

**FIGURE B.1. INDOOR INHALATION OF VAPORS
(CHILD AND ADULT RESIDENT; AND NON-RESIDENTIAL WORKER)**

Carcinogenic effects

$$RBTL_{ai} = \frac{TR \times BW \times AT_c \times 365}{IR_{ai} \times ET_{in} \times ED \times EF \times SF_i}$$

Non-carcinogenic effects

$$RBTL_{ai} = \frac{THQ \times BW \times AT_{nc} \times 365 \times RfD_i}{IR_{ai} \times ET_{in} \times ED \times EF}$$

Source: RAGS, Vol. I, Part A, 1989, p. 6-44

where:

- $RBTL_{ai}$ = Risk-based target level in indoor air [mg/m^3]
- TR = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- THQ = Target hazard quotient for individual constituents [-]
- BW = Body weight [kg]
- AT_c = Averaging time for carcinogens [year]
- AT_{nc} = Averaging time for non-carcinogens [year]
- IR_{ai} = Indoor inhalation rate [m^3/hr]
- ET_{in} = Indoor Exposure time [hr/day]
- ED = Exposure duration [year]
- EF = Exposure frequency [day/year]
- RfD_i = Chemical-specific inhalation reference dose [$\text{mg}/\text{kg}\text{-day}$]
- SF_i = Chemical-specific inhalation cancer slope or potency factor [$(\text{mg}/\text{kg}\text{-day})^{-1}$]
- 365 = Converts AT_c, AT_{nc} in years to days [day/year]

**FIGURE B.2. OUTDOOR INHALATION OF VAPORS
(CONSTRUCTION WORKER)**

Carcinogenic effects

$$RBTL_{ao} = \frac{TR \times BW \times AT_c \times 365}{IR_{ao} \times ET_{out} \times ED \times EF \times SF_i}$$

Non-carcinogenic effects

$$RBTL_{ao} = \frac{THQ \times BW \times AT_{nc} \times 365 \times RfD_i}{IR_{ao} \times ET_{out} \times ED \times EF}$$

Source: RAGS, Vol. I, Part A, 1989, p. 6-44

where:

- $RBTL_{ao}$ = Risk-based target level in outdoor air [mg/m^3]
- TR = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- THQ = Target hazard quotient for individual constituents [-]
- BW = Body weight [kg]
- AT_c = Averaging time for carcinogens [year]
- AT_{nc} = Averaging time for non-carcinogens [year]
- IR_{ao} = Outdoor inhalation rate [m^3/hr]
- ET_{out} = Outdoor exposure time [hr/day]
- ED = Exposure duration [year]
- EF = Exposure frequency [day/year]
- RfD_i = Chemical-specific inhalation reference dose [$\text{mg}/\text{kg}\text{-day}$]
- SF_i = Chemical-specific inhalation cancer slope or potency factor [$(\text{mg}/\text{kg}\text{-day})^{-1}$]
- 365 = Converts AT_c, AT_{nc} in years to days [day/year]

**FIGURE B.3. DERMAL CONTACT WITH CHEMICALS IN WATER
(CHILD AND ADULT RESIDENT; NON-RESIDENTIAL WORKER; AND CONSTRUCTION WORKER)**

Carcinogenic effects

$$RBTL_{dw} = \frac{TR \times BW \times AT_c \times 365 \times 1000}{SF_d \times SA_{gw} \times EV_{gw} \times Z \times EF \times ED}$$

Non-carcinogenic effects

$$RBTL_{dw} = \frac{THQ \times BW \times AT_{nc} \times 365 \times 1000 \times RfD_d}{SA_{gw} \times EV_{gw} \times Z \times EF \times ED}$$

For organic chemicals,

If $t_{event} \leq t^*$, then $Z = 2 \times FA \times K_p \sqrt{6\tau_{event} \frac{t_{event}}{\pi}}$

If $t_{event} > t^*$, then $Z = FA \times K_p \left[\frac{t_{event}}{1+B} + 2\tau_{event} \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right]$

For inorganic chemicals, $Z = K_p \times t_{event}$

where:

- $RBTL_{dw}$ = Risk-based target level for dermal contact with groundwater [mg/L]
- TR = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- THQ = Target hazard quotient for individual constituents [-]
- BW = Body weight [kg]
- AT_c = Averaging time for carcinogens [year]
- AT_{nc} = Averaging time for non-carcinogens [year]
- SA_{gw} = Skin surface area available for contact with water [cm²]
- EV_{gw} = Event frequency [event/day]
- ED = Exposure duration [year]
- EF = Exposure frequency [day/year]
- RfD_d = Chemical-specific dermal reference dose [mg/kg-day]
- SF_d = Chemical-specific dermal cancer slope or potency factor [mg/(kg-day)]⁻¹
- 365 = Converts AT_c, AT_{nc} in years to days [day/year]
- 1000 = Conversion factor from cm³ to L [cm³/L]
- t_{event} = Event duration [hr/event]
- t^* = Chemical-specific time to reach steady-state [hr]
- Z = Chemical-specific dermal factor [cm/event]
- K_p = Chemical-specific dermal permeability coefficient [cm/hr]
- FA = Chemical-specific fraction absorbed in water [-]
- τ_{event} = Chemical-specific lag time [hr/event]
- B = Chemical-specific relative contribution of permeability coefficient [-]

$$B = K_p \frac{\sqrt{MW}}{2.6}$$

$$\log K_p = -2.80 + 0.66 \log K_{ow} - 0.0056 MW$$

If $B < 0.6$ or $B = 0.6$, then, $t^* = 2.4 \tau_{event}$

If $B > 0.6$ then, $t^* = 6 \tau_{event} \times (b - \sqrt{b^2 - c^2})$

where,

$$c = \frac{1 + 3B + 3B^2}{3(1 + B)}$$

$$b = 2 \times \frac{(1 + B)^2}{\pi} - c$$

$$\tau_{event} = 0.105 \times 10^{(0.0056 MW)}$$

Source: Modified from RAGS, Vol. I, Part E, 2004.

where:

MW = Molecular weight [g/mole]

K_{ow} = Octanol water partition coefficient [L/kg]

b, c = Correlation coefficient which have been fitted to the data from Flynn, G.L. (1990)

**FIGURE B.4. DOMESTIC WATER USE (CHILD AND ADULT RESIDENT)
(ONLY FOR CHEMICALS WITHOUT MAXIMUM CONTAMINANT LEVELS)**

Carcinogenic effects

$$RBTL_w = \frac{TR \times BW \times AT_c \times 365}{ED \times EF \times \left[(SF_o \times IR_w) + (SF_i \times ET \times K_f \times IR_a) + \left(\frac{SF_d}{1000} \times SA_{wb} \times EV_{wb} \times Z_{wb} \right) \right]}$$

Non-carcinogenic effects

$$RBTL_w = \frac{THQ \times BW \times AT_{nc} \times 365}{ED \times EF \times \left[\left(\frac{1}{RfD_o} \times IR_w \right) + \left(\frac{1}{RfD_i} \times K_f \times ET \times IR_a \right) + \left(\frac{SA_{wb} \times EV_{wb} \times Z_{wb}}{RfD_d \times 1000} \right) \right]}$$

For organic chemicals,

$$\text{If } t_{wb-event} \leq t^*, \text{ then } Z_{wb} = 2 \times FA \times K_p \sqrt{6\tau_{event} \frac{t_{wb-event}}{\pi}}$$

$$\text{If } t_{wb-event} > t^*, \text{ then } Z_{wb} = FA \times K_p \left[\frac{t_{wb-event}}{1+B} + 2\tau_{event} \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right]$$

For inorganic chemicals, $Z_{wb} = K_p \times t_{wb-event}$

Note: $K_f = 0$ for non-volatile chemicals (i.e., chemicals with a molecular weight > 200 and Henry's law constant (dimensionless) $< 4.2 \times 10^{-4}$ or Henry's law constant (atm-m³/mol) $< 1.5 \times 10^{-5}$).

