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Background Document on Development of Risk-Based Remediation Goals for Contaminated Land Management
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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 $(mg/kg\text{-}day)^{-1}$.

Detection Limit (DL) — The lowest amount that can be distinguished from the normal "noise" of an analytical instrument or method.

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

ASTDR	Agency for Toxic Substances and Disease Registry
ASTM	American Society for Testing and Materials
COC	Chemical of Concern
CSF	Cancer Slope Factor
DL	Detection Limit
HEAST	Health Effects Assessment Summary Tables
IRIS	Integrated Risk Information System
NAPL	Non-aqueous Phase Liquid
RBRG $_{soil\text{-}dc}$	Risk-Based Remediation Goal for direct contact with soil
RBRG $_{soil\text{-}in}$	Risk-Based Remediation Goal for a chemical in soil volatilizing into indoor air
RBRG $_{gw\text{-}in}$	Risk-Based Remediation Goal for a chemical in groundwater volatilizing into indoor air
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 these RBRGs.

The following three different types of RBRGs have been developed:

1. $RBRG_{soil\text{-}dc}$ - Soil RBRGs protective of direct contact with soil (including inhalation of vapors, inhalation of dusts, dermal contact, and incidental ingestion).
2. $RBRG_{soil\text{-}in}$ - Soil RBRGs protective of volatilization from soil into indoor air.
3. $RBRG_{gw\text{-}in}$ - 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 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.

Figures 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 $RBRG_{soil\text{-}in}$, 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-m3/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 $RBRG_{soil\text{-}in}$ addresses only one route of exposure, the $RBRG_{soil\text{-}dc}$ addresses four routes of exposure: ingestion, dermal, inhalation of volatiles, and inhalation of particulates. Each of the four 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. Because soil RBRGs were developed for two pathways, the lower of the RBRGs calculated for direct contact with soil and volatilization from soil to indoor air was selected as the final soil RBRG.

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.

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 each of the three 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 direct contact with soil exposure pathway, conceptual models illustrate the migration of diffusing vapors from surface soil to ambient air (Figure 3a) and the migration of particulates from surface soil to ambient air (Figure 3b). 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 4). Key parameters that influence inter-media migration, as depicted in Figure 4 – Volatilization from Soil to Indoor Air, include the source-building separation (L_T), the thickness of the contaminated soil layer (L_i), 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 air exchange rate (ER). 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 5). Key parameters that influence inter-media migration, as depicted in Figure 5 – 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 air exchange rate (ER). This model is essentially the same as the model used for the volatilization from soil to indoor air pathway in that both models 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 User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings (USEPA, 1997a).

Section 4
EQUATIONS FOR CALCULATING RISK-BASED REMEDIATION GOALS

Three sets of risk-based Remediation Goals (RBRGs) were developed:

- $RBRG_{soil\text{-}dc}$ - Soil RBRGs protective of direct contact with soil (including inhalation of vapors, inhalation of dusts, dermal contact, and incidental ingestion).
- $RBRG_{soil\text{-}in}$ - Soil RBRGs protective of volatilization from soil into indoor air;
- $RBRG_{gw\text{-}in}$ - 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 protective of direct contact ($RBRG_{soil\text{-}dc}$). 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 soil to ambient air and particulate entrainment from soil to ambient air. These equations were also derived from ASTM (ASTM, 2000).

Figures 4 and 5 present the equations used to calculate the RBRGs for soil protective of inhalation of indoor air ($RBRG_{soil\text{-}in}$) and groundwater protective of inhalation of indoor air ($RBRG_{gw\text{-}in}$), respectively. 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 4a presents the equation for calculating the risk-based concentration for indoor air, which is also the allowable concentration inside an urban residential block, a rural residence or an industrial building ($C_{building}$).

Figure 6 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 6 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 7 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) surface conditions; and, in some cases, (4) building conditions. Tables 1a, 1b, 3, 5, and 7 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, and the appropriate units. A separate table has been prepared for each type of parameter (Tables 2, 4, 6, and 8) that provides 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 presented in Tables 1a and 1b were specific for Hong Kong, or default values derived from the USEPA references [e.g. Exposure Factors Handbook (USEPA, 1997b)], or interim values. Table 1a presents the exposure values relevant to the adult receptor while Table 1b shows the values applicable to the child receptor. 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 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 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 2.

Soil parameter values are used to calculate RBRGs protective of direct contact with soil and volatilization from soil to indoor air. The sources of soil parameter values presented in Table 3 include Government Departments and other references in Hong Kong. Default values were derived from either ASTM (ASTM, 2000) or USEPA (USEPA, 1997a), which were the sources of the two equations and models for these pathways. Definitions and details of these values are presented in Table 4.

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 5 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 6.

Surface parameters are used to calculate RBRGs for direct contact with soil. The sources of surface parameter values presented in Table 7 include local Hong Kong references, ASTM and US EPA. Definitions and details of these values are presented in Table 8.

Section 6
TOXICITY INDICES

6.1 Hierarchy of Sources

Available toxicity indices, including cancer slope factors (CSFs) and noncancer reference doses (RfDs), 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)
- 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.

Table 9 presents the Summary of Available Toxicity Information for Chemicals of Concern along with the source of the values. Most values were obtained from the stated references published in 1999-2002. Toxicity values may be reviewed, modified, or changed when additional scientific information becomes available.

6.2 Toxicity Indices

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 noncarcinogenic health effects of substances that are also carcinogens.

Cancer risk is measured as the cancer slope factor which is the result of application of a low-dose extrapolation procedure and is presented as the risk per (mg/kg)/day.

Chemicals are classified as to whether they exhibit cancer and noncancer 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 noncancer 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 noncancer toxicity index is necessary to develop an RBRGs. RBRGs protective of cancer health effects and noncancer health effects are calculated separately.

Some of the RBRGs are protective of more than one exposure route. The direct contact with soil exposure pathway incorporates ingestion, dermal, inhalation of volatiles and inhalation of particulates. In order to incorporate the ingestion and dermal routes of exposure into the calculation

of the $RBRG_{soil\text{-}dc}$, an oral CSF or RfD is required. In order to incorporate the inhalation exposure routes, an inhalation CSF or RfD is necessary. If toxicity values are available for only one exposure route, e.g., only oral values are available, the RBRG is based on the oral route only.

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.

6.3 Supplemental Toxicity Information

In addition to the toxicity indices, relative absorption factors (RAFs) are needed to calculate the RBRGs protective of 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, 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 10 presents a list of the physical/chemical properties used to develop RBRGs along with definitions and the units for these values.

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:

$H = K_{AW}$ 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' = Dimensionless Henry's Law Constant
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):

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

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):

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

Where:
mw = molecular weight of chemical

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

$Kd = K_{oc}$ 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 7 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: $\log_{10}$ Koc = 0.45EC + 0.43
For aromatics: $\log_{10}$ Koc = 0.10 EC + 2.3

Solubility (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 cm2/sec and that the diffusivity for water (D_w) be set at 0.00001 cm^2/sec (TPHCWG, 1996).

