THEORY

BUILDING WAKE DISPERSION

DATE: December 2023

The Building Wake dispersion Model (BWM) includes the effect of building wakes on dispersion. The following cases are considered: (1) steady-state or instantaneous emission from the roof or within the recirculation zone downwind of the building, (2) steady-state vertical release from the chimney at the top of the building. The model is based on the building-wake formulation developed by TNO.

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ABSTRACT

In the case of a release of a pollutant from the roof or a chimney at the top of a building, the dispersion of the resulting plume may be affected by the building wake (recirculation zone) downwind of the building. A model for including the effects of a building wake is proposed. The following cases are considered: (1) steady-state or instantaneous emission from the roof or within the recirculation zone downwind of the building, (2) steady-state vertical release from the chimney at the top of the building. The model is based on the building-wake formulation developed by TNO (SDI model for roof/lee release, and Dutch National Model for chimney release).

Compared to the TNO model, the following major extensions to the model have been made:

- building: allow for angle between length-axis of building and mean-wind direction
- building wake: allow option for established Fackrell formula for building wake length, ensure mass of conservation in choice of building wake dimensions and formula for building wake concentration
- additional checking for applicability of model (e.g. added criterion for too heavy cloud)
- ambient data: ambient data are automated to be chosen to that of the building height (roof/lee release) or stack height (chimney release), instead of taken to be at 10 meter height
- inclusion of ideal-gas thermodynamics
- extended averaging-time logic fully compatible with UDM
- allowance of initial air in released pollutant for roof/lee release
- the instantaneous SDI model takes into account a residence time for the cloud to remain in the wake, prior to moving downwind

The above model has been implemented in a new standalone building-wake dispersion program called BWM. This program can be run standalone from an Excel spreadsheet (including automated editing, browsing and Excel plots, multiple runs).

The building-wake model has been integrated into the PHAST consequence modelling package and the risk-analysis package SAFETI. The input to BWM includes a possible link with the warehouse fire model for obtaining warehouse-fire data. The output generated by the BWM model is used in SAFETI for subsequent risk calculations.

The BWM results have been verified against results from the TNO program SDI for the case of roof/lee release. In addition they have also been verified using a simple spreadsheet program and hand calculations.

Possible areas of further development and improvements have been identified. This may include further updating of the BWM implementation to take into account the latest version of the Dutch National Model.

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1 INTRODUCTION

Background

As part of work for RIVM, DNV has implemented a warehouse fire model in the risk-analysis package SAFETI[i]. Amongst other things, the warehouse model calculates the release of a mixture of toxic combustion products from ventilation holes at the top of a building. The dispersion of the resulting toxic plume will be affected by the building wake (recirculation zone) downwind of the building.

The warehouse fire model is partly based on the Dutch CPR-15/2 regulatory method for carrying out a quantitative risk analysis for storage of hazardous materials[ii]. This method considers the cases of emission of hazardous materials from the top of the building (e.g. toxic combustion products due to fire) or within the building wake (e.g. due to accident during reloading). For these cases it assumes that the pollutant is fully taken up by the recirculation zone, and it adopts the SDI model[iii,iv] to calculate the short distance concentration.

The SDI model considers either an instantaneous release (for short duration) or a continuous release (for long duration). For distances larger than 100m, the SDI model assumes no building-wake effects and uses methods from the TNO yellow book[v,vi] to calculate dispersion. Otherwise the SDI model first sets the maximum concentration in the recirculation zone, which is assumed to be uniform. Subsequently the zone is considered to be a 'virtual area source' and dispersion downwind of this source is calculated using the Gaussian dispersion model.

In the case of a release from a chimney at the top of the building, the plume will not be affected by the building wake for large chimney heights, and only partly affected for intermediate chimney heights (lowering of the plume; modified Gaussian plume model). This is described in detail by a building-wake extension[vii] of the Dutch National Model[viii] for passive air pollution. Note that the plume-rise formula adopted in this model includes effects of plume rise both due to momentum and buoyancy.

