Annex C

Background Document on Development of Risk-Based Remediation Goals for Contaminated Land Management

Hong Kong SAR Government
Environmental Protection Department
April 2007

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Glossary

Administered dose	The mass of substance given to an organism and in contact with an exchange boundary (e.g., gastrointestinal tract) per unit body weight per unit time (e.g., mg/kg-day).
Cancer Slope Factor (CSF)	A plausible upper-bound estimate of the probability of a cancer response per unit intake of a chemical over a lifetime. The slope factor is used to estimate an upper-bound probability of an individual developing cancer as a result of exposure to a particular level of a potential carcinogen. The cancer slope factor is given in units of the reciprocal of milligrams of chemical per kilogram of body weight per day $(mg/kg\text{-}day)^{-1}$.
Exposure	Contact of a receptor with a chemical or physical agent. Exposure is quantified as the amount of the agent at the exchange boundaries of the receptor (e.g. skin, lungs, gut) and available for absorption.
Exposure factor	An estimated, predicted, or measured value for an exposure parameter which may be expressed as a contact rate (e.g. milligrams of soil per day), duration of time (e.g. years), measurement of bodyweight (e.g. kilograms), or skin surface area (e.g. square centimeters).
Exposure pathway	The course a toxic chemical takes from the source area to a receptor. Each exposure pathway includes a source or release from a source, a point of exposure, and an exposure route. If the exposure point is not at the source, a transport medium is also involved.
Exposure point	A location of potential contact between a receptor and a release of toxic chemicals. An exposure point may be an area or zone of potential exposure, as well as a single discrete point.
Exposure route	The mechanism by which a receptor inhales, consumes, absorbs, or otherwise takes in a toxic chemical at an exposure point.
Groundwater	means any water beneath the earth's surface in the zone of saturation.
Hazard quotient	Ratio of the intake to the reference dose.
Intake	A measure of exposure expressed as the mass of a substance in contact with the exchange boundary per unit body weight per unit time (e.g. mg/kg-day). Also termed the normalized exposure rate; equivalent to administered dose.
Integrated Risk Information System (IRIS)	A US EPA data base containing verified reference doses (RfDs) and cancer slope factors (CSFs) and up-to-date health risk and US EPA regulatory information for numerous chemicals.

Non-aqueous Phase Liquid (NAPL)	Chemicals that are insoluble or only slightly soluble in water that exist as a separate liquid phase.
Receptor	Any person that is or may be affected by a release of toxic chemicals.
Reference Dose (RfD)	An estimate of a daily exposure level for the human population including sensitive subpopulations, that is likely to be without an appreciable risk of deleterious effects during a lifetime, or portion of a lifetime. The RfD is given in units of milligrams of chemical per kilogram of body weight per day.
Release	Means any spilling, leaking, pouring, emitting, emptying, discharging, injecting, pumping, escaping, leaching, dumping, or disposing of a toxic chemical into the environment (including the abandonment or discarding of barrels, containers, and other closed receptacles containing hazardous wastes or hazardous constituents).
Remediation	An action, including removal, chemical, physical, or biological treatment of soil, groundwater, or other environmental media, intended to restore or improve the land condition impacted by chemical contamination.
Risk assessment	An analysis of the potential for adverse effects caused by a toxic chemical at a site and to determine the need for remedial action or to develop cleanup levels where remedial action is required.
Site	Defined by the likely physical distribution of the toxic chemicals from a source area. A site could be an entire property or facility, a defined area or portion of a facility or property, or multiple facilities or properties.
Soil	Means any unconsolidated mineral and organic matter overlying bedrock that has been subjected to and influenced by geologic and other environmental factors, excluding sediment.
Soil saturation limit	The contaminant concentration in soil at which the absorptive limits of the soil particles, the solubility limits of the soil pore water and saturation of soil pore air have been reached.
Toxicity value	A numerical expression of a substance's dose-response relationship that is used in risk assessments. The most common toxicity values used are reference doses (RfD) for noncarcinogenic effects and cancer slope factors (CSFs) for carcinogenic effects.
Vadose zone	Means the unsaturated zone below the ground surface and above the water table.

Zone of saturation	Means any part of the earth's crust in which all voids are filled with water.

Abbreviations

ATSDR	Agency for Toxic Substances and Disease Registry
ASTM	American Society for Testing and Materials
COC	Chemical of Concern
CSF	Cancer Slope Factor
HEAST	Health Effects Assessment Summary Tables
IRIS	Integrated Risk Information System
NAPL	Non-aqueous Phase Liquid
RBRG $_{soil}$	Risk-Based Remediation Goal for soil
RBRG $_{gw}$	Risk-Based Remediation Goal for groundwater
RfD	Reference Dose
STSC	Superfund Technical Support Center (USEPA)
SVOC	Semi-volatile Organic Chemical
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Chemical

Section 1
INTRODUCTION

1.1 General

Risk-based Remediation Goals (RBRGs) have been developed for 54 chemicals of concern in Hong Kong. For interested parties, this Background Document provides technical details on the scientific approach used to develop the RBRGs.

The following two different types of RBRGs have been developed:

1. $RBRG_{soil}$ - Soil RBRGs protective of exposure to soil contaminants via the pathways from indoor inhalation of vapors from subsurface soil and; outdoor inhalation of vapors from surface soil, inhalation of dusts, dermal contact, and incidental ingestion.
2. $RBRG_{gw}$ - Groundwater RBRGs protective of volatilization from groundwater into indoor air.

Technical details are provided on the following key features of the RBRG development process:

- Selection of chemicals of concern (COCs)
- Conceptual models of chemical transport pathways
- Equations for calculating RBRGs
- Site and exposure parameter values used to calculate RBRGs
- Toxicity values
- Physical/chemical properties

The development of RBRGs for soil and groundwater required the compilation of information in several technical areas including: (1) the types of chemicals likely to be encountered at contaminated sites in Hong Kong; (2) models that could be used to predict exposures to these chemicals by humans; (3) inputs for the models on details such as the length of time workers typically spend at an industrial site and the level of air exchange typical for buildings in Hong Kong; (4) toxicity information on the chemicals of concern; and (5) physical and chemical property data, such as the water solubility and soil to water partition coefficients of each chemical.

This information was collected in a systematic manner using peer-reviewed references from a variety of international and local sources. In some cases, technical and policy decisions were required to select the method deemed most appropriate for Hong Kong. The following sections present both the technical details and decisions inherent in the RBRG development process.

Figure 1 illustrates the information necessary to develop RBRGs for each exposure route within each of the exposure pathways. RBRGs were calculated using worksheet programs for all chemicals for which the appropriate toxicity indices and physical/chemical properties could be obtained. If information was not available for a particular exposure route, the RBRG was calculated on the basis of the remaining exposure routes.

For example, in order to develop an $RBRG_{gw}$, which addresses only one route of exposure, i.e. inhalation, either a cancer (CSF) or noncancer (RfD) inhalation toxicity index, and the condition of Henry's Law Constant greater than 1 in 100,000 atm-m^3/mol are necessary. If both a cancer and noncancer toxicity index are available, two RBRGs were developed. The lower of the two RBRGs is selected as the final RBRG for that exposure pathway.

While the $RBRG_{gw}$ addresses only one route of exposure, the $RBRG_{soil}$ addresses five routes of exposure: ingestion, dermal contact, outdoor inhalation of volatiles from surface soils, outdoor inhalation of particulates and indoor inhalation of vapors from subsurface soils. Each of the exposure routes has its own set of requirements, and in the case of inhalation of volatiles, a Henry's Law Constant of greater than 1 in 100,000 atm-m^3/mol was required. This value is considered the threshold below which chemicals are not considered volatile and the exposure route is no longer significant. If the information necessary to address a particular exposure route was not available, or the condition was not met, the RBRG was calculated on the basis of the other exposure routes for which information was complete.

Figure 2 illustrates the process for developing RBRGs. As described in the following sections, a database of physical/chemical properties and toxicity indices was developed for the chemicals of concern. Parameter values pertinent to exposure, soil characteristics, land surface characteristics, and building design and operation were then selected, depending on the exposure pathway. For example, building parameters were only pertinent for calculating RBRGs for the soil to indoor air and groundwater to indoor air pathways. A set of intermediate calculations is then performed, incorporating, where necessary, parameter values and physical/chemical property values. The RBRGs are calculated for cancer and noncancer endpoints. For chemicals with both cancer and noncancer RBRGs, the lower of these concentrations is selected as the RBRG.

Finally, a non-risk based ceiling limit soil concentration of 10^4 mg/kg and a ceiling limit of groundwater concentration of 10^4 mg/L were applied to those relatively less toxic inorganic, volatile and semi-volatile COCs to cap the very high calculated values so that the final RBRGs are scientifically sensible. This ceiling limit application has been adopted in the US (USEPA Region 9, 2004) and Dutch (RIVM, 2001) risk based standard guidelines where a value of 10^5 mg/kg or mg/L was applied. The ceiling limit concentration for RBRGs can be considered as a more conservative value in comparison to the US and Dutch approach.

Section 2
SELECTION OF CHEMICALS OF CONCERN

RBRGs have been developed for 54 COCs which were selected on the basis that either they are known to occur in the Hong Kong environment, or are in use locally.

The COCs are grouped into the following chemical classes:

- Volatile organic chemicals (VOCs) – 13 chemicals
- Semi-volatile organic chemicals (SVOCs) – 19 chemicals
- Metals – 15 chemicals
- Dioxins and Polychlorinated Biphenyls (PCBs) – 2 chemicals
- Petroleum carbon ranges – 3 groups
- Other inorganic compounds – 1 chemical
- Organometallics – 1 chemical

For the petroleum carbon ranges, five hydrocarbon fractions separated into aliphatics and aromatics were initially defined as chemicals of concern. The fractions were selected, with modifications, from those recommended in Volume 5 of the TPHCWG Series (TPHCWG, 1999). The initial five carbon fractions were:

- C6 - C8 aliphatics (Carbon numbers from 6 to 8)
- C9 - C16 aliphatics (Carbon numbers from 9 to 16)
- C9 - C16 aromatics (Carbon numbers from 9 to 16)
- C17 - C35 aliphatics (Carbon numbers from 17 to 35)
- C17 - C35 aromatics (Carbon numbers from 17 to 35)

The aromatics within the fraction C6 - C8 have not been included. The compounds within this fraction, benzene, toluene, ethylbenzene and xylenes (BTEX) are included in the list of VOCs and their effects are best evaluated individually. While no toxicity values exist for Total Petroleum Hydrocarbons (TPH), toxicity information is available on the petroleum carbon fractions and therefore RBRGs were developed for the above five fractions accordingly.

However, few analytical laboratories around the world are currently set up to conduct analyses to completely separate aliphatic and aromatic compounds, as an interim solution, RBRGs have been developed for the following three petroleum carbon ranges with no differentiation between aliphatic or aromatic components:

- C6 - C8
- C9 - C16
- C17 - C35

RBRGs for these carbon ranges were derived from the RBRGs for the initial five carbon ranges using the following ratios:

- RBRG for C6-C8 was taken 100% from the RBRG for C6-C8 aliphatics.

- RBRG for C9-C16 was the sum of 80% of the RBRG for C9-C16 aliphatics and 20% of the RBRG for C9-C16 aromatics.

- RBRG for C17-C35 was the sum of 80% of the RBRG for C17-C35 aliphatics and 20% of the RBRG for C17-C35 aromatics.

The ratio of 80/20 for aliphatics/aromatics is based on the fact that the weight percent of aromatics is seldom more than 20% in typical hydrocarbon products (CCME, 2000).

Soil and groundwater collected at sites contaminated with petroleum are to be analyzed using a method that can fractionate the material into the above three categories based on carbon numbers plus BTEX.

Section 3
CONCEPTUAL MODELS OF CHEMICAL TRANSPORT PATHWAYS

Conceptual models have been identified and developed for the exposure pathways for which RBRGs were developed. The conceptual models illustrate inter-media transport, e.g., volatilization from soil to ambient air and volatilization from groundwater to indoor air, and identify the key parameters in the models used to characterize each exposure pathway. For a particular exposure pathway, conceptual models were first derived, then equations were selected on the basis of the models.

For the soil exposure pathway, conceptual models illustrate the migration of diffusing vapors from surface soil to ambient air (Figure 3a), the migration of particulates from surface soil to ambient air (Figure 3b) and the volatilization of vapors from subsurface soils to indoor air (Figure 3c). Two exposure routes, ingestion and dermal contact, are represented by equations in Figure 3 but do not have associated conceptual models.

Key parameters that influence inter-media migration, as depicted in Figure 3a - Volatilization Factor – Surficial Soil to Ambient Air (VF_{ss}), include the ambient air velocity (wind speed) in the mixing zone (U_{air}), the mixing zone, or breathing zone height for someone standing on top of contaminated soil (δ_{air}) and the dimensions of the contaminated source including thickness (L_{ss}) and width (W). This model was adapted from Standard Guide for Risk-Based Corrective Action published by the American Society of Testing and Materials (ASTM, 2000).

Key parameters that influence inter-media migration as depicted in Figure 3b – Particulate Concentration – Total Respirable Particulate Concentration Originating from Surficial Source (VF_p), also include the ambient air velocity (wind speed) in the mixing zone (U_{air}), the mixing zone, or breathing zone height for someone standing on top of contaminated soil (δ_{air}), and the dimensions of the contaminated source including thickness (L_{ss}) and width (W). This model was also adapted from Standard Guide for Risk-Based Corrective Action published by the American Society of Testing and Materials (ASTM, 2000).