Section 8
GENERAL REFERENCE

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Table 1a
Exposure Parameter Values for Adult Scenario

Direct Contact - Soil			Parameter Value for Each Land Use / Receptor			
Symbol	Parameter	Units	Urban Residential	Rural Residential	Industrial	Public Parks
AT_{nc}	Averaging Time for non-carcinogens	years	30	30	25	30
AT_c	Averaging Time for carcinogens	years	70	70	70	70
BW	Body Weight	kg	50	50	60	50
ED	Exposure Duration	years	30	30	25	30
EF	Exposure Frequency	days/year	350	350	300	104
IR_s	Ingestion Rate-soil	mg/day	100	100	100	100
IR_{air}	Daily Inhalation Rate - outdoor	m^3/day	4.5	6	20	6
M	Soil to skin adherence factor	mg/cm^2-day	0.08	0.08	0.08	0.08
SA	Seasonally-averaged skin surface area	cm^2	2,300	2,950	2,950	2,950

Indoor Air - Soil and Groundwater					
Symbol	Parameter	Units	Urban Residential	Rural Residential	Industrial
AT_{nc}	Averaging Time for non-carcinogens	years	30	30	25
AT_c	Averaging Time for carcinogens	years	70	70	70
BW	Body Weight	kg	50	50	60
ED	Exposure Duration	years	30	30	25
EF	Exposure Frequency	days/year	350	350	300
IR_{air}	Daily Inhalation Rate - indoor	m^3/day	21	20	12.5

Table 1b
Exposure Parameter Values for Child Scenario

Direct Contact - Soil			Parameter Value for Each Land Use		
Symbol	**Parameter**	**Units**	**Urban Residential**	**Rural Residential**	**Public Parks**
AT_{ncc}	Averaging Time for non-carcinogens	years	6	6	6
BW_c	Body Weight	kg	15	15	15
ED_c	Exposure Duration	years	6	6	6
IR_{sc}	Ingestion Rate-soil	mg/day	200	200	200
IR_{airc}	Daily Inhalation Rate - outdoor	m^3/day	2.3	3	3
M_c	Soil to skin adherence factor	mg/cm^2-day	0.2	0.2	0.2
SA_c	Seasonally-averaged skin surface area	cm^2	1,200	1,500	1,500

Indoor Air - Soil and Groundwater				
Symbol	**Parameter**	**Units**	**Urban Residential**	**Rural Residential**
AT_{ncc}	Averaging Time for non-carcinogens	years	6	6
BW_c	Body Weight	kg	15	15
ED_c	Exposure Duration	years	6	6
IR_{airc}	Daily Inhalation Rate - indoor	m^3/day	10	10

Table 2
Details for Exposure Parameter Values

Symbol	Parameter	Units	Definition	Source	Details
AT_{nc}	Averaging Time for Adults	years	Length of time (in days, months or years) over which	Interim	Averaging time for noncarcinogens equals exposure duration for Adults and Children.
AT_{ncc}	Averaging Time for Children	years	exposure is ongoing.	Default (US EPA, 1997b)	
AT_c	Averaging Time	years	The time equals to a standard life expectancy.	Default (US EPA, 1997b)	Averaging time for carcinogens equals to lifetime of 70 years.
BW	Body Weight for Adults	kilograms	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).
BW_c	Body Weight for Children	kilograms	A weight that is representative of children.	Default (US EPA, 1997b)	Average of 15 kg for children from birth to 6 years.
ED	Exposure Duration for Adults	years	Length of time over which exposure is ongoing.	Interim	Conservative value for typical residence times and employment times based on professional judgement.
ED_c	Exposure Duration for Children	years		Default (US EPA, 1997b)	Based on EPA Exposure Factors Handbook (EPA,1997b).
EF	Exposure Frequency	days/year	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.
IR_s	Ingestion Rate- Soil for Adults	mg/day	The amount of soil consumed per day during	Default	Ingestion rate for residents and park visitors (200 mg/day for ages from
IR_{sc}	Ingestion Rate- Soil for Children	mg/day	mouthing of objects or unintentional hand-to-mouth activity.	(US EPA, 1997b)	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 for Adults	m^3/day	The amount of air breathed per day while engaged	Interim	Inhalation rates for urban residential based on moderate
IR_{airc}	Daily Inhalation Rate - outdoor for Children	m^3/day	in various outdoor work or leisure activities.		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 for Adults	mg/cm^2-day	The amount of soil that remains on a square	Default	Value for adult based on the value for an urban/suburban gardener.
M_c	Soil to skin adherence factor for Children	mg/cm^2-day	centimeter of skin following contact with soil during work or leisure activities.	(US EPA, 1998)	
SA	Skin surface area for Adults	cm^2	The area of skin, in square centimeters, that is	Interim	Values for urban residential sites
SA_c	Skin surface area for Children	cm^2	exposed to soil during various work or leisure activities, accounting for seasonal variation.		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 for Adults	m^3/day	The amount of air breathed per day while engaged	Interim	Inhalation rates for urban residential based on light activity
IR_{airc}	Daily Inhalation Rate - indoor for Children	m^3/day	in various indoor activities.		(1.0 m3/hr) for 21 hours per day; rural residential based on light activity (1.0 m3/hr) for 20 hours per day; industrial based on light activity (1.0 m3/hr) for 5 hours per day and moderate activity (1.5 m3/hr) for 5 hours per day. Inhalation factors based on EPA Exposure Factors Handbook (EPA,1997b).

Table 3
Soil Parameter Values

Symbol	Parameter	Units	Value
L_{ss}	Thickness of Surficial Soils	cm	100
ρ_b	Dry Soil Bulk Density	g/cm^3	2.0
ρ_s	Soil Particle Density	g/cm^3	2.65
w	Soil Moisture Content	%	10
θ_{air}	Soil Air-filled Porosity	cm^3-air/cm^3-soil	0.05
θ_{water}	Soil Water-filled Porosity	cm^3-water/cm^3-soil	0.20
θ_T	Soil Porosity	cm^3-air/cm^3-soil	0.25
k_v	Soil Vapor Permeability	cm^2	1.00E-08
L_i	Thickness of Soil Layer i	cm	1
L_T	Source-Building Separation	cm	1
f_{oc}	Soil Organic Carbon Weight Fraction	dimensionless	0.002

Table 4
Details for Soil Parameter Values

Symbol	Parameter	Units	Definition	Source	Details
L_{ss}	Thickness of Contaminated Surficial Soils	cm	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	The mass of a unit volume of soil.	HK	Geo Guide 1 - Geotechnical Engineering Office Civil Engineering Department, HKSAR.
ρ_s	Soil Particle Density	g/cm^3	The mass of dry soil sample divided by the volume of the mineral matter in the sample.	Default (Fetter, 1994)	For most rock and soil, the particle density is 2.65 g/cm^3.
w	Soil Moisture Content	%	The mass of the water contained in soil divided by the dry mass of soil.	Default (USEPA 1996b)	Conservative value of the soil moisture content in loam soil type.
θ_{air}	Soil Air-filled Porosity	cm^3-air/cm^3-soil	The fraction of total soil porosity that is filled with air.	HK	Calculated using equations in Figure 7.
θ_{water}	Soil Water-filled Porosity	cm^3-water/cm^3-soil	The fraction of total soil porosity that is filled with water.	HK	ditto
θ_τ	Soil Porosity	cm^3-air/cm^3-soil	The ratio of the void spaces in soil to the partial volume of the soil.	HK	ditto
k_v	Soil Vapor Permeability	cm^2	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.	HK	Calculated for sandy silt typical of fill material in Hong Kong based on equations presented in US EPA, 1997a.
L_i	Thickness of Soil Layer i	cm	The thickness of each discrete soil layer between the source of contamination.	HK	Assume there is only one type of soil layer between bottom of enclosed space floor and source of contamination. Therefore L_i is typically the same as L_T.
L_T	Source-Building Separation	cm	Distance between the source of the contamination and the bottom of the enclosed space floor.	HK	Value of 1 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.
f_{oc}	Soil Organic Carbon Weight Fraction	dimensionless	The amount of solid phase organic carbon in natural organic matter which can bind chemicals in soil.	HK	Value for general fill in Hong Kong. Value also consistent with USEPA default.

