2.4.2.

Suggestions for Site-Specific Calculations for the Leaching-to-Groundwater Pathway

1. Some site-specific modifications can be made by changing the values of ρ_b , n_a , n_w , and f_{oc} in K_{sw} and R_{sw} . However, except for cases where there are significant changes in f_{oc} , this is not likely to result in large changes in the final values of RBC_{sw} .

Note that this method of screening does not incorporate values for depth to groundwater, annual precipitation, soil permeability and other site factors. Therefore, although this model is easy to develop and use as a screening tool, it is not very useful for site-specific applications.

2. A more useful way to perform site-specific calculations is to use a leaching model such as SESOIL or VLEACH (see Section B.4) to simulate transport with site-specific conditions for depth to groundwater, annual recharge, permeability and other relevant factors necessary to carry out the model simulation. Then calculate a ratio of groundwater concentration to initial soil concentration for the leaching factor as defined in equation [B-138]. This leaching factor can then be incorporated into equation [B-141] to derive values for RBC_{sw} . For an example of how this can be done with SESOIL, see Anderson (1997), or other papers in Bonazountas *et al.* (1997).

3. In cases where groundwater is not used for drinking water, but has another beneficial use with a different RBC, new RBC_{sw} standards can be calculated for the protection of this use by substituting the new water RBC for RBC_{tw} in equation [B-141]. The leaching factor can be either a generic value such as in equations [B-138] and [B-140], or a site-specific value that has been modified as discussed in notes (1) or (2) above.

Compare your RBC_{sw} value to C_{sat} to determine if exposure via this pathway is reasonable (see Section B.2.1.4).

B.3.3 Groundwater

B.3.3.1 Ingestion and Vapor Inhalation from Drinking Water

Groundwater ingestion should be considered a potential exposure pathway at any site where groundwater contamination has been detected and the contaminated groundwater is reasonably likely to be used as a source of drinking water. If volatile contaminants have been detected in the groundwater, then the combined exposure resulting from ingestion and volatile inhalation should be evaluated.

Ingestion of drinking water is a direct exposure pathway. A transport equation is not required to estimate the exposure. Estimating exposure due to the inhalation of chemicals volatilizing from drinking water, however, requires a volatilization factor (VF_w) that represents the average emission rate of contaminant vapors from typical household uses of water such as showering, washing dishes, flushing toilets, *etc.* EPA (2002a) recommends a default value for VF_w of 0.5 L/m^3 based on the work of Andelman (1990). This volatilization factor is not contaminant-specific and does not depend on the number of phases in the system. However, it is only used for volatiles.

For the purposes of this document, volatile chemicals in water are defined as those with Henry's Law constants (K_H) greater than $10^{-5} \text{ m}^3\text{-atm/mol}$ and molecular weights less than 200 g/mol (EPA, 2002a). Chemicals or TPH fractions that do not fit this definition are assigned values of $VF_w = 0 \text{ L/m}^3$. This has the effect of reducing the combined exposure pathway to a drinking water ingestion-only pathway.

Three-Phase Calculations

RBCs for the combined exposure from ingestion and inhalation of volatiles in tap water (RBC_{tw}) are calculated using equations [B-143] through [B-148].

Residential – Carcinogens

$$RBC_{tw} (\mu\text{g/L}) = \frac{ARL_C \cdot AT_C \cdot 365 \text{ d/yr}}{EF_r \cdot [(IFWadj_r \cdot SF_O) + (IFAadj_r \cdot VF_w \cdot SF_i)]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-143}]$$

Residential - Noncarcinogens

$$RBC_{tw} (\mu\text{g/L}) = \frac{ARL_n \cdot AT_{nr} \cdot 365 \text{ d/yr} \cdot BW_a}{ED_r \cdot EF_r \cdot [(IRW_a / RfD_b) + (IRA_a \cdot VF_w / RfD)]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-144}]$$

Urban Residential - Carcinogens

$$RBC_{tw} (\mu\text{g/L}) = \frac{ARL_C \cdot AT_C \cdot 365 \text{ d/yr}}{EF_u \cdot [(IFWadj_u \cdot SF_O) + (IFAadj_u \cdot VF_w \cdot SF_i)]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-145}]$$

Urban Residential - Noncarcinogens

$$RBC_{tw} (\mu\text{g/L}) = \frac{ARL_n \cdot AT_{nu} \cdot 365 \text{ d/yr} \cdot BW_a}{ED_u \cdot EF_u \cdot [(IRW_a / RfD_o) + (IRA_a \cdot VF_w / RfD_i)]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-146}]$$

Occupational - Carcinogens

$$RBC_{tw} (\mu\text{g/L}) = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot BW_a}{ED_o \cdot EF_o \cdot [(IRW_a \cdot SF_o) + (IRA_a \cdot VF_w \cdot SF_i)]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-147}]$$

Occupational - Noncarcinogens

$$RBC_{tw} (\mu\text{g/L}) = \frac{ARL_n \cdot AT_{no} \cdot 365 \text{ d/yr} \cdot BW_a}{ED_o \cdot EF_o \cdot [(IRW_a / RfD_o) + (IRA_a \cdot VF_w / RfD_i)]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-148}]$$

where:

RBC _{tw}	=	Risk-Based Concentration for Ingestion & Volatiles in Tap Water (μg/L)
ARL _c	=	Acceptable risk level – carcinogens (unitless)
ARL _n	=	Acceptable risk level – noncarcinogens (unitless)
AT _c	=	Averaging time – carcinogens (yr)
*AT _n	=	Averaging time – noncarcinogens (yr)
*BW	=	Body weight (kg)
*ED	=	Exposure duration (yr)
*EF	=	Exposure frequency (d/yr)
*IFA _{adj}	=	Age-adjusted inhalation factor for air ([m ³ -yr]/[kg-d])
*IFW _{adj}	=	Age-adjusted ingestion factor for water ([L-yr]/[kg-d])
IRA _a	=	Inhalation rate – adult (m ³ /d)
IRW _a	=	Water ingestion rate – adult (L/d)
RfD _i	=	Reference dose – inhaled (mg/kg-d)
RfD _o	=	Reference dose – oral (mg/kg-d)
SF _i	=	Cancer slope factor – inhaled (mg/kg-d) ⁻¹
SF _o	=	Cancer slope factor – oral (mg/kg-d) ⁻¹
VF _w	=	Volatilization factor from tap water (L/m ³)

* The subscripts on these parameters in the equations refer to the following: a = adult; c = child; cr = residential child; cu = urban residential child; r = residential; and u = urban residential.

Four-Phase Calculations

Since the indirect component (vapor inhalation) of this combined pathway does not depend on the number of phases, this can be treated as a direct exposure pathway. Therefore, calculate RBCs for each TPH fraction using the appropriate equation above for noncarcinogens. Then, use weight fractions for the TPH fractions in water along with equation [B-69] to calculate the overall TPH RBC.

Summary - Calculating RBCs for the Tap Water Ingestion and Volatile Inhalation Pathway

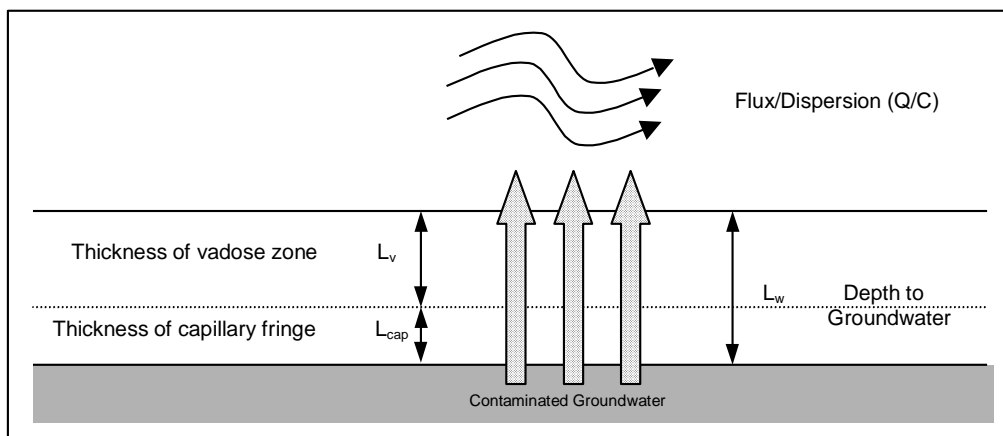
For each contaminant:

1. Check to see if the contaminant fits the definition of volatile: K_H exceeds 10^{-5} m³-atm/mol and the molecular weight is less than 200 g/mol.
2. If volatile, set $VF_w = 0.5$ L/m³. If nonvolatile, set $VF_w = 0.0$ L/m³.
3. For petroleum constituents, use equations [B-143] through [B-148] to calculate RBC_{tw} .
4. For petroleum products, use equations [B-143] through [B-148] to calculate RBCs for the petroleum fractions and then combine them using equation [B-69] to obtain the TPH RBC.

Suggestions for Site-Specific Calculations for the Tap Water Ingestion and Volatile Inhalation Pathway

Since the RBC values are based on exposure factors such as inhalation and water ingestion rates that would be difficult to develop on a site-specific basis, and since the transport factor is not derived from easily measured site-specific parameters, the Department does not recommend that you attempt to calculate site-specific values for RBC_{tw} .

B.3.3.2 Volatilization from Groundwater to Outdoor Air



Volatilization from groundwater to outdoor air should be considered a potential exposure pathway at any site where volatile contaminants have been detected in groundwater.

Because groundwater contamination is at depth, it is assumed that for the residential, urban residential, and occupational scenarios there will be no direct exposure to the contaminated groundwater. Therefore, dermal contact is not expected to contribute to the overall risk, and exposure is limited to inhalation of vapors. Note, however, that direct dermal contact is expected to contribute to risk in the construction worker and excavation worker scenarios, which are discussed in Section B.3.3.4.

Since the potential exposure is from an indirect pathway, a transport model is needed to estimate the outdoor air concentration that may result as contaminants volatilize from the groundwater and migrate into the air. The procedure used for this pathway is analogous to that used for volatilization from subsurface soils to outdoor air (Section B.3.2.2) with several groundwater-specific changes discussed below. Basically, the goal will be to estimate the contaminant flux at the surface and combine that with EPA's modeled flux/concentration relationship (Q/C , EPA (1996b)) to derive a volatilization factor. The VF will then be used along with the previously calculated RBC_{air} values to calculate the corresponding RBC values for the groundwater-to-outdoor-air pathway (RBC_{wo}).

As is the case with subsurface soil contamination (Section B.3.2.2), diffusion is taken as the main mechanism for transporting subsurface volatile contaminants to the surface, and Fick's first law of diffusion can be used as the starting point for estimating flux (see equation [B-115]). Because we are dealing with contaminated groundwater, the vapor-phase concentration of the contaminant at the source (C_{source} ; *i.e.*, the soil gas concentration right above the groundwater) can be calculated from Henry's Law as follows:

$$C_{source} = C_w \cdot H \quad [B-149]$$

where:

C_{source}	=	The vapor-phase contaminant concentration at the water table ($\mu\text{g}/\text{cm}^3$)
C_w	=	The contaminant concentration in the groundwater (mg/L)
H	=	Henry's constant (unitless)

Note that the same equation – [B-149] – represents the source concentration for either a three-phase or a four-phase system. Therefore, the result does not depend on the number of phases.

This results in a concentration gradient of:

$$\frac{\partial C}{\partial L} = \frac{C_w \cdot H}{L_w} \quad [\text{B-150}]$$

where L_w (cm) is the depth to groundwater.

The porous medium through which the contaminants must diffuse is now better represented as two layers, the capillary fringe and the vadose zone. Since these layers differ in their degree of water saturation, a *total* effective diffusion coefficient (equation [B-62]) must be used. Substituting this into Fick's first law (equation [B-115]) along with the relationship for the concentration gradient derived above yields a model for diffusive flux from groundwater contamination (J_w):

$$J_w = D_{T\text{eff}} \cdot \left(\frac{H \cdot C_w}{L_w} \right) \quad [\text{B-151}]$$

This flux model can be substituted into equation [B-86] to give:

$$Q/C = \frac{D_{T\text{eff}} \cdot H \cdot C_w}{L_w \cdot C_{\text{air}}} \quad [\text{B-152}]$$

Since $VF = C_{\text{air}}/C_w$, this equation can be rearranged and appropriate unit conversion factors added to derive the volatilization factor for the groundwater to outdoor air pathway (VF_{wo}):

$$VF_{wo} (\text{L}/\text{m}^3) = \frac{D_{T\text{eff}} \cdot H \cdot 10^3 \text{ g/kg} \cdot 10^3 \text{ L}/\text{m}^3}{(Q/C) \cdot L_w \cdot 10^2 \text{ cm/m}} \quad (\text{3 or 4 phases}) \quad [\text{B-153}]$$

VF_{wo} is contaminant-specific and, therefore, must be calculated for each compound. As noted earlier, however, it does not depend on the number of phases in the system. Therefore, four phase calculations can be carried out using the same equation as three-phase calculations.

Since, in a conservative sense, groundwater plumes are sources that are constantly moving and replenishing, there is no simple way to perform a mass balance to establish a maximum volatilization factor analogous to those calculated for soil sources.

Three-Phase Calculations

RBCs for petroleum constituents are calculated using the following equation:

$$RBC_{wo} (\mu\text{g/L}) = \frac{RBC_{air} (\mu\text{g/m}^3)}{VF_{wo} (\text{L/m}^3)} \quad [\text{B-154}]$$

Four-Phase Calculations

Since the volatilization factor for this pathway does not depend on the number of phases, the four phase calculations can be carried out using the same equation as the three-phase calculations. Therefore, calculate RBCs for each TPH fraction using the equation above. Then, use weight fractions for the TPH fractions in water along with equation [B-69] to calculate the overall TPH RBC.

Summary - Calculating RBC Values for Groundwater Volatilization to Outdoor Air Pathway

For each contaminant:

1. Use equation [B-153] to calculate VF_{wo} .
2. For petroleum constituents, use VF_{wo} along with the appropriate RBC_{air} and equation [B-154] to calculate RBC_{wo} .
3. For petroleum products, use VF_{wo} along with the appropriate RBC_{air} and equation [B-154] to calculate RBC_{wo} for each fraction. Then sum the fractions using equation [B-69] to calculate the overall TPH RBC.

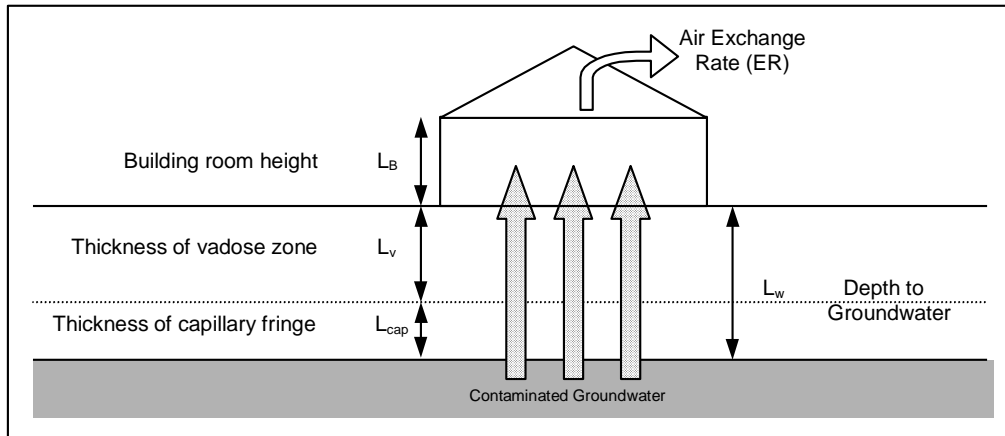
Suggestions for Site-Specific Calculations for the Groundwater-to-Outdoor-Air-Pathway

Since this is entirely an indirect pathway, site-specific efforts should be directed at modifying the generic transport factors (in this case, the volatilization factors). One of the following methods may be useful for this purpose:

1. Calculate a site-specific value for VF_{wo} by substituting your own data for L_w into equation [B-153]. Site-specific information could also be used to modify the value of D_{reft} in this equation. Note that rates of diffusion can be very sensitive to soil moisture content.
2. Select a less conservative flux model (see Section B.5) to estimate a site-specific average flux over the exposure duration. Use the model results with equation [B-55] to calculate VF_{wo} .

Compare your RBC_{wo} value to the compound solubility to determine if exposure via this pathway is reasonable (see Section B.2.1.4).

B.3.3.3 Volatilization from Groundwater to Indoor Air



Volatilization from groundwater to indoor air should be considered a potential pathway at any site where contaminants have been detected in groundwater located under or very close to existing buildings, or in areas where buildings are likely to be located in the future.

The procedure used for this pathway is analogous to that used for volatilization from subsurface soils to indoor air (Section B.3.2.3) with several groundwater-specific changes discussed below. The groundwater specific changes are similar to those discussed in Section B.3.3.2 for volatilization from groundwater to outdoor air. As with the soil-to-indoor-air pathway, these generic values are not to be applied to buildings with dirt floors or other substandard floors.

The transport equation for this pathway is again adapted from Johnson and Ettinger (1991) and is based on their derivation of an attenuation coefficient α , which they define as:

$$\alpha = \frac{C_{\text{building}}}{C_{\text{source}}} \quad [\text{B-155}]$$

where:

- α = Source attenuation coefficient (unitless)
- C_{building} = Contaminant concentration in air inside the building (g/cm^3)
- C_{source} = The vapor-phase contaminant concentration in the subsurface soil (g/cm^3)

Substituting equation [B-149] for C_{source} yields an expression that relates the air concentration in the building to the groundwater concentration.

$$\alpha = \frac{C_{\text{building}}}{C_w \cdot H} \quad [\text{B-156}]$$

Note again that the same equation – [B-149] – represents the source concentration for either a three-phase or a four-phase system. Therefore, the result does not depend on the number of phases.