For the volatilization from soil to indoor air pathway, a conceptual model illustrates the migration of diffusing vapors from subsurface soil to indoor air (Figure 3c). Key parameters that influence inter-media migration, as depicted in Figure 3c – Attenuation co-efficient (α) - Subsurface Soil to Indoor Air, include the source-building separation (L_T), the thickness of the soil vadose layer (L_{vad}), the flow rate of soil gas into the enclosed space (Q_{soil}), the area of the enclosed space below grade (A_B), the pressure differential between the soil surface and the enclosed space (ΔP), and the building ventilation rate ($Q_{building}$). These parameters aim to quantify the effects of subsurface phenomena such as air streamlines produced by the building zone of influence and physical phenomena such as cracks in the building floor that allow migration of soil gases into the building.

For the volatilization from groundwater to indoor air pathway, a conceptual model illustrates the migration of diffusing vapors from groundwater to indoor air (Figure 4a). Key parameters that influence inter-media migration, as depicted in Figure 4a – Volatilization from Groundwater to Indoor Air, include the source-building separation (L_T), the flow rate of soil gas into the enclosed space (Q_{soil}), the area of the enclosed space below grade (A_B), the pressure differential between the soil surface and the enclosed space (ΔP) and the building ventilation rate ($Q_{building}$).

Both the groundwater and soil volatilization model use an attenuation factor to estimate the chemical vapor concentration at a source area. The groundwater model then estimates a groundwater concentration associated with the vapor concentration while the soil model estimates a soil concentration associated with the vapor concentration. Both models were adapted from the User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings (USEPA, 1997a). In the groundwater model diffusion through the saturated soil layer, capillary zone and vadose zone is modeled. In the soil model, only diffusion through the vadose zone is modeled.

Section 4
EQUATIONS FOR CALCULATING RISK-BASED REMEDIATION GOALS

Two sets of Risk-based Remediation Goals (RBRGs) were developed:

- $RBRG_{soil}$ - Soil RBRGs protective of direct contact with soil (including outdoor inhalation of vapors from surface soils, outdoor inhalation of surface dusts, dermal contact, and incidental ingestion) and volatilization from subsurface soils into indoor air.
- $RBRG_{gw}$ - Groundwater RBRGs protective of volatilization from groundwater into indoor air.

The equations used to estimate the RBRG for soil and groundwater were derived and/or adapted from the following sources:

- The US Environmental Protection Agency
- The American Society for Testing and Materials
- The Johnson and Ettinger model for volatilization into indoor air

Figure 3 presents the equation used to calculate the RBRG for soil ($RBRG_{soil}$). This equation was obtained from the Standard Provisional Guide for Risk-Based Corrective Action (ASTM, 2000). This equation was selected because it is protective of exposures via ingestion, dermal, and inhalation exposures.

Figures 3a and 3b present the equations for estimating volatilization from surface soil to ambient air and, particulate entrainment from soil to ambient air. These equations were also derived from ASTM (ASTM, 2000). Figure 3c presents the equation for estimating the volatilization from subsurface soil to indoor air. This equation was derived from the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings.

Figure 4 presents the equations used to calculate the RBRGs for groundwater ($RBRG_{gw}$) protective of inhalation of indoor air for urban residential, rural residential and industrial scenarios. Figure 4a presents the equation for estimating the volatilization from groundwater to indoor air. These equations were derived from the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings. The model first appeared as a technical paper titled Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings (Johnson, Paul C., and Ettinger, Robert A., Environmental Science and Technology. Vol. 25, No. 8, 1991).

Figure 5 presents the equations for estimating the soil saturation limit, or that level above which residual chemicals may form non-aqueous phase liquids (NAPL). The equations were adopted from USEPA (USEPA, 1996b) and ASTM (ASTM, 2000). Soil saturation limits have been calculated for those organic chemicals of concern that have molecular weights less than 200 g/mol except for the petroleum carbon ranges. Those COCs that have molecular weights less than 200 g/mol are more of a concern because they are considered mobile in the subsurface environment. As the soil saturation limit equations in Figure 5 are for calculating C_{sat} for a pure chemical constituent, it is not applicable to the petroleum carbon fractions which comprise chemical mixtures. The C_{sat} values for these petroleum fractions were taken from a Canadian reference (CCME, 2000).

Figure 6 presents miscellaneous equations used to calculate the soil parameters and physical/chemical properties.

Section 5
SITE AND EXPOSURE PARAMETERS

Each of the equations used to develop RBRGs for soil and groundwater are comprised of a set of four types of parameters representing: (1) exposure; (2) soil conditions; (3) building conditions; and, in some cases, (4) surface conditions. Tables 1, 2, 3, and 4 provide a list of the parameter values used to develop RBRGs for each of the relevant receptors. These tables also present the symbol used in the equations to represent each parameter, the appropriate units, definitions, and other important details on the derivation of these values. The parameter values were chosen as far as possible from Hong Kong sources to reflect the local conditions. When no local values were available, default values from overseas sources were adopted after examining their applicability to Hong Kong conditions. When no directly applicable values could be found from local or overseas sources, interim values were chosen based on EPD's best professional judgement.

Exposure parameter values are used to calculate each of the RBRGs. The values illustrated in Table 1 present the exposure values relevant to the adult and child receptors and are specific for Hong Kong, or default values derived from the USEPA references [e.g. Exposure Factors Handbook (USEPA, 1997b)], or interim values. Separate exposure factors for children are necessary due to the higher daily intake rates of soil by children and their lower body weight (USEPA, 1991). For carcinogenic or non threshold risk, RBRGs were derived by combining the adult and child scenarios to approximate the integrated exposure from birth until the full exposure duration (ED) of 30 years, combining contact rates, body weights and exposure durations for children and adults. For non-carcinogenic or threshold risk, RBRGs were derived for children and adults separately. The lower of the two RBRGs was then selected. Definitions and details of these parameter values are presented in Table 1.

Soil parameter values are used to calculate RBRGs protective of soil through volatilization from surface soil to ambient air and subsurface soil to indoor air and of groundwater through volatilization from groundwater to indoor air. The sources of soil parameter values presented in Table 2 include ASTM (ASTM, 2000) or USEPA (USEPA, 1997a), which were the sources of the two equations and models for these pathways. The soil parameter values for sandy soil were adopted from the US EPA (1997a) as they were considered to be a conservative estimate for characterizing the soil parameters in Hong Kong. Definitions and details of these values are presented in Table 2.

Building parameter values are used to calculate RBRGs protective of volatilization from soil to indoor air and from groundwater to indoor air. The sources of building parameters presented in Table 3 include Government Departments as well as other references in Hong Kong. These values include the typical dimensions of residential and industrial buildings and lot sizes. Other parameter values were derived from these provided values, including floor-wall seam perimeters, area of the enclosed space below grade and crack depth below grade. Definitions and details of these values are presented in Table 3.

Surface parameters are used to calculate RBRGs for direct contact with soil. The sources of surface parameter values presented in Table 4 include local Hong Kong references, ASTM and US EPA. Definitions and details of these values are presented in Table 4.

Section 6
TOXICITY INDICES

6.1 Hierarchy of Sources

Available toxicity indices, including Cancer Slope Factors (CSFs), noncancer Reference Doses (RfDs) and Index Doses (ID), are essential elements in the equations used to develop RBRGs. These values were compiled for the chemicals of concern from the following hierarchy of sources:

- US EPA's Integrated Risk Information System (IRIS)
- US EPA's Health Effects Assessment Summary Tables (HEAST)
- Department for Environment, Food and Rural Affairs (DEFRA) and The Environment Agency (2002) Toxicological Reports for Individual Soil Contaminants, Report CLR9TOX1-10
- Baars AJ, Theele RMC, Janssen PJCM, Hesse JM, Apeldoorn ME, Meijerink MCM, Verdam L, Zeilmaker MJ (2001) Re-evaluation of human-toxicological maximum permissible risk levels. RIVM, Bilthoven. RIVM report 711701025
- California EPA. Office of Environmental Health Hazard Assessment
- Publications of the US EPA's Superfund Technical Support Center (STSC) (only toxicological indices which have supporting documentation on their derivation).

Publications of the Total Petroleum Hydrocarbon Criteria Working Group (TPHCWG, 1996 and 1999) provide the toxicity indices for petroleum carbon ranges.

For lead, a reference dose was adopted based on the WHO recommended value.

Table 5 presents the Summary of Available Toxicity Information for Chemicals of Concern along with the sources of the values. These values were obtained from the most up-to-date stated references published as recent as 2005. Toxicity values may be reviewed, modified, or changed when additional scientific information becomes available.

6.2 Toxicity Indices

Threshold toxicity
The oral RfD is based on the assumption that thresholds exist for certain toxic effects such as cellular necrosis. It is expressed in units of mg/kg-day. In general, the RfD is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. RfDs can also be developed for the non-carcinogenic health effects of substances that are also carcinogens.

Non-threshold Toxicity
Cancer risk can be measured as a Cancer Slope Factor (CSF) which is the result of application of a low-dose extrapolation procedure and is presented as the risk per (mg/kg)/day.

Another approach is to use Index Doses which are minimal risk levels that are derived for non-threshold chemicals where a threshold for health effects cannot be assumed (i.e. genotoxic

carcinogens and mutagens). Non-threshold chemicals carry a putative risk at any level of exposure therefore the Index Dose represents a minimal risk level with an expectation that exposures be kept as low as reasonably practicable. This approach has been adopted by the UK when deriving a number of soil guideline values.

Chemicals are classified as to whether they exhibit cancer and non-cancer health effects and whether health effects can result from ingestion, dermal exposure and/or inhalation of the chemical. For some chemicals, both a CSF and an RfD were available because the chemicals has been associated with both cancer and non-cancer health effects. If a chemical is associated with health effects resulting from ingestion exposure, an oral CSF and/or RfD is available. If a chemical is associated with health effects resulting from inhalation exposure, an inhalation CSF and/or RfD is available. Dermal exposures are evaluated using oral CSFs or RfDs.

Either a cancer or non-cancer toxicity index is necessary to develop an RBRGs. RBRGs protective of cancer health effects and non-cancer health effects are calculated separately.

Route-to-Route Extrapolation
Some of the RBRGs are protective of more than one exposure route. The soil exposure pathway incorporates ingestion, dermal absorption, inhalation of volatiles and inhalation of particulates. In order to incorporate the ingestion and dermal routes of exposure into the calculation of the $RBRG_{soil}$, an oral CSF or RfD is required. In order to incorporate the inhalation exposure routes, an inhalation CSF or RfD is necessary.

When toxicity information was available for only one route of exposure, a route-to-route extrapolation of toxicity data was undertaken. Route-to-route extrapolation can be defined as the prediction of the total amount of a substance administered by one route that would produce the same toxic endpoint or response as that obtained for a given amount of a substance administered by another route. Prior to extrapolation, EPD considered a number of key factors (e.g. target organ dose, route-specific metabolic factors) to assess whether route-to-route extrapolation was appropriate. Table 5 identifies where the route-to-route extrapolation was applied.

Total Petroleum Hydrocarbons
Toxicity values have been published by the TPHCWG for majority of the petroleum carbon fractions. These values developed by the TPHCWG were used in developing RBRGs for the five petroleum carbon fractions which are differentiated into aliphatic and aromatic components and subsequently simplified to a list of three petroleum carbon fractions which are not differentiated into aliphatic and aromatic components. Details of converting from five petroleum fractions into three fractions are described in Section 2.

Polycyclic Aromatic Hydrocarbons
In the absence of relevant toxicity information, one approach commonly used to estimate the hazard/toxicity of a mixture of structurally related chemicals with a common mechanism of action is to adopt the Toxicity Equivalency Factor (TEF) methodology. When applied to PAH mixtures, the underlying assumption of the TEF methodology is that a reference compound (usually benzo[a]pyrene) is considered to be the most potent PAH compound, and other PAHs are either equipotent to or less potent than benzo[a]pyrene. Hence the toxicity equivalent for each PAH of interest is an estimate of its relative toxicity (by an order of magnitude) in comparison to benzo[a]pyrene.

EPD considered the TEF methodology to be the most appropriate approach for dealing with carcinogenic PAHs, and benzo[a]pyrene was chosen as the reference PAH compound because its

toxicity is well characterized. This approach has also been adopted by a number of international environmental agencies when setting soil guideline values for carcinogenic PAHs (e.g. Region 9 Preliminary Remediation Goals (PRGs) (US) and Serious Risk Concentrations (SRCs) (Netherlands)). Following a review of a number of suggested TEFs, EPD decided to adopt the relative potency estimates presented by the USEPA (1993) to derive RBRGs for a number of carcinogenic PAHs (i.e. benzo[a]anthracene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, dibenzo[a,h]anthracene and indeno[1,2,3-cd]pyrene).

6.3 Supplemental Toxicity Information

In addition to the toxicity indices, relative absorption factors (RAFs) are needed to calculate the RBRGs for direct contact with soil. There are two types of RAFs; one is applicable to the oral route of exposure (RAF_o) while the other one is applicable to the dermal route of exposure (RAF_d). On the basis of USEPA's reference information, the two types of RAFs were derived for the different groups of chemicals of concern as follows:

Chemical Group	**RAF_o (unitless)**	**RAF_d (unitless)**
VOCs	1	0.5
SVOCs	1	0.25
PCBs	1	0.14
Metals	1	0.05
C6-C8 and C9-C16 petroleum carbon ranges	1	0.5
C17-C35 petroleum carbon ranges	1	0.25
Inorganic compounds	1	0.05
Organometallics	1	0.05

Section 7
PHYSICAL/CHEMICAL PROPERTIES

All of the risk algorithms used to calculate RBRGs required chemical-specific values for various physical and chemical properties. Table 6 presents a list of the physical/chemical properties used to develop RBRGs along with definitions and the units for these values. Table 7 summarises the physical/chemical values used to calculate the RBRGs.