Table 5
Building Parameter Values for Volatilization from Soil and Groundwater to Indoor Air

Symbol	Parameter	Units	Urban Residential	Rural Residential	Industrial
A_B	Area of the Enclosed Space Below Grade	cm^2	21,730,000	1,300,000	33,280,000
$Q_{building}$	Building Ventilation Rate	cm^3/sec	320,000	32500	1,500,000
L_{crack}	Enclosed Space Foundation or Slab Thickness	cm	25	25	25
L_B	Length of Building	cm	4100	1140	5200
W_B	Width of Building	cm	4100	1140	5200
H_B	Height of One Floor Grade	cm	300	300	300
X_{crack}	Floor-wall Seam Perimeter	cm	16400	4560	20800
Z_{crack}	Crack Depth Below Grade	cm	300	25	300
r_{crack}	Equivalent Crack Radius	cm	0.05	0.05	0.05
ΔP	Pressure Differential between Soil Surface and Enclosed Space	$g/cm\text{-}sec^2$	40	40	40
A_{crack}	Area of Crack	cm^2	820	220	1040
n	Crack-to-total-area ratio	unitless	3.8E-05	1.7E-04	3.1E-05

Table 6
Details for Building Parameter Values for Volatilization from Soil and Groundwater to Indoor Air

Symbol	Parameter	Units	Definition	Source	Details
A_B	Area of the Enclosed Space Below Grade	cm^2	The area of the floor in contact with the underlying soil and the total wall area below grade.	HK	Assume one floor grade (300 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. Typical building volumes and dimensions derived from Hong Kong Planning Standards and Guidelines (Planning Department, 1996) and the Buildings Ordinance.
$Q_{building}$	Building Ventilation Rate	cm^3/sec	The amount of air that passes through the volume of a building over a particular period of time.	HK	Based on 9 m^2 area required per person for industrial; Based on 20 m^2 per person for rural residential. 16 flats or 64 persons/floor for urban residential 5 litres/sec of air exchange per person 130 m^2/20 m^2 person = 6.5 persons/floor for rural residential 2700 m^2/9 m^2 per person = 300 persons/floor for industrial Urban residential: 64 persons/floor * 5 liters/sec/person * 1000 cm^3/liter = 320,000 cm^3/sec. Rural residential: 6.5 persons/floor * 5 liters /sec/person *1000 cm^3/liter = 32,491 cm^3/sec. Industrial: 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	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	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	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	An estimated value for a typical building.	HK	Hong Kong Planning Standards and Guidelines (Planning Department, 1996) and the Buildings Ordinance. Based on height of one floor grade.
X_{crack}	Floor-wall Seam Perimeter	cm	The total lengths of the four sides of the building (L_B x 2 + W_B x 2).	HK	Calculated based on lengths and widths of buildings.
Z_{crack}	Crack Depth Below Grade	cm	Length of crack below soil surface.	HK	Assumes crack runs along entire length of wall below grade. One floor (300 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	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	$g/cm\text{-}sec^2$	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	The total area of the cracks below the soil surface.	HK/Default (US EPA, 1997a)	Equal to AB * 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	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 7
Surface Parameter Values for Direct Contact with Soil

Symbol	Parameter	Units	Urban Residential	Rural Residential	Industrial	Public Parks
τ	Averaging Time for Surface Emission Vapor Flux	years	30	30	25	30
A	Source-Zone Area	cm^2	1680000	260000	2700000	18800000
U_{air}	Ambient Air Velocity in Mixing Zone	cm/sec	306	306	306	306
δ_{air}	Mixing Zone Height	cm	200	200	200	200
W	Width of Source-Zone Area	cm	1300	510	1640	4300
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

Table 8
Details for Surface Parameter Values for Direct Contact with Soil

Symbol	Parameter	Units	Definition	Source	Details
τ	Averaging Time for Surface Emission Vapor Flux	years	Length of time over which exposure to soil is on-going.	Default (US EPA, 1997b)	Emissions may be depleted over shorter period of time but are averaged over exposure period.
A	Source-Zone Area	cm^2	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	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 used to calculate various wind speed dependent parameters.
δ_{air}	Mixing Zone Height	cm	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	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	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 9
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			2.86E-01	IRIS		
Acetone	1.00E-01	IRIS						
Benzene	3.00E-03	STSC	1.50E-02	IRIS	1.71E-03	STSC	7.70E-03	IRIS
Bromodichloromethane	2.00E-02	IRIS	6.20E-02	IRIS				
Chloroform	1.00E-02	IRIS	6.10E-03	IRIS	8.60E-05	STSC	8.05E-02	IRIS
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			1.80E-03	STSC	8.57E-01	IRIS	1.80E-03	STSC
Styrene	2.00E-01	IRIS			2.86E-01	IRIS		
Tetrachloroethene	1.00E-02	IRIS	5.20E-02	STSC	1.14E-01	STSC	2.00E-03	STSC
Toluene	2.00E-01	IRIS			1.14E-01	IRIS		
Trichloroethene	6.00E-03	STSC	1.10E-02	STSC			6.00E-03	STSC
Xylenes (Total)	2.00E+00	IRIS						
SVOCs								
Acenaphthene	6.00E-02	IRIS						
Acenaphthylene	6.00E-02							
Anthracene	3.00E-01	IRIS						
Benzo(a)anthracene			7.30E-01	ECAO				
Benzo(a)pyrene			7.30E+00	IRIS				
Benzo(b)fluoranthene			7.30E-01	ECAO				
Benzo(g,h,i)perylene	3.00E-02							
Benzo(k)fluoranthene			7.30E-02	ECAO				
bis-(2-Ethylhexyl)phthalate	2.00E-02	IRIS	1.40E-02	IRIS			1.40E-02	STSC
Chrysene			7.30E-03	ECAO				
Dibenz(a,h)anthracene			7.30E+00	ECAO				
Fluoranthene	4.00E-02	IRIS						
Fluorene	4.00E-02	IRIS						
Hexachlorobenzene	8.00E-04	IRIS	1.60E+00	IRIS			1.61E+00	IRIS
Indeno(1,2,3-cd)pyrene			7.30E-01	ECAO				
Naphthalene	2.00E-02	IRIS			8.57E-04	IRIS		
Phenanthrene	3.00E-01							
Phenol	6.00E-01	IRIS						
Pyrene	3.00E-02	IRIS						
Dioxins/PCBs								
Dioxins (I-TEQ)			1.50E+05	HEAST			1.50E+05	HEAST
PCBs	2.00E-05	IRIS	2.00E+00	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						
Arsenic	3.00E-04	IRIS	1.50E+00	IRIS			1.51E+01	IRIS
Barium	7.00E-02	IRIS			1.43E-04	HEAST		
Cadmium (food)	1.00E-03							
Chromium III	1.50E+00	IRIS						
Chromium VI	3.00E-03	IRIS			2.86E-05	IRIS	4.20E+01	IRIS
Cobalt	6.00E-02	STSC			5.00E-06	STSC		
Copper	3.71E-02	HEAST						
Lead	3.60E-03	WHO						
Manganese	1.40E-01	IRIS			1.43E-05	IRIS		
Mercury	3.00E-04	IRIS						
Molybdenum	5.00E-03	IRIS						
Nickel	2.00E-02	IRIS						
Tin	6.00E-01	HEAST						
Zinc	3.00E-01	IRIS						
Petroleum Carbon Ranges								
C6 - C8 Aliphatics	5.00E+00	TPH			5.26E+00	TPH		
C9 - C16 Aliphatics	1.00E-01	TPH			2.86E-01	TPH		
C9 - C16 Aromatics	4.00E-02	TPH			5.71E-02	TPH		
C17 - C35 Aliphatics	2.00E+00	TPH						
C17 - C35 Aromatics	3.00E-02	TPH						
Inorganic Compounds								
Cyanide, free	2.00E-02	IRIS						
Organometallics								
Tributyltin Oxide	3.00E-04	IRIS						