The original version of the Dutch National Model was implemented by TNO into the program PLUIMPLUS[ix]. A 'building module' for use in PLUIMPLUS has been developed by KEMA. This module includes the building-wake extension of the Dutch National Model and also includes some further enhancements[x]. The final new Dutch National Model is described by the 'Project group Revision Dutch National Model'[xi].

Scope of work

The consequence modelling package PHAST and the risk-analysis package SAFETI currently include the Unified Dispersion Model UDM for modelling the dispersion[xii]. The UDM model currently assumes dispersion over flat terrain with uniform constant ambient conditions (ambient speed, pressure and temperature function of height only). The UDM model cannot treat the effect of obstacles or the effect of building wakes.

The objective of the current project is to include the effects of a building wake on the modelling of dispersion into PHAST and SAFETI. The following two cases are considered:

- vertical release from a chimney at the top of a rectangular building (steady-state only)
- emission from the roof of a rectangular building, or emission within the recirculation zone downwind of the building (continuous or instantaneous release).

The adopted model has been based on the TNO building-wake models (SDI[iii] and Dutch National Model[vii]) described above. A number of extensions have been applied to these models, e.g. inclusion of ideal-gas thermodynamics. An algorithm has been devised, and implemented into a new building-wake dispersion program called BWM. Figure 1 summarises the selection and integration of BWM in PHAST.

The building wake model has been implemented in a new standalone building-wake dispersion program called BWM. This program can be run standalone from an Excel spreadsheet (including automated editing, browsing and Excel plots, multiple runs).
The BWM results have been verified against results from the TNO program SDI for the case of roof/lee release.

The risk-analysis package SAFETI first carries out the PHAST consequence calculations (dispersion, fires, explosions) following the discharge of a hazardous material, and subsequently calculates probabilities using a toxic/flammable post-processor module.

The building-wake model has been integrated into the PHAST and SAFETI. The input to BWM includes a possible link with the warehouse fire model for obtaining warehouse-fire data. The output generated by the BWM model is used for subsequent risk calculations.

Plan of report

Chapter 2 first outlines the basic Gaussian dispersion model for dispersion over flat terrain. Subsequently it discusses the extension of this model to include the effects of the building wake. This is carried out for both cases of release from the roof or the circulation zone (based on TNO model SDI; continuous or instantaneous release) and the release from a chimney above the building (based on Dutch National Model; continuous release only). The above models have been integrated into the building-wake dispersion program BWM. The basic assumptions adopted by this model are summarised. 0 describes the inclusion of thermodynamics into the BWM model.

Chapter 3 includes results of the BWM program for both the case of the release from the lee or roof, and the release from a chimney. 0 includes the user's guide for the standalone model BWM.

Appendix C summarises the use of the SDI model in the Dutch QRA method for releases from a warehouse.

Chapter 4 discusses possible future developments. The results are given from a literature review regarding building-wake extensions, and several suggestions are made for modifications and extensions to the above TNO models.