Source: Modified from RAGS, Vol. I, Part E, 2004.

where:

$RBTL_w$	=	Risk-based target level for ingestion of groundwater [mg/L-H ₂ O]
TR	=	Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
THQ	=	Target hazard quotient for individual constituents [-]
BW	=	Body weight [kg]
AT_c	=	Averaging time for carcinogens [year]
AT_{nc}	=	Averaging time for non-carcinogens [year]
IR_w	=	Water ingestion rate [L/day]
IR_a	=	Indoor inhalation rate [m ³ /hr]
ED	=	Exposure duration [year]
EF	=	Exposure frequency [day/year]
K_f	=	Volatilization factor [L/m ³]
ET	=	Exposure time [hr/day]
SA_{wb}	=	Skin surface area available for whole-body contact with water [cm ²]
EV_{wb}	=	Event frequency for whole-body contact with water [event/day]
RfD_o	=	Chemical-specific oral reference dose [mg/kg-day]
RfD_i	=	Chemical-specific inhalation reference dose [mg/kg-day]
RfD_d	=	Chemical-specific dermal reference dose [mg/kg-day]
SF_o	=	Chemical-specific oral cancer slope or potency factor [mg/(kg-day)] ⁻¹
SF_i	=	Chemical-specific inhalation cancer slope or potency factor [(mg/kg-day) ⁻¹]
SF_d	=	Chemical-specific dermal cancer slope or potency factor [mg/(kg-day)] ⁻¹
365	=	Converts AT_c , AT_{nc} in years to days [day/year]
1000	=	Conversion factor from cm ³ to L [cm ³ /L]
$t_{wb-event}$	=	Event duration for whole-body contact [hr/event]
t^*	=	Chemical-specific time to reach steady-state [hr]
Z_{wb}	=	Chemical-specific dermal factor for whole-body contact [cm/event]
K_p	=	Chemical-specific dermal permeability coefficient [cm/hr]
FA	=	Chemical-specific fraction absorbed in water [-]
τ_{event}	=	Chemical-specific lag time [hr/event]
B	=	Chemical-specific relative contribution of permeability coefficient [-]

**FIGURE B.5. DERMAL CONTACT WITH CHEMICALS IN SOIL
(CHILD AND ADULT RESIDENT; NON-RESIDENTIAL WORKER; AND CONSTRUCTION WORKER)**

Carcinogenic effects

$$RBTL_{dcss} = \frac{TR \times BW \times AT_c \times 365}{EF \times ED \times SF_d \times 10^{-6} \times SA_{soil} \times EV_{soil} \times AF \times RAF_d}$$

Non-carcinogenic effects

$$RBTL_{dcss} = \frac{THQ \times BW \times AT_{nc} \times 365 \times RfD_d}{EF \times ED \times 10^{-6} \times SA_{soil} \times EV_{soil} \times AF \times RAF_d}$$

Source: Modified from RAGS, Vol. I, Part E, 2004.

where:

- $RBTL_{dcss}$ = Risk-based target level for dermal contact of chemicals in surficial soil [mg/kg]
- TR = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- THQ = Target hazard quotient for individual constituents [-]
- BW = Body weight [kg]
- AT_c = Averaging time for carcinogens [year]
- AT_{nc} = Averaging time for non-carcinogens [year]
- ED = Exposure duration [year]
- EF = Exposure frequency [day/year]
- SA_{soil} = Skin surface area available for contact with soil [cm²]
- EV_{soil} = Event frequency [event/day]
- AF = Soil to skin adherence factor [mg/cm²-event]
- RAF_d = Chemical-specific dermal relative absorption factor [-]
- SF_d = Dermal cancer slope factor [(mg/kg-day)⁻¹]
- RfD_d = Chemical-specific oral reference dose [mg/kg-day]
- 365 = Converts AT_c , AT_{nc} in years to days [day/year]

**FIGURE B.6. INGESTION OF CHEMICALS IN SOIL
(CHILD AND ADULT RESIDENT; NON-RESIDENTIAL WORKER; AND CONSTRUCTION WORKER)**

Carcinogenic effects

$$RBTL_{ingss} = \frac{TR \times BW \times AT_c \times 365}{EF \times ED \times SF_o \times 10^{-6} \times IR_{soil} \times RAF_o}$$

Non-carcinogenic effects

$$RBTL_{ingss} = \frac{THQ \times BW \times AT_{nc} \times 365 \times Rfd_o}{EF \times ED \times 10^{-6} \times IR_{soil} \times RAF_o}$$

where:

- $RBTL_{ingss}$ = Risk-based target level for ingestion of chemicals in surficial soil [mg/kg]
- TR = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- THQ = Target hazard quotient for individual constituents [-]
- BW = Body weight [kg]
- AT_c = Averaging time for carcinogens [year]
- AT_{nc} = Averaging time for non-carcinogens [year]
- ED = Exposure duration [year]
- EF = Exposure frequency [day/year]
- IR_{soil} = Soil ingestion rate [mg/day]
- RAF_o = Oral relative absorption factor [-]
- SF_o = Oral cancer slope factor [(mg/kg-day)⁻¹]
- 365 = Converts AT_c , AT_{nc} in years to days [day/year]

**FIGURE B.7. INHALATION OF VAPORS AND PARTICULATES OF CHEMICALS IN SOIL
(CHILD AND ADULT RESIDENT; NON-RESIDENTIAL WORKER; AND CONSTRUCTION WORKER)**

Carcinogenic effects

$$RBTL_{inhss} = \frac{TR \times BW \times AT_c \times 365}{EF \times ED \times SF_i \times IR_{ao} \times ET_{out} \times (VF_{ss} + VF_p)}$$

Non-carcinogenic effects

$$RBTL_{inhss} = \frac{THQ \times BW \times AT_{nc} \times 365 \times RfD_i}{EF \times ED \times ET_{out} \times IR_{ao} \times (VF_{ss} + VF_p)}$$

Note: $VF_{ss} = 0$ for non-volatile chemicals (i.e., chemicals with a molecular weight > 200 and Henry's law constant (dimensionless) < 4.2 x 10E-04 or Henry's law constant (atm·m³/mol) < 1.5 x 10E-05.

where:

- $RBTL_{inhss}$ = Risk-based target level of inhalation of chemicals in surficial soil [mg/kg]
- TR = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- THQ = Target hazard quotient for individual constituents [-]
- BW = Body weight [kg]
- AT_c = Averaging time for carcinogens [year]
- AT_{nc} = Averaging time for non-carcinogens [year]
- ED = Exposure duration [year]
- EF = Exposure frequency [day/year]
- IR_{ao} = Outdoor inhalation rate [m³/hr]
- ET_{out} = Outdoor exposure time [hr/day]
- SF_i = Inhalation cancer slope factor [(mg/kg-day)⁻¹]
- RfD_i = The chemical-specific inhalation reference dose [mg/kg-day]
- VF_p = Volatilization factor for particulate emissions from surficial soil [(mg/m³-air)/(mg/kg-soil)]
- VF_{ss} = Volatilization factor for vapor emissions from surficial soil [(mg/m³-air)/(mg/kg-soil)]
- 365 = Converts AT_c , AT_{nc} in years to days [day/year]

Note: The depth to surficial soil for a construction worker is up to the typical construction depth.

**FIGURE B.8. INHALATION OF VAPORS AND PARTICULATES, DERMAL CONTACT WITH, AND INGESTION OF CHEMICALS IN SOIL
(CHILD AND ADULT RESIDENT; NON-RESIDENTIAL WORKER; AND CONSTRUCTION WORKER)**

Carcinogenic effects

$$RBTL_{ss} = \frac{TR \times BW \times AT_c \times 365}{EF \times ED \times \left[(SF_o \times 10^{-6} \times IR_{soil} \times RAF_o) + (SF_d \times 10^{-6} \times SA_{soil} \times EV_{soil} \times AF \times RAF_d) + (SF_i \times IR_{ao} \times ET_{out} \times (VF_{ss} + VF_p)) \right]}$$

Non-carcinogenic effects

$$RBTL_{ss} = \frac{THQ \times BW \times AT_{nc} \times 365}{EF \times ED \times \left[\frac{10^{-6} \times IR_{soil} \times RAF_o}{RfD_o} + \frac{10^{-6} \times SA_{soil} \times EV_{soil} \times AF \times RAF_d}{RfD_d} + \frac{ET_{out} \times IR_{ao} \times (VF_{ss} + VF_p)}{RfD_i} \right]}$$

Source: Modified from RAGS, Vol. 1, Part E, 2004

Where:

- $RBTL_{ss}$ = Risk-based target level of surficial soil [mg/kg]
- TR = Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
- THQ = Target hazard quotient for individual constituents [-]
- BW = Body weight [kg]
- AT_c = Averaging time for carcinogens [year]
- AT_{nc} = Averaging time for non-carcinogens [year]

<i>ED</i>	=	Exposure duration [year]
<i>EF</i>	=	Exposure frequency [day/year]
<i>IR_{soil}</i>	=	Soil ingestion rate [mg/day]
<i>RAF_o</i>	=	Oral relative absorption factor [-]
<i>SA</i>	=	Skin surface area [cm ² /day]
<i>EV_{soil}</i>	=	Event frequency [event/day]
<i>AF</i>	=	Soil to skin adherence factor [mg/cm ²]
<i>RAF_d</i>	=	Dermal relative adsorption factor [-]
<i>IR_{ao}</i>	=	Outdoor inhalation rate [m ³ /hr]
<i>ET_{out}</i>	=	Outdoor Exposure time [hr/day]
<i>SF_o</i>	=	Oral cancer slope factor [(mg/kg-day) ⁻¹]
<i>SF_i</i>	=	Inhalation cancer slope factor [(mg/kg-day) ⁻¹]
<i>RfD_o</i>	=	The chemical-specific oral reference dose [mg/kg-day]
<i>RfD_i</i>	=	The chemical-specific inhalation reference dose [mg/kg-day]
<i>VF_p</i>	=	Volatilization factor for particulate emissions from surficial soil [(mg/m ³ -air)/(mg/kg-soil)]
<i>VF_{ss}</i>	=	Volatilization factor for vapor emissions from surficial soil [(mg/m ³ -air)/(mg/kg-soil)]
365	=	Converts <i>AT_c</i> , <i>AT_{nc}</i> in years to days [day/year]