The following references were used for collecting these parameter values:

- US EPA, 1996b. *Soil Screening Guidance: Technical Background Document*. Office of Solid Waste and Emergency Response, US Environmental Protection Agency, Washington, DC. (May, 1996).

- USEPA, 1986. *Superfund Public Health Evaluation Manual*. Office of Solid Waste and Emergency Response, US Environmental Protection Agency, Washington, DC. (October, 1986)

- Howard, Philip H, 1990. *Handbook of Environmental Fate and Exposure Data*. Lewis Publishers.

- Howard, Philip H., et al. 1991. *Handbook of Environmental Degradation Rates*. Lewis Publishers.

- Boethling, Robert S. and Mackay, Donald, 2000. *Handbook of Property Estimation Methods for Chemicals*. Lewis Publishers.

- HSDB, 2000. *Hazardous Substances Data Bank*. On-line Database published on TOXNET. US National Library of Medicine. http://toxnet.nlm.nih/gov.

- TPHCWG, 1997. *Selection of Representative TPH Fractions Based on Fate and Transport Considerations. Volume III.* Total Petroleum Hydrocarbon Criteria Work Group. Amherst Scientific Publishing. (February 27, 1997).

- Schwarzenbach, Rene P. et al., (1993) *Environmental Organic Chemistry*. John Wiley & Sons, Inc. (1993).

- US EPA, 1992b. *Dermal Exposure Assessment: Principles and Applications*. Office of Research and Development, US Environmental Protection Agency, Washington, DC. (January, 1992).

- Weast, Robert C. (ed.), 1989-1990. *Handbook of Chemistry and Physics*. CRC Press. (1989-1990).

In some cases it was necessary to calculate property values for chemicals because measured values were not available. Property values were calculated for some chemicals for each of the following properties:

Henry's Law Constant (H) - Henry's Law Constants were estimated using the Bond Contribution Method of Meylan and Howard (1991) reported in Handbook of Property Estimation Methods for Chemicals (Boethling and Mackay, 2000). In this method, values are assigned to the 59 possible

bonds (ex. C-H bond, C-N bond). The values for all of the bonds in a particular chemical are added, resulting in a dimensionless log (base 10) water to air partition coefficient, expressed as log K_{WA}. K_{AW} is the reciprocal of K_{WA} and can be used to calculate a Henry's Law value as:

$H = K_{AW} \text{ X } RT$

R = gas constant (8.2057 E-05 atm-m^3/mol K)
T = absolute soil and groundwater temperature in Kelvin = 298 K

Dimensionless Henry's Law Constant (H') – The dimensionless Henry's Law Constant can be converted from the Henry's Law Constant as follows:

$H' = H/RT$

Where:
H = Henry's Law Constant (atm-m^3/mol)
R = gas constant (8.2057 E-05 atm-m^3/mol K)
T = absolute soil and groundwater temperature in Kelvin = 298 K

Diffusivity in Air (D_a) - Diffusivities in air were estimated from the following formula relating diffusivity to molecular weight as presented in Environmental Organic Chemistry (Schwarzenbach, et al., 1993):

$D_a = 1.55/(mw)^{0.65}$

Where:
mw = molecular weight of chemical

Diffusivity in Water (D_w) - Diffusivities in water were estimated from the following formula relating diffusivity to molecular weight as presented in *Environmental Organic Chemistry* (Schwarzenbach, et al., 1993):

$D_w = 2.7E\text{-}03/(mw)^{0.71}$

Where:
mw = molecular weight of chemical

Soil (sorbed) -Water Partition Coefficients (K_d) – These values were calculated from the formula presented in *Soil Screening Guidance; User's Guide* (US EPA, 1996a):

$K_d = K_{oc} \text{ X } f_{oc}$

Where:
K_{oc} = Soil to organic carbon partition coefficient (cm^3/g)
f_{oc} = Fraction organic carbon in soil (g/g)

Figure 6 presents several miscellaneous equations, not otherwise listed, that were used in RBRG calculation.

For carbon fractions of petroleum hydrocarbons, physical/chemical property data were obtained from *Selection of Representative TPH Fractions Based on Fate and Transport Considerations.*

Volume III. (TPHCWG, 1996b). Physical/chemical property data were developed for five carbon fractions, differentiated as aliphatics or aromatics. RBRGs were developed for these five fractions but were then combined into three carbon fractions that do not differentiate between the aliphatic and aromatic components. The procedure for deriving the final three RBRGs from the five carbon fractions is described in Section 2.

The dimensionless Henry's Law Constant (H') for carbon fractions of petroleum hydrocarbons were calculated using the following equations:

For aliphatics: $\log_{10}H' = 0.02EC + 1.6$
For aromatics: $\log_{10}H' = -0.23EC + 1.7$

EC equals the equivalent carbon number. These values were selected based on an average of the lowest and highest EC numbers reported for individual compounds within each carbon range, as recommended in the TPHCWG guidance. The following midpoint ECs were used to calculate the property values:

- C6 – C8 aliphatics: 6.9
- C9 – C16 aliphatics: 11.9
- C9 – C16 aromatics: 15.5
- C17 – C35 aliphatics: 21.5
- C17 – C35 aromatics: 29.4

Organic carbon partition coefficients (K_{oc}) (ml/g) for carbon fractions of petroleum hydrocarbons were calculated using the following equations:

For aliphatics: $\log_{10} K_{oc} = 0.45EC + 0.43$
For aromatics: $\log_{10} K_{oc} = 0.10\ EC + 2.3$

Solubility (S) (mg/L) for carbon fractions of petroleum hydrocarbons were calculated using the following equations:

For aliphatics: $\log_{10} S = -0.55EC + 4.5$
For aromatics: $\log_{10} S = -0.21EC + 3.7$

Diffusivities in air and water as functions of equivalent carbon number for petroleum hydrocarbons are presented in the TPHCWG guidance (TPHCWG, 1996). These values do not differ significantly from compound to compound. Thus, it is recommended in the guidance that the diffusivity for air (D_a) be set at 0.1 cm^2/sec and that the diffusivity for water (D_w) be set at 0.00001 cm^2/sec (TPHCWG, 1996).

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Table 1
Exposure Parameter Values

Symbol	Parameter	Unit	Parameter Value for Each Land Use				Definition	Source	Details
			Urban Residential	Rural Residential	Industrial	Public Parks			
AT_{nc}	Averaging Time for non-carcinogens	years	30	30	25	30	Length of time (in days, months or years) over which exposure is ongoing.	Interim	Averaging time for noncarcinogens equals exposure duration for Adults.
BW	Body Weight	kg	50	50	60	50	A weight that is representative of adults.	HK	Average of 60 kg for male adults and 50 kg for female adults (Leung and Lui, 1989).
ED	Exposure Duration	years	30	30	25	30	Length of time over which exposure is ongoing.	Interim	Conservative value for typical residence times and employment times based on professional judgement.
IR_s	Ingestion Rate-soil	mg/day	100	100	100	100	The amount of soil consumed per day during mouthing of objects or unintentional hand-to-mouth activity.	Default (US EPA, 1997b)	Ingestion rate for residents and park visitors (200 mg/day for ages from birth to 6 years and 100 mg/day for ages above 6 years). Ingestion rate for industrial workers based on adult ingestion rate.
IR_{air}	Daily Inhalation Rate - outdoor	m^3/day	4.5	6	20	6	The amount of air breathed per day while engaged in various outdoor work or leisure activities.	Interim	Inhalation rates for urban residential based on moderate activity (1.5 m^3/hr) for 3 hours per day; Inhalation rates for rural residential and public parks based on moderate activity (gardening) (1.5 m^3/hr) for 4 hours per day; Inhalation rates for industrial workers based on 5 hours heavy (2.5 m^3/hr) and 5 hours of moderate (1.5 m^3/hr) activity per day. Inhalation factors based on EPA Exposure Factors Handbook (EPA,1997b).
M	Soil to skin adherence factor	mg/cm^2-day	0.08	0.08	0.08	0.08	The amount of soil that remains on a square centimeter of skin following contact with soil during work or leisure activities.	Default (US EPA, 1998)	Value for adult based on the value for an urban/suburban gardener.
SA	Seasonally-averaged skin surface area	cm^2	2,300	2,950	2,950	2,950	The area of skin, in square centimeters, that is exposed to soil during various work or leisure activities, accounting for seasonal variation.	Interim	Values for urban residential sites based on hands and forearms; values for rural, industrial and public park sites are based on hands, forearms, and face. All values are 50th percentiles from EPA Exposure Factors Handbook (EPA, 1997b). Statistics not available for HK.
IR_{air}	Daily Inhalation Rate - indoor	m^3/day	21	20	12.5		The amount of air breathed per day while engaged in various indoor activities.	Interim	Inhalation rates for urban residential based on light activity (1.0 m^3/hr) for 21 hours per day; rural residential based on light activity (1.0 m^3/hr) for 20 hours per day; industrial based on light activity (1.0 m^3/hr) for 5 hours per day and moderate activity (1.5 m^3/hr) for 5 hours per day. Inhalation factors based on EPA Exposure Factors Handbook (EPA,1997b).
AT_{ncc}	Averaging Time for non-carcinogens for children	years	6	6		6	Length of time (in days, months or years) over which exposure is ongoing.	Default (US EPA, 1997b)	Averaging time for noncarcinogens equals exposure duration for Children.
BW_c	Body Weight for children	kg	15	15		15	A weight that is representative of children.	Default (US EPA, 1997b)	Average of 15 kg for children from birth to 6 years.
ED_c	Exposure Duration for children	years	6	6		6	Length of time over which exposure is ongoing.	Default (US EPA, 1997b)	Based on EPA Exposure Factors Handbook (EPA,1997b).
IR_{sc}	Ingestion Rate-soil for children	mg/day	200	200		200	The amount of soil consumed per day during mouthing of objects or unintentional hand-to-mouth activity.	Default (US EPA, 1997b)	Ingestion rate for residents and park visitors (200 mg/day for ages from birth to 6 years and 100 mg/day for ages above 6 years).
IR_{airc}	Daily Inhalation Rate - outdoor for children	m^3/day	2.3	3		3	The amount of air breathed per day while engaged in various outdoor activities.	Interim	Inhalation rates for urban residential based on moderate activity (0.75 m^3/hr) for 3 hours per day; Inhalation rates for rural residential and public parks based on moderate activity (0.75 m^3/hr) for 4 hours per day. Inhalation factors based on EPA Exposure Factors Handbook (EPA,1997b).
M_c	Soil to skin adherence factor for children	mg/cm^2-day	0.2	0.2		0.2	The amount of soil that remains on a square centimeter of skin following contact with soil during outdoor activities.	Default (US EPA, 1998)	
SA_c	Seasonally-averaged skin surface area for children	cm^2	1,200	1,500		1,500	The area of skin, in square centimeters, that is exposed to soil during various outdoor activities, accounting for seasonal variation.	Interim	Values for urban residential sites based on hands and forearms; values for rural and public park sites are based on hands, forearms, and face. All values are 50th percentiles from EPA Exposure Factors Handbook (EPA, 1997b). Statistics not available for HK.
IR_{airc}	Daily Inhalation Rate - indoor for children	m^3/day	10	10			The amount of air breathed per day while engaged in various indoor activities.	Interim	Inhalation rates for urban residential based on light activity (0.5 m^3/hr) for 21 hours per day; rural residential based on light activity (0.5 m^3/hr) for 20 hours per day. Inhalation factors based on EPA Exposure Factors Handbook (EPA,1997b).
EF	Exposure Frequency	days/year	350	350	300	104	The number of times an exposure event occurs over a given period of time.	Interim	Assumed residents at home for 50 weeks per year. Assumed the public in general visit parks for 2 days per week. Assumed workers at work year round except Sundays and 2 week public holidays per year.
AT_c	Averaging Time for carcinogens	years	70	70	70	70	The time equals to a standard life expectancy.	Default (US EPA, 1997b)	Averaging time for carcinogens equals to lifetime of 70 years.