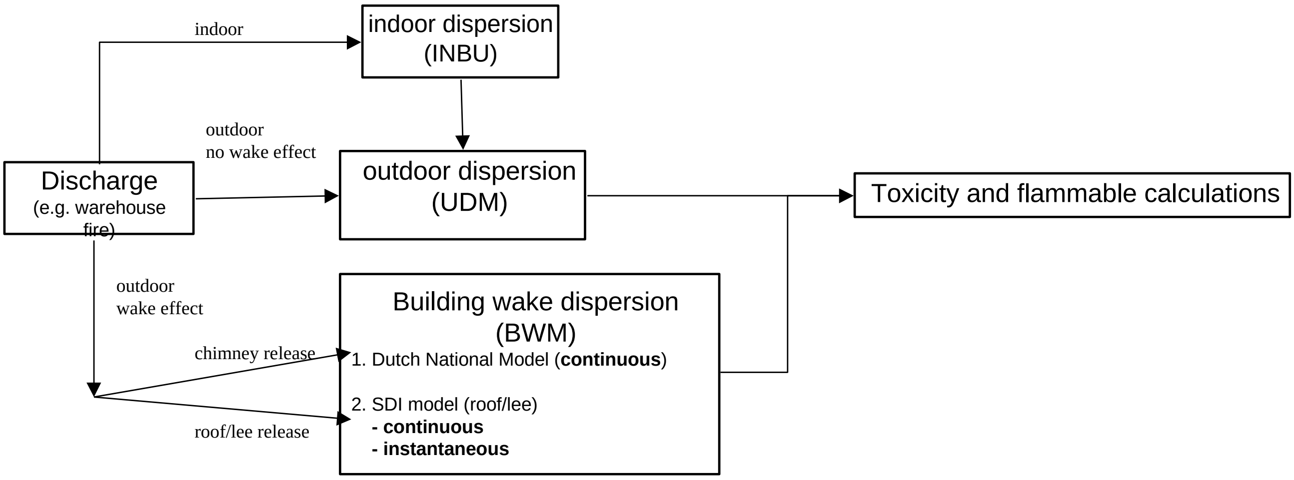


Figure 1. Selection and integration of Building Wake Model (BWM) in PHAST

2 MATHEMATICAL MODEL

In Section 2.1 the basic Gaussian dispersion model for dispersion over flat terrain is outlined for both cases of a continuous or instantaneous release.

In Sections 2.2 and 2.3 the extension of this model is discussed to include the effects of the building wake. This is carried out for both cases of release from the roof or the circulation zone (based on TNO model SDI; continuous or instantaneous release) and the release from a chimney above the building (based on Dutch National Model; continuous release only).

In Section 2.4 the integration of the above models into the building-wake dispersion program BWM has been described. The basic assumptions adopted by this model are summarised.

In 0 C the inclusion of thermodynamics into the BWM model is described.

2.1 Dispersion over flat terrain (Gaussian model)

This section describes the Gaussian dispersion model for flat terrain. The model corresponds to the old TNO yellow book[v] for distances x_e > 100 m, and to the SDI report[iii] for distances x_e < 100 m (with disturbed boundary layer). Note that this model is strictly speaking applicable to passive dispersion only, and heavy-gas effects or jet releases are not included. Sections 2.1.1 and 0 describe the case of continuous and instantaneous releases, respectively.

Use is made of Cartesian co-ordinates x, y, z with x the downwind distance from the source, y the crosswind distance and z the vertical height above the ground.

2.1.1 Continuous release

The continuous Pasquill-Gifford Gaussian model for neutral gas from a point source with strength Q = dm_c/dt (at release height h), supplies the following well-known formula for concentration c(x,y,z) in terms of the wind speed U_w and the dispersion coefficients $\sigma_y(x)$, $\sigma_z(x)$.

$$c(x,y,z) = \frac{Q}{2\pi U_w \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} \left\{ e^{-\frac{(z-h)^2}{2\sigma_z^2}} + e^{-\frac{(z+h)^2}{2\sigma_z^2}} \right\} \qquad (1)$$

The dispersion coefficient $\sigma_y(x)$ is a function of the stability class and averaging time t_{av} (s); $\sigma_z(x)$ is a function of the stability class and the surface roughness z_R.

<u>Far-field formulation</u>

According to the TNO yellow book[v] these coefficients are given in the far-field by

$$\sigma_y(x) = \left(\frac{t_{av}}{600}\right)^{0.2} a\, x^b \ , \ \sigma_z(x) = C_{ZR}\, c\, x^d \ , \ \textit{for } x > x_e = 100 \ m \qquad (2)$$

Here t_{av} is the averaging time (s), and $C_{ZR} = C_{ZR}(x;z_R)$ is the correction factor for the influence of the surface roughness z_R [$C_{ZR}(x;0.1)=1$]. The parameters a, b, c, d are given as a function of stability class in Table 1.