Since we have defined water-to-air volatilization factors as $VF = C_{air}/C_w$, and since $C_{building}$ is the air concentration in the building that must not exceed acceptable risk levels, this equation can be rearranged to arrive at a relationship that uses α to derive the volatilization factor for the groundwater-to-indoor-air pathway, VF_{wi} .

$$VF_{wi} = \alpha \cdot H \quad [B-157]$$

The infinite-source diffusion-limited equation for α (Johnson and Ettinger, 1991) is:

$$\alpha = \frac{\left(\frac{D_{Teff} \cdot A_B}{Q_B \cdot L_w} \right)}{1 + \left(\frac{D_{Teff} \cdot A_B}{Q_B \cdot L_w} \right) + \left(\frac{D_{Teff} \cdot A_B \cdot L_{crk}}{D_{crkeff} \cdot A_{crk} \cdot L_w} \right)} \quad [B-158]$$

where:

- A_B = Cross-sectional area of building (cm²)
- A_{crk} = Area of cracks available for transport into the building (cm²)
- D_{crkeff} = Effective diffusion coefficient in building cracks (cm²/s)
- D_{Teff} = Total effective diffusion coefficient between source and building (cm²/s)
- L_w = Thickness of clean soil layer between groundwater and building (cm)
- L_{crk} = Thickness of crack (building slab) (cm)
- Q_B = Building ventilation rate (cm³/s)

The porous medium through which the contaminants must diffuse is again represented as two layers, the capillary fringe and the vadose zone, which differ primarily in their degree of water saturation. Therefore the total effective diffusion coefficient (D_{Teff}) can be derived using equation [B-62]. Assuming that the cracks around the foundation and in the slab are likely to be filled with the same porous medium over which the building sits, equation [B-58] for D_{veff} can be used for D_{crkeff} . As in the previous indoor air model, equation [B-130] can be used for Q_B . A_{crk}/A_B can be expressed as the fraction of the building slab that is available for transport (f_{crk}). Making these substitutions into the equation above and using the resulting term for α in equation [B-157] produces the following equation for VF_{wi} :

$$VF_{wi} (L/m^3) = \frac{H \cdot \left(\frac{D_{Teff} \cdot 86,400 \text{ s/day}}{L_B \cdot ER \cdot L_w} \right)}{1 + \left(\frac{D_{Teff} \cdot 86,400 \text{ s/day}}{L_B \cdot ER \cdot L_w} \right) + \left(\frac{D_{Teff} \cdot L_{crk}}{D_{veff} \cdot L_w \cdot f_{crk}} \right)} \cdot 10^3 \frac{L}{m^3} \quad (3 \text{ or } 4 \text{ phases}) \quad [B-159]$$

VF_{wi} is contaminant-specific and, therefore, must be calculated for each compound. As noted earlier, however, it does not depend on the number of phases in the system. Therefore, four phase calculations can be carried out using the same equation as three-phase calculations.

Since, in a conservative sense, groundwater plumes are sources that are constantly moving and replenishing, there is no simple way to perform a mass balance to establish a maximum volatilization factor analogous to those calculated for soil sources.

Three-Phase Calculations

RBCs for petroleum constituents are calculated using the following equation:

$$RBC_{wi} (\mu\text{g/L}) = \frac{RBC_{air} (\mu\text{g/m}^3)}{VF_{wi} (\text{L/m}^3)} \quad [\text{B-160}]$$

Four-Phase Calculations

Since the volatilization factor for this pathway does not depend on the number of phases, the four phase calculations can be carried out using the same equation as the three-phase calculations. Therefore, calculate RBCs for each TPH fraction using the equation above. Then, use weight fractions for the TPH fractions in water along with equation [B-69] to calculate the overall TPH RBC.

Summary - Calculating RBCs for Groundwater Volatilization to Indoor Air Pathway

For each contaminant:

1. Use equation [B-159] to calculate VF_{wi} .
2. For petroleum constituents, use VF_{wi} along with the appropriate RBC_{air} and equation [B-160] to calculate RBC_{wi} .
3. For petroleum products, use VF_{wi} along with the appropriate RBC_{air} and equation [B-160] to calculate RBC_{wi} for each fraction. Then sum the fractions using equation [B-69] to calculate the overall TPH RBC.

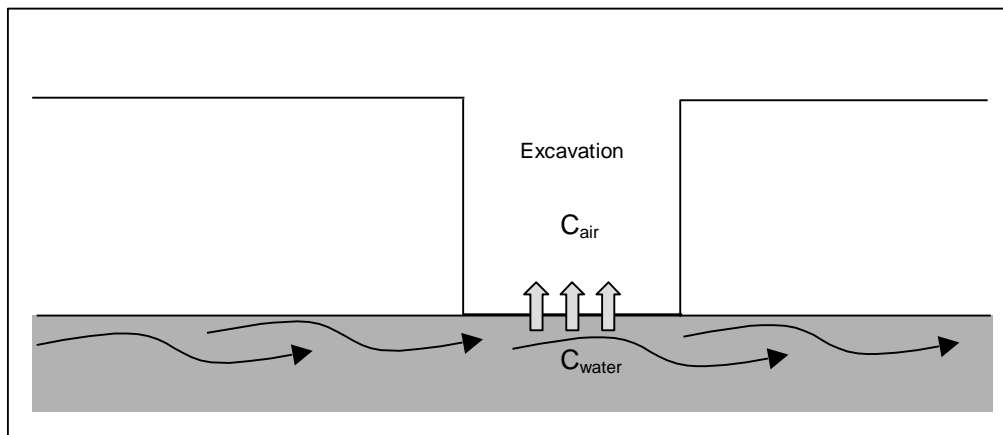
Suggestions for Site-Specific Calculations for the Groundwater-to-Indoor-Air-Pathway

Since this is an indirect pathway, you can use site-specific data to modify the generic transport factors (in this case, the volatilization factors). One of the following methods may be useful for this purpose:

1. Calculate a site-specific value for VF_{wi} by substituting your own data for L_B , L_{crk} , L_w , f_{crk} and ER into equation [B-159]. Site-specific information could also be used to modify the value of D_{Teff} and D_{veff} in this equation. Note that rates of diffusion can be very sensitive to soil moisture content. See EPA (2002b) for soil-dependent properties for the Johnson and Ettinger model.
2. Select a less conservative flux model (see Section B.5) to estimate a site-specific average flux over the exposure duration. Use the model results with equation [B-55] to calculate VF_{wi} .

Compare your RBC_{wi} value to the compound solubility to determine if exposure via this pathway is reasonable (see Section B.2.1.4).

B.3.3.4 Construction and Excavation Worker Exposures to Groundwater



Exposure of construction and excavation workers to contaminated groundwater should be considered at any site where groundwater contamination has been discovered in a location and at a depth where construction and excavation activities are likely to occur. Appropriate depths should be based on current or reasonably likely maximum depths of construction and utility excavations in the vicinity of the site and could be as deep as 10 - 15 feet, or greater in some cases.

Unlike residential, urban residential, and occupational exposure scenarios, the construction and excavation worker scenarios assume that direct contact with contaminated groundwater is likely. Therefore, risk-based concentrations for this scenario are based on a combination of volatile inhalation *and* dermal contact exposure routes. We do not expect excavation or construction workers to be wading in contaminated groundwater. Excavations and construction trenches are typically pumped before workers are allowed to enter. However, in wet areas incidental contact with groundwater and inhalation of chemicals volatilizing from the groundwater are still likely modes of exposure. Since rates for incidental ingestion of groundwater by an excavation worker are very uncertain, and since exposure by this pathway is expected to be limited when compared to inhalation and dermal contact, the incidental ingestion pathway is not included.

One of the two routes of exposure – dermal – is a direct exposure pathway. The second – inhalation – is an indirect pathway and requires a transport factor that represents volatilization from groundwater to air in the excavation. This transport factor (VF_{we}) does not depend on the number of phases in the system.

Three-Phase Calculations

RBCs for exposure of construction and excavation workers to petroleum constituents in groundwater (RBC_{we}) are calculated with equations [B-161] and [B-162].

Construction and Excavation Worker – Carcinogens

$$RBC_{we} (\mu\text{g/L}) = \frac{ARL_c \cdot AT_c \cdot 365 \text{ d/yr} \cdot BW_a}{ED_e \cdot EF_e \cdot [(IRA_a \cdot VF_{we} \cdot SF_i) + (DA_w \cdot EvF_w \cdot SA_w \cdot SF_o)]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-161}]$$

Construction and Excavation Worker – Noncarcinogens

$$RBC_{we} (\mu\text{g/L}) = \frac{ARL_n \cdot AT_{ne} \cdot 365 \text{ d/yr} \cdot BW_a}{ED_e \cdot EF_e \cdot \left[\left(\frac{IRA_a \cdot VF_{we}}{RfD_i} \right) + \left(\frac{DA_w \cdot EvF_w \cdot SA_w}{RfD_o} \right) \right]} \cdot 10^3 \mu\text{g/mg} \quad [\text{B-162}]$$

where:

RBC _{we}	=	Risk-Based Concentration for Excavation or Construction Worker Exposure to Groundwater (μg/L)
ARL _c	=	Acceptable risk level – carcinogens (unitless)
ARL _n	=	Acceptable risk level – noncarcinogens (unitless)
AT _c	=	Averaging time – carcinogens (yr)
*AT _{ne}	=	Averaging time – noncarcinogens (yr)
BW _a	=	Body weight (kg)
DA _w	=	Dermal absorption factor for groundwater (L/cm ² -event)
*ED _e	=	Exposure duration (yr)
*EF _e	=	Exposure frequency (d/yr)
EvF _w	=	Event frequency for groundwater contact (event/d)
IRA _a	=	Inhalation rate (m ³ /d)
RfD _i	=	Reference dose – inhaled (mg/kg-d)
RfD _o	=	Reference dose – oral (mg/kg-d)
SA _w	=	Skin surface contact area to groundwater (cm ²)
SF _i	=	Cancer slope factor – inhaled (mg/kg-d) ⁻¹
SF _o	=	Cancer slope factor – oral (mg/kg-d) ⁻¹
VF _{we}	=	Volatilization factor for water in an excavation (L/m ³)

* In this scenario, the subscript “e” can represent either the excavation OR construction worker depending on the situation being modeled.

Values of DA_w used for the generic RBCs are listed in Appendix E. Note that these values are not only chemical-specific, but they also depend on whether the exposure event time (t_{event}) is less than or greater than the time required for dermal absorption to reach steady state (t*). The exposure event time used for the generic RBCs for excavation worker exposure to groundwater is two hours. In most cases where site-specific RBCs are being calculated it is expected that t_{event} will remain the same. In cases where t_{event} is changed or where values of DA_w are needed for chemicals not included in the Table of RBCs, equations [B-163] and [B-164] can be used to calculate values of DA_w.⁵⁴

⁵⁴ Equations [B-163] and [B-164] are only for *organic compounds in water*. Please refer to EPA (2001b) for information about calculating DA_w for inorganics.

$$DA_w = 2 \cdot K_p \cdot \sqrt{\frac{6 \cdot \tau \cdot t_{\text{event}}}{\pi}} \cdot \left(\frac{10^{-3} \text{L}}{\text{cm}^3} \right) \quad \text{for } t_{\text{event}} < t^* \quad [\text{B-163}]$$

$$DA_w = K_p \cdot \left[\frac{t_{\text{event}}}{1+B} + 2 \cdot \tau \cdot \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right] \cdot \left(\frac{10^{-3} \text{L}}{\text{cm}^3} \right) \quad \text{for } t_{\text{event}} > t^* \quad [\text{B-164}]$$

where:

DA_w	=	Dermal absorption factor for groundwater – construction or excavation worker (L/cm ² -event)
K_p	=	Dermal permeability coefficient (cm/hr)
t_{event}	=	Duration of event exposure (hr/event)
τ	=	Lag time (hr/event)
t^*	=	Time to reach steady state (hr)
B	=	Relative hydrophobicity (unitless)
π	=	3.14 (pi – unitless)

Values for τ , t^* , K_p , and B for selected compounds can be obtained for this purpose from Exhibit B-3 in EPA (2001b). For contaminants not listed in Exhibit B-3, these parameters can be calculated using equations in Appendix A of EPA (2001b). Cases where you are considering changing t_{event} should be discussed with the Department.

Since excavation workers are generally working in confined spaces, there will be limited mixing of the air in the trench with fresh air. For the purposes of calculating the generic RBCs, it is assumed that the air concentration for volatile components in groundwater in the trench can be represented by the same volatilization factor used in Section B.3.3.4 for volatilization from tap water to indoor air. Therefore, VF_{we} is set at 0.5 L/m³ for volatile contaminants.⁵⁵ To avoid an unrealistic contribution via the inhalation pathway for nonvolatiles, VF_{we} is set to 0 for all nonvolatile constituents.

Four-Phase Calculations

Since the volatilization factor for this pathway does not depend on the number of phases, the four phase calculations can be carried out using the same equations as the three-phase calculations. Therefore, calculate RBCs for each TPH fraction using equation [B-162]. Then, use weight fractions for the TPH fractions in water along with equation [B-69] to calculate the overall TPH RBC.

⁵⁵ We realize that using the indoor volatilization factor for an excavation is conservative and are continuing to search for a more appropriate model to use to calculate VF_{we} .

Summary - Calculating RBCs for Construction and Excavation Worker Exposure to Groundwater

For each constituent or product fraction:

1. If t_{event} is two hours, select the appropriate value of DA_w from Appendix E.
2. If t_{event} is not two hours, or if the chemical is not listed in Appendix E, use equation [B-163] or [B-164] and data from EPA (1992a) to calculate DA_w .
3. Let $VF_{we} = 0.5$ for volatile contaminants and 0 for nonvolatile contaminants.
4. For petroleum constituents, use VF_{we} and DA_w in equations [B-161] and [B-162] to calculate RBC_{we} .
5. For petroleum products, use VF_{we} and DA_w in equation [B-162] to calculate RBC_{we} for each fraction and then use equation [B-69] to calculate the overall TPH RBC.

Suggestions for Site-Specific Calculations for Construction & Excavation Worker Exposure to Groundwater

Changes in t_{event} will require that you calculate site-specific values for DA_w as discussed in this section. Note that since the overall RBC is influenced by both dermal absorption *and* inhalation, the relative effect of this change depends on whether the contaminant of interest is primarily inhaled or absorbed through the skin. RBCs for volatile compounds will be affected less by changes in DA_w .

Because the RBCs for exposure to groundwater are based on exposure factors that would be difficult to develop on a site-specific basis, the Department does not recommend that you attempt to calculate site-specific RBCs for this pathway.

Special Note on "Subchronic" Exposures for Construction and Excavation Workers

As discussed in Section B.2.5.2, reference doses for noncarcinogens are meant to represent chronic exposures, which are considered to be a minimum of 7 years (10% of a 70-year lifetime). Because the default exposure duration for construction and excavation workers is less than seven years (see Appendix C), the exposures are considered *subchronic*. Since subchronic reference doses are unavailable for many compounds, the Department used chronic reference doses for these RBCs. If exposure to noncarcinogens is a problem at your site, you may want to consider the use of subchronic reference doses to calculate site-specific RBCs for this pathway. Currently available subchronic values are listed in Appendix E. DEQ's RBDM spreadsheets (DEQ, 2003a and DEQ, 2003b) have a subchronic calculation option.

B.3.4 Special Procedures for Lead

The methods for calculating RBCs presented in Sections B.3.1 through B.3.3 can generally be applied to compounds for which both inhalation and oral reference dose (RfD) or slope factor (SF) data are available. However, the RBCs for lead were not calculated using these equations. They were adapted from EPA guidance. The sources of these RBCs are discussed in this section.

B.3.4.1 Soil Cleanup Levels

EPA recommends using the Integrated Exposure Uptake Biokinetic (IEUBK) Model for setting site-specific cleanup standards for exposures of children to lead (EPA, 1994d). The IEUBK model is used to derive soil lead levels which are estimated to result in less than a 5% chance of an individual child of having a blood lead level greater than 10 $\mu\text{g}/\text{dL}$. For residential settings, EPA recommends a screening level of 400 mg/kg (EPA, 1994d). The Department uses this value for RBC_{ss} for residential and urban residential exposures.

For industrial settings, where significant exposures to young children are not anticipated, EPA has developed an alternative model which predicts blood lead levels in the fetus of an exposed pregnant woman. EPA calculates that a concentration of approximately 750 mg/kg would be protective for the fetus of an exposed worker (Stifelman, 1999). Since EPA does not provide different values for occupational exposures versus excavation worker exposures, the Department uses 750 mg/kg for RBC_{ss} for occupational, construction, and excavation worker exposures.

Since lead has no significant volatility, all of the indirect soil exposure pathways based on volatility are considered to be incomplete exposure pathways. Therefore, RBC_{air} , RBC_{so} and RBC_{si} are all designated “NA” (not applicable) in the Table of RBCs and need not be considered.

B.3.4.2 Groundwater

The lead level established in the National Primary Drinking Water Regulations (NPDWRs) is set at 15 $\mu\text{g}/\text{L}$ (EPA, 1999). This is not a health-based standard, but an action level which requires suppliers to take steps to treat their water if more than 10% of their samples exceed this limit. The Department believes that this 15 $\mu\text{g}/\text{L}$ is adequate for adult and child exposures. Therefore, the RBC_{tw} for the residential, urban residential and occupational scenarios is set to this value.

The Department believes that the potential risk to excavation workers from incidental exposure to lead in groundwater is minimal and does not consider this pathway applicable. Therefore, RBC_{we} is designated as “NA.”

As with soil, all of the indirect groundwater exposure pathways based on volatility are considered to be incomplete exposure pathways. Therefore, RBC_{wo} and RBC_{wi} are also designated “NA” in the Table of RBCs and need not be considered.

B.3.4.3 Leaching to Groundwater

The RBCs for the generic leaching-to-groundwater pathway are designed to protect groundwater for use as tap water. Therefore, the leachate from vadose zone soils contaminated with lead, after undergoing dilution and attenuation, must not exceed the value of RBC_{tw} , which is 15 $\mu\text{g/L}$.

To estimate RBC_{sw} we assume that all of the lead in a soil sample will leach into the water during a routine leaching test such as the toxicity characteristic leaching procedure (TCLP) (EPA SW-846) or the synthetic precipitation leaching procedure (SPLP) (EPA SW-846). These tests are performed on 100 grams of soil sample using 2 L of a leachate solution. The results of the leaching test are then compared to 100 times the RBC_{tw} to account for dilution and attenuation of the inorganic contaminant as it moves from the vadose zone to the groundwater.⁵⁶ Therefore, the lead leachate concentration must not exceed 100 times RBC_{tw} , or 1500 $\mu\text{g/L}$.

From these data we calculate the limit on the original soil concentration of lead.

$$RBC_{sw} \text{ (mg/kg)} = \frac{1500\mu\text{g/L} \cdot 2\text{L}}{100\text{g}} \cdot \frac{1000\text{g}}{\text{kg}} \cdot \frac{\text{mg}}{1000\mu\text{g}} = 30\text{mg/kg} \quad [\text{B-165}]$$

If you have lead at your site and want to do a site-specific test for leaching, you could use either the TCLP or the SPLP test. The results of that leaching test must not exceed 1500 $\mu\text{g/L}$. The 30 mg/kg value for RBC_{sw} in Appendix A only applies to the total concentration of lead in the original soil sample.