FIGURE B.9. INDOOR INHALATION OF VAPORS (AGE-ADJUSTED RESIDENT)

Carcinogenic effects

$$RBTL_{ai-adj} = \frac{TR \times AT_c \times 365}{IR_{ai-aa} \times SF_i}$$

Non-carcinogenic effects

$$RBTL_{ai-adj} = \frac{THQ \times AT_{nc} \times 365 \times RfD_i}{IR_{ai-aa}}$$

where

$$IR_{ai-aa} = \frac{IR_{ai-c} \times ED_c \times EF_c \times ET_{i-c}}{BW_c} + \frac{IR_{ai-a} \times ED_a \times EF_a \times ET_{i-a}}{BW_a}$$

Source: Modified from RAGS, Vol. I, Part B, 1991

Where:

$RBTL_{ai-adj}$	=	Age-adjusted risk-based target level in indoor air [mg/m^3]
TR	=	Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
THQ	=	Target hazard quotient for individual constituents [-]
AT_c	=	Averaging time for carcinogens [year]
AT_{nc}	=	Averaging time for non-carcinogens [year]
IR_{ai-aa}	=	Age-adjusted indoor inhalation rate [m^3/kg]
IR_{ai-c}	=	Resident child indoor inhalation rate [m^3/hr]
IR_{ai-a}	=	Resident adult indoor inhalation rate [m^3/hr]
ED_c	=	Exposure duration for child [year]
ED_a	=	Exposure duration for an adult [year]
EF_c	=	Exposure frequency for a child [day/year]
EF_a	=	Exposure frequency for an adult [day/year]
ET_{i-c}	=	Indoor exposure time for a child [hour/day]
ET_{i-a}	=	Indoor exposure time for an adult [hour/day]
BW_c	=	Resident child body weight [kg]
BW_a	=	Resident adult body weight [kg]
RfD_i	=	Chemical-specific inhalation reference dose [$\text{mg}/\text{kg}\text{-day}$]
SF_i	=	Chemical-specific inhalation cancer slope factor [$\text{mg}/\text{kg}\text{-day}$] ⁻¹
365	=	Conversion factor [day/year]

FIGURE B.10. DERMAL CONTACT WITH CHEMICALS IN WATER (AGE-ADJUSTED RESIDENT)

Carcinogenic effects

$$RBTL_{dcw-adj} = \frac{TR \times AT_c \times 365 \times 1000}{SF_d \times (DC_{w-c} \times Z_c + DC_{w-a} \times Z_a)}$$

Non-carcinogenic effects

$$RBTL_{dcw-adj} = \frac{THQ \times AT_{nc} \times 365 \times 1000 \times RfD_d}{DC_{w-c} \times Z_c + DC_{w-a} \times Z_a}$$

where :

$$DC_{w-c} = \frac{ED_c \times EF_c \times SA_{gw-c} \times EV_{gw-c}}{BW_c}$$

$$DC_{w-a} = \frac{ED_a \times EF_a \times SA_{gw-a} \times EV_{gw-a}}{BW_a}$$

For organic chemicals,

$$\text{If } t_{event} \leq t^*, \text{ then } Z = 2 \times FA \times K_p \sqrt{6\tau_{event} \frac{t_{event}}{\pi}}$$

If $t_{event} > t^*$, then

$$Z = FA \times K_p \left[\frac{t_{event}}{1+B} + 2\tau_{event} \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right]$$

For inorganic chemicals, $Z = K_p \times t_{event}$

Source: Modified from RAGS, Vol. I, Part E, 2004.

where:

$RBTL_{dcw-adj}$	=	Age-adjusted risk-based target level for dermal contact with chemicals in groundwater [mg/L-water]
TR	=	Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
THQ	=	Target hazard quotient for individual constituents [-]
AT_c	=	Averaging time for carcinogens [year]
AT_{nc}	=	Averaging time for non-carcinogens [year]
RfD_d	=	Chemical-specific dermal reference dose [mg/kg-day]
SF_d	=	Chemical-specific dermal cancer slope or potency factor [(mg/kg-day) ⁻¹]
365	=	Converts AT_c , AT_{nc} in years to days [day/year]
1000	=	Conversion factor from cm ³ to L [cm ³ /L]
t_{event}	=	Event duration [hr/event]
t^*	=	Chemical-specific time to reach steady-state [hr]
K_p	=	Chemical-specific dermal permeability coefficient [cm/hr]
FA	=	Chemical-specific fraction absorbed in water [-]
τ_{event}	=	Chemical-specific lag time [hr/event]
B	=	Chemical-specific relative contribution of permeability coefficient [-]
DC_{w-c}	=	Child dermal contact rate with groundwater [cm ² -event/kg]
DC_{w-a}	=	Adult dermal contact rate with groundwater [cm ² -event/kg]
EV_{gw-c}	=	Resident child event frequency [event/day]
EV_{gw-a}	=	Resident adult event frequency [event/day]
Z_c	=	Resident child chemical-specific dermal factor [cm/event]
Z_a	=	Resident adult chemical-specific dermal factor [cm/event]
SA_{gw-c}	=	Resident child skin surface area available for contact with water [cm ²]
SA_{gw-a}	=	Resident adult skin surface area available for contact with water [cm ²]
BW_c	=	Resident child body weight [kg]
BW_a	=	Resident adult body weight [kg]
ED_c	=	Resident child exposure duration [year]
ED_a	=	Resident adult exposure duration [year]
EF_c	=	Exposure frequency for a child [day/year]
EF_a	=	Exposure frequency for an adult [day/year]

**FIGURE B.11. DOMESTIC WATER USE (AGE-ADJUSTED RESIDENT)
(ONLY FOR CHEMICALS WITHOUT MAXIMUM CONTAMINANT LEVELS)**

Carcinogenic effects

$$RBTL_{w-adj} = \frac{TR \times AT_c \times 365}{\left[(SF_o \times IR_{w-aa}) + (SF_i \times K_f \times IR_{a-aa}) + \left(\frac{SF_d}{1000} \times (DC_{wb-c} \times Z_{wb-c} + DC_{wb-a} \times Z_{wb-a}) \right) \right]}$$

Non-carcinogenic effects

$$RBTL_{w-adj} = \frac{THQ \times AT_{nc} \times 365}{\left[\left(\frac{1}{RfD_o} \times IR_{w-aa} \right) + \left(\frac{1}{RfD_i} \times K_f \times IR_{a-aa} \right) + \left(\frac{(DC_{wb-c} \times Z_{wb-c} + DC_{wb-a} \times Z_{wb-a})}{RfD_d \times 1000} \right) \right]}$$

where:

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

$$IR_{a-aa} = \frac{ED_c \times EF_c \times ET_c \times IR_{a-c}}{BW_c} + \frac{ED_a \times EF_a \times ET_a \times IR_{a-a}}{BW_a}$$

$$DC_{wb-c} = \frac{ED_c \times EF_c \times SA_{wb-c} \times EV_{wb-c}}{BW_c} \quad \text{and} \quad DC_{wb-a} = \frac{ED_a \times EF_a \times SA_{wb-a} \times EV_{wb-a}}{BW_a}$$

For organic chemicals,

$$\text{If } t_{wb-event} \leq t^*, \text{ then } Z_{wb} = 2 \times FA \times K_p \sqrt{6\tau_{event} \frac{t_{wb-event}}{\pi}}$$

$$\text{If } t_{wb-event} > t^*, \text{ then } Z_{wb} = FA \times K_p \left[\frac{t_{wb-event}}{1+B} + 2\tau_{event} \left(\frac{1+3B+3B^2}{(1+B)^2} \right) \right]$$

For inorganic chemicals, $Z_{wb} = K_p \times t_{wb-event}$

Note: $K_f = 0$ for non-volatile chemicals (i.e., chemicals with a molecular weight > 200 and Henry's law constant (dimensionless) < 4.2 x 10⁻⁴ or Henry's law constant (atm-m³/mol) < 1.5 x 10⁻⁵).