Table 1. Parameters in dispersion coefficients as function of stability class
[values taken from Table II in Section 3.4 of the 1992 TNO yellow book[v].]

stability class	a (m)	b (-)	c (m)	d (-)
A	0.527	0.865	0.28	0.90
B	0.371	0.866	0.23	0.85
C	0.209	0.897	0.22	0.80
D	0.128	0.905	0.20	0.76
E	0.098	0.902	0.15	0.73
F	0.065	0.902	0.12	0.67

<u>Near-field formulation</u>

For x < x_e=100 m, TNO recommends in its SDI model to take a linear relation [linear variation of $\sigma_y(x)$ and $\sigma_z(x;z_R=0.1)$ between x=0 and x=x_e

$$\sigma_y(x) = \frac{x}{x_e}\sigma_y(x_e) = \left(\frac{t_{av}}{600}\right)^{0.2} a\, x_e^{\,b-1}\, x \qquad (3)$$

$$\sigma_z(x) = C_{ZR}\frac{x}{x_e}\sigma_z(x_e; z_R = 0.1) = C_{ZR}\, c\, x_e^{\,d-1}\, x$$

The above near-field linearisation of σy and σz is illustrated by Figure 2.

Surface-roughness correction factor and σ_z power-law

The surface-roughness correction factor is given by

$$C_{ZR} = (10 z_R)^{0.53 x^{-0.22}} \qquad (4)$$

The above curve can accurately be fitted by a near-field and a far-field power-law

$$\begin{aligned} C_{ZR} &\approx \left\{2.158\ x^{-0.073}\right\}^{^{10}\log(10 z_R)}, \quad for \quad x > 100\ m \\ &\approx \left\{2.832\ x^{-0.132}\right\}^{^{10}\log(10 z_R)}, \quad for \quad x < 100\ m \end{aligned} \qquad (5)$$

The geometric formulas for x<100 m, x>100m have been obtained from fitting between 5 and 100 m, and 100 m and 1000 m, respectively. The first formula corresponds well with Table 1 in the SDI report[iii], while the latter formula (for x>100 m) gives close results to that of the TNO yellow book (see Appendix A to Ref. v). Thus by using the above equation in the σ_z-formula, the following approximate power-law formula applies (use x_e = 100 m):

$$\begin{aligned} &\sigma_z = c' x^{d'}, \quad with \\ &\quad c' = c\ 2.158^{\ ^{10}\log(10 z_R)}, \qquad d' = d - 0.073\ ^{10}\log(10 z_R) \qquad for \quad x > 100\ m \\ &\quad c' = c\ 100^{d-1} 2.832^{\ ^{10}\log(10 z_R)}, \quad d' = 1 - 0.132\ ^{10}\log(10 z_R) \qquad for \quad x < 100\ m \end{aligned} \qquad (6)$$

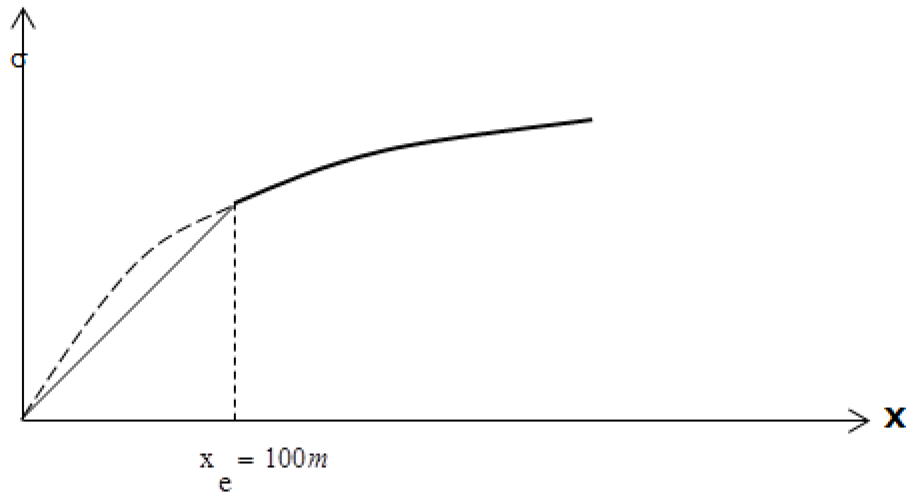


Figure 2. Near-field linearisation of Gaussian dispersion coefficients
cross-wind dispersion coefficient σ_y(x) and vertical dispersion coefficient σ_z(x;z_R=0.1); x = downwind distance from source, x_e = linearisation distance