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Definitions:

RfD = a reference dose (RfD) is the daily dose of a chemical which would not be expected to result in any adverse non-cancer health effects during a lifetime.

CSF = a cancer slope factor is an upper bound lifetime probability of an individual developing cancer as a result of an exposure to a particular level of a potential carcinogen.

Table 10
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 11
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 (cm2/sec)	Ref.	Dw Diffusivity in Water (cm2/sec)	Ref.	Koc Soil Organic Carbon/Water Partition Coefficient (cm3/g)	Ref.	Kd Soil (sorbed) / Water Partition Coefficient (cm3/g)	Ref.	Ksw Soil to Water Partition Coefficient (cm3/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			2.80E+03	SSG		
Molybdenum																
Nickel																
Tin																
Zinc																
Dioxins/PCBs																
Dioxins (I-TEQ)																
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.

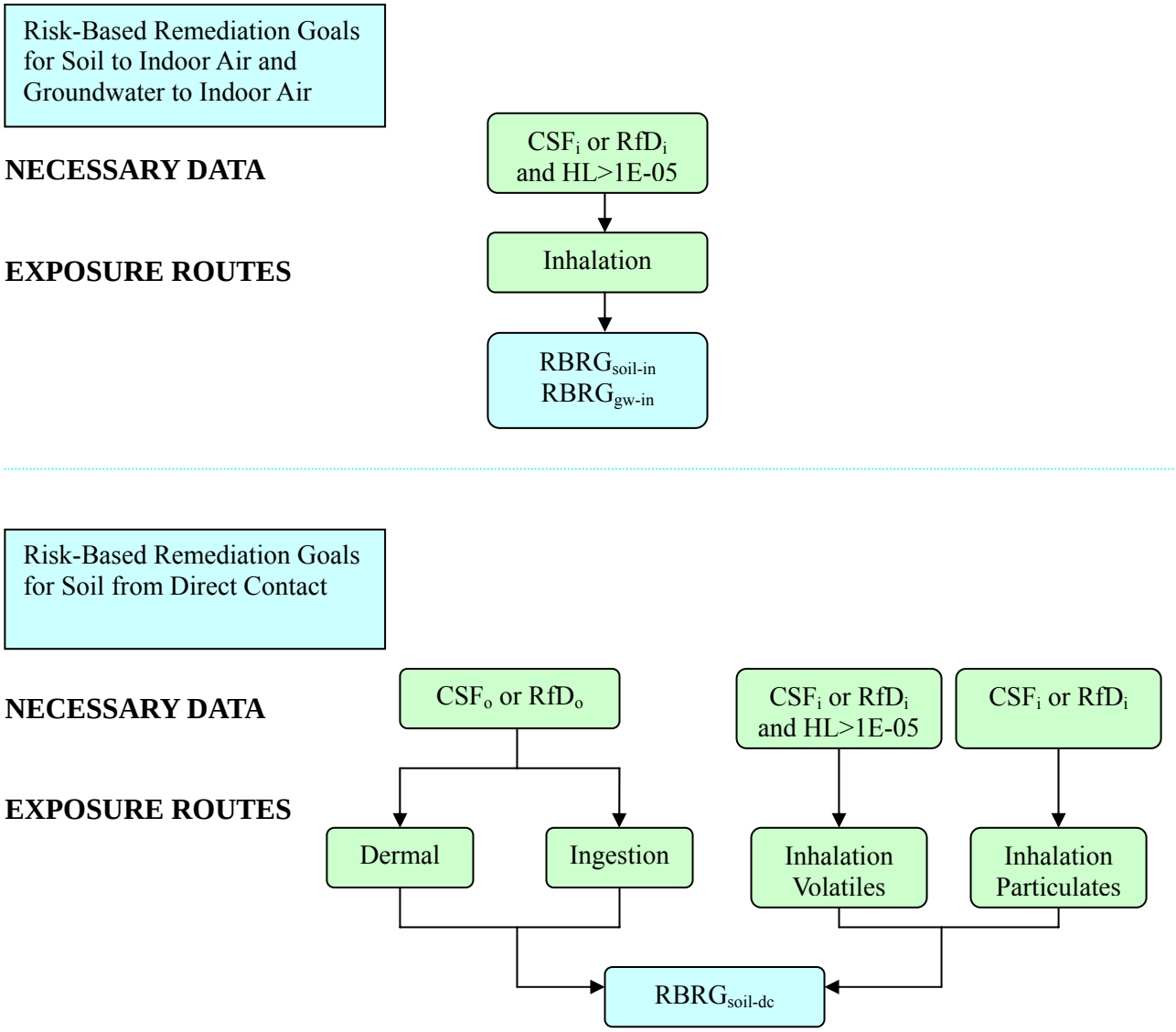
SSG : Soil Screening Guidance (EPA, 1996).