Table 2
Soil Parameter Values

Symbol	Parameter	Units	Value	Definition	Source	Details
L_{ss}	Thickness of Surficial Soils	cm	100	An estimate of the thickness of soil from which volatile chemicals may be emitted into the ambient air.	Default (ASTM, 2000)	This value is consistent with ASTM, 2000 and is based on professional judgement that soil down to 100 cm contributes to vapor emissions.
ρ_b	Dry Soil Bulk Density	g/cm^3	1.7	The mass of a unit volume of soil.	Default (ASTM, 2000)	This value is consistent with ASTM, 2000 and is based on professional judgement that soil builk density of sandy soils is $1.7 g/cm^3$.
θvair	Soil Air-filled Porosity vadose zone	cm^3-air/cm^3-soil	0.32	The fraction of total soil porosity that is filled with air in the vadose zone.	Calculated	(θ_T - θvwater)
θvwater	Soil Water-filled Porosity vadose zone	cm^3-water/cm^3-soil	0.05	The fraction of total soil porosity that is filled with water in the vadose zone.	Default (US EPA, 1997)	This value is consistent with US EPA 1997 for a sandy soil. Sand is considered to be representative of a conservative Hong Kong fill material.
$\theta\tau$	Soil Porosity	cm^3-air/cm^3-soil	0.37	The ratio of the void spaces in soil to the partial volume of the soil in the vadose zone.	Default (US EPA, 1997)	ditto
θcap air	Soil air-filled porosity capillary fringe	cm^3-air/cm^3-soil	0.14	The fraction of total soil porosity that is filled with air in the capillary zone.	Calculated	(θ_T - θ cap water)
θ cap water	Soil water filled porosity capillary fringe	cm^3-water/cm^3-soil	0.23	The fraction of total soil porosity that is filled with water in the capillary zone.	Calculated	(θ_r . (θ_T . θ_r))/(2^M)
k_v	Soil Vapor Permeability	cm^2	1.00E-08	The permeability of the porous medium to a fluid when more than one fluid is present. It is a function of the degree of saturation.	Default (US EPA, 1997)	This value is consistent with US EPA 1997 for a sandy soil. Sand is considered to be representative of a conservative Hong Kong fill material.
D	Mean grain diameter	cm	4.40E-02	The average particles size of grains of soil.	Default (US EPA, 1997)	ditto
L_{cap}	Capillary fringe thickness	cm	1.70E+01	The thickness of the capillary zone, a layer of saturated soil where groundwater is held in soil pores.	Calculated	(0.15/(D x 0.2))
L_i	Thickness of Soil Layer i	cm	3.30E+01	The thickness of the vadose zone when groundwater exists and a capillary fringe is present.	Calculated	(L_T - L_{cap})
L_T	Source-Building Separation	cm	50	Distance between the source of the contamination and the bottom of the enclosed space floor.	HK	Value of 50 cm applicable to urban, rural receptor and industrial receptor. Soil contamination is shallow in Hong Kong, therefore there is negligible buffer between the foundation and the source of contamination. For soil contamination the source-building sepration equals the thickness of the vadose zone soil layer.
f_{oc}	Soil Organic Carbon Weight Fraction	dimensionless	0.002	The amount of solid phase organic carbon in natural organic matter which can bind chemicals	HK	Value for general fill in Hong Kong. Value also consistent with USEPA default.
θ_r	Soil residual water porosity	cm^3-water/cm^3-soil	0.053	The fraction of total soil porosity that contains residual water.	Default (US EPA, 1997)	This value is consistent with US EPA 1997 for a sandy soil.
M	Van Genuchten Parameter	unitless	0.6852	Parameter used to define the water retardation in the soil.	Default (US EPA, 1997)	ditto

Table 3
Building Parameter Values for Volatilization from Soil and Groundwater to Indoor Air

Symbol	Parameter	Units	Urban Residential	Rural Residential	Industrial	Definition	Source	Details
A_B	Area of the Enclosed Space Below Grade	cm^2	21,074,000	1,299,600	32,448,000	The area of the floor in contact with the underlying soil and the total wall area below grade.	HK	Assume one floor grade (260 cm in height) below grade for urban residential and industrial. Slab on grade for rural residential. The values include the area of the floor in contact with underlying soil and the total wall area below grade. Calculated based on lengths and widths of buildings. Typical building volumes and dimensions derived from Hong Kong Planning Standards and Guidelines (Planning Department, 1996) and the Building Ordinance.
$Q_{building}$	Building Ventilation Rate	cm^3/sec	320,000	32,500	1,500,000	The amount of air that passes through the volume of a building over a particular period of time.	HK	5 litres/sec of air exchange per person. For urban residential: 16 flats or 64 persons/floor, 64 persons/floor * 5 liters/sec/person * 1000 cm^3/liter = 320,000 cm^3/sec. For rural residential: 20 m^2 per person for rural residential, 130 m^2/20 m^2 person = 6.5 persons/floor, 6.5 persons/floor * 5 liters /sec/person *1000 cm^3/liter = 32,491 cm^3/sec. For industrial: 9 m^2 area required per person for industrial, 2700 m^2/9 m^2 per person = 300 persons/floor, 300 persons/floor * 5 liters/sec/person * 1000 cm^3/liter = 1 500,000 cm^3/sec
L_{crack}	Enclosed Space Foundation or Slab Thickness	cm	25	25	25	The thickness of the ground level buffer between indoor air and the outdoor environment.	HK	A value of 25 cm was assumed for the ground floor slab, which sits on top of the ground beams and pile caps in some areas. In some areas, therefore, soil is not directly beneath the foundation.
L_B	Length of Building	cm	4,100	1,140	5,200	An estimated value for a typical building.	HK	Hong Kong Planning Standards and Guidelines (Planning Department, 1996) and the Buildings Ordinance.
W_B	Width of Building	cm	4,100	1,140	5,200	An estimated value for a typical building.	HK	Hong Kong Planning Standards and Guidelines (Planning Department, 1996) and the Buildings Ordinance.
H_B	Height of One Floor Grade	cm	260	260	260	An estimated value for a typical building.	HK	Based on typical height of one floor grade in Hong Kong.
X_{crack}	Floor-wall Seam Perimeter	cm	17,440	4,560	21,840	Lengths sides of the building and basement walls urban and industrial (L_B x 4 + H_B x 4). Lengths sides of the building Rural (L_B x 4).	HK	Calculated based on lengths and heights of one floor grade of buildings. Urban and industrial facilities are assumed to have basements, rural residences are assumed to not have basements.
Z_{crack}	Crack Depth Below Grade	cm	260	25	260	Length of crack below soil surface.	HK	Assumes crack runs along entire length of wall below grade. One floor (260 cm in height) below grade for urban residential and industrial; assume crack depth below grade equal to slab thickness (25 cm) for rural residential.
r_{crack}	Equivalent Crack Radius	cm	0.05	0.05	0.05	Used to estimate the flow rate of soil gas into a building.	HK/Default (US EPA, 1997a)	The floor-wall seam gap reported applicable for structures on raft or pad foundations only where the "gaps" are filled with joint filler. For structures founded on piles, there are normally no gaps to the exterior wall. A British serviceability limit of 0.3 mm has been established for HK. Because this results in a radius of 0.015 cm, which is the lower end of the default range provided by Johnson and Ettinger, 1991, the low end of 0.05 cm was selected as a conservative value.
ΔP	Pressure Differential between Soil Surface and Enclosed Space	g/cm-sec^2	40	40	40	Reflects the degree of building under pressurization which influences the flow rate of soil gas into a building.	Default (US EPA, 1997a)	Conservative value which reflects building underpressurization.
A_{crack}	Area of Crack	cm^2	872	228	1,092	The total area of the cracks below the soil surface.	HK/Default (US EPA, 1997a)	Equal to A_B * crack-to-total-area ratio (n). Value based on lower end of the default range for crack radius.
n	Crack-to-total-area ratio	unitless	4.14E-05	1.75E-04	3.37E-05	Used to estimate the flow rate of soil.	HK/Default (US EPA, 1997a)	Equal to r_{crack} / (A_B/x_{crack}). Value based on lower end of the default range for crack radius.

Table 4
Surface Parameter Values for Direct Contact with Soil

Symbol	Parameter	Units	Urban Residential	Rural Residential	Industrial	Public Parks	Definition	Source	Details
τ	Averaging Time for Surface Emission Vapor Flux	years	30	30	25	30	Length of time over which exposure to soil is on-going.	Interim	Emissions may be depleted over shorter period of time but are averaged over exposure period.
A	Source-Zone Area	cm^2	1,680,000	260,000	2,700,000	18,800,000	Area over which contact with soil could occur.	HK	Percentage of lot size where soil contact could occur. assumed 10% for urban residential and industrial; 20% for rural residential; 75% of public parks assumed to be an average of 2,500 m^2. Standard lot sizes provided by HK Planning Standards and Guidelines - Planning Department.
U_{air}	Ambient Air Velocity in Mixing Zone	cm/sec	306	306	306	306	Wind speed in breathing zone approximately 2 meters from ground surface.	HK	Based on meteorological data obtained from Hong Kong Observatory. Based on the mean annual wind speed of 11 kilometers/hour. This value is used to calculate various wind speed dependent parameters.
δ_{air}	Mixing Zone Height	cm	200	200	200	200	Approximate height of adult human.	Default (ASTM 2000)	Assumes quality of inhaled air is influenced by dilution and air exchange within a finite volume of air, the vertical boundary of which approximates a person's height.
W	Width of Source-Zone Area	cm	1300	510	1640	4300	Width of area where contact with soil could occur.	HK	Assumed square source zone. Standard lot sizes provided by HK Planning Standards and Guidelines - Planning Department.
P_e	Area Total Respirable Particulate Emission Flux from Source	g/cm^2-sec	6.9E-14	6.9E-14	6.9E-14	6.9E-14	Amount of respirable soil particles released from a square centimeter of soil per second.	Default (ASTM, 2000)	Based on particle emissions from surface soil assumed to be relatively continuous and constant over a period of time (years). It is based on an annual average rate of emissions based on wind erosion.

Table 5
Summary of Available Toxicity Information for Chemicals of Concern

Chemical of Concern	Oral Toxicity Values				Inhalation Toxicity Values			
	RfDo (mg/kg/day)	Source	CSFo (mg/kg/day)-1	Source	RfDi (mg/kg/day)	Source	CSFi (mg/kg/day)-1	Source
VOCs								
2-Butanone	6.00E-01	IRIS			1.43E+00	IRIS		
Acetone	9.00E-01	IRIS			9.00E-01 [r]	IRIS		
Benzene	2.90E-04	DEFRA			9.10E-04	DEFRA		
Bromodichloromethane	2.00E-02	IRIS	6.20E-02	IRIS	2.0E-02 [r]	IRIS	6.20E-02 [r]	IRIS
Chloroform	1.00E-02	IRIS			1.40E-02	IRIS	1.90E-02	Calif EPA
Ethylbenzene	1.00E-01	IRIS			2.90E-01	IRIS		
Methylene Chloride	6.00E-02	IRIS	7.50E-03	IRIS	8.57E-01	HEAST	1.65E-03	IRIS
Methyl tert-Butyl Ether	8.57E-01 [r]	IRIS	1.80E-03	Calif EPA	8.57E-01	IRIS	9.10E-04	Calif EPA
Styrene	2.00E-01	IRIS			2.86E-01	IRIS		
Tetrachloroethene	1.00E-02	IRIS	5.40E-01	IRIS	1.70E-01	IRIS	2.07E-02	IRIS
Toluene	8.00E-02	IRIS			1.42E+00	IRIS		
Trichloroethene	5.00E-02	RIVM	1.30E-02	Calif EPA	5.70E-02	RIVM	7.00E-03	Calif EPA
Xylenes (Total)	2.00E-01	IRIS			2.85E-02	IRIS		
SVOCs								
Acenaphthene	6.00E-02	IRIS			6.00E-02 [r]	IRIS		
Acenaphthylene	6.00E-02	IRIS			6.00E-02 [r]	IRIS		
Anthracene	3.00E-01	IRIS			3.00E-01 [r]	IRIS		
Benzo(a)anthracene	2.00E-04	DEFRA (TEF)			7.00E-07	DEFRA (TEF)		
Benzo(a)pyrene	2.00E-05	DEFRA			7.00E-08	DEFRA		
Benzo(b)fluoranthene	2.00E-04	DEFRA (TEF)			7.00E-07	DEFRA (TEF)		
Benzo(g,h,i)perylene	3.00E-02	d			3.00E-02 [r]	d		
Benzo(k)fluoranthene	2.00E-03	DEFRA (TEF)			7.00E-06	DEFRA (TEF)		
bis-(2-Ethylhexyl)phthalate	2.00E-02	IRIS	1.40E-02	IRIS	2.00E-02 [r]	IRIS	1.40E-02 [r]	IRIS
Chrysene	2.00E-02	DEFRA (TEF)			7.00E-05	DEFRA (TEF)		
Dibenz(a,h)anthracene	2.00E-05	DEFRA (TEF)			7.00E-08	DEFRA (TEF)		
Fluoranthene	4.00E-02	IRIS			4.00E-02 [r]	IRIS		
Fluorene	4.00E-02	IRIS			4.00E-02 [r]	IRIS		
Hexachlorobenzene	8.00E-04	IRIS	1.60E+00	IRIS	8.00E-04 [r]	IRIS	1.60E+00 [r]	IRIS
Indeno(1,2,3-cd)pyrene	2.00E-04	DEFRA (TEF)			7.00E-07	DEFRA (TEF)		
Naphthalene	2.00E-02	IRIS			8.57E-04	IRIS		
Phenanthrene	3.00E-01	IRIS			3.00E-01 [r]	IRIS		
Phenol	3.00E-01	IRIS			see note a			
Pyrene	3.00E-02	IRIS			3.00E-02 [r]	IRIS		
PCBs								
PCBs	2.00E-05	IRIS	2.00E+00	IRIS	2.00E-05 [r]	IRIS	4.00E-01	IRIS

Chemical of Concern	Oral Toxicity Values				Inhalation Toxicity Values			
	RfDo (mg/kg/day)	Source	CSFo (mg/kg/day)-1	Source	RfDi (mg/kg/day)	Source	CSFi (mg/kg/day)-1	Source
Metals								
Antimony	4.00E-04	IRIS			4.00E-04 [r]	IRIS		
Arsenic	3.00E-04	DEFRA			2.00E-06	DEFRA		
Barium	2.00E-01	IRIS			1.43E-04	HEAST		
Cadmium (food)	1.00E-03	IRIS	see note e				6.30E+00	IRIS
Chromium III	1.50E+00	IRIS			1.50E+00 [r]	IRIS		
Chromium VI	3.00E-03	IRIS	see note f		2.86E-05	IRIS	4.20E+01	IRIS
Cobalt	2.00E-02	PPRTV			5.71E-06	PPRTV		
Copper	4.00E-02	HEAST			4.00E-02 [r]	HEAST		
Lead	3.50E-03	WHO			1.43E-04	WHOa		
Manganese	1.40E-01	IRIS			1.43E-05	IRIS		
Mercury	3.00E-04	IRIS (see note b)			8.57E-05	IRIS (see note c)		
Molybdenum	5.00E-03	IRIS			5.00E-03 [r]	IRIS		
Nickel	2.00E-02	IRIS	see note g		2.00E-02 [r]	IRIS	8.40E-01	IRIS
Tin	6.00E-01	HEAST			6.00E-01 [r]	HEAST		
Zinc	3.00E-01	IRIS			3.00E-01 [r]	IRIS		
Petroleum Carbon Ranges								
C6 - C8 Aliphatics	5.00E+00	TPHCWG			5.26E+00	TPHCWG		
C9 - C16 Aliphatics	1.00E-01	TPHCWG			2.86E-01	TPHCWG		
C9 - C16 Aromatics	4.00E-02	TPHCWG			5.71E-02	TPHCWG		
C17 - C35 Aliphatics	2.00E+00	TPHCWG			2.00E+00 [r]	TPHCWG		
C17 - C35 Aromatics	3.00E-02	TPHCWG			3.00E-02 [r]	TPHCWG		
Inorganic Compounds								
Cyanide, free	2.00E-02	IRIS			2.00E-02 [r]	IRIS		
Organometallics								
Tributyltin Oxide	3.00E-04	IRIS			3.00E-04 [r]	IRIS		

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Notes:

a) route-to-route extrapolation is not appropriate, because phenol can be a direct contact irritant, and so portal-of-entry effects are a potential concern (ATSDR)
b) Oral reference dose for mercuric chloride
c) Inhalation reference dose for elemental mercury
d) Benzo(g.h.i)perylene value based on pyrene due to structural similarity
e) Route-to-route extrapolation is not appropriate. Cadmium is classified as a probable human carcinogen (Group B1) via the inhalation route however, there are no positive studies of orally ingested cadmium for carcinogencity quantitation (IRIS).
f) Route-to-route extrapolation is not appropriate. Chromium (VI) is a known human carcinogen (Group A) by the inhalation route of exposure however, carcinogencity by the oral route of exposure cannot be determined and it is classified as Group D (IRIS).
g) Route-to-route extrapolation is not appropriate. The nickel carcinogenic assessment is based on the inhalation exposure to nickel refinery dust by refinery workers in several epidemiologic studies and on laboratory studies. Oral exposure to nickel has been assessed based on soluble salts of nickel and currently IRIS has not evaluated soluble salts of nickel, as a class of compounds, for potential human carcinogenicity.