2.1.2 Instantaneous release

Initial cloud (time t=0)

In the instantaneous Gaussian model for neutral gas from an elevated puff release with mass m_c (kg), the concentration is less than 100% at the source because of initial air absorption due to turbulence. The initial cloud concentration C_o (kg/m^3) is related to the initial pollutant mole fraction y_c^o by

$$C_0 = y_c^o \frac{M_c}{M_a} \rho_a(P_a, T_a) \quad (7)$$

where M_c is the molecular weight of the pollutant, M_a the molecular weight of air, and $\rho_a(P_a,T_a)$ the ambient density at the atmospheric pressure P_a and temperature T_a (effects of humidity are ignored).

If the initial cloud is assumed to be homogeneously distributed over a sphere with the initial concentration C_o and radius R_o, the cloud radius R_o can be determined from the following formula for the pollutant mass m_c

$$m_c = \frac{4}{3}\pi R_o^3 C_o \quad (8)$$

In reality however a Gaussian concentration distribution would be more appropriate. Therefore, spherical expansion of the cloud is assumed with an exponential decay with the radius R(x)[2],

$$c(R, x=0) = C_o e^{-R^2/2\sigma_o^2}, \ with \ \sigma_o = R_0 \sqrt[3]{\frac{2}{3\sqrt{2\pi}}} \approx 0.64 R_0 \quad (9)$$

where the value of σ_o is derived by imposing mass conservation.

Drifting cloud (time t>0); near-field linear Gaussian dispersion

The instantaneous cloud will drift in the downwind direction. The downwind distance of the centre of the instantaneous cloud from the release point is given by $x_{cld} = U_w t$, while the cloud growth is given by the dispersion coefficients σ_{xi}, σ_{yi}, σ_{zi}. For x_{cld}<100m, spherical expansion is assumed with a cloud radius $R = R(x_{cld}=U_w t)$ and the concentration is given by

$$c(R;\ x_{cld} = U_w t) = C_{max}(x_{cld}) e^{-\frac{R^2(x_{cld})}{2\sigma_R^2(x_{cld})}}, \ with \ C_{max}(x) = \frac{m}{(2\pi)^{3/2}\sigma_R^3(x_{cld})}, \ x_{cld} < 100\,m \quad (10)$$

Here C_{max} is the maximum concentration; the radial dispersion coefficient $\sigma_R(x_{cld})$ is given by

$$\sigma_R^2(x_{cld}) = \sigma_0^2 + \frac{\sigma_{xi}^2(x_{cld}) + \sigma_{yi}^2(x_{cld}) + \sigma_{zi}^2(x_{cld})}{3}, \quad x_{cld} < 100 \text{ m} \quad (11)$$

with the down-wind, cross-wind and vertical dispersion coefficients $\sigma_{xi}(x)$,$\sigma_{yi}(x)$, $\sigma_{zi}(x)$ given by

$$\sigma_{xi}(x) = \frac{x}{100}\sigma_{xi}(100), \ \sigma_{yi}(x) = \frac{x}{100}\sigma_{yi}(100), \ \sigma_{zi}(x) = \frac{x}{100}\sigma_{zi}(100), \ x < 100 \text{ m} \quad (12)$$
$$\sigma_{xi}(x) = 0.13x, \ \sigma_{yi}(x) = 0.5\,a\,x^b, \sigma_{zi}(x) = C_{ZR}\ c\ x^d \approx c' x^{d'}, \qquad x > 100 \text{ m}$$

with a, b, c, d given by Table 1. Notice that time-averaging is not applicable for instantaneous releases. Also the formula adopted for σ_{yi} corresponds to the choice of the ‘instantaneous averaging time’ t_{ins} = 18.75 sec. [0.5 = $(t_{ins}/600)^{0.2}$]. Finally note that the formula for σ_{xi} is applicable at ground level; σ_{xi} will be strongly dependent on the source height since it is primarily influenced by the increase of the wind with the height.