Source: Modified from RAGS, Vol. I, Part E, 2004.

where:

$RBTL_{w-adj}$	=	Age-adjusted risk-based target level for ingestion of groundwater [mg/L-H ₂ O]
TR	=	Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
THQ	=	Target hazard quotient for individual constituents [-]
AT_c	=	Averaging time for carcinogens [year]
AT_{nc}	=	Averaging time for non-carcinogens [year]
RfD_o	=	Chemical-specific oral reference dose [mg/kg-day]
RfD_d	=	Chemical-specific dermal reference dose [mg/kg-day]
SF_o	=	Chemical-specific oral cancer slope or potency factor [(mg/kg-day) ⁻¹]
SF_i	=	Chemical-specific inhalation cancer slope or potency factor [(mg/kg-day) ⁻¹]
SF_d	=	Chemical-specific dermal cancer slope or potency factor [mg/(kg-day)] ⁻¹
IR_{w-aa}	=	Age-adjusted groundwater ingestion rate [L/kg]
IR_{w-c}	=	Resident child groundwater ingestion rate [L/day]
IR_{a-c}	=	Resident child inhalation rate [m ³ /hr]
IR_{w-a}	=	Resident adult groundwater ingestion rate [L/day]

IR_{a-a}	=	Resident adult inhalation rate [m^3/hr]
DC_{wb-c}	=	Child dermal whole-body contact rate with groundwater [cm^2 -event/kg]
DC_{wb-a}	=	Adult dermal whole-body contact rate with groundwater [cm^2 -event/kg]
BW_c	=	Resident child body weight [kg]
BW_a	=	Resident adult body weight [kg]
ED_c	=	Resident child exposure duration [year]
ET_c	=	Resident child exposure time [hr/day]
ET_a	=	Resident adult exposure time [hr/day]
ED_a	=	Resident adult exposure duration [year]
EF_c	=	Exposure frequency for a child [day/year]
EF_a	=	Exposure frequency for an adult [day/year]
K_f	=	Volatilization factor [L/m^3]
SA_{wb}	=	Skin surface area available for whole-body contact with water [cm^2]
EV_{wb}	=	Event frequency for whole-body contact with water [event/day]
365	=	Conversion factor [day/year]
1000	=	Conversion factor from cm^3 to L [cm^3/L]
$t_{wb-event}$	=	Event duration for whole-body contact [hr/event]
t^*	=	Chemical-specific time to reach steady-state [hr]
Z_{wb}	=	Chemical-specific dermal factor for whole-body contact [cm/event]
K_p	=	Chemical-specific dermal permeability coefficient [cm/hr]
FA	=	Chemical-specific fraction absorbed in water [-]
τ_{event}	=	Chemical-specific lag time [hr/event]
B	=	Chemical-specific relative contribution of permeability coefficient [-]

FIGURE B.12. DERMAL CONTACT WITH CHEMICALS IN SOIL (AGE-ADJUSTED RESIDENT)

Carcinogenic effects

$$RBTL_{dcss-adj} = \frac{TR \times AT_c \times 365}{SF_d \times SA_{soil-aa} \times RAF_d \times 10^{-6}}$$

Non-carcinogenic effects

$$RBTL_{dcss-adj} = \frac{THQ \times AT_{nc} \times 365 \times RfD_d}{SA_{soil-aa} \times RAF_d \times 10^{-6}}$$

where:

$$SA_{soil-aa} = \frac{ED_c \times EF_c \times AF_c \times SA_{soil-c} \times EV_{soil-c}}{BW_c} + \frac{ED_a \times EF_a \times AF_a \times SA_{soil-a} \times EV_{soil-a}}{BW_a}$$

Source: Modified from RAGS, Vol. I, Part E, 2004.

where:

$RBTL_{dcss-adj}$	=	Age-adjusted risk-based target level for dermal contact with soil [mg/kg-wet soil]
TR	=	Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
THQ	=	Target hazard quotient for individual constituents [-]
AT_c	=	Averaging time for carcinogens [year]
AT_{nc}	=	Averaging time for non-carcinogens [year]
EF_c	=	Exposure frequency for a child [day/year]
EF_a	=	Exposure frequency for an adult [day/year]
RAF_d	=	Dermal relative absorption factor [-]
AF_c	=	Resident child soil to skin adherence factor [mg/cm ² -event]
AF_a	=	Resident adult soil to skin adherence factor [mg/cm ² -event]
RfD_d	=	Chemical-specific dermal reference dose [(mg/kg-day)]
SF_d	=	Chemical-specific dermal cancer slope or potency factor [(mg/kg-day) ⁻¹]
SA_{aa}	=	Age-adjusted skin surface area [mg/ kg]
BW_c	=	Resident child body weight [kg]
BW_a	=	Resident adult body weight [kg]
ED_c	=	Resident child exposure duration [year]
ED_a	=	Resident adult exposure duration [year]
SA_{soil-c}	=	Resident child skin surface area available for contact with soil [cm ² /day]
SA_{soil-a}	=	Resident adult skin surface area available for contact with soil [cm ² /day]
EV_{soil-c}	=	Resident child event frequency [event/day]
EV_{soil-a}	=	Resident Child event frequency [event/day]
365	=	Conversion factor [day/year]
10^{-6}	=	Conversion factor [kg/mg]

FIGURE B.13. INGESTION OF CHEMICALS IN SOIL (AGE-ADJUSTED RESIDENT)

Carcinogenic effects

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

Non-carcinogenic effects

$$RBTL_{ingss-adj} = \frac{THQ \times AT_{nc} \times 365 \times RfD_o}{IR_{s-aa} \times RAF_o \times 10^{-6}}$$

where :

$$IR_{s-aa} = \frac{ED_c \times EF_c \times IR_{s-c}}{BW_c} + \frac{ED_a \times EF_a \times IR_{s-a}}{BW_a}$$

Source: Modified from RAGS, Vol. I, Part A, 1989

where:

$RBTL_{ingss-adj}$	=	Risk-based target level for ingestion of soil [mg/kg-wet soil]
TR	=	Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
THQ	=	Target hazard quotient for individual constituents [-]
AT_c	=	Averaging time for carcinogens [year]
AT_{nc}	=	Averaging time for non-carcinogens [year]
RAF_o	=	Oral relative absorption factor [-]
RfD_o	=	Chemical-specific oral reference dose [mg/kg-day]
SF_o	=	Chemical-specific oral cancer slope or potency factor [(mg/kg-day) ⁻¹]
IR_{s-aa}	=	Age-adjusted soil ingestion rate [mg/kg]
IR_{s-c}	=	Resident child soil ingestion rate [mg/day]
IR_{s-a}	=	Resident adult soil ingestion rate [mg/day]
BW_c	=	Resident child body weight [kg]
BW_a	=	Resident adult body weight [kg]
ED_c	=	Resident child exposure duration [year]
ED_a	=	Resident adult exposure duration [year]
EF_c	=	Exposure frequency for a child [day/year]
EF_a	=	Exposure frequency for an adult [day/year]
365	=	Conversion factor [day/year]
10^{-6}	=	Conversion factor [kg/mg]

**FIGURE B.14. INHALATION OF VAPORS AND PARTICULATES OF CHEMICALS IN SOIL
(AGE-ADJUSTED RESIDENT)**

Carcinogenic effects

$$RBTL_{ss-adj} = \frac{TR \times AT_c \times 365}{IR_{ao-aa} \times SF_i \times (VF_{ss} + VF_p)}$$

Non-carcinogenic effects

$$RBTL_{ss-adj} = \frac{THQ \times AT_{nc} \times 365 \times RfDi}{IR_{ao-aa} \times (VF_{ss} + VF_p)}$$

where:

$$IR_{ao-aa} = \frac{IR_{ao-c} \times ED_c \times EF_c \times ET_{o-c}}{BW_c} + \frac{IR_{ao-a} \times ED_a \times EF_a \times ET_{o-a}}{BW_a}$$

Note: $VF_{ss} = 0$ for non-volatile chemicals (i.e., chemicals with a molecular weight > 200 and Henry's law constant (dimensionless) $< 4.2 \times 10^{-4}$ or Henry's law constant (atm-m³/mol) $< 1.5 \times 10^{-5}$).