In cases where the groundwater is not used for tap water, but has another beneficial use with a different RBC, new lead RBC_{sw} standards could be calculated using an equation similar to the one above. Or, you could apply a leaching test to a soil sample and if the results were less than 100 times the new standard, the site would pass the leaching test for lead.

⁵⁶ This is the process required for inorganics being cleaned up under OAR 340-122-0045.

B.3.5 Summary of Iterative Method of TPH RBC Calculation

The method used for indirect pathways in the DEQ TPH RBC spreadsheet (DEQ, 2003b) starts with an initial estimate for the TPH RBC, calculates the noncarcinogenic risk from exposure to that concentration for a specific pathway, and, if the risk (hazard quotient) is greater than 1.00, revises the estimate for TPH RBC downward and repeats the process until it converges on the value of TPH RBC for which risk = 1.00. The steps for this process are summarized below:

1. Make an initial estimate of the TPH RBC.

The DEQ spreadsheet sets the initial estimate at the maximum TPH that results when all of the air space is occupied by product.

$$\text{TPH}_{\text{max}} \text{ (mg/kg)} = \frac{n_{\text{a3}} \cdot \rho_{\text{p}} \cdot 10^6}{\rho_{\text{b}}} \quad [\text{B-166}]$$

where:

- n_{a3} = the air-filled porosity for the system before any product is added (*i.e.*, the air-filled porosity of the comparable three-phase system) (unitless)
- ρ_{p} = the density of the petroleum product (g/cm^3)
- ρ_{b} = the bulk density of the soil sample (g/cm^3)

2. Solve for mole fractions of all constituents in the system.

The DEQ spreadsheet starts with an initial estimate of mole fractions and reevaluates the estimate until the answer converges to where the sum of the mole fractions of all of the TPH fractions equals 1.00. This is done as follows:

- a. Calculate the mole fraction of each TPH fraction and constituent in the product using the composition of the product and the molecular weights of the TPH fractions and constituents. Use these values for the initial estimate.
- b. Use the initial estimate for the TPH RBC to calculate an initial estimate of the product-filled porosity, n_{p} . This is simply a rearrangement of equation [B-166]:

$$n_{\text{p}} = \frac{\text{TPHEstimate(mg/kg)} \cdot \rho_{\text{b}}}{\rho_{\text{p}} \cdot 10^6} \quad [\text{B-167}]$$

- c. Use the estimated value of n_{p} along with properties of the product and fractions to estimate R_{sw} for all of the fractions with equation [B-49]. Remember that n_{a} for a four-phase system is n_{a} for a three-phase system minus n_{p} and that n_{w} is held constant.
- d. Use the values of R_{sw} to calculate equilibrium mole fractions using equation [B-50].
- e. Add the equilibrium values for all of the mole fractions. If the sum = 1.00 you have the correct equilibrium values. Calculate source concentrations and transport factors using

these mole fractions and then go onto the risk calculation (step 3). If the sum is not = 1.00, change the estimated value of n_p ⁵⁷ and return to step c.

3. Use the equations in this guidance document to calculate the risk (*i.e.*, the hazard quotient (HQ)) for each fraction for a specific pathway. Add the HQs to obtain the total for all of the fractions (the hazard index (HI)).

If $HI < 1.0$ on the initial estimate of TPH (*i.e.*, TPH_{max}), then this product does not create an unacceptable risk via this pathway. This pathway can be excluded for this product.

If $HI > 1.0$ lower the estimated value of TPH RBC and return to step 2.

If $HI = 1.0$, the estimated value for TPH is the TPH RBC for this pathway.

Repeat these steps for each pathway.

⁵⁷ Start by lowering the value of n_p . This should bring the sum of the mole fractions closer to 1.00. You may have to raise n_p if, on a given guess, you lower the value too much and the resulting sum of mole fractions goes below 1.00.

B.4 Modeling Resources

The models used for calculating the generic risk-based concentrations in Appendix A were selected because they are generally easy to use in spreadsheets and broadly applicable to the conditions being modeled. Models of this type are appropriate for calculating screening levels. In some cases they may also be used for site-specific calculations by modifying appropriate input parameters. However, in many cases their simplicity also means that they lack the flexibility to be of much use for site-specific calculations. In those cases, alternative models may be more beneficial.

While the Department does not officially approve or endorse particular references, models, or software packages, the information in this section is provided in hopes that it will expedite your search for additional modeling resources. Note that many other excellent resources are available and this list should not be considered a definitive guide, but rather a place to start. For brevity only the authors and titles are listed here. Please refer to Appendix L for complete citations.

B.4.1 General References

The following are a few excellent references that provide broad background information on matters related to contaminant transport as well as specific information on modeling techniques, fate and transport mechanisms, *etc.*

Anderson and Woessner, 1992, *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*

Domenico and Schwartz, 1990, *Physical and Chemical Hydrogeology*

EPA, 1996b, *Soil Screening Guidance: Technical Background Document*⁵⁸

Fetter, 1993, *Contaminant Hydrogeology*

Freeze and Cherry, 1979, *Groundwater*

B.4.2 Modeling Guides

ASTM and EPA have published a number of guidance documents over the years on various aspects of groundwater and vadose zone modeling.

ASTM, 1999, *RBCA Fate and Transport Models: Compendium and Selection Guidance*

ASTM, 1995a, *Standard Guide for Defining Initial Conditions in Ground-Water Flow Modeling*

ASTM, 1994a, *Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information*

⁵⁸ This is one of EPA's better reference documents. It provides an excellent background on matters related to contaminant fate and transport.

ASTM, 1994b, *Standard Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application*

ASTM, 1993, *Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem*

ASTM, 1992, *Standard Guide for Evaluating Mathematical Models for the Environmental Fate of Chemicals*

EPA, 1994b, *Evaluation of Unsaturated/Vadose Zone Models for Superfund Sites*

EPA, 1994c, *Identification and Compilation of Unsaturated/Vadose Zone Models*

EPA, 1993, *Compilation of Ground-Water Models*

EPA, 1992c, *Fundamentals of Ground-Water Modeling*

EPA, 1992d, *Quality Assurance and Quality Control in the Development and Application of Ground-Water Models*

B.4.3 Computer Models

In addition to the models discussed in Section B.3, you may want to use the models listed below to experiment with site-specific calculations for the pathways listed. References to related articles or documentation are also included.

Volatilization to outdoor air:

EPA's EMSOFT model incorporates Jury's finite source equations.

EPA, 1997a, *EMSOFT: Exposure Model for Soil-Organic Fate and Transport User's Guide*

Volatilization to indoor air:

EPA has developed spreadsheets for both the finite and infinite source term versions of the Johnson and Ettinger model.

EPA, 1997b, *User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings*

The American Petroleum Institute has developed guidance for site-specific refinements to the Johnson and Ettinger model.

API, 1998, *Assessing the Significance of Subsurface Contaminant Vapor Migration to Enclosed Spaces: Site-Specific Alternatives to Generic Estimates*

Leaching to groundwater:

SESOIL is a well-documented model that is sufficiently complex to adapt to a wide variety of conditions.

Bonazountas *et al.*, 1997, *SESOIL in Environmental Fate and Risk Modeling*

Hetrick *et al.*, 1993, *The New SESOIL User's Guide*

VLEACH is a much simpler leaching model, but still useful for site-specific applications.

EPA, 1996d, *VLEACH: A One-Dimensional Finite Difference Vadose Zone Leaching Model (Version 2.2a)*

Rosenbloom *et al.*, 1993, *Application of VLEACH to Vadose Zone Transport of VOCs at an Arizona Superfund Site*

EPA (1996b) provides a summary of nine vadose zone leaching models including SESOIL and VLEACH. For a more detailed comparison of four different leaching models, including SESOIL, please refer to:

Sanders, 1994, *Calculation of Soil Cleanup Criteria for Volatile Organic Compounds as Controlled by the Soil-to-Groundwater Pathway: Comparison of Four Unsaturated Soil Zone Leaching Models*

B.4.4 Internet Modeling Resources

There are many on-line sites that offer information about modeling. This document cannot list them all. Listed below are a few links to Internet sites with information on modeling and free or inexpensive software.

- Fate, Exposure and Risk Analysis (EPA)
<https://www.epa.gov/fera>
- United States Geological Service (USGS) Water Resources Applications Software
<http://water.usgs.gov/software/>
- International Ground Water Modeling Center, Colorado School of Mines, Golden, CO
<http://igwmc.mines.edu/>

Appendix C: Exposure Factors

Parameter (unit)	Symbol	Residential		Urban Residential		Occupational		Construction Worker		Excavation Worker	
			Note		Note		Note		Note		Note
ACCEPTABLE RISK LEVELS											
Acceptable Risk Level - Carcinogens	ARLc	1.00E-06	1	=		=		=		=	
Acceptable Risk Level - Noncarcinogens	ARLn	1	1	=		=		=		=	
EXPOSURE PARAMETERS											
Averaging Time - Carcinogen (yr)	ATc	70	2	=		=		=		=	
Averaging Time - Noncarcinogen (yr)	ATn	30	2	11	2	25	2	1	2	1	2
Averaging Time - Noncarcinogen, Child (yr)	ATnc	6	2	6	2	NA		NA		NA	
Body Weight - Adult (kg)	BWa	70	3	=		=		=		=	
Body Weight - Child (kg)	BWc	15	3	=		NA		NA		NA	
Exposure Duration - Adult (yr)	ED	30	3	11	4	25	3	1	21	1	6
Exposure Duration - Child (yr)	EDc	6	3	6	4	NA		NA		NA	
Exposure Frequency (day/yr)	EF	350	3	175	3a	250	6	250	6	9	6
Event Frequency - Groundwater (events/day)	EvFwe	NA		NA		NA		2	6	=	
Event Time - Groundwater (hr/event)	t _{event}	NA		NA		NA		2	6	=	
Inhalation Rate - Adult (m ³ /day)	IRA	20	4	20	4	7	4a	7	4a	7	4a
Inhalation Rate - Child (m ³ /day)	IRAc	8.3	4	=		NA		NA		NA	
Soil Ingestion Rate - Adult (mg/day)	IRS	100	6	100	6	100	6	330	21	330	21
Soil Ingestion Rate - Child (mg/day)	IRSc	200	4	200	4	NA		NA		NA	
Water Ingestion Rate - Adult (L/day)	IRW	2.0	2	2.0	2	0.7	4a	NA		NA	
Water Ingestion Rate - Child (L/day)	IRWc	1.5	2	=		NA		NA		NA	
Skin Surface Area - Adult to Soil (cm ²)	SA	5700	4	5700	4	3300	4	3300	4	3300	4
Skin Surface Area - Child to Soil (cm ²)	SAC	2800	4	=		NA		NA		NA	
Skin Surface Area - Adult to Groundwater (cm ²)	SAw	NA		NA		NA		5700	4	5700	4
Soil to Skin Adherence Factor - Adult (mg/cm ² -day)	AF	0.07	5a	0.07	5a	0.10	5b	0.30	5c	0.30	5c
Soil to Skin Adherence Factor - Child (mg/cm ² -day)	AFc	0.20	5d	=		NA		NA		NA	
AGE-ADJUSTED EXPOSURE FACTORS											
Inhalation Factor - Air (m ³ -yr/kg-d)	IFAadj	10.18	7	4.75	7a	NA		NA		NA	
Ingestion Factor - Soil (mg-yr/kg-d)	IFSadj	114	7	87	7a	NA		NA		NA	
Ingestion Factor - Water (L-yr/kg-d)	IFWadj	1.29	7	0.74	7a	NA		NA		NA	
Surface Area Factor - Skin (mg-yr/kg-d)	SFSadj	361	7	253	7a	NA		NA		NA	

Appendix C: Exposure Factors (continued)

Parameter (unit)	Symbol	Residential	Urban Residential	Occupational	Construction Worker	Excavation Worker
		Note	Note	Note	Note	Note
SITE PARAMETERS						
Soil Bulk Density (g/cm ³)	ρ_b	1.70	8	=	=	=
Soil Particle Density (g/cm ³)	ρ_s	2.74	9	=	=	=
Soil Porosity	n	0.38	8	=	=	=
Air Content - Vadose Zone Soils	n_a	0.26	10	=	=	=
Air Content - Cap. Fringe Soils	n_{acap}	0.038	10	=	=	=
Air Content - Foundation Cracks	n_{acrck}	0.26	10	=	=	=
Water Content - Vadose Zone Soils	n_w	0.12	8	=	=	=
Water Content - Cap. Fringe Soils	n_{wcap}	0.342	8	=	=	=
Water Content - Foundation Cracks	n_{wcrk}	0.12	11	=	=	=
Vadose Zone Thickness (cm)	L_v	295	12	=	=	=
Capillary Fringe Thickness (cm)	L_{cap}	5.00	8	=	=	=
Fraction Organic Carbon (shallow soil)	f_{oc}	0.005	8a	=	=	=
Depth to Groundwater (cm)	L_w	300	8	=	=	=
Groundwater Dilution-Attenuation Factor	DAF	60	19	=	=	=
SOIL CONTAMINATION PARAMETERS						
Thickness of Contaminated Surface Soils (cm)	L_{ss}	100	8	=	=	=
Fraction of Site with Surface Soil Contamination	f_{ss}	0.50	16	=	=	=
Thickness of Clean Surface Soils (cm)	L_c	100	8	=	=	=
Thickness of Subsurface Contamination (cm)	L_s	200	8	=	=	=
Fraction of Site with Subsurface Vol. To Outdoor Air	f_{so}	0.50	17	=	=	=
Thickness of Clean Soils Under Building (cm)	L_{cb}	100	8	=	=	=
Thickness of Contaminated Soils Under Building (cm)	L_{sb}	200	8	=	=	=
Fraction of Contaminated Soils Under Building	f_{sb}	0.50	18	=	=	=
Particulate Emission Factor for Soils (kg/m ³)	PEF	7.58E-10	13	=	=	=

Appendix C: Exposure Factors (continued)

Parameter (unit)	Symbol	Residential		Urban Residential		Occupational		Construction Worker		Excavation Worker	
			Note		Note		Note		Note		Note
BUILDING PARAMETERS											
Building Air Exchange Rate (1/day)	ER	24	14	=		48	14	NA		NA	
Building Height (indoor air mixing zone) (cm)	L _B	200	8	=		300	8	NA		NA	
Foundation Wall Thickness (cm)	L _{crk}	15	8	=		=		NA		NA	
Foundation Crack Fraction	f _{crk}	0.0010	15	=		=		NA		NA	
VOLATILIZATION FACTORS											
Averaging time for Volatilization -Adults (yr)	t _{vol}	25	16	=		=		=		=	
Averaging time for Volatilization -Children (yr)	t _{volc}	6	16	=		NA		NA		NA	
Max. Soil to Building Vol. Factor (kg/m ³)	VF _{silmax}	3.88E-03	18	3.88E-03	18	1.29E-03	18	NA		NA	
Max. <u>Surface</u> Soil Vol. Factor - Adult (kg/m ³)	VF _{ssmax}	1.57E-05	16	1.57E-05	16	1.57E-05	16	1.57E-05	16	1.57E-05	16
Max. <u>Surface</u> Soil Vol. Factor - Child (kg/m ³)	VF _{ssmax}	6.53E-05	16	=		NA		NA		NA	
Max. Soil to Outdoor Air Vol. Factor - Adult (kg/m ³)	VF _{somax}	3.13E-05	17	3.13E-05	17	3.13E-05	17	NA		NA	
Volatile Organics Dispersion Term (g/m ² -s per kg/m ³)	Q/C	6.88E+01	13	=		=		=		=	
MISCELLANEOUS PARAMETERS											
Ideal Gas Law Constant (m ³ -atm/K-mol)	R	8.21E-05	20	=		=		=		=	
Absolute Temperature (K)	T	2.93E+02	20	=		=		=		=	

Notes and References for Table of Exposure Factors:

= This exposure parameter is the same as the residential value.

NA This exposure parameter is not required for any of the RBCs.