Drifting cloud (time t>0); far-field nonlinear Gaussian dispersion

For x_{cld}>100 m the well-known passive Pasquill-Gifford dispersion formula is adopted for the concentration c(x,y,z,t) in terms of the wind speed U_w and the dispersion coefficients $\sigma_{xi}=\sigma_{xi}(x_{cld}-100+x_{vx})$, $\sigma_{yi}=\sigma_{yi}(x_{cld}-100+x_{vy})$, $\sigma_{zi}=\sigma_{zi}(x_{cld}-100+x_{vz})$[3]:

[2] Note that this implies that the puff assumes to remain spherical. For a puff releases at or near the ground-level the spherical assumption may not be appropriate.

[3] Note that C_{max} should be considered the maximum concentration for an elevated cloud only (σ_z<<h). However Section 2.2 in the SDI report does not mention this.

$$c(x, y, z, t) = C_{\max}(x_{cld}) e^{-\frac{(x-U_w t)^2}{2\sigma_{xi}^2}} e^{-\frac{y^2}{2\sigma_{yi}^2}} \left\{ e^{-\frac{(z-h)^2}{2\sigma_{zi}^2}} + e^{-\frac{(z+h)^2}{2\sigma_{zi}^2}} \right\}, \text{ with } x_{cld} = U_w t > 100 \text{ m} \quad (13)$$

with the maximum concentration given by

$$C_{\max}(x_{cld}) = \frac{m_c}{(2\pi)^{3/2} \sigma_{xi} \sigma_{yi} \sigma_{zi}}, \quad x_{cld} > 100 \text{ m} \quad (14)$$

where the virtual distances x_{vx}, x_{vy}, x_{vz} are set such that $\sigma_{xi}(x_{vx}) = \sigma_{yi}(x_{vy}) = \sigma_{zi}(x_{vz}) = \sigma_R(x_{cld}=100)$.

Cloud passage time

Particularly for toxic clouds, the cloud passage time is relevant. The passage time is the period that the concentration at a given location is higher than a given lower-limit concentration. In line with the TNO yellow book, this lower-limit concentration is selected to be 10% of the maximum concentration C_{max}. The passage time t_{pas} is equal to the ratio of the cloud length $L_c(x_{cld})$ and the wind speed U_w, where the cloud length L_c is defined by the area with maximum concentration larger than 10%. Thus $L_c = 4.3\ \sigma_R(x_{cld})$ for $x_{cld} < 100$ m and $L_c = 4.3\ \sigma_{xi}(x_{cld})$ for $x_{cld} > 100$ m.

2.2 Release from roof or within recirculation zone (SDI model)

2.2.1 Continuous release

Section 2.3.1 in the SDI report[iii] discusses the method adopted in the TNO short-distance emission model SDI in case of a continuous release from a roof of the building or within the recirculation zone downwind of the building. The building has a length l_b, width b_b, and height h_b. The recirculation area has a length L_x, a half-width L_y, and a height L_z. Thus the recirculation zone corresponds to $0 < X < L_x$, $0 < |y| < L_y$, $0 < z < L_z$. Here $X = x – l_b/2$ is the downwind distance from the downwind edge of building , and x is the downwind distance from the middle of the building. See Section 2.4.2 for a discussion of the evaluation of the building wake dimensions L_x, L_y, L_z.