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
$RBRG_{soil\text{-}in}$	:	Risk-Based Remediation Goal for soil to indoor air
$RBRG_{gw\text{-}in}$	:	Risk-Based Remediation Goal for groundwater to indoor air
$RBRG_{soil\text{-}dc}$	:	Risk-Based Remediation Goal for soil from direct contact
HL	:	Henry's Law Constant (atm m^3/mol)

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

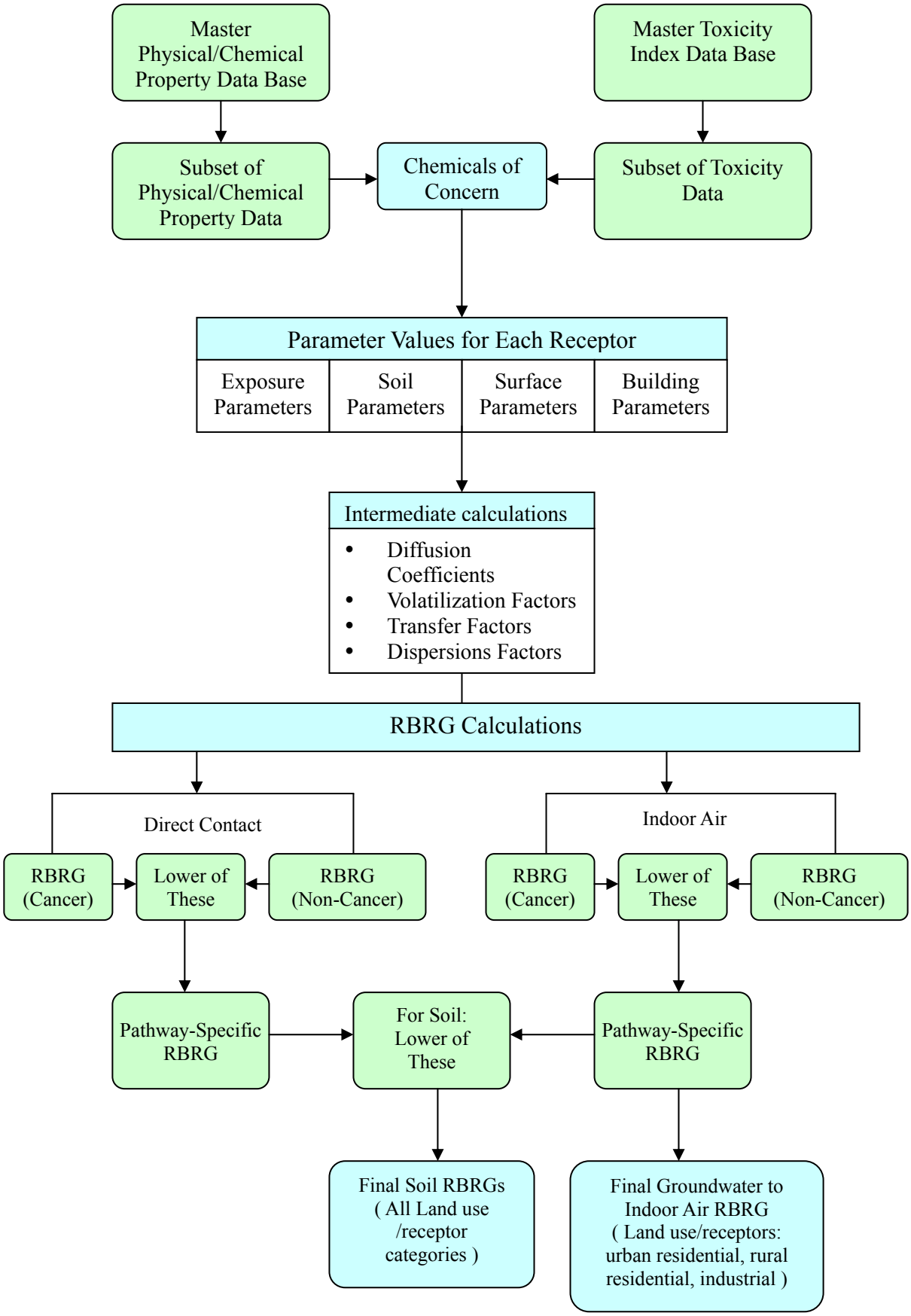


Figure 3
RBRGs for Surficial Soil (Direct Contact via ingestion of soil, inhalation of vapors and particulates, and dermal contact)

(see Figure 3a and 3b for calculation of VF_{ss} and VF_p)

Noncarcinogens :

$$\text{Adult } RBRG_{soil-dc} = \frac{\frac{THQ \cdot BW \cdot AT_{nc} \cdot CF_1}{EF \cdot ED}}{\left[CF_2 \cdot \left(\frac{IR_s \cdot RAF_o}{RfD_o} + \frac{SA \cdot M \cdot RAF_d}{RfD_o}\right) + \left(\frac{IR_{air}\left(VF_{ss} + VF_p\right)}{RfD_i}\right) \cdot CF_3\right]} \quad (1a)$$

$$\text{Child } RBRG_{soil-dc} = \frac{\frac{THQ \cdot BW_c \cdot AT_{ncc} \cdot CF_1}{EF \cdot ED_c}}{\left[CF_2 \cdot \left(\frac{IR_{sc} \cdot RAF_o}{RfD_o} + \frac{SA_c \cdot M_c \cdot RAF_d}{RfD_o}\right) + \left(\frac{IR_{airc}\left(VF_{ss} + VF_p\right)}{RfD_i}\right) \cdot CF_3\right]} \quad (1b)$$

adapted from ASTM,2000 and EPA,1989

Where:

$RBRG_{soil-dc}$	Risk-Based Remediation Goal for Surficial Soil Direct Contact (mg/kg)		
AT_{nc}	Defined Averaging Time for Noncarcinogens - Adult (years)		
AT_{ncc}	Defined Averaging Time for Noncarcinogens - Child (years)		
BW	Body Weight - Adult (kg)		
BW_c	Body Weight - Child (kg)		
ED	Exposure Duration - Adult (years)		
ED_c	Exposure Duration - Child (years)		
EF	Exposure Frequency (days/year)		
IR_{air}	Daily Inhalation Rate - Adult (m^3/day)	CF_1	(365 days/year)
IR_{airc}	Daily Inhalation Rate - Child (m^3/day)		
IR_s	Soil Ingestion Rate - Adult (mg/day)	CF_2	(10^{-6} kg/mg)
IR_{sc}	Soil Ingestion Rate - Child (mg/day)		
M	Soil to Skin Adherence Factor - Adult (mg/cm^2-day)	CF_3	(10^3 cm^3kg/m^3g)
M_c	Soil to Skin Adherence Factor - Child (mg/cm^2-day)		
RAF_d	Dermal Relative Absorption Factor		
RAF_o	Oral Relative Absorption Factor		
RfD_i	Chronic Inhalation Reference Dose (mg/kg-day)		
RfD_o	Chronic Oral Reference Dose (mg/kg-day)		
SA	Seasonally-averaged Skin Surface Area - Adult (cm^2)		
SA_c	Seasonally-averaged Skin Surface Area - Child (cm^2)		
THQ	Target Hazard Quotient for Individual Chemicals		
VF_{ss}	Volatilization Factor, surficial soil to ambient air (g-soil/cm^3-air)		
VF_p	Total Respirable Particulate Concentration from Soil Source (g-soil/cm^3-air)		

Figure 3 (cont'd)
RBRGs for Surficial Soil (Direct Contact via ingestion of soil, inhalation of vapors and particulates, and dermal contact)

Carcinogens :

$$\text{Integrated Adult and Child RBRG}_{\text{soil - dc}} = \frac{\text{Risk} \cdot AT_c \cdot CF_1}{\dfrac{EF}{A + B + C}}$$

$$A = CF_2\left[\left(\frac{ED_c \cdot IR_{sc}}{BW_c} + \frac{(ED - ED_c)\cdot IR_s}{BW}\right)\cdot SF_o \cdot RAF_o\right] \qquad \text{Soil Ingestion (1c)}$$