[r] route-to-route extrapolation applied
TEF: Toxicity Equivalency Factor (US EPA (1993) Provisional Guidance for Quantitative Risk Assessment of Polycyclic Aromatic Hydrocarbons)

Table 6
Definitions of Physical/Chemical Properties

Symbol	Parameter	Definition	Units
H(1)	Henry's Law Constant	Ratio of the partial pressure of a compound in air to its concentration in water at equilibrium. An air-water partitioning coefficient.	atm-m^3/mol
H'	Dimensionless Henry's Law Coefficient	Air and water concentration units both in mg/L (or equivalent).	dimensionless
D_a	Diffusivity of a Chemical in Air	Movement of a molecule in air as a result of differences in concentration. Used to calculate the dispersive component of chemical transport. The higher the dispersivity, the more likely a chemical is to move in response to concentration gradients.	cm^2/sec
D_w	Diffusivity of a Chemical in Water	Movement of a molecule in water as a result of differences in concentration.	cm^2/sec
K_{oc}	Soil Organic Carbon / Water Partition Coefficient	A measure of the tendency of a chemical to partition between organic carbon in soil or sediment and water.	cm^3/g
K_d	Soil (sorbed) to Water Partition Coefficient	A measure of the chemical partitioning between soil or sediment and water.	cm^3/g
K_{sw}	Soil to Water Partition Coefficient	A measure of the chemical partitioning between soil and water in the vadose zone in sub-surface soil.	cm^3/g

Notes:
(1) Values based on 25 degrees centigrade consistent with soil and groundwater temperatures at approximately 10 feet below ground.

Table 7
Summary of Physical/Chemical Properties

Chemical of Concern	S Solubility in Water (mg/ L)	Ref.	H Henry's Law (atm-m3/mol)	Ref.	H' Henry's Law (dimensionless)	Ref.	Da Diffusivity in Air (cm^2/sec)	Ref.	Dw Diffusivity in Water (cm^2/sec)	Ref.	Koc Soil Organic Carbon/Water Partition Coefficient (cm^3/g)	Ref.	Kd Soil (sorbed) / Water Partition Coefficient (cm^3/g)	Ref.	Ksw Soil to Water Partition Coefficient (cm^3/g)	Ref.
VOCs																
Acetone	1.00E+06	SSG	3.88E-05	SSG	1.59E-03	SSG	1.24E-01	SSG	1.14E-05	SSG	5.70E-01	SSG	1.14E-03	CALC	1.01E-01	CALC
Benzene	1.75E+03	SSG	5.55E-03	SSG	2.28E-01	SSG	8.80E-02	SSG	9.80E-06	SSG	5.89E+01	SSG	1.18E-01	CALC	2.23E-01	CALC
Bromodichloromethane	6.74E+03	SSG	1.60E-03	SSG	6.56E-02	SSG	2.98E-02	SSG	1.06E-05	SSG	5.50E+01	SSG	1.10E-01	CALC	2.11E-01	CALC
2-Butanone	2.68E+05	PHEM	2.74E-05	PHEM	1.12E-03	CALC	9.61E-02	SCHW	1.29E-05	SCHW	4.50E+00	PHEM	9.00E-03	CALC	1.09E-01	CALC
Chloroform	7.92E+03	SSG	3.67E-03	SSG	1.50E-01	SSG	1.04E-01	SSG	1.00E-05	SSG	3.98E+01	SSG	7.96E-02	CALC	1.83E-01	CALC
Ethylbenzene	1.69E+02	SSG	7.88E-03	SSG	3.23E-01	SSG	7.50E-02	SSG	7.80E-06	SSG	3.63E+02	SSG	7.26E-01	CALC	8.33E-01	CALC
Methyl tert-Butyl Ether	5.10E+04	HSDB	5.87E-04	HSDB	2.40E-02	CALC	8.43E-02	SCHW	1.12E-05	SCHW	6.00E+00	HSDB	1.20E-02	CALC	1.13E-01	CALC
Methylene Chloride	1.30E+04	SSG	2.19E-03	SSG	8.98E-02	SSG	1.01E-01	SSG	1.17E-05	SSG	1.17E+01	SSG	2.34E-02	CALC	1.25E-01	CALC
Styrene	3.10E+02	SSG	2.75E-03	SSG	1.13E-01	SSG	7.10E-02	SSG	8.00E-06	SSG	7.76E+02	SSG	1.55E+00	CALC	1.65E+00	CALC
Tetrachloroethene	2.00E+02	SSG	1.84E-02	SSG	7.54E-01	SSG	7.20E-02	SSG	8.20E-06	SSG	1.55E+02	SSG	3.10E-01	CALC	4.27E-01	CALC
Toluene	5.26E+02	SSG	6.64E-03	SSG	2.72E-01	SSG	8.70E-02	SSG	8.60E-06	SSG	1.82E+02	SSG	3.64E-01	CALC	4.70E-01	CALC
Trichloroethene	1.10E+03	SSG	1.03E-02	SSG	4.22E-01	SSG	7.90E-02	SSG	9.10E-06	SSG	1.66E+02	SSG	3.32E-01	CALC	4.42E-01	CALC
Xylenes (Total)	1.75E+02	SSG	6.75E-03	SSG	2.76E-01	SSG	7.80E-02	SSG	8.75E-06	SSG	3.86E+02	SSG	7.72E-01	CALC	8.78E-01	CALC
SVOCs																
Acenaphthene	4.24E+00	SSG	1.55E-04	SSG	6.36E-03	SSG	4.21E-02	SSG	7.69E-06	SSG	7.08E+03	SSG	1.42E+01	CALC	1.43E+01	CALC
Acenaphthylene	3.93E+00	PHEM	1.48E-03	PHEM	6.05E-02	CALC	5.91E-02	SCHW	7.62E-06	SCHW	2.50E+03	PHEM	5.00E+00	CALC	5.10E+00	CALC
Anthracene	4.34E-02	SSG	6.50E-05	SSG	2.67E-03	SSG	3.24E-02	SSG	7.74E-06	SSG	2.95E+04	SSG	5.90E+01	CALC	5.91E+01	CALC
Benzo(a)anthracene	9.40E-03	SSG	3.35E-06	SSG	1.37E-04	SSG	5.10E-02	SSG	9.00E-06	SSG	3.98E+05	SSG	7.96E+02	CALC	7.96E+02	CALC
Benzo(a)pyrene	1.62E-03	SSG	1.13E-06	SSG	4.63E-05	SSG	4.30E-02	SSG	9.00E-06	SSG	1.02E+06	SSG	2.04E+03	CALC	2.04E+03	CALC
Benzo(b)fluoranthene	1.50E-03	SSG	1.11E-04	SSG	4.55E-03	SSG	2.26E-02	SSG	5.56E-06	SSG	1.23E+06	SSG	2.46E+03	CALC	2.46E+03	CALC
Benzo(g,h,i)perylene	7.00E-04	PHEM	5.34E-08	PHEM	2.2E-06	CALC	4.01E-02	CALC	4.99E-06	CALC	1.60E+06	PHEM	3.20E+03	CALC	3.20E+03	CALC
Benzo(k)fluoranthene	8.00E-04	SSG	8.29E-07	SSG	3.40E-05	SSG	2.26E-02	SSG	5.56E-06	SSG	1.23E+06	SSG	2.46E+03	CALC	2.46E+03	CALC
bis-(2-Ethylhexyl)phthalate	3.40E-01	SSG	1.02E-07	SSG	4.18E-06	SSG	3.51E-02	SSG	3.66E-06	SSG	1.51E+07	SSG	3.02E+04	CALC	3.02E+04	CALC
Chrysene	1.60E-03	SSG	9.46E-05	SSG	3.88E-03	SSG	2.48E-02	SSG	6.21E-06	SSG	3.98E+05	SSG	7.96E+02	CALC	7.96E+02	CALC
Dibenzo(a,h)anthracene	2.49E-03	SSG	1.47E-08	SSG	6.03E-07	SSG	2.02E-02	SSG	5.18E-06	SSG	3.80E+06	SSG	7.60E+03	CALC	7.60E+03	CALC
Fluoranthene	2.06E-01	SSG	1.61E-05	SSG	6.60E-04	SSG	3.02E-02	SSG	6.35E-06	SSG	1.07E+05	SSG	2.14E+02	CALC	2.14E+02	CALC
Fluorene	1.98E+00	SSG	6.36E-05	SSG	2.61E-03	SSG	3.63E-02	SSG	7.88E-06	SSG	1.38E+04	SSG	2.76E+01	CALC	2.77E+01	CALC
Hexachlorobenzene	6.20E+00	SSG	1.32E-03	SSG	5.41E-02	SSG	5.42E-02	SSG	5.91E-06	SSG	5.50E+04	SSG	1.10E+02	CALC	1.10E+02	CALC
Indeno(1,2,3-cd)pyrene	2.20E-05	SSG	1.60E-06	SSG	6.56E-05	SSG	1.90E-02	SSG	5.66E-06	SSG	3.47E+06	SSG	6.94E+03	CALC	6.94E+03	CALC
Naphthalene	3.10E+01	SSG	4.83E-04	SSG	1.98E-02	SSG	5.90E-02	SSG	7.50E-06	SSG	2.00E+03	SSG	4.00E+00	CALC	4.10E+00	CALC
Phenanthrene	1.00E+00	PHEM	1.59E-04	PHEM	6.5E-03	CALC	5.34E-02	SCHW	6.81E-06	SCHW	1.40E+04	PHEM	2.80E+01	CALC	2.81E+01	CALC
Phenol	8.28E+04	SSG	3.97E-07	SSG	1.63E-05	SSG	8.20E-02	SSG	9.10E-06	SSG	2.88E+01	SSG	5.76E-02	CALC	1.58E-01	CALC
Pyrene	1.35E-01	SSG	1.10E-05	SSG	4.51E-04	SSG	2.72E-02	SSG	7.24E-06	SSG	1.05E+05	SSG	2.10E+02	CALC	2.10E+02	CALC
Metals																
Antimony																
Arsenic																
Barium																
Cadmium																
Chromium III																
Chromium VI																
Cobalt																
Copper																
Lead																
Manganese																
Mercury			1.14E-02	SSG	4.67E-01	SSG	3.07E-02	SSG	6.30E-06	SSG	5.20E+01	SSG	2.80E+03	SSG		
Molybdenum																
Nickel																
Tin																
Zinc																
PCBs																
PCBs	3.10E-02	PHEM	1.07E-03	PHEM	4.38E-02	CALC	3.59E-02	SCHW	4.42E-06	SCHW	3.09E+05	SSG	6.18E+02	CALC	6.18E+02	CALC
Petroluem Carbon Ranges																
C6-C8 Aliphatics	5.23E+00	TPH	1.34E+00	CALC	5.46E+01	TPH	1.00E-01	TPH	1.00E-05	TPH	3.34E+03	TPH	6.68E+00	CALC	8.02E+00	CALC
C9-C16 Aliphatics	8.62E-03	TPH	1.69E+00	CALC	6.90E+01	TPH	1.00E-01	TPH	1.00E-05	TPH	6.32E+05	TPH	1.26E+03	CALC	1.27E+03	CALC
C9-C16 Aromatics	2.80E+00	TPH	3.35E-04	CALC	1.37E-02	TPH	1.00E-01	TPH	1.00E-05	TPH	7.06E+03	TPH	1.41E+01	CALC	1.42E+01	CALC
C17-C35 Aliphatics	4.73E-08	TPH	2.62E+00	CALC	1.07E+02	TPH	1.00E-01	TPH	1.00E-05	TPH	1.27E+10	TPH	2.55E+07	CALC	2.55E+07	CALC
C17-C35 Aromatics	3.33E-03	TPH	2.10E-07	CALC	8.58E-06	TPH	1.00E-01	TPH	1.00E-05	TPH	1.75E+05	TPH	3.49E+02	CALC	3.49E+02	CALC
Other Inorganic Compounds																
Cyanide, free																
Organometalics																
TBT/ TBTO																

Notes:

BOET: Boethling and MacKay, 2000.