1. Acceptable risk levels are specified in statute (ORS 465.315) and defined in rule (OAR 340-122-0115).
2. EPA (1989)
3. EPA (1991b)
 - 3a. Professional judgment: EF for urban resident = 1/2 residential EF
4. EPA (1997c)
 - 4a. Incorporates time spent at work (8 hr/24 hr day)
5. EPA (2001a)
 - 5a. Mean for residential adult gardener
 - 5b. Mean for commercial gardener used to represent upper end commercial exposure
 - 5c. 95th percentile construction worker
 - 5d. 95th percentile daycare child
6. DEQ (1998b)
7. Calculated from equations given in EPA (1998a).
 - 7a. Modified for urban scenario by analogy to equations given in EPA (1998a).
8. ASTM (1995b)
 - 8a. f_{oc} is an average of ASTM (1995b) and EPA (1996b) defaults.
9. Calculated from $\rho_s = \rho_b/(1-n)$.
10. Calculated from $n_a=n-n_w$; $n_{acap}=n-n_{wcap}$; $n_{acrk}=n-n_{wcrk}$.
11. n_{wcrk} assumed = n_w .
12. Calculated from $L_v = L_w - L_{cap}$
13. EPA (1996b)
14. Estimated from data reported in Michigan DEQ (1998).
15. Derived from range of floor-wall seem gaps given in EPA (1997b).
16. Refer to Section B.3.2.1 in RBDM (DEQ, 2003).
17. Refer to Section B.3.2.2 in RBDM (DEQ, 2003).
18. Refer to Section B.3.2.3 in RBDM (DEQ, 2003).
19. Refer to Section B.3.2.4 in RBDM (DEQ, 2003).
20. Refer to discussion of Henry's Law Constants in Section B.2.1.2 in RBDM (DEQ, 2003).
21. EPA (2002c)

Appendix D: Chemical Data

Data used for Constituent RBC Calculations

Chemical	Vol	Mol. Wt. (g/mol)	S		P		C _{sat}		K _{oc}		K _H		H		D _{air}		D _w	
	Class		(mg/L)	Note	($\mu\text{g}/\text{m}^3$)	Note 4a	(mg/kg)	Note 4b	(cm^3/g)	Note	($\text{m}^3\text{-atm}/\text{mol}$)	Note	Note 6	(cm^2/s)	Note	(cm^2/s)	Note	
	Note 1	Note 2		Note	Note 4a	Note 4b		Note		Note	Note 6		Note		Note		Note	
Benzene	v	78	1.75E+03	3	4.04E+08	7.01E+02	5.89E+01	5	5.55E-03	3	2.31E-01	8.80E-02	3	9.80E-06	3			
Toluene	v	92	5.26E+02	3	1.45E+08	5.38E+02	1.82E+02	5	6.64E-03	3	2.76E-01	8.70E-02	3	8.60E-06	3			
Ethylbenzene	v	106	1.69E+02	3	5.54E+07	3.27E+02	3.63E+02	5	7.88E-03	3	3.28E-01	7.50E-02	3	7.80E-06	3			
Xylenes	v	106	1.75E+02	3a	4.90E+07	3.58E+02	3.86E+02	5a	6.73E-03	3a	2.80E-01	7.80E-02	3a	8.75E-06	3a			
iso-propylbenzene	v	120	3.00E+01	9	1.62E+07	3.35E+02	2.20E+03	9	1.30E-02	9	5.41E-01	7.50E-02	9	7.80E-06	9			
n-propylbenzene	v	120	1.40E+01	9	7.57E+06	1.98E+02	2.80E+03	9	1.30E-02	9	5.41E-01	7.50E-02	9	7.80E-06	9			
1,2,4-trimethylbenzene	v	120	5.70E+01	9	1.35E+07	1.06E+03	3.70E+03	9	5.70E-03	9	2.37E-01	7.50E-02	9	7.10E-06	9			
1,3,5-trimethylbenzene	v	120	5.00E+01	9	1.60E+07	2.11E+02	8.20E+02	9	7.70E-03	9	3.20E-01	7.50E-02	9	7.10E-06	9			
Acenaphthene	v	154	4.24E+00	3	2.73E+04	1.04E+02	4.90E+03	5	1.55E-04	3	6.45E-03	4.21E-02	3	7.69E-06	3			
Anthracene	v	178	4.34E-02	3	1.17E+02	6.40E+00	2.95E+04	5	6.50E-05	3	2.70E-03	3.24E-02	3	7.74E-06	3			
Benz[a]anthracene	nv	228	9.40E-03	3	1.31E+00	1.87E+01	3.98E+05	5	3.35E-06	3	1.39E-04	5.10E-02	3	9.00E-06	3			
Benzo[b]fluoranthene	nv	252	1.50E-03	3	6.93E+00	9.23E+00	1.23E+06	5	1.11E-04	3	4.62E-03	2.26E-02	3	5.56E-06	3			
Benzo[k]fluoranthene	nv	252	8.00E-04	3	2.76E-02	4.92E+00	1.23E+06	5	8.29E-07	3	3.45E-05	2.26E-02	3	5.56E-06	3			
Benzo[a]pyrene	nv	252	1.62E-03	3	7.61E-02	8.26E+00	1.02E+06	5	1.13E-06	3	4.70E-05	4.30E-02	3	9.00E-06	3			
Chrysene	nv	228	1.60E-03	3	6.30E+00	3.18E+00	3.98E+05	5	9.46E-05	3	3.93E-03	2.48E-02	3	6.21E-06	3			
Dibenz[a,h]anthracene	nv	278	2.49E-04	3	1.52E-04	4.73E+00	3.80E+06	5	1.47E-08	3	6.11E-07	2.02E-02	3	5.18E-06	3			
Fluoranthene	nv	202	2.06E-01	3	1.38E+02	1.10E+02	1.07E+05	5	1.61E-05	3	6.70E-04	3.02E-02	3	6.35E-06	3			
Fluorene	v	166	1.98E+00	3	5.23E+03	1.37E+02	1.38E+04	5	6.35E-05	3	2.64E-03	3.63E-02	3	7.88E-06	3			
Indeno[1,2,3-cd]pyrene	nv	276	2.20E-05	3	1.46E-03	3.82E-01	3.47E+06	5	1.60E-06	3	6.65E-05	1.90E-02	3	5.66E-06	3			
Naphthalene	v	128	3.10E+01	3	6.23E+05	3.12E+02	2.00E+03	5	4.83E-04	3	2.01E-02	5.90E-02	3	7.50E-06	3			
Pyrene	nv	202	1.35E-01	3	6.18E+01	7.09E+01	1.05E+05	5	1.10E-05	3	4.58E-04	2.72E-02	3	7.24E-06	3			
MTBE	v	88	5.10E+04	7	1.25E+09	6.65E+03	1.12E+01	7	5.87E-04	7	2.44E-02	1.10E-01	8	1.05E-05	8			
EDB (1,2-dibromoethane)	v	188	3.40E+03	9	4.53E+07	7.25E+02	2.81E+01	9	3.20E-04	9	1.33E-02	7.33E-02	9	8.06E-06	9			
EDC (1,2-dichloroethane)	v	99	8.52E+03	3	3.45E+08	1.40E+03	1.74E+01	5	9.74E-04	3	4.05E-02	1.04E-01	3	9.90E-06	3			
Lead	NA	207	NA	10	NA	NA	NA	10	NA	10	NA	NA	10	NA	10			

Appendix D: Chemical Data (continued)

Data used for TPH RBC Calculations

Fuel Fraction or Constituent	Vol Class	MW (g/mol)	Density (g/cm ³)	S (mg/L)	P (ug/m ³)	K _H (m ³ -atm/mol)	H'	Log K _{oc}	K _{oc} (cm ³ /g)	D _{air} (cm ² /s)	D _w (cm ² /s)
Aliphatic C5-C6	v	81	0.68	3.6E+01	1.2E+09	7.94E-01	33	2.9	7.9E+02	1.0E-01	1.0E-05
Aliphatic >C6-C8	v	100	0.73	5.4E+00	2.7E+08	1.20E+00	50	3.6	4.0E+03	1.0E-01	1.0E-05
Aliphatic >C8-C10	v	130	0.73	4.3E-01	3.4E+07	1.92E+00	80	4.5	3.2E+04	1.0E-01	1.0E-05
Aliphatic >C10-C12	v	160	0.76	3.4E-02	4.1E+06	2.89E+00	120	5.4	2.5E+05	1.0E-01	1.0E-05
Aliphatic >C12-C16	nv	200	0.77	7.6E-04	4.0E+05	1.25E+01	520	6.7	5.0E+06	1.0E-01	1.0E-05
Aliphatic >C16-C21	nv	270	0.78	2.5E-06	1.2E+04	1.18E+02	4900	8.8	6.3E+08	1.0E-01	1.0E-05
Aliphatic >C21-C34	nv	400	0.78	1.5E-11	1.5E+00	2.41E+03	100000	10.0	1.1E+10	1.0E-01	1.0E-05
Aromatic >C8-C10	v	120	0.87	6.5E+01	3.1E+07	1.15E-02	0.48	3.2	1.6E+03	1.0E-01	1.0E-05
Aromatic >C10-C12	v	130	0.90	2.5E+01	3.5E+06	3.37E-03	0.14	3.4	2.5E+03	1.0E-01	1.0E-05
Aromatic >C12-C16	v	150	1.02	5.8E+00	3.1E+05	1.27E-03	0.053	3.7	5.0E+03	1.0E-01	1.0E-05
Aromatic >C16-C21	v	190	1.23	6.5E-01	8.5E+03	3.13E-04	0.013	4.2	1.6E+04	1.0E-01	1.0E-05
Aromatic >C21-C34	nv	240	1.28	6.6E-03	4.4E+00	1.61E-05	0.00067	5.1	1.3E+05	1.0E-01	1.0E-05
n-Hexane	v	86	0.70	1.8E+01	9.0E+07	1.20E-01	5.0	2.9	8.9E+02	2.0E-01	7.8E-06
Benzene	v	78	0.88	1.8E+03	4.0E+08	5.55E-03	0.23	1.8	5.9E+01	8.8E-02	9.8E-06
Toluene	v	92	0.87	5.3E+02	1.5E+08	6.64E-03	0.28	2.3	1.8E+02	8.7E-02	8.6E-06
Ethylbenzene	v	106	0.87	1.7E+02	5.5E+07	7.88E-03	0.33	2.6	3.6E+02	7.5E-02	7.8E-06
Total Xylenes	v	106	0.88	1.8E+02	4.9E+07	6.73E-03	0.28	2.6	3.9E+02	7.8E-02	8.8E-06
1,2,4-trimethylbenzene	v	120	0.88	5.7E+01	6.2E+04	5.70E-03	0.24	3.6	3.7E+03	7.5E-02	7.1E-06
1,3,5-trimethylbenzene	v	120	0.87	5.0E+01	1.6E+07	7.70E-03	0.32	2.9	8.2E+02	7.5E-02	7.1E-06
Naphthalene	v	128	1.15	3.1E+01	6.2E+05	4.83E-04	0.02	3.3	2.0E+03	5.9E-02	7.5E-06

Notes and References for Table of Chemical Data:

- nv This chemical is classified as “nonvolatile” for purposes of the exposure calculations in this document.
- v This chemical is classified as “volatile” for purposes of the exposure calculations in this document.
- 1. Volatility is based on EPA (1991a). A “volatile” constituent has a Henry’s constant $> 10^{-5} \text{ m}^3\text{-atm/mol}$ and a molecular weight $< 200 \text{ g/mol}$.
- 2. Molecular weights can be obtained from many common chemical handbooks and chemistry texts. No specific reference was used here.
- 3. Values from Table 36 (S and H) and Table 37 (D_{air} and D_w) in EPA (1996b).
 - a. These are the average values for the three xylene isomers.
- 4. a. Vapor pressure is calculated from the relationship $P = H * S * 1000000$, where H is the dimensionless Henry’s constant, S is the solubility in mg/L, and 1000000 is a conversion factor yielding units of $\mu\text{g/m}^3$ for direct comparison to RBC_{air} values.
 - b. C_{sat} is calculated using equation [B-21]. See Section B.2.1.4.
- 5. K_{ocs} are the “Calculated Values” from Table 39 in EPA (1996b).
 - a. This is the average Koc value for the three xylene isomers.
- 6. Dimensionless Henry’s constants are calculated from the relationship $H = K_H / R * T$ where K_H is the Henry’s constant in $\text{m}^3\text{-atm/mol}$, R is the ideal gas law constant ($8.21 \times 10^{-5} \text{ m}^3\text{-atm/K-mol}$), and T is the absolute temperature (293 K).
- 7. Howard (1993)
- 8. D_{air} and D_w estimated using equation [B-57]. See Section B.2.3.2.
- 9. EPA (2002a)
- 10. NA : These data are not applicable since the lead RBCs are not calculated by the Department. See Section B.3.4.

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Appendix E: Toxicological Data

Data used for Constituent RBC Calculations

Chemical	Risk Type	Chronic								Subchronic				RAF _d	K _p (cm/hr)	τ (hr)	t* (hr)	B	DA _w (L/cm ² -event)	
		SF _o (mg/Kg-day) ⁻¹		SF _i (mg/Kg-day) ⁻¹		RfD _o (mg/Kg-day)		RfD _i (mg/Kg-day)		RfD _o (mg/Kg-day)		RfD _i (mg/Kg-day)								
			Note		Note		Note		Note		Note		Note							Note 5
Benzene	c	0.055	1j	0.027	1j	0.004	2	0.0086	1k,2	-	-	0.00E+00	1.50E-02	2.90E-01	7.00E-01	1.00E-01	6	3.68E-05		
Toluene	nc	NA		NA		0.2	1f	0.11	1d,2	2	12	0.26	12	0.00E+00	3.10E-02	3.50E-01	8.40E-01	1.00E-01	6	8.02E-05
Ethylbenzene	nc	NA		NA		0.1	1c	0.29	1c,2	0.11	12	-	-	0.00E+00	4.90E-02	4.20E-01	1.01E+00	2.00E-01	6	1.31E-04
Xylenes	nc	NA		NA		0.2	1k	0.029	1k,2	-	-	-	-	0.00E+00	5.30E-02	4.20E-01	1.01E+00	2.00E-01	6	1.42E-04
iso-propylbenzene	nc	NA		NA		0.1	1g	0.11	1g,2	-	-	-	-	0.00E+00	7.46E-02	4.93E-01	1.18E+00	3.14E-01	7	2.09E-04
n-propylbenzene	nc	NA		NA		0.04	4	0.04	3	-	-	-	-	0.00E+00	8.74E-02	4.93E-01	1.18E+00	3.68E-01	7	2.44E-04
1,2,4-trimethylbenzene	nc	NA		NA		0.05	4	0.0017	4	-	-	-	-	0.00E+00	1.10E-01	4.93E-01	1.18E+00	4.65E-01	7	3.05E-04
1,3,5-trimethylbenzene	nc	NA		NA		0.05	4	0.0017	4	0.5	12	-	-	0.00E+00	3.81E-02	4.93E-01	1.18E+00	1.60E-01	7	1.09E-04
Acenaphthene	nc	NA		NA		0.06	1f	0.06	3	-	-	-	-	0.00E+00	8.41E-02	7.65E-01	1.84E+00	4.01E-01	7	2.96E-04
Anthracene	nc	NA		NA		0.3	1e	0.3	3	-	-	-	-	0.00E+00	1.61E-01	1.04E+00	4.00E+00	8.25E-01	7	6.42E-04
Benz[a]anthracene	c	0.73	4	0.73	3	NA		NA		-	-	-	-	1.30E-01	4.70E-01	2.03E+00	8.53E+00	2.80E+00	6	2.62E-03
Benzo[b]fluoranthene	c	0.73	4	0.73	3	NA		NA		-	-	-	-	1.30E-01	7.00E-01	2.77E+00	1.20E+01	4.30E+00	6	4.55E-03
Benzo[k]fluoranthene	c	0.073	4	0.073	3	NA		NA		-	-	-	-	1.30E-01	7.60E-01	2.71E+00	1.18E+01	4.64E+00	7	4.89E-03
Benzo[a]pyrene	c	7.3	4	7.3	3	NA		NA		-	-	-	-	1.30E-01	7.00E-01	2.69E+00	1.17E+01	4.30E+00	6	4.49E-03
Chrysene	c	0.0073	4	0.0073	3	NA		NA		-	-	-	-	1.30E-01	4.70E-01	2.03E+00	8.53E+00	2.80E+00	6	2.62E-03
Dibenz[a,h]anthracene	c	7.3	4	7.3	3	NA		NA		-	-	-	-	1.30E-01	1.50E+00	3.88E+00	1.76E+01	9.70E+00	6	1.15E-02
Fluoranthene	nc	NA		NA		0.04	1e	0.04	3	0.4	12	-	-	1.30E-01	2.20E-01	1.45E+00	5.68E+00	1.20E+00	6	1.04E-03
Fluorene	nc	NA		NA		0.04	1b	0.04	3	0.4	12	-	-	0.00E+00	1.12E-01	8.93E-01	2.14E+00	5.55E-01	7	4.13E-04
Indeno[1,2,3-cd]pyrene	c	0.73	4	0.73	3	NA		NA		-	-	-	-	1.30E-01	1.11E+00	3.69E+00	1.65E+01	7.06E+00	6	8.30E-03
Naphthalene	nc	NA		NA		0.02	1i	0.00086	1i,2	-	-	-	-	0.00E+00	4.70E-02	5.60E-01	1.34E+00	2.00E-01	6	1.41E-04
Pyrene	nc	NA		NA		0.03	1e	0.03	3	-	-	-	-	1.30E-01	2.76E-01	1.42E+00	5.64E+00	1.51E+00	7	1.29E-03
MTBE (methyl t-butyl ether)	c	0.0018	13	0.0018	13	0.86	2	0.86	1e,2	-	-	-	-	0.00E+00	3.45E-03	3.27E-01	7.84E-01	1.25E-02	6	9.11E-06
EDB (1,2-dibromoethane)	c	85	1g	0.77	1g	0.000057	10	0.000057	10	-	-	-	-	0.00E+00	1.75E-03	1.19E+00	2.85E+00	9.21E-03	6	7.43E-06
EDC (1,2-dichloroethane)	c	0.091	1c	0.091	3	0.03	4	0.0014	4	-	-	-	-	0.00E+00	4.01E-03	3.76E-01	9.03E-01	1.53E-02	6	1.10E-05
Lead	NA	NA	9	NA	9	NA	9	NA	9	NA	9	NA	9	NA	NA	NA	NA	NA	9	NA

Appendix E: Toxicological Data (continued)

Data used for TPH RBC Calculations

Chemical	Risk Type	Chronic				Subchronic		RAFD	Kp (cm/hr)	τ (hr)	t* (hr)	B	DAw (L/cm ² -event)
		SF _o (mg/Kg-day) ⁻¹	SF _i (mg/Kg-day) ⁻¹	RfD _o (mg/Kg-day)	RfD _i (mg/Kg-day)	RfD _o (mg/Kg-day)	RfD _i (mg/Kg-day)						
		Note 11	Note 11	Note 11	Note 11	Note 11	Note 11						
Aliphatic C5-C6	nc	NA	NA	5.7	5.7	-	-	0.00E+00	6.30E-02	2.98E-01	7.16E-01	2.18E-01	1.49E-04
Aliphatic >C6-C8	nc	NA	NA	5.7	5.7	-	-	0.00E+00	1.43E-01	3.81E-01	9.15E-01	5.49E-01	3.45E-04
Aliphatic >C8-C10	nc	NA	NA	0.1	0.3	-	-	0.00E+00	3.81E-01	5.61E-01	2.25E+00	1.67E+00	1.11E-03
Aliphatic >C10-C12	nc	NA	NA	0.1	0.3	-	-	0.00E+00	1.02E+00	8.26E-01	3.62E+00	4.94E+00	3.61E-03
Aliphatic >C12-C16	nc	NA	NA	0.1	0.3	-	-	1.30E-01	4.37E+00	1.38E+00	6.41E+00	2.38E+01	2.01E-02
Aliphatic >C16-C21	nc	NA	NA	2	2	-	-	1.30E-01	4.31E+01	3.41E+00	1.61E+01	2.72E+02	3.11E-01
Aliphatic >C21-C34	nc	NA	NA	2	2	-	-	1.30E-01	5.00E+01	1.82E+01	8.58E+01	3.84E+02	8.34E-01
Aromatic >C8-C10	nc	NA	NA	0.04	0.06	-	-	0.00E+00	6.01E-02	4.93E-01	1.18E+00	2.53E-01	1.70E-04
Aromatic >C10-C12	nc	NA	NA	0.04	0.06	-	-	0.00E+00	7.15E-02	5.61E-01	1.35E+00	3.14E-01	2.13E-04
Aromatic >C12-C16	nc	NA	NA	0.04	0.06	-	-	0.00E+00	8.72E-02	7.26E-01	1.74E+00	4.11E-01	2.98E-04
Aromatic >C16-C21	nc	NA	NA	0.03	0.03	-	-	0.00E+00	1.11E-01	1.22E+00	2.92E+00	5.90E-01	4.80E-04
Aromatic >C21-C34	nc	NA	NA	0.03	0.03	-	-	1.30E-01	2.29E-01	2.32E+00	9.13E+00	1.37E+00	1.37E-03
n-Hexane	nc	NA	NA	0.06	0.057	0.6	0.057	0.00E+00	5.90E-02	3.18E-01	7.64E-01	2.11E-01	1.43E-04
Benzene	nc	0.055	0.027	0.004	0.0086	-	-	0.00E+00	1.50E-02	2.90E-01	7.00E-01	1.00E-01	3.68E-05
Toluene	nc	NA	NA	0.2	0.11	2	0.26	0.00E+00	3.10E-02	3.50E-01	8.40E-01	1.00E-01	8.02E-05
Ethylbenzene	nc	NA	NA	0.1	0.29	0.11	-	0.00E+00	4.90E-02	4.20E-01	1.01E+00	2.00E-01	1.31E-04
Total Xylenes	nc	NA	NA	0.2	0.029	-	-	0.00E+00	5.30E-02	4.20E-01	1.01E+00	2.00E-01	1.42E-04
1,2,4-trimethylbenzene	nc	NA	NA	0.05	0.0017	-	-	0.00E+00	1.10E-01	4.93E-01	1.18E+00	4.65E-01	3.05E-04
1,3,5-trimethylbenzene	nc	NA	NA	0.05	0.0017	0.5	-	0.00E+00	3.81E-02	4.93E-01	1.18E+00	1.60E-01	1.09E-04
Naphthalene	nc	NA	NA	0.02	0.00086	-	-	0.00E+00	4.70E-02	5.60E-01	1.34E+00	2.00E-01	1.41E-04