Source: Modified from RAGS, Vol. I, Part B, 1991

where:

$RBTL_{ss-adj}$	=	Age-adjusted risk-based target level in surficial soil [mg/kg]
TR	=	Target risk or the increased chance of developing cancer over a lifetime due to exposure to a chemical [-]
THQ	=	Target hazard quotient for individual constituents [-]
VF_{ss}	=	Volatilization factor for vapor emissions from surficial soil [kg-soil/m ³ -air]
VF_p	=	Volatilization factor for particulate emissions from surficial soil [kg-soil/m ³ -air]
IR_{ao-aa}	=	Age-adjusted outdoor inhalation rate [m ³ /kg]
IR_{ao-c}	=	Resident child outdoor inhalation rate [m ³ /hr]
IR_{ao-a}	=	Resident adult outdoor inhalation rate [m ³ /hr]
AT_c	=	Averaging time for carcinogens [year]
AT_{nc}	=	Averaging time for non-carcinogens [year]
ED_c	=	Exposure duration for child [year]
ED_a	=	Exposure duration for an adult [year]
EF_c	=	Exposure frequency for a child [day/year]
EF_a	=	Exposure frequency for an adult [day/year]
ET_{o-c}	=	Outdoor exposure time for a child [hour/day]
ET_{o-a}	=	Outdoor exposure time for an adult [hour/day]
RfD_i	=	Chemical-specific inhalation reference dose [mg/kg-day]
SF_i	=	Chemical-specific inhalation cancer slope factor [(mg/kg-day) ⁻¹]
365	=	Conversion factor [day/year]

FIGURE B.15. INHALATION OF VAPORS AND PARTICULATES, DERMAL CONTACT WITH, AND INGESTION OF CHEMICALS IN SOIL (AGE-ADJUSTED RESIDENT)

Carcinogenic effects

$$RBTL_{ss-combined} = \frac{TR \times AT_c \times 365}{(SF_o \times 10^{-6} \times IR_{s-aa} \times RAF_o) + (SF_d \times 10^{-6} \times SA_{soil-aa} \times RAF_d) + SF_i \times IR_{ao-aa} \times (VF_{ss} + VF_p)}$$

Non-carcinogenic effects

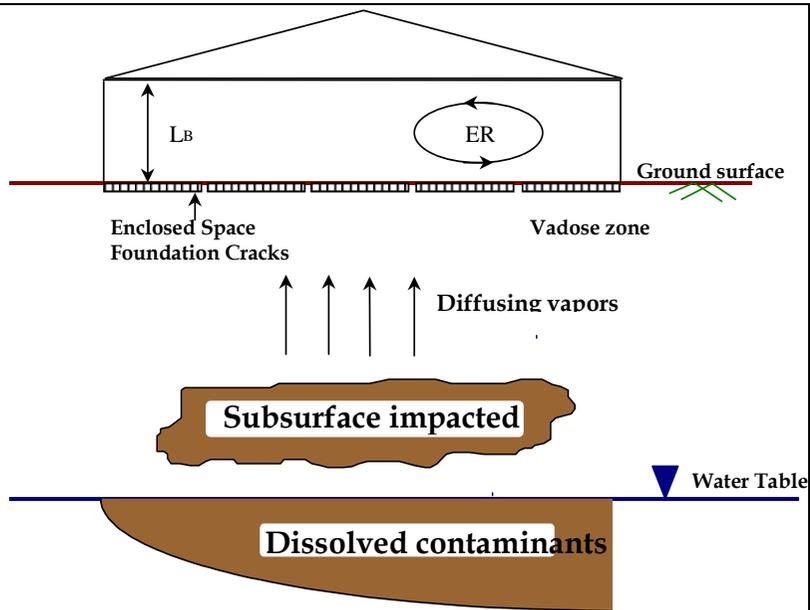
$$RBTL_{ss-combined} = \frac{THQ \times AT_{nc} \times 365}{\frac{1}{RfD_o} \times 10^{-6} \times IR_{s-aa} \times RAF_o + \frac{1}{RfD_d} \times 10^{-6} \times SA_{soil-aa} \times RAF_d + \frac{1}{RfD_i} \times IR_{ao-aa} \times (VF_{ss} + VF_p)}$$

Note: All parameters are defined under the individual pathway equations.

Note: $VF_{ss} = 0$ for non-volatile chemicals (i.e., chemicals with a molecular weight > 200 and Henry's law constant (dimensionless) < 4.2×10^{-4} or Henry's law constant (atm-m³/mol) < 1.5×10^{-5}).

Source: Modified from RAGS, Vol. I, Part E, 2004.

FIGURE B.16. SUBSURFACE SOIL VAPOR CONCENTRATIONS PROTECTIVE OF INDOOR VAPOR INHALATION



$$RBTL_{svi} = \frac{RBTL_{ai}}{VF_{sv}}$$

where:

$RBTL_{svi}$ = Risk-based target level for indoor inhalation of vapors from subsurface [$\text{mg}/\text{m}^3\text{-air}$]

$RBTL_{ai}$ = Risk-based target level for indoor inhalation of air [$\text{mg}/\text{m}^3\text{-air}$]

VF_{sv} = Volatilization factor from subsurface soil vapor to indoor (enclosed space) air [-]

Source: ASTM E1739-95

FIGURE B.17. SUBSURFACE SOIL CONCENTRATIONS PROTECTIVE OF INDOOR VAPOR INHALATION

$$RBTL_{si} = \frac{RBTL_{ai}}{VF_{seps}}$$

where:

- $RBTL_{si}$ = Risk-based target level for indoor inhalation of vapors from subsurface soils [mg/kg-soil]
- $RBTL_{ai}$ = Risk-based target level for indoor inhalation of air [mg/m^3 -air]
- VF_{seps} = Volatilization factor from subsurface soil to indoor (enclosed space) air [$(\text{mg}/\text{m}^3\text{-air})/(\text{mg}/\text{kg}\text{-soil})$]

Source: ASTM E1739-95

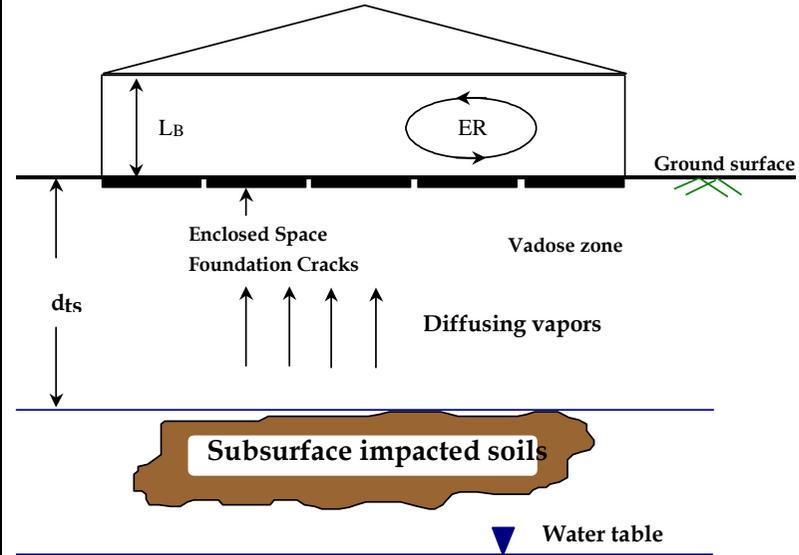


FIGURE B.18. GROUNDWATER CONCENTRATIONS PROTECTIVE OF INDOOR VAPOR INHALATION

$$RBTL_{wi} = \frac{RBTL_{ai}}{VF_{wesp}}$$

where:

- $RBTL_{wi}$ = Risk-based target level for indoor inhalation of vapors from groundwater [mg/L-water]
- $RBTL_{ai}$ = Risk-based target level for indoor inhalation of air (mg/m^3 -air)
- VF_{wesp} = Volatilization factor from groundwater to indoor (enclosed space) air [$(\text{mg}/\text{m}^3$ -air)/(mg/L-water)]

Source: ASTM E1739-95

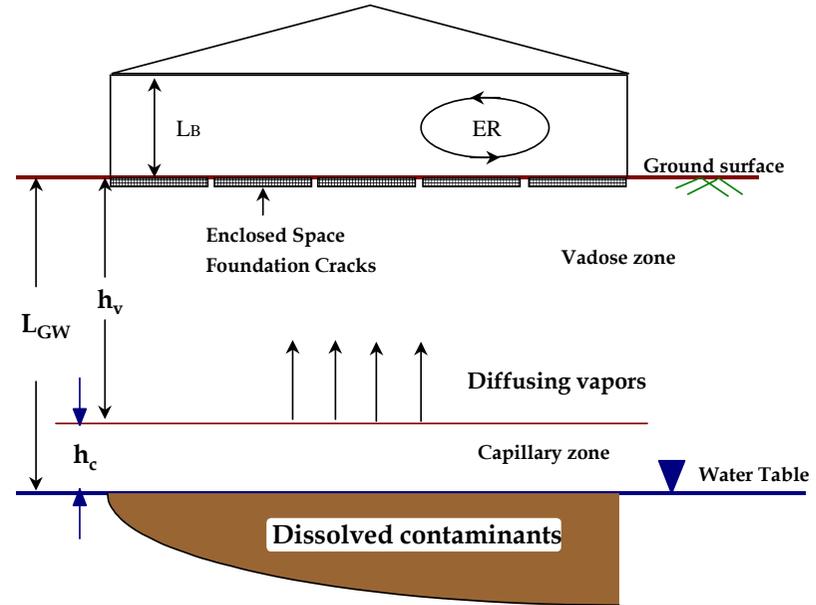


FIGURE B.19. GROUNDWATER CONCENTRATIONS PROTECTIVE OF OUTDOOR VAPOR INHALATION

$$RBTL_{wi} = \frac{RBTL_{ao}}{VF_{wamb}}$$

where:

$RBTL_{wi}$ = Risk-based target level for indoor inhalation of vapors from groundwater [mg/L-water]

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

VF_{wamb} = Volatilization factor from groundwater to outdoor air [(mg/m³-air)/(mg/L-water)]

Source: ASTM E1739-95

**FIGURE B.20.A. VOLATILIZATION FACTORS
(SURFICIAL SOIL TO OUTDOOR AIR)**

$$VF_{ss} = \left[Q/C \times \frac{(3.14 \times D_A \times \tau)^{1/2}}{(2 \times \rho_s \times D_A)} \times 10^{-4} \right]^{-1}$$

where:

$$D_A = \frac{(\theta_{as}^{10/3} \times D^a \times H + \theta_{ws}^{10/3} \times D^w) / \theta_T^2}{\rho_s \times K_{sv} + \theta_{ws} + \theta_{as} \times H}$$

or

$$VF_{ss} = \frac{W_a \times \rho_s \times d_s}{U_m \times \delta_a \times \tau} \times 10^3$$

Use smaller of the two VF_{ss} .