CALC: Calculated values from references.

DEH: Dermal Exposure Assessment: Principles and Applications (EPA, 1992).

PHEM: Public Health Evaluation Manual (EPA, 1986).

SCHW: Schwarzenbach, 1993.

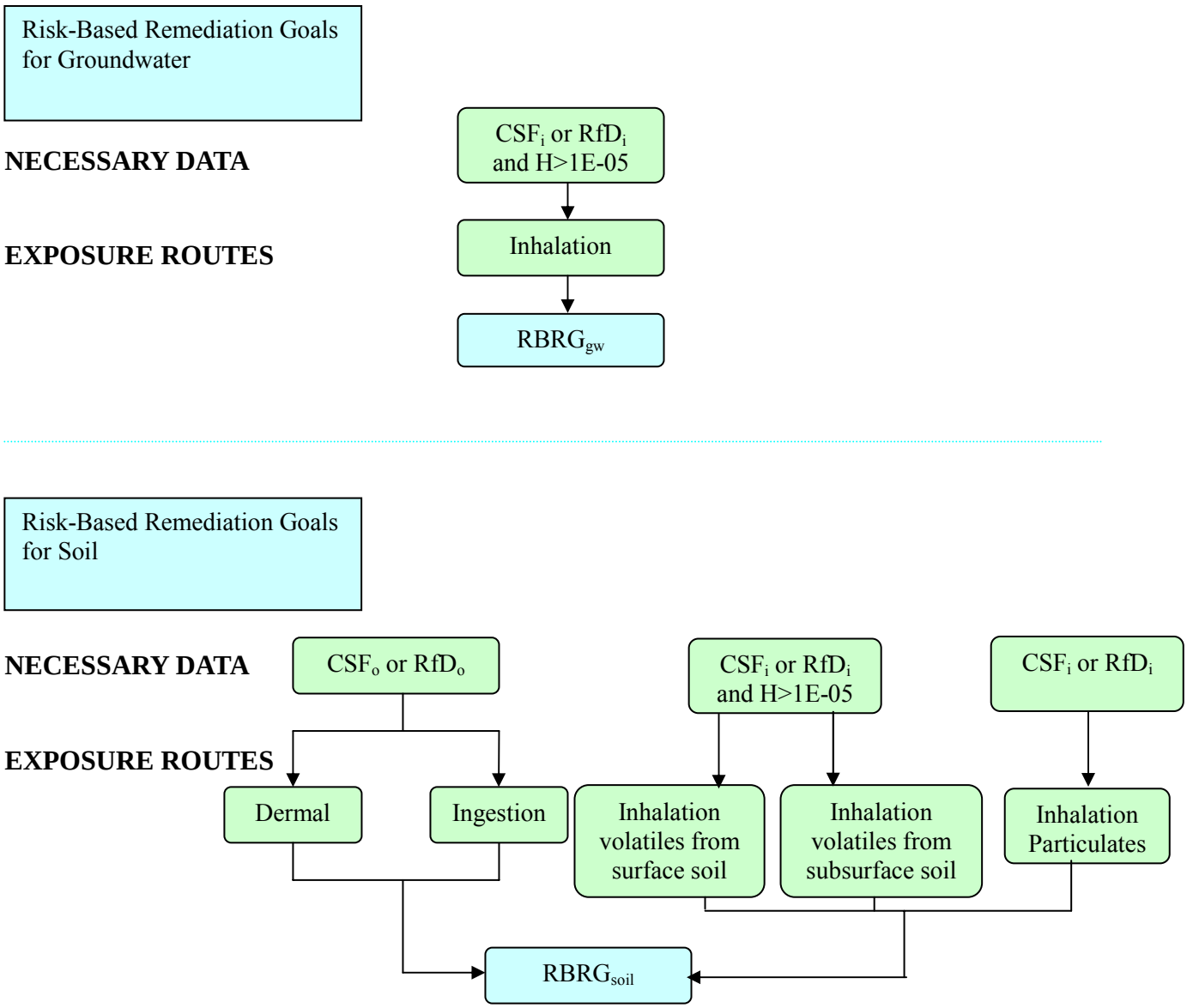
SSG : Soil Screening Guidance (EPA, 1996).

TPH: TPHCWG, 1997.

HOW: Howard, 1990.

HSDB: HSDB, 2000.

Figure 1 – Information Necessary for Developing RBRGs



Note: RBRGs are based on pathways for which necessary data could be obtained

CSF_i	:	Cancer Slope Factor – Inhalation
CSF_o	:	Cancer Slope Factor – Oral
RfD_i	:	Reference Dose – Inhalation
RfD_o	:	Reference Dose – Oral
$RBRG_{gw}$	:	Risk-Based Remediation Goal for groundwater to indoor air
$RBRG_{soil}$	:	Risk-Based Remediation Goal for soil from direct and indirect contact
H	:	Henry's Law Constant (atm-m^3/mol)

Figure 2 – General Flow Diagram for Calculation and Selection of RBRGs

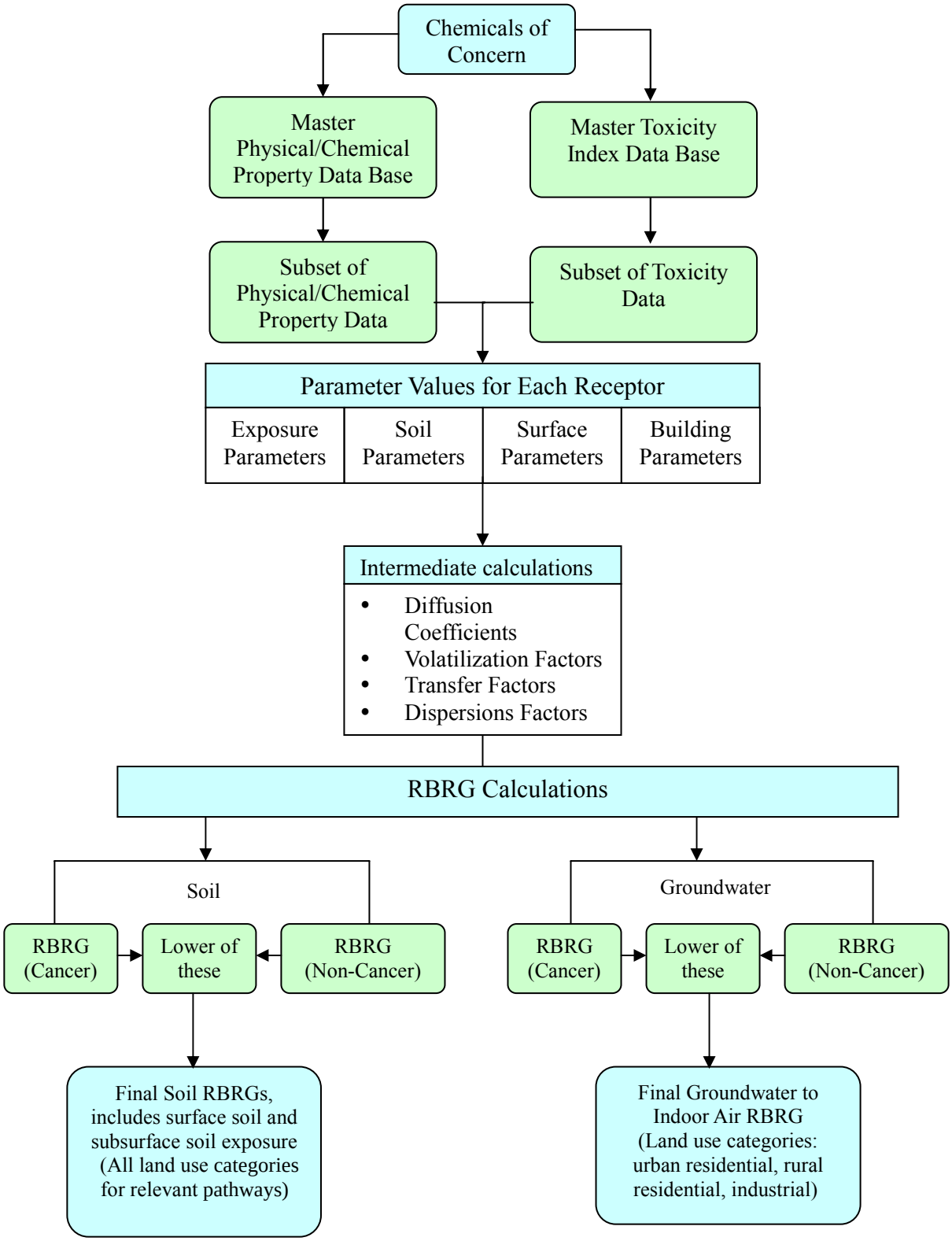


Figure 3
RBRGs for Soil (Direct Contact via ingestion of soil and dermal contact. Indirect Contact via inhalation of vapors from surface soils to ambient air, inhalation of particulates and inhalation of vapors from subsurface soils to indoor air)

(see Figures 3a, 3b and 3c for calculation of VF_{ss}, VF_p and α)

Threshold compounds for adults :

$$\text{Adult RBRG}_{soil} = \frac{\frac{THQ \cdot BW \cdot AT_{nc} \cdot CF_1}{EF \cdot ED}}{[Ao + Ad + Ass + Ap + Aia]} \qquad (1a)$$

where

$$Ao = CF_2 \cdot \left(\frac{IR_s \cdot RAF_o}{RfD_o}\right)$$ Soil Ingestion (1b)

$$Ad = CF_2 \cdot \left(\frac{SA \cdot M \cdot RAF_d}{RfD_o}\right)$$ Dermal Contact (1c)

$$Ass = CF_3 \cdot \left(\frac{IR_{air} \cdot VF_{ss}}{RfD_i}\right)$$ Inhalation of vapors from surface soil (1d)

$$Ap = CF_3 \cdot \left(\frac{IR_{air} \cdot VF_p}{RfD_i}\right)$$ Inhalation of particulates (1e)

$$Aia = \frac{\alpha \cdot IR_{air} \cdot H' \rho_b}{RfD_i \cdot CF_{IA1} \cdot CF_{IA2} \cdot CF_{IA3} \cdot (\theta_{w,vad} + K_d \rho_b + H' \theta_{a,vad})}$$ Inhalation of vapors from subsurface soils (1f)

adapted from ASTM,2000 and EPA,1989

Where:

AT_{nc}	Defined Averaging Time for Noncarcinogens - Adult (years)	K_{oc}	Soil Organic Carbon Partition Coefficient = K_d / f_{oc} (cm^3/g)
BW	Body Weight - Adult (kg)	M	Soil to Skin Adherence Factor - Adult (mg/cm^2-day)
CF_1	Conversion Factor (365 days/year)	RAF_d	Dermal Relative Absorption Factor
CF_2	Conversion Factor (10^{-6} kg/mg)	RAF_o	Oral Relative Absorption Factor
CF_3	Conversion Factor (10^3 cm^3kg/m^3g)	$RBRG_{soil}$	Risk-Based Remediation Goal for Soil (mg/kg)
CF_{IA1}	Conversion Factor ($10^{-6}m^3/cm^3$)	RfD_i	Chronic Inhalation Reference Dose (mg/kg-day)
CF_{IA2}	Conversion Factor (10^{-3} g/mg)	RfD_o	Chronic Oral Reference Dose (mg/kg-day)
CF_{IA3}	Conversion Factor (10^6 mg/kg)	SA	Seasonally-averaged Skin Surface Area - Adult (cm^2)
ED	Exposure Duration - Adult (years)	THQ	Target Hazard Quotient for Individual Chemicals
EF	Exposure Frequency (days/year)	VF_p	Total Respirable Particulate Concentration from Soil Source ($g\text{-soil}/cm^3\text{-air}$)
f_{oc}	Soil Organic Carbon Weight Fraction	VF_{ss}	Volatilization Factor, surficial soil to ambient air ($g\text{-soil}/cm^3\text{-air}$)
H'	Dimensionless Henry's Law Constant	α	Infinite Source Attenuation Coefficient (unitless)
IR_{air}	Daily Inhalation Rate - Adult (m^3/day)	ρ_b	Soil Dry Bulk Density (g/cm^3)
IR_s	Daily Ingestion Rate – Adult (mg/day)	$\theta_{a,vad}$	Soil Air-filled Porosity in Vadose Zone (cm^3/cm^3)
K_d	Soil (sorbed) Water Partition Coefficient = K_{oc}* f_{oc} (cm^3/g)	$\theta_{w,vad}$	Soil Water-filled Porosity in Vadose Zone (cm^3/cm^3)

Figure 3 (cont'd)
RBRGs for Soil (Direct Contact via ingestion of soil and dermal contact. Indirect Contact via inhalation of vapors from surface soils to ambient air, inhalation of particulates and inhalation of vapors from subsurface soils to indoor air)

(see Figures 3a, 3b and 3c for calculation of VF_{ss}, VF_p and α)