Notes and References for Table of Toxicological Data:

- c This chemical is a known or suspected carcinogen.
- nc This chemical is a noncarcinogen.
- There is no subchronic RfD value available for this chemical as of the date of this document.
- 1. U. S. EPA, Office of Research and Development, Integrated Risk Information System (IRIS)
 - 1a. IRIS, 1987
 - 1b. IRIS, 1990
 - 1c. IRIS, 1991
 - 1d. IRIS, 1992
 - 1e. IRIS, 1993
 - 1f. IRIS, 1994
 - 1g. IRIS, 1997
 - 1i. IRIS, 1998
 - 1j. IRIS, 2000
 - 1k. IRIS, 2003
- 2. Converted from inhalation reference concentration (RfC in mg/m³) by the following relationship: $RfDi = RfC * 20 \text{ m}^3/\text{day} / 70 \text{ kg}$.
- 3. Route extrapolation, RfDi assumed to be equivalent to RfDo, or SFi assumed to be equivalent to SFo.
- 4. U.S. EPA, Office of Research and Development, National Center for Environmental Assessment (NCEA).
 - 4a. 1993
 - 4b. 2002
- 5. Dermal absorption fraction values are from Exhibit 3-4 in EPA (2001b).
- 6. Kp, t, t*, and B are from Exhibit B-3 in EPA (2001b).
- 7. Kp, t, t*, and B were calculated from equations given in Appendix A in EPA (2001b).
- 8. DAw is calculated from equations given in EPA (2001b). See Section B.3.3.4.
- 9. NA: These data are not applicable since the lead RBCs are not calculated by the Department. See Section B.3.4.
- 10. EPA, 1997e.
- 11. See Appendix G for the toxicity factors for the TPH fractions.
- 12. ORNL (2003).
- 13. California Environmental Protection Agency (CalEPA), Office of Environmental Health Hazard Assessment (OEHHA):
 - SFo – Public Health Goal for Methyl Tertiary Butyl Ether (MTBE) in Drinking Water, March 1999.
 - SFi – Air Toxics Hot Spots Program Risk Assessment Guidelines, Part II, Technical Support Document for Describing Available Cancer Potency Factors, 19 December 2002.
- 14. For the TPH fractions, Kp, t, t*, and B were calculated from equations given in Appendix A in EPA (2001b). Kp was calculated from Kow using the relationship $\log(Koc) + 0.21 = \log(Kow)$ from Table 4 in TPHCWG (1997a).

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Appendix F: Generic Petroleum Products

F.1 Composition of Generic Products

Table F.1 lists the weight fractions of all of the TPH fractions and constituents for each of the three generic petroleum products with RBCs listed in Appendix A.

Table F.1: Composition of Generic Products Used for TPH RBCs

Fuel Fraction or Component	Weight Fraction in Generic Product		
	Gasoline	Diesel and Heating Oil	Transformer Mineral Insulating Oil
Aliphatic C5-C6	2.06E-01	0.00E+00	0.00E+00
Aliphatic > C6-C8	2.20E-01	0.00E+00	0.00E+00
Aliphatic > C8-C10	9.00E-02	2.00E-02	1.00E-03
Aliphatic > C10-C12	3.00E-02	7.00E-02	3.00E-03
Aliphatic > C12-C16	0.00E+00	3.50E-01	1.60E-01
Aliphatic > C16-C21	0.00E+00	3.40E-01	7.00E-01
Aliphatic > C21-C34	0.00E+00	0.00E+00	0.00E+00
Aromatic > C8-C10	9.02E-02	2.52E-03	1.00E-03
Aromatic > C10-C12	2.25E-02	7.40E-03	1.00E-03
Aromatic > C12-C16	0.00E+00	8.00E-02	7.00E-03
Aromatic > C16-C21	0.00E+00	1.20E-01	8.00E-02
Aromatic > C21-C34	0.00E+00	0.00E+00	4.60E-02
n-Hexane	2.40E-02	0.00E+00	0.00E+00
Benzene	2.50E-02	2.90E-04	0.00E+00
Toluene	1.20E-01	1.80E-03	0.00E+00
Ethylbenzene	2.00E-02	6.80E-04	0.00E+00
Total Xylenes	1.10E-01	5.00E-03	0.00E+00
1,2,4-trimethylbenzene	3.00E-02	0.00E+00	0.00E+00
1,3,5-trimethylbenzene	9.80E-03	1.80E-03	0.00E+00
Naphthalene	2.50E-03	2.60E-03	0.00E+00

Notes and References for Petroleum Composition Data:

Generic gasoline, diesel, and transformer mineral insulating oil weight-fraction data are from Park and San Juan (2000), except as follows:

- The n-hexane value for gasoline is taken from Table 4 in TPHCWG (1998b).
- The Aliphatic C5-C6 fraction for gasoline from Park and San Juan (2000) is reduced by the amount of n-hexane.
- The BTEX data for diesel are taken from Table 10 in TPHCWG (1998b).
- The Aromatic >C8-C10 fraction for diesel from Park and San Juan (2000) is reduced by the amount of ethylbenzene and xylenes.

The raw data are "corrected" by subtracting out constituents that are also detected in one of the petroleum fractions. For example, the sum of the ethylbenzene and xylene concentrations are subtracted from the Aromatic >C8-C10 fraction so that they will not be accounted for twice in the calculation of risk-based concentrations.

"Transformer Mineral Insulating Oil" represents the composition of transformer mineral insulating oils used in the power industry. The composition of other mineral oils may differ from the values in this table.

F.2 Estimating Composition of Mixtures

If you have a mixture of gasoline and diesel you can use this method to estimate the fractions for each product. To do that, however, you will first have to estimate what portion of each constituent can be attributed to each product. You can make such an estimate by calculating what the fraction in each product would be if the composition of the gasoline and diesel were like the original generic compositions listed in Section F.1. The fractions can be estimated from the following equation:

$$\text{Fraction from Gasoline} = \frac{\text{WF in Gasoline} * \text{TPH-Gx}}{\text{WF in Gasoline} * \text{TPH-Gx} + \text{WF in Diesel} * \text{TPH-Dx}} \quad [\text{F-1}]$$

where:

- WF in Gasoline = the weight fraction of a constituent, like benzene, in gasoline
- WF in Diesel = the weight fraction of the same constituent in diesel
- TPH-Gx = the concentration of gasoline in the sample
- TPH-Dx = the concentration of diesel in the same sample

The concentrations can then be calculated as follows:

$$\text{Estimated Concentration in Gasoline} = \text{Fraction in Gasoline} * \text{Measured Concentration} \quad [\text{F-2}]$$

$$\text{Estimated Conc. in Diesel} = \text{Measured Conc. in Diesel} - \text{Estimated Concentration in Gasoline} \quad [\text{F-3}]$$

Example: You are working on a site where TPH-HCID test results show that you are dealing with a mixture of gasoline and diesel contamination. Tests on a soil sample gave the following results: 1500 ppm TPH-Gx; 4200 ppm TPH-Dx; 8.2 ppm benzene; 65 ppm toluene; 18 ppm ethylbenzene; 72 ppm total xylenes; 84 ppm 1,2,4-TMB; 16 ppm 1,3,5-TMB; and 5.8 ppm naphthalene.

The data in Section F.1 show that the weight fraction of benzene is 0.025 in gasoline and 0.00029 in diesel. Therefore, the fraction of benzene from gasoline is estimated to be:

$$\text{Fraction of benzene from gasoline} = \frac{0.025 * 1500}{0.025 * 1500 + 0.00029 * 4200} = 0.97$$

$$\text{Conc. of benzene in gasoline} = 0.97 * 8.2 \text{ ppm} = 8.0 \text{ ppm}$$

$$\text{Conc. of benzene in diesel} = 8.2 \text{ ppm} - 8.0 \text{ ppm} = 0.2 \text{ ppm}$$

Therefore, about 8.0 ppm is from gasoline and 0.2 ppm is from diesel.

A similar calculation for naphthalene yields:

$$\text{Fraction of naphthalene from gasoline} = \frac{0.0025 * 1500}{0.0025 * 1500 + 0.0026 * 4200} = 0.26$$

$$\text{Conc. of benzene in gasoline} = 0.26 * 5.8 \text{ ppm} = 1.5 \text{ ppm}$$

$$\text{Conc. of benzene in diesel} = 5.8 \text{ ppm} - 1.5 \text{ ppm} = 4.3 \text{ ppm}$$

Repeat this process for each of the other constituents and use the results with "Method 1" discussed in Section 3.1.5.2 to estimate the TPH fractions in gasoline and diesel. The estimated fractions and the constituent concentrations can then be used to calculate site-specific TPH RBCs.

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Appendix G: Toxicity Information for Petroleum Hydrocarbons

Chemical toxicity is evaluated on the basis of derived acceptable daily intakes for non-carcinogenic effects, and slope factors for potential carcinogenic effects. The derivation of these factors is explained in Sections G.1 and G.2. Section G.3 summarizes how available data were employed to estimate the toxicity of the TPH fractions used to calculate the TPH RBCs listed in Appendix A.

G.1 Non-carcinogenic Toxic Effects

The numeric indicators of toxicity are Reference Dose (RfD) values cited in the EPA's Integrated Risk Information System (IRIS) (EPA, 2003a) or other acceptable sources. RfDs for chronic exposure are the maximum daily concentrations (expressed as milligrams of chemical per kilogram of body weight per day – mg/kg-day) that would be allowable without observed health effects (EPA, 1989). IRIS provides RfD values for oral exposure. The values are derived from data from animal studies or observations made in human epidemiological studies relating intake to non-carcinogenic effects. The highest exposure level not causing adverse effects, the no-observed-adverse-effect-level (NOAEL), is determined from available studies reported in the literature. The NOAEL is then divided by an appropriate uncertainty factor (typically 100 to 1,000) to yield the RfD. RfDs are designed to be protective of sensitive populations.

IRIS currently reports inhalation toxicity information as reference concentrations (RfC), expressed as mg/m³. To convert the RfC to an RfD for inhalation (RfD_i), the following relationship is used:

$$\text{RfD (mg/kg-day)} = \text{RfC} \cdot \frac{\text{IR}}{\text{BW}} = \text{RfC (mg/m}^3\text{)} \cdot \frac{20 \text{ m}^3/\text{day}}{70 \text{ kg}} \quad [\text{G-1}]$$

where:

- RfD_i = Reference Dose, inhalation (mg/kg-day)
- RfC = Reference Concentration (mg/m³)
- IR = Inhalation rate (m³/day)
- BW = Body Weight (kg)

RfDs for the oral and inhalation routes of human exposure are listed in Appendix E. For exposure durations of less than seven years, EPA and DEQ guidance allow the use of subchronic toxicity values. However, typically only chronic RfDs are available. EPA states that the IRIS database does not include subchronic RfD values because they have not undergone adequate review. Therefore, the typical conservative and practical approach is to use chronic toxicity values for subchronic exposure.

Nevertheless, for the few subchronic toxicity values that are available, we have provided a mechanism in the Department's spreadsheets (DEQ, 2003a and 2003b) to calculate RBCs based on subchronic values. *This applies only to the exposure scenarios with limited duration (construction and excavation workers).* Where subchronic values are not available, the default chronic values are used.

G.2 Potential Carcinogenic Effects

Derivation of acceptable intakes for carcinogens, using the same approach as non-carcinogens, is not possible given the EPA's assumption that carcinogens do not have threshold levels. Instead, potential adverse effects are evaluated based on the probability of contracting cancer. Slope factors, also called carcinogenic potency factors, are derived by the EPA for chemicals with possible carcinogenic effects in humans. The oral slope factor is expressed as the excess lifetime risk of cancer, per milligram of chemical intake, per kilogram of body weight, per day [(mg/kg-day)⁻¹].

IRIS currently quantifies potential inhalation risk from carcinogenic chemicals in terms of a unit risk factor (ug/m³)⁻¹. To convert the unit risk factor to a slope factor for inhalation (SF_i), the following relationship was used:

$$SF_i (\text{mg/kg} \cdot \text{day})^{-1} = \text{URF} \cdot \frac{\text{BW}}{\text{IR}} = \text{URF} (\mu\text{g}/\text{m}^3)^{-1} \cdot \frac{1000 \mu\text{g}}{\text{mg}} \cdot \frac{70 \text{ kg}}{20 \text{ m}^3/\text{day}} \quad [\text{G-2}]$$

where:

- SF_i = Slope Factor, inhalation (mg/kg-day)⁻¹
- URF = Unit Risk Factor (ug/m³)⁻¹
- IR = Inhalation rate (m³/day)
- BW = Body Weight (kg)

Slope factors for the potentially carcinogenic chemicals are listed in Appendix E. The EPA derives carcinogenic potency factors using a linearized multistage model that estimates a plausible upper bound on risk. The approach likely overstates the risk of cancer.

G.3 Toxicity for Petroleum Products

The evaluation of risk from exposure to TPH is difficult because toxicity data are not available for petroleum products. Therefore, we cannot simply look up a reference dose for gasoline or diesel and carry out the RBC calculations as we did for individual chemicals. For this reason, the "TPH fraction" approach was developed by the TPHCWG.

G.3.1 TPH Fractions and Toxicity Surrogates

To evaluate whole product risk, petroleum is first divided into a series of petroleum "fractions." These fractions are selected on the basis of chemical and physical properties. All of the components within a specific fraction have similar solubilities, volatilities, Henry's constants, *etc.*, and will, therefore, behave similarly in the environment.

After selecting fractions, toxicity data for the components of each fraction are evaluated and used to assign a reference dose that is thought to be representative of a conservative noncarcinogenic risk for that fraction. That usually means that the reference dose for the most toxic known component is used for the fraction.

In some cases the toxicity of a specific member of a fraction is much greater than the rest of the members (*i.e.*, that component has a much lower reference dose). If that component is only a small part of the total fraction, then assigning a conservative reference dose to the entire fraction would be overestimating the risk. To avoid this, the risk from individual high-risk constituents is treated separately and the remaining members of the fraction are assigned a more representative toxicity. This is what the DEQ has done with n-hexane, 1,2,4-trimethylbenzene (1,2,4-TMB), 1,3,5-trimethylbenzene (1,3,5-TMB), and naphthalene.

There are also cases where a component dominates the fraction both in quantity and toxicity. In these cases the entire fraction is represented by the concentration and toxicity of that specific component. This is the case for benzene and toluene, which represent the entire exposures for the C5-C6 and >C6-C8 aromatic fractions, respectively.

The basic petroleum fractions used in this document were developed by the TPH Criteria Working Group (TPHCWG, 1997a). These fractions and the modifications made by the DEQ to address certain individual constituents are shown in Table G.1. The carbon numbers used to designate the fractions are “equivalent carbon numbers” based on a compound’s boiling point or elution time on a gas chromatograph. For more information on equivalent carbon numbers, see TPHCWG (1997a).

Table G.1: TPH Fractions and Constituents Used for Calculating TPH RBCs

Aliphatic Hydrocarbon Fractions	Aromatic Hydrocarbon Fractions
C5-C6 and n-hexane ¹	Benzene ²
>C6-C8	Toluene
>C8-C10, 1,2,4-TMB and 1,3,5-TMB	>C8-C10, Ethylbenzene and Total Xylenes
>C10-C12	>C10-C12 and Naphthalene
>C12-C16	>C12-C16
>C16-C21	>C16-C21
>C21-C34	>C21-C34

1 When a component is listed along with a range, the concentration of the component is subtracted from the range so that its risk is not counted twice.

2 When a component is used in place of a range, that is the only component evaluated within that fraction.

The choice of surrogates for these fractions is discussed below.

G.3.2 Aliphatics

Seven aliphatic hydrocarbon fractions are used to evaluate TPH toxicity: C5-6, >C6-8, >C8-10, >C10-12, >C12-16, >C16-21, and >C21-34. The low molecular weight aliphatics (<C8) are the most difficult to evaluate. The most toxic aliphatic in this range is n-hexane, which is a potent neurotoxin with an RfD of 0.06 mg/kg-day (EPA, 2003a). None of the other aliphatics appear to have toxic effects similar to n-hexane. The active neurotoxic metabolite of n-hexane is

2,5-hexanedione, a gamma diketone. The only other constituent that may be metabolized to a similar gamma diketone is n-heptane (metabolized to 2,5-heptanedione), but n-heptane is negative for neurotoxicity in animal studies. Given the lack of constituents in this fraction with toxicity similar to n-hexane, it is reasonable to evaluate hexane separately. This will require either a special analysis for n-hexane or an assumption about the fraction of the product that is likely to be n-hexane.

There is little toxicity information available for low molecular weight aliphatics other than n-hexane. For the past few years, information on the toxicity of cyclohexane has been available. Cyclohexane appears to be more representative of the other chemicals in the fraction with regard to toxicity than n-hexane or n-heptane. The inhalation RfD for cyclohexane is 5.7 mg/kg-day, which is also the oral RfD by route extrapolation (TPHCWG, 1997b).

There is limited toxicity information for the medium molecular weight aliphatics (>C8-10, >C10-12, >C12-16). The TPHCWG evaluated relevant studies, including unpublished data, and concluded based on subchronic rat toxicity studies that an appropriate NOAEL for this class of compounds was 100 mg/kg-day. Using EPA's standard approach for uncertainty considerations (in this case a factor of 1000), the TPHCWG converted this value to an RfD of 0.1 mg/kg-day (TPHCWG, 1997b). EPA has the same RfDo value for the medium molecular weight aliphatics, and an RfDi value of 0.3 mg/kg/day (ORNL 2003).