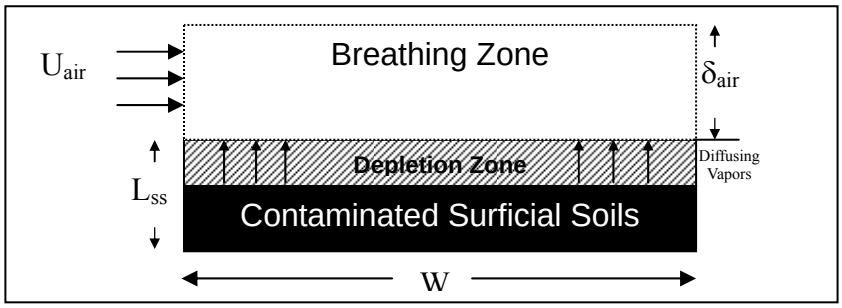
$$B = CF_2\left[\left(\frac{ED_c \cdot SA_c \cdot M_c}{BW_c} + \frac{(ED - ED_c)\cdot SA \cdot M}{BW}\right)\cdot SF_o \cdot RAF_d\right] \qquad \text{Dermal contact (1d)}$$

$$C = CF_3\left[\left(\frac{ED_c \cdot IR_{airc}}{BW_c} + \frac{(ED - ED_c)\cdot IR_{air}}{BW}\right)\cdot (VF_{ss} + VF_p)\cdot SF_i\right] \qquad \text{Inhalation of soil vapour and particulates (1e)}$$

Where:

$RBRG_{soil-dc}$	Risk-Based Remediation Goal for Surficial Soil Direct Contact (mg/kg)		
AT_c	Defined Carcinogen Averaging Time (years)		
BW	Body Weight - Adult (kg)		
BW_c	Body Weight - Child (kg)		
ED	Exposure Duration - Adult (years)		
ED_c	Exposure Duration - Child (years)		
EF	Exposure Frequency (days/year)		
IR_{air}	Daily Inhalation Rate - Adult (m^3/day)	CF_1	(365 days/year)
IR_{airc}	Daily Inhalation Rate - Child (m^3/day)		
IR_s	Soil Ingestion Rate - Adult (mg/day)	CF_2	(10^{-6} kg/mg)
IR_{sc}	Soil Ingestion Rate - Child (mg/day)		
M	Soil to Skin Adherence Factor - Adult (mg/cm^2-day)	CF_3	(10^3 cm^3kg/m^3g)
M_c	Soil to Skin Adherence Factor - Child (mg/cm^2-day)		
RAF_d	Dermal Relative Absorption Factor		
RAF_o	Oral Relative Absorption Factor		
Risk	Target Excess Individual Lifetime Cancer Risk		
SA	Seasonally-averaged Skin Surface Area - Adult (cm^2)		
SA_c	Seasonally-averaged Skin Surface Area - Child (cm^2)		
SF_i	Slope Factor – inhalation $(mg/kg\text{-}day)^{-1}$		
SF_o	Slope Factor – oral $(mg/kg\text{-}day)^{-1}$		
VF_{ss}	Volatilization Factor, surficial soil to ambient air (g-soil/cm^3-air)		
VF_p	Total Respirable Particulate Concentration from Soil Source (g-soil/cm^3-air)		

Figure 3a
Volatilization Factor – Surficial Soil to Ambient Air



$$VFss = \frac{\rho_b}{DF_{amb}} \sqrt{\frac{4 \cdot D_{eff,\,vad}}{\pi \cdot \tau \cdot 31536000_{sec/year}} \cdot \frac{H'}{Ksw \cdot \rho_b}} \quad (1c)$$

or

$$VF_{ss} = \frac{L_{ss} \cdot \rho_b}{DF_{amb} \cdot \tau \cdot 31536000_{sec/year}} \quad (1d)$$

(choose whichever is lower)

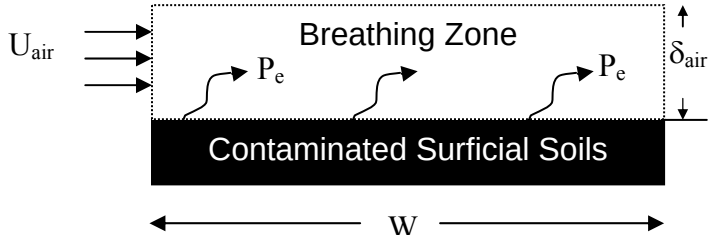
$$DF_{amb} = \frac{U_{air} \cdot W \cdot \delta_{air}}{A} \quad (1e)$$

$$D_{eff,vad} = D_a \cdot \left(\frac{\theta_a^{3.33}}{\theta_\tau^2} \right) + D_w \cdot \left(\frac{\theta_w^{3.33}}{H' \cdot \theta_\tau^2} \right) \quad (1f)$$

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



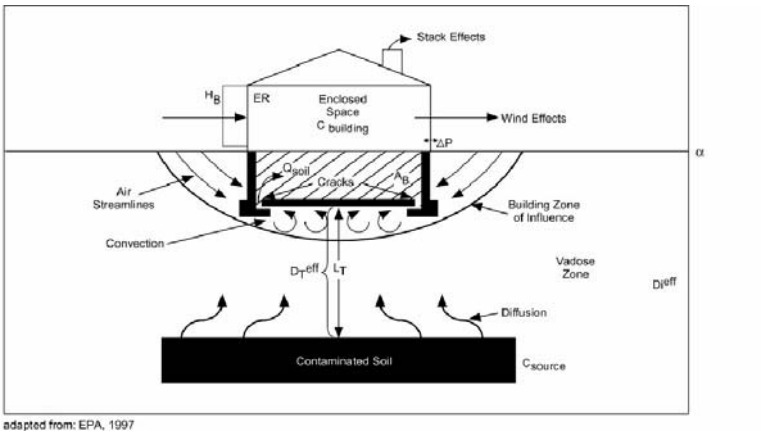
$$VF_p = \frac{P_e}{DF_{amb}} \qquad (1g)$$

$$DF_{amb} = \frac{U_{air} \cdot W \cdot \delta_{air}}{A} \qquad (1h)$$

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 4
RBRG for Soil
(Volatilization from Soil to Indoor Air)



adapted from: EPA, 1997

$$RBRG_{soil-in} = \frac{C_{source} \cdot \left(\theta_w + K_d \cdot \rho_b + H' \cdot \theta_a\right) \cdot CF_1}{H' \cdot \rho_b} \quad (3a)$$

$$C_{source} = \frac{C_{building}}{\alpha} \quad (3b)$$

$$C_{building} = RBC_{air} \quad (3c)$$

$$\alpha = \frac{\left[\left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) \text{ x } \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right]}{\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) + \left(\frac{D_T^{eff} A_B}{Q_{soil} L_T}\right)\left[\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) - 1\right]\right]} \quad (3d)$$

$$A_{crack} = \eta \bullet A_b \quad (3e)$$

$$\eta = \frac{r_{crack}}{\left(A_B / X_{crack}\right)} \quad (3f)$$

$$D_i^{eff} = D_a\left(\theta_{a,i}^{3.33} / \theta_T^2\right) + \left(D_w / H'\right)\left(\theta_{w,i}^{3.33} / \theta_T^2\right) \quad (3g)$$

$$D_T^{eff} = \frac{L_T}{\left[\sum_{i=0}^{n} L_i / D_i^{eff}\right]} \quad (3h)$$

$$Q_{soil} = \frac{2\pi \Delta P k_v X_{crack}}{\mu \ln\left[\frac{2Z_{crack}}{r_{crack}}\right]} \quad (3i)$$