Source: Soil Screening Guidance, 1996

where:

- VF_{ss} = Volatilization factor from surficial soil to outdoor (ambient) air [kg-soil/m³-air]
- Q/C = Inverse of the mean concentration at the center of square source [(g/m²-s)/(kg/m³)]
- D_A = Apparent diffusivity [cm²/s]
- τ = Averaging time for vapor flux [s]
- ρ_s = Vadose zone dry soil bulk density of surficial soil [g-soil/cm³-soil]
- K_{sv} = Chemical-specific solid-water sorption coefficient [cm³-H₂O/g-soil]
- D^a = Chemical-specific diffusion coefficient in air [cm²/s]
- D^w = Chemical-specific diffusion coefficient in water [cm²/s]
- θ_T = Total soil porosity in the surficial soils [cm³/cm³-soil]
- θ_{as} = Volumetric air content in the surficial soils [cm³-air/cm³-soil]
- θ_{ws} = Volumetric water content in the surficial soils [cm³-H₂O/cm³-soil]
- H = Chemical-specific Henry's Law constant [(L-H₂O)/(L-air)]
- 10^{-4} = Conversion factor [m²/cm²]
- W_a = Dimension of soil source area parallel to wind direction [cm]
- d_s = Depth to base of surficial soil zone [cm]
- U_m = Mean annual wind speed [m/s]
- δ_a = Breathing zone height [cm]
- 10^3 = Conversion factor [(cm³-kg)/(m³-g)]

Note: Surficial soil properties are assumed same as the vadose zone properties.

**FIGURE B.20.B. VOLATILIZATION FACTORS
(PARTICULAR EMISSIONS FROM SURFICIAL SOIL)**

$$VF_p = \left[\frac{Q/C \times 3600}{0.036 \times (1 - V) \times (U_m/U_t)^3 \times F(x)} \right]^{-1}$$

Source: Soil Screening Guidance, 1996

where:

- VF_p = Volatilization factor for particulate emissions from surficial soil [kg-soil/m³-air]
- Q/C = Inverse of the mean concentration at the center of square source [(g/m²-s)/(kg/m³)]
- V = Fraction of vegetative cover [-]
- U_m = Mean annual wind speed [m/s]
- U_t = Equivalent threshold value of wind speed at 7 m [m/s]
- $F(x)$ = Function dependent on U_m/U_t derived using Cowherd *et al.* 1985 [-]
- 0.036 = Empirical constant [g/m²-hr]

**FIGURE B.20.C. VOLATILIZATION FACTORS
(SUBSURFACE SOIL VAPOR TO INDOOR AIR)**

$$VF_{sv} = \frac{\left[\frac{D_s^{eff} / d_{sv}}{ER \times L_B} \right]}{1 + \left[\frac{D_s^{eff} / d_{sv}}{ER \times L_B} \right] + \left[\frac{D_s^{eff} / d_{sv}}{(D_{crack}^{eff} / L_{crack}) \times \eta} \right]}$$

Source: ASTM E1739-95

where:

- VF_{sv} = Volatilization factor from subsurface soil vapor to indoor (enclosed space) air [-]
- θ_{ws} = Volumetric water content in vadose zone soils [$\text{cm}^3\text{-H}_2\text{O}/\text{cm}^3\text{-soil}$]
- θ_{as} = Volumetric air content in vadose zone soils [$\text{cm}^3\text{-air}/\text{cm}^3\text{-soil}$]
- d_{sv} = Depth to subsurface soil vapor samples taken [cm]
- L_B = Enclosed space volume/infiltration area ratio [cm]
- L_{crack} = Enclosed space foundation or wall thickness [cm]
- ER = Enclosed space air exchange rate [1/s]
- D_s^{eff} = Effective diffusion coefficient in soil based on vapor-phase concentration [cm^2/s]
- D_{crack}^{eff} = Effective diffusion coefficient through foundation cracks [cm^2/s]
- η = Area fraction of cracks in foundation and/or walls [$\text{cm}^2\text{-cracks}/\text{cm}^2\text{-total area}$]

**FIGURE B.20.D. VOLATILIZATION FACTORS
(SUBSURFACE SOIL TO INDOOR AIR)**

$$VF_{seep} = \frac{\frac{H \times \rho_s}{[\theta_{ws} + (K_{sv} \times \rho_s) + (H \times \theta_{as})]} \times \left[\frac{D_s^{eff} / d_{ts}}{ER \times L_B} \right]}{1 + \left[\frac{D_s^{eff} / d_{ts}}{ER \times L_B} \right] + \left[\frac{D_{crack}^{eff} / d_{ts}}{(D_{crack}^{eff} / L_{crack}) \times \eta} \right]} \times 10^3$$

Source: ASTM E1739-95

where:

- VF_{seep} = Volatilization factor from subsurface soil to indoor (enclosed space) air [m^3 -air/(mg/kg-soil)]
- H = Vadose zone specific Henry's Law constant [L-H₂O/L-air]
- ρ_s = Dry soil bulk density [g-soil/cm³-soil]
- θ_{ws} = Volumetric water content in vadose zone soils [cm³-H₂O/cm³-soil]
- K_{sv} = $f_{ocv} \times K_{oc}$
= Chemical-specific soil-water sorption coefficient in vadose zone [cm³-H₂O/g-soil]
- θ_{as} = Volumetric air content in vadose zone soils [cm³-air/cm³-soil]
- d_{ts} = Depth to subsurface soil sources [cm]
- L_B = Enclosed space volume/infiltration area ratio [cm]
- L_{crack} = Enclosed space foundation or wall thickness [cm]
- ER = Enclosed space air exchange rate [1/s]
- D_s^{eff} = Effective diffusion coefficient in soil based on vapor-phase concentration [cm²/s]
- D_{crack}^{eff} = Effective diffusion coefficient through foundation cracks [cm²/s]
- η = Area fraction of cracks in foundation and/or walls [cm²-cracks/ cm²-total area]
- 10^3 = Conversion factor [(cm³-kg)/(m³-g)]

**FIGURE B.20.E. VOLATILIZATION FACTORS
(GROUNDWATER TO INDOOR AIR)**

$$VF_{wesp} = \frac{H \times \left[\frac{D_{ws}^{eff} / L_{GW}}{ER \times L_B} \right]}{1 + \left[\frac{D_{ws}^{eff} / L_{GW}}{ER \times L_B} \right] + \left[\frac{D_{ws}^{eff} / L_{GW}}{(D_{crack}^{eff} / L_{crack}) \times \eta} \right]} \times 10^3$$

Source: ASTM E1739-95

where:

- VF_{wesp} = Volatilization factor from groundwater to indoor (enclosed space) air [(mg/m³-air)/(mg/L-H₂O)]
- H = Vadose zone chemical specific Henry's Law constant [(L-H₂O)/(L-air)]
- L_{GW} = Depth to groundwater [cm]
- L_B = Enclosed space volume/infiltration area ratio [cm]
- L_{crack} = Enclosed space foundation or wall thickness [cm]
- ER = Enclosed space air exchange rate [1/s]
- D_{ws}^{eff} = Effective diffusion coefficient between groundwater and soil surface [cm²/s]
- D_{crack}^{eff} = Effective diffusion coefficient through foundation cracks [cm²/s]
- η = Area fraction of cracks in foundation and/or walls [cm²-cracks/ cm²-total area]
- 10^3 = Conversion factor [L/m³]

**FIGURE B.20.F. VOLATILIZATION FACTORS
(GROUNDWATER TO OUTDOOR AIR)**

$$VF_{wamb} = \frac{H}{1 + \left(\frac{100 \times U_m \times \delta_a \times L_{GW}}{W_{ga} \times D_{ws}^{eff}} \right)} \times 10^3$$

where:

- VF_{wamb} = Volatilization factor from groundwater to outdoor air [(mg/m³-air)/(mg/L-water)]
- H = Vadose zone chemical specific Henry's Law constant [(L-water)/(L-air)]
- U_m = Mean annual wind speed [m/s]
- δ_a = Breathing zone height [cm]
- L_{GW} = Depth to groundwater [cm]
- D_{ws}^{eff} = Effective diffusion coefficient between groundwater and soil surface [cm²/s]
- W_{ga} = Dimension of soil source area parallel to wind direction [cm]
- 100 = Conversion factor [cm/m]
- 10³ = Conversion factor [L/m³]

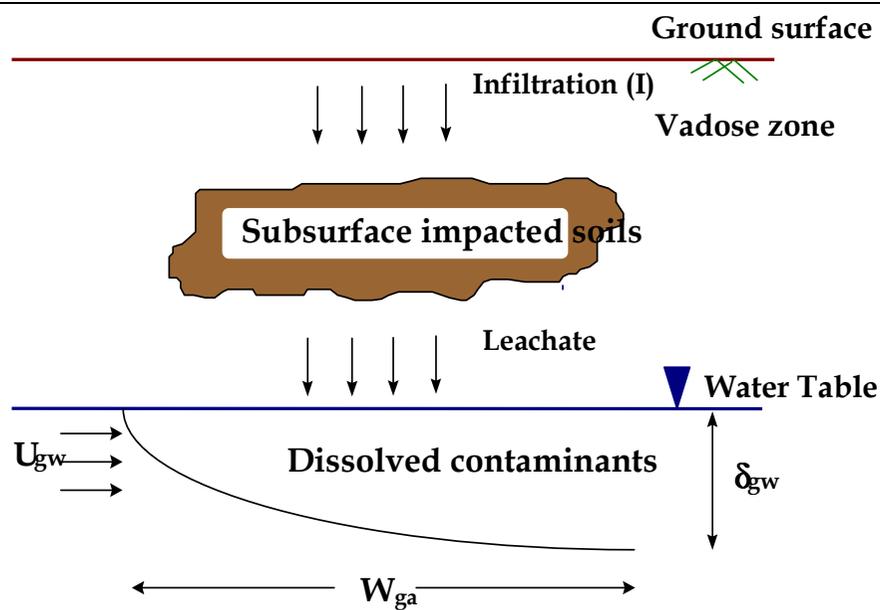
Source: ASTM E1739-95

FIGURE B.21. EFFECTIVE DIFFUSION COEFFICIENTS

<p>D_s^{eff} : effective diffusion coefficient in soil based on vapor-phase concentration [cm²/s]</p> $D_s^{eff} = D^a \times \frac{\theta_{as}^{3.33}}{\theta_T^{2.0}} + D^w \times \frac{1}{H} \times \frac{\theta_{ws}^{3.33}}{\theta_T^{2.0}}$ <p>where:</p> <ul style="list-style-type: none"> D^a = Chemical-specific diffusion coefficient in air [cm²/s] D^w = Chemical-specific diffusion coefficient in water [cm²/s] θ_{as} = Volumetric air content in capillary fringe soils [cm³-air/cm³-soil] θ_{ws} = Volumetric water content in capillary fringe soils [cm³-H₂O/cm³-soil] θ_T = Total soil porosity in the impacted zone [cm³/cm³-soil] H = Chemical-specific Henry's Law constant [L-H₂O/L-air] 	<p>D_{ws}^{eff} : effective diffusion coefficient between groundwater and surface soil [cm²/s]</p> $D_{ws}^{eff} = (h_c + h_v) \times \left[\frac{h_{cap}}{D_{cap}^{eff}} + \frac{h_v}{D_s^{eff}} \right]^{-1}$ <p>where:</p> <ul style="list-style-type: none"> h_c = Thickness of capillary fringe [cm] h_v = Thickness of vadose zone [cm] D_{cap}^{eff} = Effective diffusion coefficient through capillary fringe [cm²/s] D_s^{eff} = Effective diffusion coefficient in soil based on vapor-phase concentration [cm²/s] L_{GW} = Depth to groundwater ($h_c + h_v$) [cm]
<p>D_{cap}^{eff} : effective diffusion coefficient for the capillary fringe [cm²/s]</p> $D_{cap}^{eff} = D^a \times \frac{\theta_{acap}^{3.33}}{\theta_T^{2.0}} + D^w \times \frac{1}{H} \times \frac{\theta_{wcap}^{3.33}}{\theta_T^{2.0}}$ <p>where:</p> <ul style="list-style-type: none"> D^a = Chemical-specific diffusion coefficient in air [cm²/s] D^w = Chemical-specific diffusion coefficient in water [cm²/s] θ_{acap} = Volumetric air content in capillary fringe soils [cm³-air/cm³-soil] θ_{wcap} = Volumetric water content in capillary fringe soils [cm³-H₂O/cm³-soil] θ_T = Total soil porosity [cm³/cm³-soil] H = Chemical-specific Henry's Law constant [L-H₂O/L-air] 	<p>D_{crack}^{eff} : effective diffusion coeff. through foundation cracks [cm²/s]</p> $D_{crack}^{eff} = D^a \times \frac{\theta_{acrack}^{3.33}}{\theta_T^{2.0}} + D^w \times \frac{1}{H} \times \frac{\theta_{wcrack}^{3.33}}{\theta_T^{2.0}}$ <p>where:</p> <ul style="list-style-type: none"> D^a = Chemical-specific diffusion coefficient in air [cm²/s] D^w = Chemical-specific diffusion coefficient in water [cm²/s] θ_{acrack} = Volumetric air content in foundation/wall cracks [cm³-air/cm³-total volume] θ_{wcrack} = Volumetric water content in foundation/wall cracks [cm³-H₂O/cm³-total volume] θ_T = Total soil porosity [cm³/cm³-soil] H = Chemical-specific Henry's Law constant [L-H₂O/L-air]

Source: ASTM E1739-95

FIGURE B.22. SUBSURFACE SOIL CONCENTRATIONS PROTECTIVE OF LEACHING TO GROUNDWATER



$$RBTL_{SL} = \frac{RBTL_w}{LF_{SW}}$$

where:

- $RBTL_{SL}$ = Risk-based target level for leaching to groundwater from subsurface soil [mg/kg-soil]
- $RBTL_w$ = Risk-based target level for ingestion of groundwater [mg/L-H₂O]
- LF_{SW} = Leaching Factor (from subsurface soil to groundwater) [(mg/L-H₂O)/(mg/kg-soil)]

Source: ASTM E1739-95

FIGURE B.23. LEACHING FACTOR FROM SUBSURFACE SOIL TO GROUNDWATER

$$LF_{SW} = \frac{\rho_s}{[\theta_{ws} + K_{sv} \rho_s + H \times \theta_{as}] \times \left(1 + \frac{U_{gw} \times \delta_{gw}}{I \times W_{ga}} \right)}$$

where:

- LF_{SW} = Leaching factor from subsurface soil to groundwater [(mg/L-H₂O)/(mg/kg-soil)]
- ρ_s = Vadose zone dry soil bulk density [g-soil/cm³-soil]
- θ_{ws} = Volumetric water content in vadose zone soils [cm³-H₂O/cm³-soil]
- K_{sv} = $f_{ocv} \times K_{oc}$ = Chemical-specific soil-water sorption coefficient in vadose zone [cm³-H₂O/g-soil]
- H = Chemical-specific Henry's Law constant [L-H₂O/L-air]
- θ_{as} = Volumetric air content in the vadose zone soils [cm³-air/cm³-soil]
- U_{gw} = Ki = Groundwater Darcy Velocity [cm/yr]
- K = Hydraulic conductivity of the saturated zone [cm/year]
- i = Hydraulic gradient in the saturated zone [-]
- δ_{gw} = Groundwater mixing zone thickness [cm]
- I = Infiltration rate of water through vadose zone [cm/year]
- W_{ga} = Groundwater dimension parallel to groundwater flow direction [cm]

This equation consists of two parts (i) the Summer's model and (ii) equilibrium conversion of the leachate concentration to a soil concentration on a dry weight basis.