The TPHCWG also derived a toxicity value for high molecular weight aliphatics (>C16-21 and >C21-34). They reviewed subchronic and chronic feeding studies on white mineral oils. The mineral oils were highly refined mixtures of branched-chain and cyclic alkanes, with essentially no aromatic compounds. The critical study they chose identified a NOAEL of 200 mg/kg-day for formation of liver granulomas in F344 rats. The TPHCWG converted this to an RfD of 2 mg/kg-day using an uncertainty factor of 100 (TPHCWG, 1997b).

G.3.3 Aromatics

Benzene and other low-weight aromatics (<C8) are evaluated on a chemical-specific basis. This approach is essentially consistent with that proposed by the TPHCWG and the Massachusetts Department of Environmental Protection (MADEP). MADEP was the first regulatory agency to promote an evaluation of TPH based on fractions. Of the medium- and high-weight aromatics, the carcinogenic PAHs are addressed on a chemical-specific basis. This is consistent with the past RBDM approach for PAHs. The non-carcinogenic effects of the remaining heavier-weight aromatics are considered in five fractions: >C8-10, >C10-12, >C12-16, >C16-21, and >C21-34.

RfDs for constituents belonging to the middle-weight aromatic fractions (>C8-10, >C10-12, >C12-16) are listed in Table G.2 (TPHCWG, 1997b; EPA, 2003a; EPA, 2003b).

Table G.2: RfDs for Middle-Weight Aromatic Constituents

Constituent	RfDo (mg/kg-day)	RfDi (mg/kg-day)
Isopropylbenzene	0.1	0.11
Acenaphthene	0.06	0.06
Biphenyl	0.05	0.05
1,2,4-Trimethylbenzene	0.05	0.0017
1,3,5-Trimethylbenzene	0.05	0.0017
n-Propylbenzene	0.04	0.04
Naphthalene	0.02	0.00086

Naphthalene has the lowest RfDo and a much lower RfDi than the other typical constituents of this class. The trimethylbenzenes are also much more toxic than the other compounds by the inhalation route. Therefore, the trimethylbenzenes and naphthalene are evaluated as individual compounds so that a more representative RfD can be used for the fractions. (Also, the most toxic effects of naphthalene are on the respiratory system, whereas the other chemicals are primarily toxic to the kidneys.) EPA's RfDs for this general class of compounds is RfDo = 0.04 mg/kg/day, and RfDi = 0.06 mg/kg/day (ORNL 2003).

RfDs for constituents belonging to the heavy-weight aromatic fractions (>C16-21 and >C21-34) are listed in Table G.3 (EPA, 2003a).

Table G.3: RfDs for Heavy-Weight Aromatic Constituents

Constituent	RfDo (mg/kg-day)	RfDi (mg/kg-day)
Anthracene	0.3	0.3
Fluorene	0.04	0.04
Fluoranthene	0.04	0.04
Pyrene	0.03	0.03

The primary effects of pyrene and fluoranthene are on the kidneys. The RfDs are similar for the compounds in this range. To be conservative, the lowest RfD (for pyrene) is used for the fractions >C16-C21 and >C21-C34.

Table G.4 summarizes the surrogate chemicals and toxicity factors used for the TPH fractions.

Table G.4: Surrogate Chemicals and RfDs for TPH Fractions

TPH Fraction	Surrogate Chemical	Oral RfDo ^a (mg/kg-day)	Inhalation RfDi ^a (mg/kg-day)
ALIPHATICS			
Hexane	Individual Constituent	0.06	0.06
C5-C6	Cyclohexane	5.7	5.7
>C6-C8	Cyclohexane	5.7	5.7
>C8-C10	b	0.1	0.3
>C10-C12	b	0.1	0.3
>C12-C16	b	0.1	0.3
>C16-C21	Mineral Oil	2	2
>C21-C34	Mineral Oil	2	2
AROMATICS			
C5-C6	Individual Constituents	c	c
>C6-C8	Individual Constituents	c	c
>C8-C10	n-propylbenzene	0.04	0.06
>C10-C12	Biphenyl	0.04	0.06
>C12-C16	Biphenyl	0.04	0.06
>C16-C21	Pyrene	0.03	0.03
>C21-C34	Pyrene	0.03	0.03

Notes:

- a. RfD = Reference Dose, where RfDo = oral and RfDi = inhalation reference dose.
- b. RfD determined for class of chemicals, not a specific surrogate.
- c. Chemical-specific RfD for each individual constituent.

Appendix H: Additional Cleanup Program Risk Requirements

Comparing site concentrations with either default or site-specific RBCs is an efficient means of determining if there is unacceptable risk at a site, and uses assumptions and calculations similar to those used in standard risk assessments. However, the approach as presented in this RBDM guidance document does not fully meet the requirements of a risk assessment under DEQ's Environmental Cleanup program regulations. To allow the RBDM approach to be used for conducting a risk assessment for a site, the modifications presented in this appendix should be incorporated. Four additional considerations are required:

- Calculation of central tendency exposure in addition to reasonable maximum exposure;
- Explicit calculation of risk;
- Evaluation of cumulative risk; and
- Evaluation of uncertainty.

These modifications are considered relatively minor, so for many sites, the responsible party is encouraged to use the RBDM approach. Sites with less typical exposure scenarios (such as those involving sediment contact or ingestion of contaminated biota) will need to more closely follow DEQ's risk assessment guidance.

H.1 Central Tendency Exposure RBCs

Soil and groundwater cleanup levels are based on the reasonable maximum exposure (RME) as required by the cleanup rules. However, the rules also require that the central tendency exposure (CTE) be calculated. The CTE is useful for evaluating uncertainty and the need for additional safeguards at the site if RME RBCs can not be achieved.

The appropriate concentration value for comparison with CTE RBCs is the arithmetic mean. The CTE input parameters shown in Table H.1 are generally based on the arithmetic mean.⁵⁹ Although decisions regarding the acceptability of concentrations will be made using RME values, during the feasibility study stage it may be valuable to consider central tendency exposure. This will be particularly important if it is not feasible to remediate the site the reasonable maximum exposure RBC levels.

H.2 Presentation of Calculated Risk and Cumulative Risk

The direct comparison of concentrations with RBCs is the most straightforward means of determining whether there are acceptable concentrations at the site. As discussed earlier, this approach is essentially the inverse of that used in a standard risk assessment. However, it is a simple matter to relate the two approaches. Presenting results in terms of risk will meet the rules for conducting risk assessments.

⁵⁹ The DEQ spreadsheets for constituent and TPH RBCs (DEQ, 2003a and DEQ, 2003b) include an option for selecting either RME or CTE exposure parameters.

Table H.1: Central Tendency Exposure Input Parameters¹

Parameter (unit)	Symbol	Residential	Urban Residential	Occupational	Construction Worker	Excavation Worker
Acceptable Risk Level - Carcinogens	ARLc	1.0E-06	=	=	=	=
Acceptable Risk Level - Noncarcinogens	ARLn	1	=	=	=	=
EXPOSURE PARAMETERS						
Averaging Time - Carcinogen (yr)	ATc	70	=	=	=	=
Averaging Time - Noncarcinogen (yr)	ATn	30	11	25	1	1
Averaging Time - Noncarcinogen, Child (yr)	ATnc	6	6	NA	NA	NA
Body Weight - Adult (kg)	BWa	70	=	=	=	=
Body Weight - Child (kg)	BWc	15	=	NA	NA	NA
Exposure Duration - Adult (yr)	ED	9	4	6	0.5	0.5
Exposure Duration - Child (yr)	EDc	6	4	NA	NA	NA
Exposure Frequency (day/yr)	EF	350	175	250	250	9
Event Frequency - Groundwater (events/day)	EvFwe	NA	NA	NA	2	=
Event Time - Groundwater (hr/event)	t _{event}	NA	NA	NA	2	=
Inhalation Rate - Adult (m ³ /day)	IRA	20	20	7	7	7
Inhalation Rate - Child (m ³ /day)	IRAc	8.3	=	NA	NA	NA
Soil Ingestion Rate - Adult (mg/day)	IRS	50	50	50	100	100
Soil Ingestion Rate - Child (mg/day)	IRSc	100	100	NA	NA	NA
Water Ingestion Rate - Adult (L/day)	IRW	1.4	1.4	0.5	NA	NA
Water Ingestion Rate - Child (L/day)	IRWc	0.9	=	NA	NA	NA
Skin Surface Area - Adult to Soil (cm ²)	SA	5700	5700	3300	3300	3300
Skin Surface Area - Child to Soil (cm ²)	SAC	2800	=	NA	NA	NA
Skin Surface Area - Adult to Groundwater (cm ²)	SAw	NA	NA	NA	5700	5700
Soil to Skin Adherence Factor - Adult (mg/cm ² -d)	AF	0.01	0.01	0.02	0.1	0.1
Soil to Skin Adherence Factor - Child (mg/cm ² -d)	AFc	0.04	=	NA	NA	NA

Notes and References for Table of Central Tendency Exposure Parameters:

- 1 All other exposure parameters remain the same as shown in Appendix C.
- = This exposure parameter is the same as the next listed value to the left.
- NA This exposure parameter is not required for any of the RBCs.

For carcinogens, the RBC is calculated using an acceptable risk level of 10^{-6} . Because risk is proportional to concentration, the conversion equation is:

$$\text{ELCR} = \frac{\text{Concentration}}{\text{RBC}} \times 10^{-6} \quad [\text{H-1}]$$

where:

ELCR = Excess lifetime cancer risk
 Concentration = Chemical concentration (mg/kg or $\mu\text{g/L}$)
 RBC = Risk-Based Concentration (mg/kg or $\mu\text{g/L}$)

For non-carcinogens, using an acceptable hazard quotient of 1, the conversion equation is:

$$\text{HQ} = \frac{\text{Concentration}}{\text{RBC}} \times 1 \quad [\text{H-2}]$$

where:

HQ = Hazard quotient
 Concentration = Chemical concentration (mg/kg or $\mu\text{g/L}$)
 RBC = Risk-Based Concentration (mg/kg or $\mu\text{g/L}$)

Reports submitted for cleanups carried out under UST program rules will usually not have to submit an explicit calculation of cumulative risk. It will be considered on a case-by-case basis. However, reports submitted for cleanups under the Environmental Cleanup rules are required to include a calculation of cumulative risk. A suggested approach for evaluating cumulative cancer and noncancer risks from the numbers in the Table of RBCs is as follows:

- Locate each of the site contaminants in the Table of RBCs and record its RBC for the appropriate media and pathways. Note whether the contaminant is considered a carcinogen (indicated by “c”) or a noncarcinogen (indicated by “nc”).
- For each carcinogen, take the site-specific concentration and divide that value by the RBC. Add the results for all of the carcinogens and multiply this sum by 10^{-6} to estimate the cumulative risk from exposure to carcinogens (equation [H-3]). A risk of greater than 10^{-6} for any *individual* carcinogen or greater than 10^{-5} for the *sum* of all of the carcinogens may require further evaluation and should be discussed with the Department.

$$\text{Risk} = \left[\left(\frac{\text{conc}_x}{\text{RBC}_x} \right) + \left(\frac{\text{conc}_y}{\text{RBC}_y} \right) + \left(\frac{\text{conc}_z}{\text{RBC}_z} \right) \right] \cdot 10^{-6} \quad [\text{H-3}]$$

- For each noncarcinogen, take the site-specific concentration and divide that value by the RBC. Add the results for all of the noncarcinogens to obtain the Hazard Index [HI] for the site (equation [H-4]). A hazard index of 1 meets the definition of acceptable risk in ORS 465.315. A hazard index value greater than 1 requires further evaluation and possibly remediation, and should be discussed with the Department.

$$\text{Hazard Index} = \left[\left(\frac{\text{conc}_x}{\text{RBC}_x} \right) + \left(\frac{\text{conc}_y}{\text{RBC}_y} \right) + \left(\frac{\text{conc}_z}{\text{RBC}_z} \right) \right] \quad [\text{H-4}]$$

Sites that have sufficient numbers and concentrations of contaminants to potentially warrant an assessment of cumulative risk should be discussed with the Department.

An example summary risk table, using the example discussed in Section 3.1.6, is shown in Table H.2.

Table H.2: Example Summary Risk Table

Chemical	UCL ¹ or Maximum Concentration (mg/Kg)	RBC _{SS} Residential Soil ² (mg/Kg)	Calculated Risk	
			Excess Lifetime Cancer Risk	Hazard Quotient
Benzene	105	6.9	1.5 x 10 ⁻⁵	NA
Benzo[a]pyrene	1.2	0.062	1.9 x 10 ⁻⁵	NA
Toluene	15	2600	NA	0.006
Naphthalene	55	34	NA	1.6
TOTAL ³			3 x 10 ⁻⁵	2

¹ 90% upper confidence limit of the mean (see Section 3.1.7)

² Risk-based concentrations for direct soil exposure

³ The total calculated risk should be rounded off to one significant figure.

The conclusion of the risk assessment is the same as that obtained from comparing soil concentrations with RBCs: the soil concentrations of benzene, benzo[a]pyrene, and naphthalene are unacceptable. In this example, the excess lifetime cancer risk from residential soil exposure to benzene and benzo[a]pyrene both exceed the regulatory limit of 1 x 10⁻⁶. In addition, the cumulative risk exceeds the limit of 1 x 10⁻⁵. Also, the concentration of naphthalene constitutes an unacceptable risk since the hazard quotient exceeds 1. Note, however, that if TPH is also being evaluated, and naphthalene is present as a normal component of the TPH, then a risk evaluation of the TPH will suffice. In this case, naphthalene, as a non-carcinogenic component of TPH, would not need to be evaluated separately. However, if there is a naphthalene source unrelated to TPHgasoline, TPHdiesel, or TPHmineral oil, such as at a manufactured gas plant, then naphthalene would need to be evaluated as a separate constituent.

For the pathways involving transport, in many cases RBCs will not be available because the soil saturation limit or the water solubility limit is exceeded. Table A indicates these circumstances with either “>C_{sat}” or “>S” (see Section B.2.1.4). To calculate risk in these cases, you will need to use the soil saturation limit or water solubility limit, and a hypothetical value representing an RBC in the absence of the saturation or water solubility limit. Soil saturation limits and water

solubility limits are available on the ChemData page in the RBDM spreadsheet (DEQ, 2003b). To see the hypothetical RBCs (in excess of physical limits), use the “Show All Values” option in the main menu.

As an example, we will use benzene (105 mg/kg) and naphthalene (6,100 mg/kg) in soil at a site where the relevant pathway is volatilization from subsurface soil to indoor occupational air. An RBC_{si} value is available in Table A for benzene (1.2 mg/kg), but not for naphthalene. The “>C_{sat}” note indicates that the RBC_{si} for naphthalene exceeds the soil saturation limit. After we use the “Show All Values” option, we see that the hypothetical RBC_{si} for naphthalene in excess of the soil saturation limit is 3,400 mg/kg. The hazard quotient should not be calculated using the actual naphthalene concentration (6,100 mg/kg) because it is greater than the soil saturation limit of 312 mg/kg. The additional naphthalene in soil above the soil saturation limit will not result in any more naphthalene in the vapor phase than is present at the soil saturation limit. Therefore, to calculate the hazard quotient, it is the soil saturation limit that should be compared with the hypothetical RBC_{si}, as shown in Table H.3.

Table H.3: Example Summary Risk Table Using Soil Saturation Limit

Chemical	UCL ¹ or Maximum Concentration (mg/kg)	Soil Saturation Limit (mg/kg)	RBC _{si} Occupational Soil ² (mg/kg)	Calculated Risk	
				Excess Lifetime Cancer Risk	Hazard Quotient
Benzene	105	701	1.2	9 x 10 ⁻⁵	NA
Naphthalene	6,100	312	3,400 ³	NA	0.09
TOTAL				9 x 10 ⁻⁵	0.09

¹ 90% upper confidence limit of the mean (see Section 3.1.7)

² Risk-based concentration for subsurface soil volatilization to indoor air

³ Hypothetical RBC in excess of soil saturation limit

H.3 Uncertainty Evaluation

A section on uncertainty should be included in your report. In this section you should evaluate qualitatively and quantitatively (if possible) the uncertainty in your exposure analysis (*i.e.*, the conceptual site model), toxicity analysis, and risk characterization results. This evaluation will allow managers to consider the uncertainty associated with the risk assessment and address it in the feasibility study.

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Appendix I: Screening Evaluation

Environmental Cleanup Program rules [OAR 340-122-0080(5)] allow for the screening of contaminants prior to preparation of a baseline risk assessment. For non-tank sites using this risk-based decision making guidance, the baseline risk assessment should be conducted as presented in Appendix H, or according to DEQ human health risk assessment guidance (DEQ 2000b). Contaminants detected at the site that haven't been screened should be designated as "Contaminants of Interest" (COIs), while those that have been screened-in should be designated as "Contaminants of Potential Concern" (COPCs). Following the baseline risk assessment, contaminants that did not meet acceptable risk levels should be designated as "Contaminants of Concern" (COCs). COIs are screened on the basis of detection levels, background, and risk, as described below, to determine whether they qualify as COPCs that should be carried forward in the risk assessment.

Frequency of Detection: COIs that are infrequently detected may be artifacts in the data due to sampling, analytical, or other errors. COIs detected in less than five percent of the samples site-wide for a given media need not be selected as COPCs. Note that this assumes that detection limits have been set low enough for both ecological and human health purposes and that adequate sampling has occurred.

Background Concentration: If the maximum detected concentration of a naturally occurring COI is less than the concentration selected as a background value (derived either from the appropriate literature or from site-specific sampling), it need not be selected as a COPC. The concept of background does not apply to anthropogenic inorganic or organic contaminants [OAR 340-122-0040(2)(d)].

Concentration-Risk Screen: Any screening must take into consideration the potential for risk to be posed by exposure to: (a) individual COIs, (b) multiple COIs simultaneously within a given medium, and (c) individual or multiple COIs within different media. An individual COI in any given medium must be retained as a COPC if

$$C / RBC > 1 \quad [I-1]$$

where C is its concentration (90 percent upper confidence limit on the arithmetic mean, or maximum concentration) in a given medium, and RBC is either the RBC as established in this guidance, the U.S. EPA Region 9 Preliminary Remedial Goal (PRG) (EPA, 2002), or the DEQ SOCLEAN value for that chemical under a site-appropriate exposure scenario (OAR 340-122-0045).