Where:

$RBRG_{soil-in}$	=	Risk-Based Concentration in Soil Protective of Indoor Air (mg/kg)
α	=	Infinite Source Attenuation Coefficient (unitless)
D_T^{eff}	=	Total Overall Effective Diffusion Coefficient (cm^2/sec)
A_B	=	Area of the Enclosed Space Below Grade (cm^2)
L_T	=	Source-building Separation (cm)
Q_{soil}	=	Volumetric Flow Rate of Soil Gas entering the Enclosed Space (cm^3/sec)
L_{crack}	=	Enclosed Space Foundation or Slab Thickness (cm)
C_{source}	=	Vapor Concentration of Contaminant at the Source (g/cm^3)
$C_{building}$	=	Concentration of Contaminant in the Building (g/cm^3)
$Q_{building}$	=	Building Ventilation Rate (cm^3/sec)
H'	=	Dimensionless Henry's Law Constant
ρ_b	=	Soil Dry Bulk Density (g/cm^3)
θ_w	=	Soil water-filled porosity (cm^3/cm^3)
K_d	=	Soil (sorbed) water partition coefficient = K_{oc}* f_{oc} (cm^3/g)
θ_a	=	Soil air-filled porosity (cm^3/cm^3)
K_{oc}	=	Soil Organic Carbon Partition Coefficient = K_d / f_{oc} (cm^3/g)
f_{oc}	=	Soil Organic Carbon Weight Fraction
L_i	=	Thickness of Soil Layer i (cm)
D_i^{eff}	=	Effective Diffusion Coefficient Across Soil Layer i (cm^2/sec)
ΔP	=	Pressure Differential between Soil Surface and the Enclosed Space ($g/cm\text{-}sec^2$)
L_B	=	Length of Building (cm)
RBC_{air}	=	Risk-Based Concentration for Air (mg/m^3)
n	=	Number of Soil Layers
A_{crack}	=	Area of Crack (cm^2)
π	=	3.14159
k_v	=	Soil Vapor Permeability (cm^2)
X_{crack}	=	Floor-wall Seam Perimeter (cm)
μ	=	Viscosity of Air = 0.183 g/cm-sec
Z_{crack}	=	Crack Depth Below Grade (cm)
r_{crack}	=	Equivalent Crack Radius (cm)
CF_1	=	Conversion Factor (10^6 mg/kg)

D_i^{eff}	=	Diffusivity Across Soil Layer i (cm^2/sec)
D_a	=	Diffusivity in air (cm^2/sec)
θ_T	=	Soil Porosity (cm^3/cm^3)
D_w	=	Diffusivity in Water (cm^2/sec)
D_{crack}	=	D_i^{eff} of Soil Zone Near Building (cm^2/sec)
η	=	Crack-to-Total Area Ratio (unitless)

Figure 4a
RBC for Air (applicable to both Fig. 4 and 5)

(used to calculate $RBRG_{soil\text{-}in}$ and $RBRG_{gw\text{-}in}$)

Noncarcinogens :

$$\text{Adult } RBC_{air} = \frac{THQ \cdot RfD_i \cdot BW \cdot AT_{nc} \cdot CF_1 \cdot CF_2 \cdot CF_3}{IR_{air} \cdot ED \cdot EF} \qquad (3j)$$

$$\text{Child } RBC_{air} = \frac{THQ \cdot RfD_i \cdot BW_c \cdot AT_{ncc} \cdot CF_1 \cdot CF_2 \cdot CF_3}{IR_{airc} \cdot ED_c \cdot EF} \qquad (3k)$$

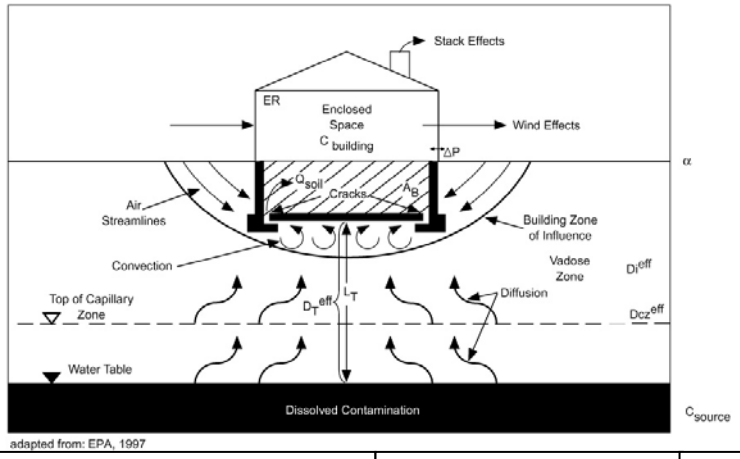
Carcinogens :

$$\text{Integrated Adult and Child } RBC_{air} = \frac{\dfrac{\text{Risk} \cdot AT_c \cdot CF_1 \cdot CF_2 \cdot CF_3}{EF}}{\left(\dfrac{ED_c \cdot IR_{airc}}{BW_c} + \dfrac{(ED - ED_c) \cdot IR_{air}}{BW}\right) \cdot SF_i} \qquad (3l)$$

Where:

RBC_{air}	Risk-Based Concentration for Air (g/cm^3)
AT_c	Defined Carcinogen Averaging Time (years)
AT_{nc}	Defined Averaging Time for Noncarcinogens - Adult (years)
AT_{ncc}	Defined Averaging Time for Noncarcinogens - Child (years)
BW	Body Weight - Adult (kg)
BW_c	Body Weight - Child (kg)
ED	Exposure Duration - Adult (years)
ED_c	Exposure Duration - Child (years)
EF	Exposure Frequency (days/year)
IR_{air}	Daily Inhalation Rate - Adult (m^3/day) – indoor
IR_{airc}	Daily Inhalation Rate - Child (m^3/day) – indoor
RfD_i	Chronic Inhalation Reference Dose (mg/kg-day)
Risk	Target Excess Individual Lifetime Cancer Risk
SF_i	Slope Factor – inhalation $(mg/kg\text{-}day)^{-1}$
THQ	Target Hazard Quotient for Individual Chemicals
CF_1	(365 days/year)
CF_2	(10^{-3} g/mg)
CF_3	($10^{-6} m^3/cm^3$)