Threshold compounds for children:

$$\text{Child } RBRG_{soil} = \frac{\frac{THQ \cdot BW_c \cdot AT_{ncc} \cdot CF_1}{EF \cdot ED_c}}{[Co + Cd + Css + Cp + Cia]} \qquad (2a)$$

where

$$Co = CF_2 \cdot \left(\frac{IR_{sc} \cdot RAF_o}{RfD_o} \right)$$ Soil Ingestion (2b)

$$Cd = CF_2 \cdot \left(\frac{SA_c \cdot M_c \, RAF_d}{RfD_o} \right)$$ Dermal Contact (2c)

$$Css = CF_3 \cdot \left(\frac{IR_{airc} \cdot VF_{ss}}{RfD_i} \right)$$ Inhalation of vapors from surface soil (2d)

$$Cp = CF_3 \cdot \left(\frac{IR_{airc} \cdot VF_p}{RfD_i} \right)$$ Inhalation of particulates (2e)

$$Cia = \frac{\alpha \cdot IR_{airc} \cdot H' \rho_b}{RfD_i \cdot CF_{IA1} \cdot CF_{IA2} \cdot CF_{IA3} \cdot (\theta_{w,vad} + K_d \rho_b + H' \theta_{a,vad})}$$ Inhalation of vapors from subsurface soils (2f)

adapted from ASTM,2000 and EPA,1989

Where:

AT_{ncc}	Defined Averaging Time for Noncarcinogens - Child (years)	K_{oc}	Soil Organic Carbon Partition Coefficient = K_d / f_{oc} (cm^3/g)
BW_c	Body Weight - Child (kg)	M_c	Soil to Skin Adherence Factor - Child (mg/cm^2-day)
CF_1	Conversion Factor (365 days/year)	RAF_d	Dermal Relative Absorption Factor
CF_2	Conversion Factor (10^{-6} kg/mg)	RAF_o	Oral Relative Absorption Factor
CF_3	Conversion Factor (10^3 cm^3kg/m^3g)	$RBRG_{soil}$	Risk-Based Remediation Goal for Soil (mg/kg)
CF_{IA1}	Conversion Factor ($10^{-6}m^3/cm^3$)	RfD_i	Chronic Inhalation Reference Dose (mg/kg-day)
CF_{IA2}	Conversion Factor (10^{-3} g/mg)	RfD_o	Chronic Oral Reference Dose (mg/kg-day)
CF_{IA3}	Conversion Factor (10^6 mg/kg)	SA_c	Seasonally-averaged Skin Surface Area - Child (cm^2)
ED_c	Exposure Duration - Child (years)	THQ	Target Hazard Quotient for Individual Chemicals
EF	Exposure Frequency (days/year)	VF_p	Total Respirable Particulate Concentration from Soil Source ($g\text{-soil}/cm^3\text{-air}$)
f_{oc}	Soil Organic Carbon Weight Fraction	VF_{ss}	Volatilization Factor, surficial soil to ambient air ($g\text{-soil}/cm^3\text{-air}$)
H'	Dimensionless Henry's Law Constant	α	Infinite Source Attenuation Coefficient (unitless)
IR_{airc}	Daily Inhalation Rate - Child (m^3/day)	ρ_b	Soil Dry Bulk Density (g/cm^3)
IR_{sc}	Daily Ingestion Rate – Child (mg/day)	$\theta_{a,vad}$	Soil Air-filled Porosity in Vadose Zone (cm^3/cm^3)
K_d	Soil (sorbed) Water Partition Coefficient = K_{oc}* f_{oc} (cm^3/g)	$\theta_{w,vad}$	Soil Water-filled Porosity in Vadose Zone (cm^3/cm^3)

Figure 3 (cont'd)
RBRGs for Soil (Direct Contact via ingestion of soil and dermal contact. Indirect Contact via inhalation of vapors from surface soils to ambient air, inhalation of particulates and inhalation of vapors from subsurface soils to indoor air)

(see Figures 3a, 3b and 3c for calculation of VF_{ss}, VF_p and α)

Non threshold compounds :

$$\text{Integrated Adult and Child } RBRG_{soil} = \frac{\frac{Risk \cdot AT_c \cdot CF_1}{EF}}{[NTo + NTd + NTss + NTp + NTia]} \qquad (3a)$$

where

$$NTo = CF_2 \cdot \left[\left(\frac{ED_c \cdot IR_{sc}}{BW_c} + \frac{(ED - ED_c) \cdot IR_s}{BW}\right) \cdot SF_o \cdot RAF_o\right]$$ Soil Ingestion (3b)

$$NTd = CF_2 \cdot \left[\left(\frac{ED_c \cdot SA_c \cdot M_c}{BW_c} + \frac{(ED - ED_c) \cdot SA \cdot M}{BW}\right) \cdot SF_o \cdot RAF_d\right]$$ Dermal Contact (3c)

$$NTss = CF_3 \cdot \left[\left(\frac{ED_c \cdot IR_{airc}}{BW_c} + \frac{(ED - ED_c) \cdot IR_{air}}{BW}\right) \cdot VF_{ss} \cdot SF_i\right]$$ Inhalation of vapors from surface soil (3d)

$$NTp = CF_3 \cdot \left[\left(\frac{ED_c \cdot IR_{airc}}{BW_c} + \frac{(ED - ED_c) \cdot IR_{air}}{BW}\right) \cdot VF_p \cdot SF_i\right]$$ Inhalation of particulates (3e)

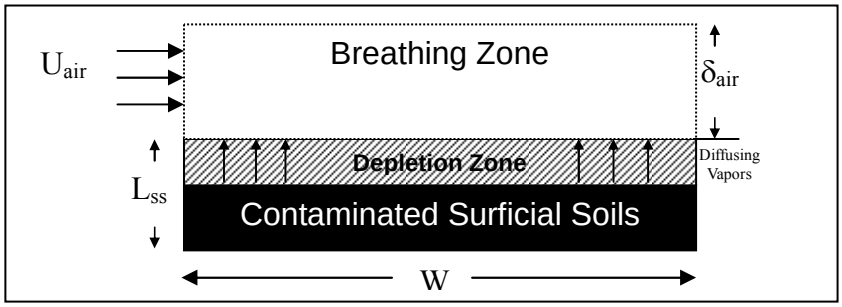
$$NTia = \frac{\left(\frac{ED_c \cdot IR_{airc}}{BW_c} + \frac{(ED - ED_c) \cdot IR_{air}}{BW}\right) \cdot \alpha \cdot SF_i \cdot H' \rho_b}{CF_{IA1} \cdot CF_{IA2} \cdot CF_{IA3} \cdot (\theta_{w,vad} + K_d \rho_b + H' \theta_{a,vad})}$$ Inhalation of vapors from subsurface soils (3f)

adapted from ASTM,2000 and EPA,1989

where:

AT_c	Defined Averaging Time for Carcinogens (years)	K_d	Soil (sorbed) Water Partition Coefficient = K_{oc}* f_{oc} (cm^3/g)
BW	Body Weight - Adult (kg)	K_{oc}	Soil Organic Carbon Partition Coefficient = K_d / f_{oc} (cm^3/g)
BW_c	Body Weight - Child (kg)	M	Soil to Skin Adherence Factor - Adult (mg/cm^2-day)
CF_1	Conversion Factor (365 days/year)	M_c	Soil to Skin Adherence Factor - Child (mg/cm^2-day)
CF_2	Conversion Factor (10^{-6} kg/mg)	RAF_d	Dermal Relative Absorption Factor
CF_3	Conversion Factor (10^3 cm^3kg/m^3g)	RAF_o	Oral Relative Absorption Factor
CF_{IA1}	Conversion Factor ($10^{-6}m^3/cm^3$)	$RBRG_{soil}$	Risk-Based Remediation Goal for Soil (mg/kg)
CF_{IA2}	Conversion Factor (10^{-3} g/mg)	Risk	Target Excess Individual Lifetime Cancer Risk
CF_{IA3}	Conversion Factor (10^6 mg/kg)	SA	Seasonally-averaged Skin Surface Area - Adult (cm^2)
ED	Exposure Duration - Adult (years)	SA_c	Seasonally-averaged Skin Surface Area - Child (cm^2)
ED_c	Exposure Duration - Child (years)	SF_i	Slope Factor – inhalation $(mg/kg\text{-}day)^{-1}$
EF	Exposure Frequency (days/year)	SF_o	Slope Factor – oral $(mg/kg\text{-}day)^{-1}$
f_{oc}	Soil Organic Carbon Weight Fraction	VF_p	Total Respirable Particulate Concentration from Soil Source ($g\text{-}soil/cm^3\text{-}air$)
H'	Dimensionless Henry's Law Constant	VF_{ss}	Volatilization Factor, surficial soil to ambient air ($g\text{-}soil/cm^3\text{-}air$)
IR_{air}	Daily Inhalation Rate - Adult (m^3/day)	α	Infinite Source Attenuation Coefficient (unitless)
IR_{airc}	Daily Inhalation Rate - Child (m^3/day)	ρ_b	Soil Dry Bulk Density (g/cm^3)
IR_s	Soil Ingestion Rate - Adult (mg/day)	$\theta_{a,vad}$	Soil Air-filled Porosity in Vadose Zone (cm^3/cm^3)
IR_{sc}	Soil Ingestion Rate - Child (mg/day)	$\theta_{w,vad}$	Soil Water-filled Porosity in Vadose Zone (cm^3/cm^3)

Figure 3a
Volatilization Factor – Surficial Soil to Ambient Air



$$VFss = \frac{\rho_b}{DF_{amb}} \sqrt{\frac{4 \cdot D_{eff,\,vad}}{\pi \cdot \tau \cdot 31536000_{sec/year}} \cdot \frac{H'}{Ksw \cdot \rho_b}} \quad (4a)$$

or

$$VF_{ss} = \frac{L_{ss} \cdot \rho_b}{DF_{amb} \cdot \tau \cdot 31536000_{sec/year}} \quad (4b)$$

(choose whichever is lower)

$$DF_{amb} = \frac{U_{air} \cdot W \cdot \delta_{air}}{A} \quad (4c)$$

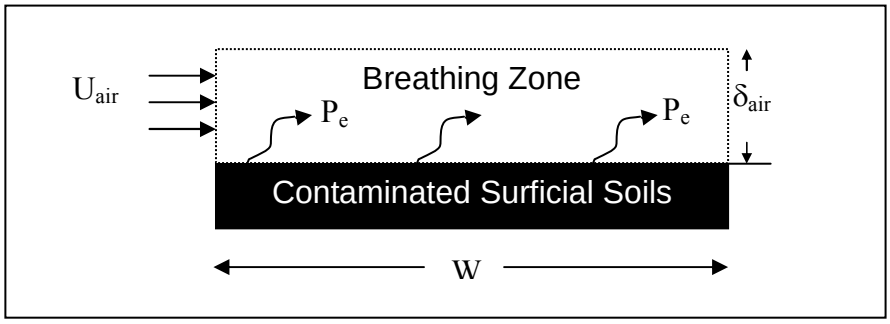
$$D_{eff,\,vad} = D_a \cdot \left(\frac{\theta_a^{3.33}}{\theta_\tau^2} \right) + D_w \cdot \left(\frac{\theta_w^{3.33}}{H' \cdot \theta_\tau^2} \right) \quad (4d)$$

adapted from ASTM,2000

Where:

VF_{ss}	Volatilization Factor – Surficial Soil to Ambient Air (g-soil/cm^3-air)
$D_{eff,vad}$	Effective Diffusion Coefficient for Vadose Zone Soils (cm^2/sec)
DF_{amb}	Dispersion Factor for Ambient Air (cm/sec)
H'	Dimensionless Henry's Law Constant
K_{sw}	Soil to Water Partition Coefficient – Vadose zone (cm^3-water/g-soil)
L_{ss}	Thickness of Surficial Soils (cm)
ρ_b	Dry Soil Bulk Density (g/cm^3)
τ	Averaging Time for Surface Emission Vapor Flux (years)
A	Source-Zone Area (cm^2)
U_{air}	Ambient Air Velocity in Mixing Zone (cm/sec)
δ_{air}	Mixing Zone Height (cm)
D_a	Diffusivity of a Chemical in Air (cm^2/sec)
D_w	Diffusivity of a Chemical in Water (cm^2/sec)
θ_a	Soil Air-filled Porosity (cm^3-air/cm^3-soil)
θ_w	Soil Water-filled Porosity (cm^3-water/cm^3-soil)
θ_τ	Soil Porosity (cm^3-air/cm^3-soil)
W	Width of Source-Zone Area (cm)
π	3.14159

Figure 3b
Particulate Concentration – Total Respirable Particulate Concentration from Surficial Soil



$$VF_p = \frac{P_e}{DF_{amb}} \qquad (5a)$$

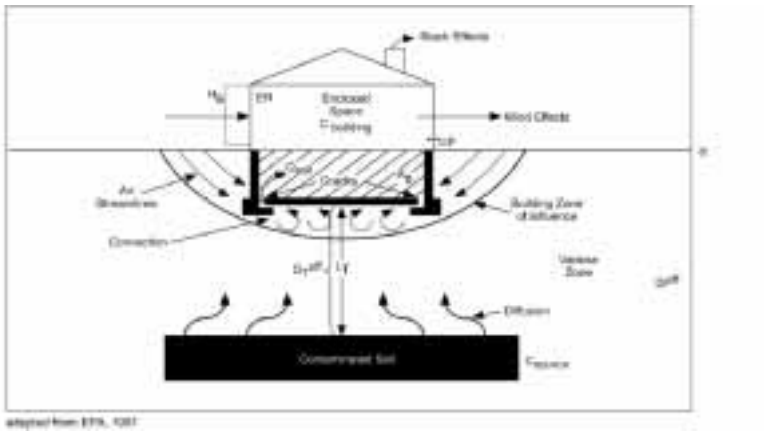
$$DF_{amb} = \frac{U_{air} \cdot W \cdot \delta_{air}}{A} \qquad (5b)$$

adapted from ASTM,2000

Where:

VF_p	Total Respirable Particulate Concentration from Soil Source (g-soil/cm^3-air)
DF_{amb}	Dispersion Factor for Ambient Air (cm/sec)
P_e	Area Total Respirable Particulate Emission Flux from Source (g/cm^2-sec)
A	Source-Zone Area (cm^2)
U_{air}	Ambient Air Velocity in Mixing Zone (cm/sec)
W	Width of Source-Zone Area (cm)
δ_{air}	Mixing Zone Height (cm)