To account for the combined impact of multiple chemicals, a COI must also be retained as a COPC if

$$\Sigma(C / RBC) > 1 \text{ and } C / RBC > 1/N \quad [I-2]$$

where N is the total number of COIs in a given medium.

If a COI is detected in multiple media (*e.g.*, in both soil and groundwater), it must be retained as a COPC if

$$\Sigma(C / RBC) > 1 \quad [I-3]$$

for concentrations C of the specific contaminant in the different media.

If an RBC is not available for a given COI, that COI must be identified as a COPC and retained for further discussion as a potential data gap in the risk assessment.

An example of screening individual and multiple chemicals in one medium is provided in Table I-1.

Table I-1 Example Screening Table (Soil)

Chemical	UCL ¹ or Maximum Concentration (mg/kg)	RBC _{ss} Residential Soil (mg/kg)	C/RBC	Is this Chemical a COPC?	
				Is C/RBC > 1?	Is C/RBC > 1/N? ²
Benzene	105	6.9	15	Yes	Yes
Toluene	15	2600	0.0058	No	No
Benzo[a]pyrene	1.2	0.062	19	Yes	Yes
Naphthalene	55	34	1.6	Yes	Yes
n-Propylbenzene	ND ³ (<0.05)	840	NA ⁴	No	No
1,2,4-Trimethylbenzene	43	48	0.90	No	Yes
TOTAL			37		

¹ 90% upper confidence limit of the mean (see Section 3.1.7)

² N = 6, 1/N = 0.17

³ ND = not detected

⁴ NA = not applicable if chemical not detected

Benzene, benzo[a]pyrene, and naphthalene are screened in as individual COPCs, but toluene and 1,2,4-trimethylbenzene are not. However, 1,2,4-trimethylbenzene is screened in as a multiple COPC and should continue to be evaluated. Toluene and n-propylbenzene are screened out.

An example of screening chemicals in multiple media is provided in Table I-2. In this example, benzene, benzo[a]pyrene, and naphthalene would all be screened in as COPCs based on concentrations in one medium (soil). However, 1,2,4-trimethylbenzene would be screened in only on the basis of its concentrations in multiple media (soil and groundwater). Toluene and n-propylbenzene are screened out.

Table I-2 Example Screening Table (Multiple Media)

Chemical	C/RBC Soil	C/RBC Groundwater	$\Sigma(C/RBC)$	Is $\Sigma(C/RBC) > 1?$
Benzene	15	680	695	Yes
Toluene	0.0058	1.0	1.0	No
Benzo[a]pyrene	19	ND	19	Yes
Naphthalene	1.6	0.55	2.2	Yes
n-Propylbenzene	ND	ND	NA	No
1,2,4-Trimethylbenzene	0.90	0.90	1.8	Yes

Screening of chemicals is also discussed in DEQ's human health risk assessment guidance (DEQ 2000b).

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Appendix J: Calculating RBCs for Chlorinated and Other Compounds

This guidance document focuses on development of RBCs for petroleum hydrocarbons and chemicals associated with fuel mixtures. However, there is no reason the RBDM approach should be limited to petroleum hydrocarbons. Often it will be useful to evaluate other chemicals, and the approach described here can be generalized to chemicals other than petroleum hydrocarbons. The RBDM spreadsheet includes blank lines where information regarding chemicals of interest can be added.

To demonstrate how to include other chemicals in the RBDM process, this appendix provides an example for chlorinated solvents. Other than petroleum hydrocarbons, the next class of compounds typically found at cleanup sites is chlorinated solvents. Tetrachloroethene (perchloroethylene, or PCE) is the most common dry cleaning solvent. Other cleaning solvents that may be used at industrial sites include 1,1,1-trichloroethane (1,1,1-TCA), trichloroethene (TCE), and dichloroethene (DCE). Chlorinated alkenes such as PCE are capable of being degraded by soil microbes. Typical dechlorination products of PCE include TCE, cis- and trans-1,2-DCE, and vinyl chloride. In addition to determining which solvents may be present at a site, associated chemicals, such as stabilizing agents, should be considered. For instance, 1,4-dioxane is frequently used as a stabilizing agent in TCE solvents.

Once the chemicals of interest have been established, the chemical-specific properties should be compiled. The primary sources of information should match those used in developing the values shown in Appendix E. The references for the input values are provided in Table J.1.

The toxicological and physical values should be added to the RBDM spreadsheet in the rows provided at the bottom of the spreadsheet. Provide the appropriate designation for each chemical as a carcinogen or non-carcinogen. Values indicated by shading in the spreadsheet will be calculated automatically, and do not need to be added.

Table J.2 provides toxicological data, and Table J.3 provides chemical data for some chlorinated solvents and related chemicals. These values were used to calculate the RBCs shown in Table J.4. In order to print out the information for the additional chemicals listed below the petroleum hydrocarbons, the main menu on the RBDM spreadsheet has a “New Entries” check box that limits the output to only the chemicals added to the spreadsheet.⁶⁰

J.1 Degradation of Chlorinated Solvents

An important consideration in screening chlorinated solvents is the potential for concentrations of degradation products to increase over time. For instance, under reductive subsurface conditions, PCE can degrade to TCE, then DCE, and finally vinyl chloride. Further degradation would result in production of non-toxic carbon dioxide. However, vinyl chloride is more toxic than PCE, so it is possible that an acceptable concentration of PCE (below screening level RBCs) may eventually degrade to unacceptable concentrations of vinyl chloride.

⁶⁰ When the “New Entries” checkbox is not checked, only the original petroleum hydrocarbon data are printed. When it is checked, only the new chemical data are printed.

This may be of more concern in soil. A complicating factor in groundwater is that at the same time microbial degradation is occurring (for instance, reducing DCE to vinyl chloride), other attenuation mechanisms such as dispersion and dilution act to decrease all chemical concentrations. Evaluation of chemical concentrations over time is therefore complicated, but should not be ignored.

To address potential degradation of chlorinated solvents, the following additional factors should be considered during the screening stage:

- **Elapsed time since the initial release:** Recent releases may not yet show indications of degradation.
- **Type of subsurface environment(s):** A reducing environment could more readily degrade PCE. An oxidative environment may be necessary to degrade vinyl chloride.
- **Existing plans for remediation:** If a treatment process is planned, the potential for producing degradation products should be considered.
- **Other groundwater attenuation mechanisms:** Dispersion and dilution may be important in reducing overall chemical concentrations.

A simple comparison of chemical concentrations with RBCs may therefore not be sufficient to screen out chemicals. The Department may require a further risk evaluation of some chemicals if it is suspected that concentrations of degradation products could increase. Also, the potential for concentrations of degradation products to increase over time should be considered in the uncertainty evaluation (see Appendix H).

J.2 Calculation of RBCs for Vinyl Chloride

For most of the chlorinated solvents, the modeling applied is the same as that used for petroleum hydrocarbon constituents. However, for vinyl chloride, a modified procedure is required because of specific toxicity concerns.

J.2.1 Cancer Slope Factors

EPA's integrated risk information system (IRIS) report for vinyl chloride includes two derivations of cancer slope factors, one based on the linearized multistage procedure, and one based on the LED₁₀ approach. The results are similar, but the LED₁₀ approach is used here because that is the current recommendation by EPA (based on EPA's 1996 proposed cancer risk assessment guidelines). The LED₁₀ is the 95% lower confidence limit on a dose associated with a 10% excess cancer incidence. For vinyl chloride, LED₁₀ values are slightly more conservative than slope factors based on the linearized multistage procedure.

Slope factors are provided separately for lifetime exposure as an adult, and lifetime exposure beginning from birth. The values differ by a factor of 2. The oral slope factors are 0.75 (mg/kg-day)⁻¹ for adult exposure and 1.5 (mg/kg-day)⁻¹ for child/adult exposure.

Unit risk factors are provided in IRIS for inhalation exposure. These are 4.4×10^{-6} risk per $\mu\text{g}/\text{m}^3$ for adult exposure, and 8.8×10^{-6} risk per $\mu\text{g}/\text{m}^3$ for adult/child exposure. To be incorporated into the RBDM spreadsheet, these values need to be converted to units of risk per mg/kg/day:

$$\text{SF}_i = \frac{\text{IUR} \cdot 1000 \mu\text{g}/\text{mg} \cdot \text{BW}}{\text{IR}} \quad [\text{J-1}]$$

where:

SF _i	=	Cancer slope factor for inhalation (risk per mg/kg-day)
IUR	=	Inhalation unit risk factor (risk per $\mu\text{g}/\text{m}^3$)
BW	=	Body weight (70 kg)
IR	=	Inhalation rate (20 m^3/day)

Using the standard DEQ default values shown, the inhalation slope factors are calculated to be $0.016 (\text{mg}/\text{kg}\text{-day})^{-1}$ for adult exposure and $0.031 (\text{mg}/\text{kg}\text{-day})^{-1}$ for child/adult exposure.

Rather than use the child/adult slope factors, DEQ uses another approach to incorporate early-life exposure, as presented below.

J.2.2 Incorporation of Early-Life Exposure in Derivation of RBCs

The standard residential exposure scenario considers exposure to both children and adults. Ingestion rates, inhalation rates, and other factors are different for children and adults, and these differences are taken into account when calculating residential RBCs. Because the exposure calculations for carcinogens and noncarcinogens have different underlying assumptions, the method used to account for these adult/child differences depends on whether the contaminant is classified as a carcinogen or a noncarcinogen.

For carcinogens, residential exposure is calculated for the first 30 years of life, and then averaged over a 70-year lifetime. To account for differences in exposures to children and adults over the 30-year period, weighted averages are calculated for the exposure factors assuming 6 years of exposure at a childhood exposure rate, and 24 years of exposure at an adult exposure rate. This general approach cannot be used for vinyl chloride.

EPA concludes that because the effects of early-life exposure are qualitatively and quantitatively different from those of later exposures, it is not appropriate to prorate early-life exposures as if they were received at a proportionately lesser rate over a full lifetime. This feature of vinyl chloride toxicity must be considered in the derivation of RBCs for residential exposure.

Following EPA's example, early-life exposure is estimated assuming a lifetime of exposure using the lower (adult) slope factor. For an exposure scenario involving both early-life and adult exposure, the early-life exposure (which is a single value and is not pro-rated for reduced exposure time) is added to exposure as an adult (which can be pro-rated). "Adult" exposure in this case can also include child exposure beyond the initial early-life exposure.

To show explicitly how early-life and adult exposure are incorporated, the following shows how the site-specific residential inhalation RBC was calculated:

$$RBC_{air} = \frac{ARL_c \cdot AT_c \cdot 365 \text{ days/yr}}{EF_r \cdot IFA_{adj} \cdot SFi} \cdot 10^3 \mu\text{g/mg} \quad [J-2]$$

where:

- RBC_{air} = Risk based concentration for inhalation of air (μg/m³)
- ARL_c = Acceptable risk level, carcinogens (10⁻⁶)
- AT_c = Averaging time, carcinogens (70 years)
- EF_r = Exposure frequency, residential (350 days/year)
- IFA_{adj} = Age-adjusted ingestion factor for air (m³-yr/kg-day)
- SF_i = Slope factor, inhalation (0.016 [mg/kg-day]⁻¹)

The age-adjusted ingestion factor for inhalation is:

$$IFA_{adj} = \frac{ED_c \cdot IRA_c}{BW_c} + \frac{(ED_r - ED_c) \cdot IRA_r}{BW_a} \quad [J-3]$$

where:

- IFA_{adj} = Age-adjusted inhalation factor for air (m³-yr/kg-day)
- ED_c = Exposure duration, child (6 years)
- ED_r = Exposure duration, resident (30 years residential, 70 years lifetime)
- IRAc = Air inhalation rate, child (8.3 m³/day)
- IRAr = Air inhalation rate, adult, residential (20 m³/day)
- BW_c = Body weight, child (15 kg)
- BW_a = Body weight, adult (70 kg)

For default residential exposure, IFA_{adj} is 10.18 m³-yr/kg-day. However, a value assuming a lifetime of 70 years must also be calculated for vinyl chloride exposure (21.6 m³-yr/kg-day).

Early-life exposure was assumed to be equivalent to a lifetime of adult exposure (70 years).

$$\begin{aligned} RBC_{early-life} &= \frac{10^{-6} \cdot 70 \text{ yr} \cdot 365 \text{ days/yr}}{350 \text{ days/yr} \cdot 21.6 \text{ m}^3 \text{ - yr/kg - day} \cdot 0.016 (\text{mg/kg - day})^{-1}} \cdot 10^3 \mu\text{g/mg} \quad [J-4] \\ &= 0.21 \mu\text{g/m}^3 \end{aligned}$$

For a residential adult, the RBC is:

$$\begin{aligned} RBC_{adult} &= \frac{10^{-6} \cdot 70 \text{ yr} \cdot 365 \text{ days/yr}}{350 \text{ days/yr} \cdot 10.18 \text{ m}^3 \text{ - yr/kg - day} \cdot 0.016 (\text{mg/kg - day})^{-1}} \cdot 10^3 \mu\text{g/mg} \quad [J-5] \\ &= 0.45 \mu\text{g/m}^3 \end{aligned}$$

The RBC for combined exposure as a child and adult is calculated using the following relationship:

$$\frac{1}{\text{RBC}_{\text{early-life/adult}}} = \frac{1}{\text{RBC}_{\text{early-life}}} + \frac{1}{\text{RBC}_{\text{adult}}} \quad \text{[J-6]}$$

$$\text{RBC}_{\text{early-life/adult}} = \frac{1}{\frac{1}{\text{RBC}_{\text{early-life}}} + \frac{1}{\text{RBC}_{\text{adult}}}} \quad \text{[J-7]}$$

$$\text{RBC}_{\text{early-life/adult}} = \frac{1}{\frac{1}{0.21} + \frac{1}{0.45}}$$

$$= 0.14 \mu\text{g}/\text{m}^3$$

A similar approach was used in calculating the RBCs for the standard exposure scenarios.

A responsible party is not expected to calculate site-specific RBCs for vinyl chloride. In the calculation of site-specific RBCs, DEQ guidance is to allow modifications only to input parameters affecting transport factors, and not to the standard exposure factors of direct pathways such as drinking water ingestion. Therefore, the relevant RBCs for vinyl chloride shown in Table J.4 are expected to apply to most sites.

Given the special method required, the RBDM spreadsheet (DEQ, 2003b) is currently not programmed to correctly calculate RBCs for residential exposures to vinyl chloride.

Table J.1: Sources of Information for Toxicological and Chemical Data

Parameters	References	Comments
Toxicological Values (Slope factors and RfDs)	<ol style="list-style-type: none"> 1) EPA Integrated Risk Information System (IRIS, https://www.epa.gov/iris) 2) EPA <i>Health Effects Assessment Summary Tables</i> (HEAST), EPA-540-R-97-036, July 1997 3) EPA National Center for Environmental Assessment (NCEA) Superfund Health Risk Technical Support Center (STSC) 4) Other EPA documents 5) Agency for Toxic Substances and Disease Registry (ATSDR) <i>Toxicological Profiles</i> (https://www.atsdr.cdc.gov/toxprofiles/index.asp) 	DEQ rules require the hierarchy of references to be followed. EPA Region 9's table of Preliminary Remediation Goals (PRGs) is a convenient summary of toxicity information that follows the same hierarchy.
RAF _d	<i>Developing Risk-Based Cleanup Levels at Resource Conservation and Recovery Act Sites in Region 10</i> , Interim Final Guidance, U.S. EPA Region 10, 1998b	Table 4-5
K _p , t, t*, B	<i>Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment)</i> , Interim Review Draft, EPA/540/R/99/005, U.S. EPA, September 2001.	Appendix B, Exhibit B-3, or the equations in Appendix A.
Molecular weight	Common chemistry handbooks	
Solubility and Henry's Constant	<i>Soil Screening Guidance: Technical Background Document</i> , EPA/540/R-95/128, U.S. EPA 1996	Table 36
D _{air} and D _w	<i>Soil Screening Guidance: Technical Background Document</i> , EPA/540/R-95/128, U.S. EPA 1996	Table 37
K _{oc}	<i>Soil Screening Guidance: Technical Background Document</i> , EPA/540/R-95/128, U.S. EPA 1996	Table 39. For consistency, calculated values should be used.

Table J.2: Toxicological Data for Chlorinated Solvents

Chemical	Risk Type	SF _o		SF _i		Chronic				Subchronic				RAF _d	K _p (cm/hr)	τ (hr)	t* (hr)	B	DA _w (L/cm ² -event)	
		(mg/Kg-day) ⁻¹		(mg/Kg-day) ⁻¹		RfD _o (mg/Kg-day)		RfD _i (mg/Kg-day)		RfD _o (mg/Kg-day)		RfD _i (mg/Kg-day)								
			Note		Note		Note		Note		Note		Note							Note 5
1,1-Dichloroethene	nc	NA		NA		0.05	1	0.057	1, 2	-		-		0.00E+00	1.20E-02	3.70E-01	8.90E-01	0.00E+00	6	3.29E-05
cis-1,2-Dichloroethene	nc	NA		NA		0.01	8	0.01	3	-		-		0.00E+00	7.70E-03	3.70E-01	8.90E-01	0.00E+00	6	2.11E-05
trans-1,2-Dichloroethene	nc	NA		NA		0.02	1	0.02	3	-		-		0.00E+00	7.70E-03	3.70E-01	8.90E-01	0.00E+00	6	2.11E-05
Tetrachloroethene	c	0.54	11	0.021	10	0.01	1	0.17	4	0.1	12	-		0.00E+00	3.30E-02	9.10E-01	2.18E+00	2.00E-01	6	1.23E-04
1,1,1-Trichloroethane	nc	NA		NA		0.28	1	0.63	2	-		-		0.00E+00	1.30E-02	6.00E-01	1.43E+00	1.00E-01	6	4.08E-05
Trichloroethene	c	0.4	9	0.4	9	0.0003	9	0.01	9	-		-		0.00E+00	1.20E-02	5.80E-01	1.39E+00	1.00E-01	6	3.71E-05
Vinyl chloride Residential	c	1.5	1	0.031	1, 2	0.003	1	0.029	1, 2	-		-		0.00E+00	5.60E-03	2.40E-01	5.70E-01	0.00E+00	6	1.39E-05
Vinyl chloride Occupational	c	0.75	1	0.016	1, 2	0.003	1	0.029	1	-		-		0.00E+00	5.60E-03	2.40E-01	5.70E-01	0.00E+00	6	1.39E-05
1,4-Dioxane	c	0.011	1	0.011	3	NA		NA		-		-		3.00E-02	3.30E-04	3.30E-01	8.00E-01	0.00E+00	6	8.78E-07

Notes and References for Table J.2:

c This chemical is a known or suspected carcinogen.

nc This chemical is a noncarcinogen.