Figure 5
RBRG for Groundwater
(Volatilization from Groundwater to Indoor Air)



adapted from: EPA, 1997

$$RBRG_{gw-in} = C_{source} \cdot CF_1 \cdot CF_2 / H' \quad (4a)$$

$$C_{source} = \frac{C_{building}}{\alpha} \quad (4b)$$

$$C_{building} = RBC_{air} \quad (4c)$$

$$\alpha = \frac{\left[\left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) x \exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right)\right]}{\left[\exp\left(\frac{Q_{soil} L_{crack}}{D^{crack} A_{crack}}\right) + \left(\frac{D_T^{eff} A_B}{Q_{building} L_T}\right) + \left(\frac{D_T^{eff} A_B}{Q_{soil} L_T}\right)\left[\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack} A_{crack}}\right) - 1\right]\right]} \quad (4d)$$

$$A_{crack} = \eta \cdot A_B \quad (4e)$$

$$\eta = \frac{r_{crack}}{(A_B / X_{Crack})} \quad (4f)$$

$$D_i^{eff} = D_a\left(\theta_{a,i}^{3.33} / \theta_T^2\right) + \left(D_w / H'\right)\left(\theta_{w,i}^{3.33} / \theta_T^2\right) \quad (4g)$$

$$D_T^{eff} = \frac{L_T}{\left[\sum_{i=0}^{n} L_i / D_i^{eff}\right]} \quad (4h)$$

$$Q_{soil} = \frac{2\pi \Delta P k_v X_{crack}}{\mu \ln\left[\frac{2 Z_{crack}}{r_{crack}}\right]} \quad (4i)$$

Where:

α	=	Infinite Source Attenuation Coefficient (unitless)			
D_T^{eff}	=	Total Overall Effective Diffusion Coefficient (cm^2/sec)			
A_B	=	Area of the Enclosed Space Below Grade (cm^2)			
L_T	=	Source-building Separation (cm)			
Q_{soil}	=	Volumetric Flow Rate of Soil Gas entering the Enclosed Space (cm^3/sec)			
L_{crack}	=	Enclosed Space Foundation or Slab Thickness (cm)			
C_{source}	=	Vapor Concentration of Contaminant at the Source (g/cm^3)			
$C_{building}$	=	Concentration of Contaminant in the Building (g/cm^3)			
$Q_{building}$	=	Building Ventilation Rate (cm^3/sec)			
$RBRG_{gw-in}$	=	Risk-Based Concentration for Groundwater (mg/L)			
H'	=	Dimensionless Henry's Law Constant			
ρ_b	=	Soil Dry Bulk Density (g/cm^3)			
θ_w	=	Soil water-filled porosity (cm^3/cm^3)			
K_d	=	Soil (sorbed) water partition coefficient = $K_{oc} * f_{oc}$ (cm^3/g)			
θ_a	=	Soil air-filled porosity (cm^3/cm^3)			
K_{oc}	=	Soil Organic Carbon Partition Coefficient = K_d / f_{oc} (cm^3/g)			
f_{oc}	=	Soil Organic Carbon Weight Fraction			
L_i	=	Thickness of Soil Layer i (cm)			
D_i^{eff}	=	Effective Diffusion Coefficient Across Soil Layer i (cm^2/sec)			
L_T	=	Distance between the Source of Contamination and the Bottom of the Enclosed Space Floor (cm)			
ΔP	=	Pressure Differential between Soil Surface and the Enclosed Space ($g/cm\text{-}sec^2$)			
D_a	=	Diffusivity in air (cm^2/sec)			
π	=	3.14159	θ_T	=	Soil Porosity (cm^3/cm^3)
k_v	=	Soil Vapor Permeability (cm^2)	D_w	=	Diffusivity in Water (cm^2/sec)
X_{crack}	=	Floor-wall Seam Perimeter (cm)	n	=	Number of Soil Layers
A_{crack}	=	Area of Crack (cm^2)	η	=	Crack-to-Total Area Ratio (unitless)
μ	=	Viscosity of Air = 0.183 g/cm-sec	D_{crack}	=	D_i^{eff} of Soil Zone Near Building (cm^2/sec)
Z_{crack}	=	Crack Depth Below Grade (cm)	CF_1	=	Conversion Factor (10^3 mg/g)
r_{crack}	=	Equivalent Crack Radius (cm)	CF_2	=	Conversion Factor (10^3 cm^3/L)
RBC_{air}	=	Risk-Based Concentration in Air (g/cm^3)			

Figure 6
Soil Saturation Limit

Soil Saturation Limit for Unsaturated Soil

$$C_{sat\text{-}un} = \left(\frac{S}{\rho_b}\right)\left(K_d\rho_b + \theta_w + H'\theta_a\right) \qquad (5a)$$

Soil Saturation Limit for Saturated Soil

$$C_{sat\text{-}s} = \left(\frac{S}{\rho_b}\right)\left(K_d\rho_b + \theta_w\right) \quad \text{where } \theta_w = \theta_T \qquad (5b)$$

Soil Saturation Limit

$$C_{sat} = \text{the lower of } C_{sat\text{-}un} \text{ or } C_{sat\text{-}s} \qquad (5c)$$

adapted from EPA, 1996 and ASTM, 2000

Where:

$C_{sat\text{-}un}$	Soil Saturation Limit for Unsaturated Soil (mg/kg)
$C_{sat\text{-}s}$	Soil Saturation Limit for Saturated Soil (mg/kg)
C_{sat}	Soil Saturation Limit (mg/kg)
S	Solubility in Water (mg/L-water)
ρ_b	Dry Soil Bulk Density $= (\rho_s (1- \theta_T))$ (kg/L)
K_d	Soil (sorbed) Water Partition Coefficient $= K_{oc} f_{oc}$ (L/kg)
K_{oc}	Soil Organic Carbon/Water Partition Coefficient (L/kg)
f_{oc}	Fraction Organic Carbon in Soil (g/g)
θ_w	Water-filled Soil Porosity (L_{water}/L_{soil})
H'	Dimensionless Henry's Law Constant
θ_a	Air-filled Soil Porosity (L_{air}/L_{soil})
θ_T	Total Soil Porosity (L_{pore}/L_{soil})
ρ_s	Soil Particle Density (kg/L)

Figure 7
Miscellaneous Equations

Soil (sorbed) to Water Partition Coefficient

$$K_d = K_{oc}\, f_{oc}$$

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

$$K_{sw} = \left(\frac{\theta_w + (K_d \rho_b) + (H' \theta_a)}{\rho_b} \right)$$

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)
S	=	Solubility Limit (mg/L)
ρ_b	=	Dry Soil Bulk Density (g/cm^3)
θ_a	=	Soil Air Content (cm^3-air/cm^3-soil)
θ_w	=	Soil Water Content (cm^3-water/cm^3-soil)

Soil Air-filled Porosity

$$\theta_a = \theta_T - \theta_w$$

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)

Soil Porosity

$$\theta_T = 1 - (\rho_b / \rho_s)$$

Where:
θ_T = Soil Porosity (cm^3-air/cm^3-soil)
ρ_b = Dry Soil Bulk Density (g/cm^3)
ρ_s = Soil Particle Density (g/cm^3)

Soil Water-filled Porosity

$$\theta_w = \frac{w \cdot \rho_b}{\rho_w}$$

Where:
θ_w = Soil Water-filled Porosity (cm^3/cm^3)
w = Soil Moisture Content (%)
ρ_b = Dry Soil Bulk Density (g/cm^3)
ρ_w = Water Density (g/cm^3)

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

$$H' = \frac{H}{RT}$$

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)