Figure 3c
Infinite source attenuation co-efficient (α) – Sub-surface Soil to Indoor Air



$$\alpha = \frac{\left[\left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) x \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right]}{\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) + \left(\frac{D_T^{eff} A_B}{Q_{soil} L_T}\right)\left[\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) - 1\right]\right]} \quad (6a)$$

$$D_{vad}^{eff} = D_a\left(\frac{\theta_{a,vad}^{3.33}}{\theta_t^2}\right) + \left(\frac{D_w}{H'}\right)\left(\frac{\theta_{w,vad}^{3.33}}{\theta_t^2}\right) \quad (6b)$$

$$D_T^{eff} = \frac{L_T}{\left(L_{vad} / D_{vad}^{eff}\right)} \quad (6c)$$

$$Q_{soil} = \frac{2\pi \Delta P k_v X_{crack}}{\mu \ln\left[\frac{2 Z_{crack}}{r_{crack}}\right]} \quad (6d)$$

$$A_{crack} = \eta \cdot A_B \quad (6e)$$

$$\eta = \frac{r_{crack}}{\left(A_B / X_{crack}\right)} \quad (6f)$$

adapted from EPA,1997

Where:

A_B	Area of the Enclosed Space Below Grade (cm^2)	ΔP	Pressure Differential between Soil Surface and the Enclosed Space ($g/cm\text{-}sec^2$)
A_{crack}	Area of Crack (cm^2)	$Q_{building}$	Building Ventilation Rate (cm^3/sec)
D_a	Diffusivity in Air (cm^2/sec)	Q_{soil}	Volumetric Flow Rate of Soil Gas entering the Enclosed Space (cm^3/sec)
D_{crack}	D_{vad}^{eff} of Soil Zone (Vadose Layer) Near Building (cm^2/sec)	r_{crack}	Equivalent Crack Radius (cm)
D_{vad}^{eff}	Diffusivity Across Vadose Soil Layer (cm^2/sec)	X_{crack}	Floor-wall Seam Perimeter (cm)
D_w	Diffusivity in Water (cm^2/sec)	Z_{crack}	Crack Depth Below Grade (cm)
D_T^{eff}	Total Overall Effective Diffusion Coefficient (cm^2/sec)	α	Infinite Source Attenuation Coefficient (unitless)
H'	Dimensionless Henry's Law Constant	η	Crack-to-Total Area Ratio (unitless)
k_v	Soil Vapor Permeability (cm^2)	μ	Viscosity of Air = 0.183 g/cm-sec
L_{crack}	Enclosed Space Foundation or Slab Thickness (cm)	π	3.14159
L_T	Source-building Separation (cm)	$\theta_{a,vad}$	Soil Air-filled Porosity in the Vadose Zone (cm^3/cm^3)
L_{vad}	Thickness of Soil Vadose Layer (cm)	θ_t	Soil Porosity (cm^3/cm^3)
		$\theta_{w,vad}$	Soil Water-filled Porosity in the Vadose Zone (cm^3/cm^3)

Figure 4
RBRG for Groundwater (Inhalation of vapors from groundwater to indoor air)

(see Figure 4a for calculation of α)

Threshold compounds:

$$\text{Adult } RBRG_{gw} = \frac{\frac{THQ \cdot BW \cdot AT_{nc} \cdot CF_1}{EF \cdot ED}}{[Ag]} \quad (7a)$$

$$\text{Child } RBRG_{gw} = \frac{\frac{THQ \cdot BW_c \cdot AT_{ncc} \cdot CF_1}{EF \cdot ED_c}}{[Cg]} \quad (7b)$$

where

$$Ag = \frac{\alpha \cdot IR_{air} \cdot H'}{RfD_i \cdot CF_{IA1} \cdot CF_{IA2} \cdot CF_{IA4} \cdot CF_{IA5}} \quad (7c)$$

$$Cg = \frac{\alpha \cdot IR_{airc} \cdot H'}{RfD_i \cdot CF_{IA1} \cdot CF_{IA2} \cdot CF_{IA4} \cdot CF_{IA5}} \quad (7d)$$

Non-threshold compounds:

$$\text{Integrated Adult and Child } RBRG_{gw} = \frac{\frac{Risk \cdot AT_c \cdot CF_1}{EF}}{[NTg]} \quad (7e)$$

where

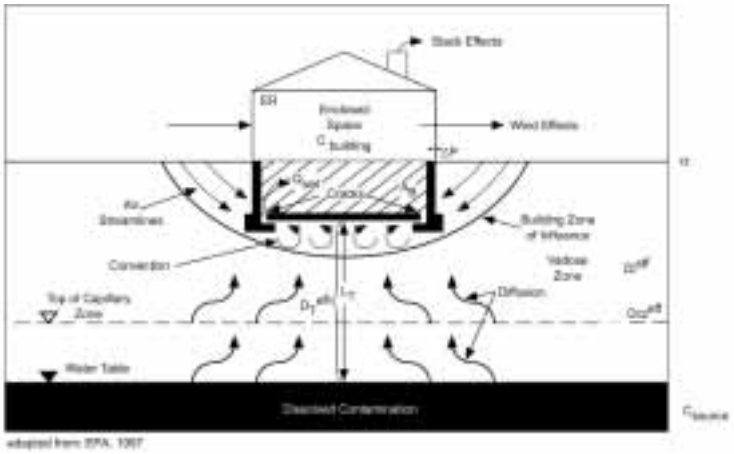
$$NTg = \frac{\left(\frac{ED_c \cdot IR_{airc}}{BW_c} + \frac{(ED - ED_c) \cdot IR_{air}}{BW}\right) \cdot \alpha \cdot SF_i \cdot H'}{CF_{IA1} \cdot CF_{IA2} \cdot CF_{IA4} \cdot CF_{IA5}} \quad (7f)$$

adapted from ASTM, 2000 and EPA,1989

Where:

AT_c	Defined Averaging Time for Carcinogens (years)	ED_c	Exposure Duration - Child (years)
AT_{nc}	Defined Averaging Time for Noncarcinogens – Adult (years)	EF	Exposure Frequency (days/year)
AT_{ncc}	Defined Averaging Time for Noncarcinogens - Child (years)	H'	Dimensionless Henry's Law Constant
BW	Body Weight – Adult (kg)	IR_{airc}	Daily Inhalation Rate - Child (m^3/day)
BW_c	Body Weight - Child (kg)	IR_{air}	Daily Inhalation Rate - Adult (m^3/day)
CF_1	Conversion Factor (365 days/year)	$RBRG_{gw}$	Risk-Based Remediation Goal for Groundwater (mg/L)
CF_{IA1}	Conversion Factor ($10^{-6} m^3/cm^3$)	RfD_i	Chronic Inhalation Reference Dose (mg/kg-day)
CF_{IA2}	Conversion Factor (10^{-3} g/mg)	Risk	Target Excess Individual Lifetime Cancer Risk
CF_{IA4}	Conversion Factor (10^3 mg/g)	SF_i	Slope Factor – Inhalational $(mg/kg\text{-}day)^{-1}$
CF_{IA5}	Conversion Factor (10^3 cm^3/L)	THQ	Target Hazard Quotient for Individual Chemicals
ED	Exposure Duration – Adult (years)	α	Infinite Source Attenuation Coefficient (unitless)

Figure 4a
RBRG for Groundwater
(Volatilization from Groundwater to Indoor Air)



adapted from: EPA, 1997

$$\alpha = \frac{\left[\left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) x \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right]}{\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) + \left(\frac{D_T^{eff} A_B}{Q_{soil} L_T}\right)\left[\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) - 1\right]\right]} \quad (8a)$$

$$D_{vad}^{eff} = D_a\left(\frac{\theta_{a,vad}^{3.33}}{\theta_t^2}\right) + \left(\frac{D_w}{H'}\right)\left(\frac{\theta_{w,vad}^{3.33}}{\theta_t^2}\right) \quad (8b)$$

$$D_{cap}^{eff} = D_a\left(\frac{\theta_{a,cap}^{3.33}}{\theta_t^2}\right) + \left(\frac{D_w}{H'}\right)\left(\frac{\theta_{w,cap}^{3.33}}{\theta_t^2}\right) \quad (8c)$$

$$D_T^{eff} = \frac{L_T}{\left(L_{vad}/D_{vad}^{eff} + L_{cap}/D_{cap}^{eff}\right)} \quad (8d)$$

$$A_{crack} = \eta \cdot A_B \quad (8e)$$

$$\eta = \frac{r_{crack}}{\left(A_B / X_{crack}\right)} \quad (8f)$$

$$Q_{soil} = \frac{2\pi \Delta P k_v X_{crack}}{\mu \ln\left[\frac{2 Z_{crack}}{r_{crack}}\right]} \quad (8g)$$

adapted from EPA,1997

Where:

A_B	Area of the Enclosed Space Below Grade (cm^2)	ΔP	Pressure Differential between Soil Surface and the Enclosed Space ($g/cm\text{-}sec^2$)
A_{crack}	Area of Crack (cm^2)	$Q_{building}$	Building Ventilation Rate (cm^3/sec)
D_a	Diffusivity in Air (cm^2/sec)	Q_{soil}	Volumetric Flow Rate of Soil Gas entering the Enclosed Space (cm^3/sec)
D_{crack}	D_{vad}^{eff} of Soil Zone (Vadose Layer) Near Building (cm^2/sec)	r_{crack}	Equivalent Crack Radius (cm)
D_{cap}^{eff}	Diffusivity Across Capillary Soil Layer (cm^2/sec)	X_{crack}	Floor-wall Seam Perimeter (cm)
D_{vad}^{eff}	Diffusivity Across Vadose Soil Layer (cm^2/sec)	Z_{crack}	Crack Depth Below Grade (cm)
D_w	Diffusivity in Water (cm^2/sec)	α	Infinite Source Attenuation Coefficient (unitless)
D_T^{eff}	Total Overall Effective Diffusion Coefficient (cm^2/sec)	η	Crack-to-Total Area Ratio (unitless)
H'	Dimensionless Henry's Law Constant	μ	Viscosity of Air = 0.183 g/cm-sec
k_v	Soil Vapor Permeability (cm^2)	π	3.14159
L_{cap}	Thickness of Soil Capillary Layer (cm)	$\theta_{a,cap}$	Soil Air-filled Porosity in Capillary Zone (cm^3/cm^3)
		$\theta_{a,vad}$	Soil Air-filled Porosity in Vadose Zone (cm^3/cm^3)
L_{crack}	Enclosed Space Foundation or Slab Thickness (cm)	θ_t	Soil Porosity (cm^3/cm^3)
L_T	Source-building Separation (cm)	$\theta_{w,cap}$	Soil Water-filled Porosity in Capillary Zone (cm^3/cm^3)
L_{vad}	Thickness of Soil Vadose Layer (cm)	$\theta_{w,vad}$	Soil Water-filled Porosity in Vadose Zone (cm^3/cm^3)

Figure 5
Soil Saturation Limit

Soil Saturation Limit for Unsaturated Soil

$$C_{sat} = \left(\frac{S}{\rho_b}\right)\left(K_d \rho_b + \theta_{w,vad} + H' \theta_{a,vad}\right) \qquad (9a)$$

adapted from EPA, 1996 and ASTM, 2000

Where:

C_{sat}	Soil Saturation Limit (mg/kg)
S	Solubility in Water (mg/L-water)
ρ_b	Dry Soil Bulk Density
K_d	Soil (sorbed) Water Partition Coefficient $= K_{oc} f_{oc}$ (L/kg)
$\theta_{w, vad}$	Water-filled Soil Porosity in Vadose Zone (cm^2/cm^2)
H'	Dimensionless Henry's Law Constant
$\theta_{a, vad}$	Air-filled Soil Porosity in Vadose Zone (cm^2/cm^2)

Figure 6
Miscellaneous Equations

Soil (sorbed) to Water Partition Coefficient

$$K_d = K_{oc}\, f_{oc} \qquad (10a)$$

Where:
K_d = Soil (sorbed) Water Partition Coefficient (cm^3/g)
K_{oc} = Soil Organic Carbon/Water Partition Coefficient (cm^3/g)
f_{oc} = Fraction Organic Carbon in Soil (g/g)

Soil to Water Partition Coefficient – Vadose Zone

$$K_{sw} = \left(\frac{\theta_{w,vad} + (K_d\, \rho_b) + (H'\, \theta_{a,vad})}{\rho_b} \right) \qquad (10b)$$

Where:

K_{sw}	=	Soil to Water Partition Coefficient – Vadose zone (cm^3/g)
H'	=	Dimensionless Henry's Law Coefficient
K_d	=	Soil (sorbed) Water Partition Coefficient (cm^3/g)
ρ_b	=	Dry Soil Bulk Density (g/cm^3)
$\theta_{a,\,vad}$	=	Soil Air Content in Vadose Zone (cm^3-air/cm^3-soil)
$\theta_{w,\,vad}$	=	Soil Water Content in Vadose Zone (cm^3-water/cm^3-soil)

Soil Air-filled Porosity

$$\theta_a = \theta_T - \theta_w \qquad (10c)$$

Where:
θ_a = Soil Air-filled Porosity (cm^3-air/cm^3-soil)
θ_T = Soil Porosity (cm^3-air/cm^3-soil)
θ_w = Soil Water-filled Porosity (cm^3-water/cm^3-soil)

Conversion from Henry's Law to Dimensionless Henry's Law

$$H' = \frac{H}{RT} \qquad (10d)$$

Where:
H' = Dimensionless Henry's Law Constant
H = Henry's Law Constant (atm-m3/mol)
R = Universal Gas Constant (atm-m3/mol-K)
T = Ambient Temperature (K)