1. U. S. EPA, Office of Research and Development, Integrated Risk Information System (IRIS)

2. Converted from inhalation reference concentration (RfC in mg/m³) by the following relationship: RfDi = RfC * 20 m³/day / 70 kg.

3. Route extrapolation, RfDi assumed to be equivalent to RfDo, or SFi assumed to be equivalent to SFo.

4. U.S. EPA, Office of Research and Development, National Center for Environmental Assessment.

5. Dermal absorption from soil is not evaluated for volatile chemicals (EPA, 2001b).

6. K_p, t, t*, and B are from Exhibit B-3 in EPA (2001b).

7. DA_w is calculated from equations given in EPA (2001b). See Section B.3.3.4.

8. EPA, 1997e

9. EPA, 2001b

10. EPA, 2003a

11. EPA, 2003b

12. ORNL, 2003

Table J.3: Chemical Data for Chlorinated Solvents

Chemical	Vol	Mol. Wt. (g/mol)	S (mg/L)		P ($\mu\text{g}/\text{m}^3$)	C _{sat} (mg/kg)	K _{oc} (cm^3/g)		K _H ($\text{m}^3\text{-atm}/\text{mol}$)		H	D _{air} (cm^2/s)		D _w (cm^2/s)
	Class		Note 2	Note 3	Note 4a	Note 4b	Note 5	Note 3	Note 5	Note 3	Note 3			
	Note 1													
1,1-Dichloroethene	v	97	2.25E+03		2.44E+09	1.20E+03	5.89E+01		2.61E-02		1.09E+00	9.00E-02		1.04E-05
cis-1,2-Dichloroethene	v	97	3.50E+03		5.94E+08	9.59E+02	3.55E+01		4.08E-03		1.70E-01	7.36E-02		1.13E-05
trans-1,2-Dichloroethene	v	97	6.30E+03		2.46E+09	2.47E+03	5.25E+01		9.38E-03		3.90E-01	7.07E-02		1.19E-05
Tetrachloroethene	v	166	2.00E+02		1.53E+08	1.93E+02	1.55E+02		1.84E-02		7.65E-01	7.20E-02		8.20E-06
1,1,1-Trichloroethane	v	133	1.33E+03		9.51E+08	9.71E+02	1.10E+02		1.72E-02		7.15E-01	7.80E-02		8.80E-06
Trichloroethene	v	131	1.10E+03		4.71E+08	1.06E+03	1.66E+02		1.03E-02		4.28E-01	7.90E-02		9.10E-06
Vinyl chloride	v	63	2.76E+03		3.10E+09	9.26E+02	1.86E+01		2.70E-02		1.12E+00	1.06E-01		1.23E-06
1,4-Dioxane	nv	88	1.00E+06		2.00E+08	1.56E+05	1.70E+01		4.80E-06		2.00E-04	5.00E-02		1.00E-05

Notes and References for Table J.3:

- nv This chemical is classified as “nonvolatile” for purposes of the exposure calculations in this document.
- v This chemical is classified as “volatile” for purposes of the exposure calculations in this document.
- 1. Volatility is based on EPA (1991a). A “volatile” constituent has a Henry’s constant $> 10^{-5} \text{ m}^3\text{-atm}/\text{mol}$ and a molecular weight $< 200 \text{ g/mol}$.
- 2. Molecular weights can be obtained from many common chemical handbooks and chemistry texts. No specific reference was used here.
- 3. Values from Table 36 (S and H), Table 37 (D_{air} and D_w), and Table 39 (“Calculated Value” K_{oc}) in EPA (1996b).
- 4. a. Vapor pressure is calculated from the relationship $P = H * S * 1000000$, where H is the dimensionless Henry’s constant, S is the solubility in mg/L, and 1000000 is a conversion factor yielding units of $\mu\text{g}/\text{m}^3$ for direct comparison to RBC_{air} values.
b. C_{sat} is calculated using equation [B-21]. See Section B.2.1.4.
- 5. Dimensionless Henry’s constants are calculated from the relationship $H = K_H / R * T$ where K_H is the Henry’s constant in $\text{m}^3\text{-atm}/\text{mol}$, R is the ideal gas law constant ($8.21 \times 10^{-5} \text{ m}^3\text{-atm}/\text{K}\text{-mol}$), and T is the absolute temperature (293 K).

Table J.4: Generic RBCs for Chlorinated Solvents

Contaminated Medium		SOIL mg/Kg (ppm)										SOIL mg/Kg (ppm)					
Exposure Pathway		Surface Soil Ingestion, Dermal Contact, and Inhalation RBC _{SS}										Volatilization to Outdoor Air RBC _{SO}					
Receptor Scenario		Residential		Urban Residential		Occupational		Construction Worker		Excavation Worker		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note		Note		Note
1,1-Dichloroethene	nc, v	1,200		2,300	>Csat	26,000	>Csat	12,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
cis-1,2-Dichloroethene	nc, v	210		420		4,900	>Csat	2,300	>Csat	65,000	>Csat	-	>Csat	-	>Csat	-	>Csat
trans-1,2-Dichloroethene	nc, v	420		840		9,700	>Csat	4,600	>Csat	-	>MAX	2,300		2,300		-	>Csat
Tetrachloroethene	c, v	1.1		3.0		5.1		40		1,100	>Csat	11		23		62	
1,1,1-Trichloroethane	nc, v	9,900	>Csat	20,000	>Csat	-	>MAX	76,000	>Csat	-	>MAX	-	>Csat	-	>Csat	-	>Csat
Trichloroethene	c, v	0.67		2.3		3.4		41		1,100	>Csat	0.57		1.2		3.3	
Vinyl chloride	c, v	0.33		0.73		3.7		29		800		4.6		5.5		82	
1,4-Dioxane	c, nv	53		140		240		1,800		50,000		83		180		470	

Table J.4: Generic RBCs for Chlorinated Solvents (Continued)

Contaminated Medium		SOIL mg/Kg (ppm)						SOIL mg/Kg (ppm)					
Exposure Pathway		Vapor Intrusion into Buildings RBC _{si}						Leaching to Groundwater RBC _{sw}					
Receptor Scenario		Residential		Urban Residential		Occupational		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note
1,1-Dichloroethene	nc, v	54		54		640		11		11		43	
cis-1,2-Dichloroethene	nc, v	9.4		9.4		110		1.0		1.0		4.0	
trans-1,2-Dichloroethene	nc, v	19		19		230		2.9		2.9		11	
Tetrachloroethene	c, v	0.088		0.19		1.5		0.0053		0.0093		0.037	
1,1,1-Trichloroethane	nc, v	590		590		-	>Csat	140		140		560	
Trichloroethene	c, v	0.0055		0.012		0.094		0.0017		0.0034		0.0099	
Vinyl chloride	c, v	0.037		0.045		2.0		0.00048		0.00057		0.0099	
1,4-Dioxane	c, nv	100		220		1,700		0.048		0.083		0.35	

Table J.4: Generic RBCs for Chlorinated Solvents (Continued)

Contaminated Medium		GROUNDWATER µg/L (ppb)						GROUNDWATER µg/L (ppb)					
Exposure Pathway		Ingestion & Inhalation from Tap Water RBC _{tw}						Volatilization to Outdoor Air RBC _{wo}					
Receptor Scenario		Residential		Urban Residential		Occupational		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note
1,1-Dichloroethene	nc, v	340		340		1,400		540,000		540,000		2,200,000	
cis-1,2-Dichloroethene	nc, v	61		61		240		410,000		410,000		1,600,000	
trans-1,2-Dichloroethene	nc, v	120		120		490		500,000		500,000		2,000,000	
Tetrachloroethene	c, v	0.091		0.16		0.63		1,500		3,200		8,600	
1,1,1-Trichloroethane	nc, v	3,200		3,200		13,000		-	>S	-	>S	-	>S
Trichloroethene	c, v	0.029		0.059		0.17		110		240		650	
Vinyl chloride	c, v	0.024		0.028		0.49		350		420		6,200	
1,4-Dioxane	c, nv	5.2		8.9		37		1,600,000		3,400,000		9,100,000	

Table J.4: Generic RBCs for Chlorinated Solvents (Continued)

Contaminated Medium		GROUNDWATER µg/L (ppb)						GROUNDWATER µg/L (ppb)		AIR (see notes) µg/m ³					
Exposure Pathway		Vapor Intrusion into Buildings RBC _{wi}						GW in Excavation RBC _{we}		Inhalation RBC _{air}					
Receptor Scenario		Residential		Urban Residential		Occupational		Excavation Worker		Residential		Urban Residential		Occupational	
Contaminant of Concern	Note		Note		Note		Note		Note		Note		Note		Note
1,1-Dichloroethene	nc, v	27,000		27,000		330,000		41,000		210		210		830	
cis-1,2-Dichloroethene	nc, v	34,000		34,000		410,000		7,600		37		37		150	
trans-1,2-Dichloroethene	nc, v	32,000		32,000		390,000		15,000		73		73		290	
Tetrachloroethene	c, v	78		170		1,300		240		0.34		0.73		1.9	
1,1,1-Trichloroethane	nc, v	520,000		520,000		-	> ^s	390,000		2,300		2,300		9,200	
Trichloroethene	c, v	6.6		14		110		130		0.018		0.038		0.10	
Vinyl chloride	c, v	16		19		840		1,100		0.14		0.17		2.6	
1,4-Dioxane	c, nv	660,000		1,400,000		11,000,000		1,800,000		0.65		1.4		3.7	

Appendix K: Glossary

Additives: Chemicals added to gasoline to improve performance. The following additives have been determined to present health risks and are included on Oregon's Table of RBCs: lead, methyl tertiary-butyl ether (MTBE), 1,2-dibromoethane (ethylene dibromide, EDB), and 1,2-dichloroethane (ethylene dichloride, EDC).

ARL - Acceptable Risk Level: The level of risk above which some action must be taken to reduce exposure to the contaminants of concern. ARLs in Oregon are 1×10^{-6} excess cancer risk for an individual carcinogen and a hazard index = 1 for noncarcinogens.

ASTM - American Society for Testing and Materials: ASTM is a not-for-profit organization that writes and publishes standard test methods, specifications, practices, guides, classifications, and terminology used for materials, products, systems, and services.

Average Daily Dose: A measure of contaminant exposure that has been normalized to body weight and exposure duration. The average daily dose is usually expressed in units of mg/kg-d.

BTEX - Benzene, Toluene, Ethylbenzene, and total Xylenes: Chemicals typically found in gasoline, diesel and heating oil, and occasionally found in waste or used oil products.

CAP - Corrective Action Plan: A proposal required by OAR 340-122-0250 which describes conditions at a UST cleanup site, proposes protective cleanup levels, and gives a detailed explanation of how the site will be remediated to meet the cleanup levels.

Compliance Point: A location selected between the source area of contamination and the potential points of exposure where concentrations of contaminants of concern must be at or below the appropriate risk-based concentrations in media such as groundwater and soil.

COCs - Contaminants of Concern: COPCs that exceed site-specific risk-based concentrations and must be addressed by a remedial action. Also known as constituents of concern or chemicals of concern.

COIs – Contaminants of Interest: Contaminants that are suspected or known to be at a site based on site history or the results of preliminary testing, but which have not yet been screened against any generic risk-based concentrations or other screening criteria. Also known as constituents of interest or chemicals of interest.

COPCs - Contaminants of Potential Concern: COIs that exceed generic screening criteria and must be retained for additional evaluation in the site-specific risk assessment process. Also known as constituents of potential concern or chemicals of potential concern.

Csat – Saturation Concentration: The theoretical concentration above which free product can start to appear in the soil.

CSM - Conceptual Site Model: A summary, based on what you know about your site, that identifies all of the suspected or potential sources of contamination, where they are located, how they are likely to move, and who is likely to be affected by them.

DEQ - Department of Environmental Quality: State of Oregon environmental agency.

Ecological Risk Assessment: A qualitative appraisal of the actual or potential effects of constituents of concern on plants, animals and sensitive habitats such as wetlands.

Engineering Controls: Modifications to a site or facility (for example, slurry walls, capping, drinking water treatment plant) to reduce or eliminate the potential exposure to a constituent of concern, or taste and odor nuisance conditions.

EPA - Environmental Protection Agency: Federal environmental agency.

Exposure: Contact of a person, animal, *etc.* with a constituent of concern at an exchange boundary (*e.g.*, skin, lungs, liver), which makes the constituent available for absorption.

Exposure Pathway: The path that a chemical takes from a source area to an exposed organism. An exposure pathway describes the mechanism by which an individual or population is exposed to a chemical originating from a site. Each exposure pathway includes a source, a point of exposure, and an exposure route. If the exposure point differs from the source, a transport/exposure medium (*e.g.*, air or water) or media also are included.

Exposure Point: The point at which a person, animal or sensitive habitat may come in contact with a constituent of concern originating from a source of contamination.

HI - Hazard Index: The sum of two or more hazard quotients for multiple noncarcinogenic constituents of concern and/or multiple exposure pathways. $HI > 1$ implies that there may be an adverse effect associated with the exposure.

HQ - Hazard Quotient: The amount of exposure to a noncarcinogenic compound in a specified period of time divided by the reference dose for that compound. $HQ > 1$ implies that there may be an adverse effect associated with the exposure.

Institutional Controls: The restriction on use or access to a contaminated site (for example, engineering controls, deed restrictions, restrictive zoning) to reduce or eliminate potential exposure to a constituent of concern.

IRIS - Integrated Risk Information System: Database of toxicity information maintained by the U.S. Environmental Protection Agency.

LED₁₀ – Lower Effects Dose 10: The LED₁₀ is the 95% lower confidence limit on an effects dose associated with a 10% excess cancer incidence.

LF - Leaching Factor: The ratio between a modeled or estimated concentration in groundwater and the source concentration in the soil that produces that concentration. Leaching Factor is a specific case of a Transport Factor. Units for LF are usually kg/L. (See equation [B-138].)

MTBE - Methyl tertiary-butyl ether: Gasoline additive used to increase the oxygen content of fuel to meet EPA oxyfuel regulations. MTBE is also used as an octane enhancer.

NAPL – Non-aqueous phase liquid: A liquid, usually made up of a mixture of organic compounds, that does not dissolve in water and, therefore, forms a separate layer that either floats on water (a light NAPL, or LNAPL), or sinks to the bottom of water (a dense NAPL, or DNAPL).

NCEA - National Center for Environmental Assessment: A branch of the U.S. Environmental Protection Agency's Office of Research and Development. NCEA serves as the national resource center for the overall process of human health and ecological risk assessments; the integration of hazard, dose-response, and exposure data and models to produce risk characterizations.

PAHs - Polynuclear Aromatic Hydrocarbons: Constituents of concern typically found in diesel motor fuel and heating oil. The most commonly tested PAHs include acenaphthene, anthracene, benz[a]anthracene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, chrysene, dibenz[a,h]anthracene, fluoranthene, fluorene, indeno[1,2,3-cd]pyrene, naphthalene, and pyrene.

Pathway: The route that a contaminant takes when moving from the area where it was initially released to where it comes into contact with a receptor. For purposes of this document, pathways are considered to be “**direct**” when the receptor is at the source location and no additional contaminant transport is required. For example, if petroleum is spilled onto the soil and a child ingests some of the contaminated soil, that pathway is direct. Pathways are considered “**indirect**” if additional transport is required. For example, if precipitation leaches petroleum contaminants from the soil to the groundwater, and the contaminants are subsequently ingested in drinking water, that pathway is indirect.

RBC - Risk-Based Concentration: The concentration of a chemical in a given medium (*e.g.*, air, soil or groundwater) which corresponds to the acceptable risk level for a defined exposure.

RBDM - Risk-Based Decision Making: A process for identifying necessary and appropriate action throughout the corrective action process based on known or anticipated risks to human health and the environment.

Receptors: Persons, plants, animals, structures, surface waters and water supply systems that are or may be adversely affected by a release of petroleum products containing constituents of concern.

Residual Saturation: The concentration above which free product can start to flow through the soil.

RfD - Reference Dose: A toxicity value for evaluating noncarcinogenic effects in humans resulting from exposure to a chemical of concern. RfDo is the reference dose for oral exposures, and RfDi is the reference dose for inhalation exposures.

Risk Assessment: An analysis of the potential for adverse health effects caused by a constituent of concern from a site to determine the need for remedial action or to the development of target levels where remedial action is required.

Site: The area defined by the extent (horizontal and vertical) of migration of the constituents of concern. As used in this generic sense, site can cover one or more parcels of land defined by property boundaries.

SF - Slope Factor: A toxicity value for evaluating carcinogenic effects in humans resulting from exposure to a chemical of concern. SF_o is the slope factor for oral exposures, and SF_i is the slope factor for inhalation exposures.

SPLP – Synthetic Precipitation Leaching Procedure: EPA method for determining the concentration of material that leaches out of a solid sample. The leachate for this test is designed to simulate slightly acidic rain. This is Method 1312 in SW-846.

SW-846 – Test Methods for Evaluating Solid Waste, Physical/Chemical Methods: This is the EPA's Office of Solid Waste official compendium of analytical and sampling methods that have been evaluated and approved for use in complying with certain regulations.

TCLP – Toxicity Characteristic Leaching Procedure: EPA method for determining the concentration of material that leaches out of a solid sample. The leachate for this test is designed to simulate landfill leachate. This is Method 1311 in SW-846.

TF - Transport Factor: The ratio between a modeled or estimated concentration in one medium to the source concentration in another medium that produces that concentration. Volatilization Factors and Leaching Factors are specific examples of Transport Factors. Transport Factors are used to estimate RBCs for indirect pathways.

TPH - Total Petroleum Hydrocarbons: A measure of the concentration or mass of petroleum hydrocarbon constituents present in a given amount of soil, water or air. The term is often associated with the analytical method used to make the measurement, such as TPH-Gx for gasoline range hydrocarbons and TPH-Dx for diesel range hydrocarbons (see Table 2.2).

TPHCWG - Total Petroleum Hydrocarbon Criteria Working Group: A national workgroup made up of representatives from industry, government, and academia that developed scientifically defensible information that can be used to establish cleanup levels that are protective of human health at petroleum-contaminated sites.

Transformer Mineral Insulating Oil - Transformer mineral insulating oil is the insulating oil used in the operation of a variety of electrical equipment used in the transmission and distribution of electricity. Cleanup levels in this document assume that the mineral insulating oil is free of polychlorinated biphenyls (PCBs)

VF - Volatilization Factor: The ratio between a modeled or estimated concentration in the air and the source concentration in soil or groundwater that produces that concentration (see equation [B-55].). Volatilization Factor is a specific case of a Transport Factor. Units for VF are usually kg/m³.

Appendix L: References

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