Source: ASTM E1739-95

FIGURE B.24. SOIL CONCENTRATION AT WHICH DISSOLVED PORE WATER AND VAPOR PHASES BECOME SATURATED

Single Component

$$C_s^{SAT} = \frac{S}{\rho_s} \times [H \times \theta_{as} + \theta_{ws} + K_{sv} \rho_s]$$

Multiple Components

$$C_s^{SAT} = \frac{S_{ei}}{\rho_s} \times [H \times \theta_{as} + \theta_{ws} + K_{sv} \rho_s]$$

where:

- C_s^{SAT} = Soil concentration at which dissolved pore water and vapor phases become saturated [(mg/kg-soil)]
- S = Pure component solubility in water [mg/L-H₂O]
- S_{ei} = Effective solubility of component i in water = $x_i \times S$ [mg/L-H₂O]
- x_i = Mole fraction of component i = $(w_i \times MW_{avg}) / MW_i$ [-]
- w_i = Weight fraction of component i [-]
- MW_{avg} = Average molecular weight of mixture [g/mole]
- MW_i = Molecular weight of component i [g/mole]
- ρ_s = Vadose zone dry soil bulk density [g-soil/cm³-soil]
- H = Chemical-specific Henry's Law constant [L-H₂O/L-air]
- θ_{as} = Volumetric air content in the vadose zone soils [cm³-air/cm³-soil]
- θ_{ws} = Volumetric water content in vadose zone soils [cm³-H₂O/cm³-soil]
- K_{sv} = $f_{ocv} \times K_{oc}$ = Chemical-specific soil-water sorption coefficient in vadose zone [cm³-H₂O/g-soil]
- f_{ocv} = Fraction organic carbon in vadose zone [g-C/g-soil]

Source: ASTM E1739-95

FIGURE B.25. SOIL VAPOR CONCENTRATION AT WHICH VAPOR PHASE BECOMES SATURATED

Single Component

$$C_v^{SAT} = \frac{P^s \times MW}{R \times T} \times 10^6$$

Multiple Components

$$C_v^{SAT} = \frac{x_i \times P_i^s \times MW_i}{R \times T} \times 10^6$$

where:

- C_v^{SAT} = Soil vapor concentration at which vapor phase become saturated [mg/m³-air]
- P^s = Saturate vapor pressure [atm]
- P_i^s = Effective vapor pressure of component *i* in water = $x_i \times P^s$ [atm]
- R = Ideal gas constant [0.08206 atm•L/mol•K]
- T = Temperature [K]
- S_{ei} = Effective solubility of component *i* in water = $x_i \times S$ [mg/L-H₂O]
- x_i = Mole fraction of component *i* = $(w_i \times MW_{avg})/MW_i$ [-]
- w_i = Weight fraction of component *i* [-]
- MW_{avg} = Average molecular weight of mixture [g/mole]
- MW_i = Molecular weight of component *i* [g/mole]
- ρ_s = Vadose zone dry soil bulk density [g-soil/cm³-soil]
- 10^6 = Conversion factor [(g/L)/(mg/m³)]

Source: ASTM E1739-95

FIGURE B.26. DOMENICO MODEL: DILUTION ATTENUATION FACTOR (DAF) IN THE SATURATED ZONE

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

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

where:

- C = Dissolved-phase concentration [mg/L]
- C_o = Dissolved-phase concentration at the source (at $x=y=z=0$) [mg/L]
- v = Retarded seepage velocity [m/sec]
- λ = Overall first order bio-decay rate [1/day]
- α_x = Longitudinal dispersivity [m]
- α_y = Lateral dispersivity [m]
- α_z = Vertical dispersivity [m]
- x, y, z = Spatial coordinates [m]
- t = Time [day]
- x = Distance along the centerline measured from the downgradient edge of the groundwater source [m]
- Y = GW source dimension perpendicular to GW flow direction [m]
- Z = GW source (mixing zone) thickness [m]
- DAF = $C_o/C(x)$

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

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

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

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

Note: Compare to ASTM E1739-95, p. 31, where $Y = S_w Z = S_d, v = u$, and $C_o = C_{source}$

Source: Domenico, P.A. and F.W. Schwartz, 1990, Physical and Chemical Hydrogeology. John Wiley and Sons, NY, 824 p. (Eqn. 17.21)

FIGURE B.27. ALLOWABLE SOIL AND GROUNDWATER CONCENTRATION FOR GROUNDWATER RESOURCE PROTECTION

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

$$\text{Allowable groundwater concentration at the POC [mg/L]} = \text{Target groundwater concentration at the POE} \times \frac{DAF_{POE}}{DAF_{POD}}$$

where:

- POE* = Point of exposure
- POD* = Point of demonstration
- DAF_{POE}* = Dilution attenuation factor between the point of exposure and source estimated using Domenico's equation
- DAF_{POD}* = Dilution attenuation factor between the point of demonstration and source estimated using Domenico's equation
- DAF_{unsat}* = Dilution attenuation factor in the unsaturated zone
- LF_{SW}* = Dry soil leaching factor [(mg/L-water)/(mg/kg-soil)]

Concentration at POE is expressed in mg/L-water. Additional relationships used in the calculation of allowable soil and groundwater concentration with chemical degradation:

$$\text{First order decay rate [1/day]} = \frac{0.693}{\text{Half Life}}; \quad v = \frac{Ki}{\theta_{TS} R_s}$$

$$\text{Retardation factor for organics in the saturated zone } (R_s) = 1 + \left(\frac{\rho_{ss} \times K_{ss}}{\theta_{TS}} \right), \quad K_{ss} = f_{ocs} \times K_{oc} \text{ (for organics only)}$$

where:

- v* = Regarded seepage velocity [cm/year]
- K* = Hydraulic conductivity in saturated zone [cm/year]
- i* = Hydraulic gradient in saturated zone [-]
- ρ_{ss}* = Saturated zone dry soil bulk density [g-soil/cm³-soil]
- K_{ss}* = Chemical-specific soil-water sorption coefficient in the saturated zone [cm³-H₂O/g-soil]
- K_{oc}* = Chemical-specific normalized partition coefficient [cm³/g-C]
- θ_{TS}* = Total porosity in the saturated zone [cm³/g-C]
- f_{ocs}* = Fractional organic carbon content in the saturated zone [g-C/g-soil]

FIGURE B.28. ALLOWABLE SOIL AND GROUNDWATER CONCENTRATION PROTECTIVE OF INDOOR INHALATION FOR RESIDENT AND NON-RESIDENTIAL WORKER

Allowable soil concentration at the source [mg/kg] = Target groundwater concentration below on/off - site building $\times \frac{DAF_{bldg}}{LF_{sw}} \times DAF_{unsat}$

Allowable groundwater concentration at the POD [mg/L] = Target groundwater concentration below on/off - site building $\times \frac{DAF_{bldg}}{DAF_{POD}}$

where:

- POD* = Point of demonstration
 - DAF_{bldg}* = Dilution attenuation factor between the on/off-site building and source estimated using Domenico's equation
 - DAF_{POD}* = Dilution attenuation factor between the point of demonstration and source estimated using Domenico's equation
 - DAF_{unsat}* = Dilution attenuation factor in the unsaturated zone
 - LF_{sw}* = Dry soil leaching factor [(mg/L-water)/(mg/kg-soil)]
- Concentration below on/off-site building is expressed in mg/L-water

FIGURE B.29. STREAM PROTECTION: ALLOWABLE GROUNDWATER CONCENTRATION AT THE POINT OF DISCHARGE

$$C_{gw} = \frac{C_{sw}(Q_{gw} + Q_{sw})}{Q_{gw}} - C_{su} \left(\frac{Q_{sw}}{Q_{gw}} \right)$$

$$Q_{gw} = (Z + \sqrt{\alpha_z X_s}) \times (Y + 2\sqrt{\alpha_y X_s}) \times U_{gw}$$

where:

- Q_{gw} = Impacted groundwater discharge into the stream [ft³/day]
- C_{gw} = Allowable concentration in groundwater at the point of discharge into the stream [mg/L]
- Q_{sw} = Stream flow upstream of the point of groundwater discharge (stream flow rate) [ft³/day]
- C_{sw} = Allowable concentration at the downstream edge of the stream's mixing zone, i.e., the applicable stream water quality criteria [mg/L]
- C_{su} = The COCs' concentration upstream of the groundwater plume discharge [mg/L]
- Y = GW source dimension perpendicular to GW flow direction [ft]
- Z = GW source (mixing zone) thickness [ft]
- α_y = Lateral dispersivity [ft]
- α_z = Vertical dispersivity [ft]
- X_s = Distance from the downgradient edge of the groundwater source to the stream [ft]
- U_{gw} = Darcy velocity [ft/day]

FIGURE B. 30. STREAM PROTECTION: ALLOWABLE SOIL AND GROUNDWATER CONCENTRATION AT THE SOURCE & POD

$$\text{Allowable soil concentration at the source [mg/kg]} = \text{Target concentration [mg/L] at the POE} \times \frac{DAF_{POE}}{LF_{SW}} \times DAF_{unsat}$$

$$\text{Allowable groundwater concentration at the POC [mg/L]} = \text{Target concentration [mg/L] at the POE} \times \frac{DAF_{POE}}{DAF_{POD}}$$

where:

- POE* = Point of exposure
- POD* = Point of demonstration
- DAF_{POE}* = Dilution attenuation factor between the point of exposure and source estimated using Domenico's equation
- DAF_{POD}* = Dilution attenuation factor between the point of demonstration and the source estimated using Domenico's equation
- DAF_{unsat}* = Dilution attenuation factor in the unsaturated zone
- LF_{SW}* = Dry soil leaching factor [(mg/L-H₂O)/(mg/kg-soil)]

For calculation of *DAF_{POE}* and *DAF_{POD}*, please refer to Domenico's model.