The SDI model for continuous releases is summarised in Figure 3. The downwind dispersion is split into three zones ($X = x- l_b/2$ = downwind distance from building) :

(1) uniform concentration along recirculation zone ($½l_b<x<L_x+½l_b$; $0<X<L_x$)
(2) near-field linearised Gaussian dispersion ($L_x<X<X_e$; present for $L_x<X_e$ only)
(3) far-field non-linear Gaussian dispersion ($X>X_e$)

The calculation of the dispersion for the above zones is described below.

In recirculation zone ($0<X<L_x$)

The concentration within the recirculation zone is assumed to be uniform according to a formula proposed by Builtjes[xiii,4]

$$c(x,y,z) = \frac{Q}{KAU_w} \text{, inside recirculation zone (no other buildings)} \quad (15)$$

where U_w is the wind speed (m/s), Q the release rate (kg/s), and

- A = building area perpendicular to wind direction
- K = 1 in general case. K varies from 0.2 to 1.5, TNO recommends to choose worst-case value K=0.2. Note that this worst-case estimate may be too conservative for best-estimate calculations.

For $X< L_x$, the above uniform concentration is assumed within the recirculation zone ($|y| < L_y$, $z < L_z$) and a zero concentration outside. Note that the above formula is applicable if no building is present in the recirculation zone with building width larger than the building causing the recirculation.[5]

Downwind of recirculation zone (case of presence of linear Gaussian dispersion: $L_x<X_e$)

At $X = L_x$, the virtual point-source approach from Section 3.7 of the TNO yellow book[v] is adopted to derive the concentration downwind to $X=L_x$ from that upwind of $X=L_x$. Linearised Gaussian dispersion is adopted for $L_x<X<X_e$ and non-linear Gaussian dispersion is adopted for $X>X_e$.

The algorithm for determining the concentration for $L_x<X<X_e$ is as follows[6]:

1. Set source dimensions at $X=L_x$: half-width L_y, height L_z
2. Set dispersion coefficients at $X= L_x$: $\sigma_y=L_y/1.25$, $\sigma_z=L_z/1.25$[7]
3. Calculate downwind distances for virtual source X_{vy}, X_{vz}: set X_{vy}, X_{vz} such that $\sigma_y(X_{vy})= L_y/1.25$, $\sigma_z(X_{vz})= L_z/1.25$ and with $\sigma_y(X)$, $\sigma_z(X)$ formulas valid for $X<X_e$ [see Equation (3) and Equation (6)]

   $$X_{vy} = \sigma_y/[a(t_{av}/600)^{0.2} X_e^{b-1}] = L_y /[1.25a(t_{av}/600)^{0.2} X_e^{b-1}]$$

   $$X_{vz} = \{\sigma_z/c'\}^{1/d'} = \{L_z /[1.25c']\}^{1/d'}$$

4. Calculate concentration c(x,y,z) for $L_x < X < X_e = 100$ m from Equation (1) with h=0, using the near-field formulas (3) and (6) for setting $\sigma_y = \sigma_y(X-L_x+X_{vy})$ and $\sigma_z=\sigma_z(X-L_x+X_{vz})$:

[4] A uniform concentration is assumed within the recirculation zone, and zero outside. This type of concentration distribution could be applied by choosing appropriate (large) values for the exponents in the UDM concentration profile.

[5] The SDI report also considers the case of another building being present in the recirculation zone. Let X_b be the building distance ($X_b < L_x$). An extra correction is needed for the concentration inside the recirculation zone if the building width is larger than the width b_b of the building causing the recirculation: $c(x,y,z) = [L_x/X_b] [Q/(KAU_w)]$. This extra correction is not included in BWM at this stage.

[6] Note that the values for $x > L_x$ correspond to an averaging time of t_{av}. In the lee the concentrations are maximum concentrations irrespective of this concentration level (no time averaging).

[7] Note that this converts the top-hat cross-wind profile at $X=L_x$ to an equivalent Gaussian profile. Note that this may be considered to be carried out more gradually, e.g. by adopting the UDM concentration profile. This profile allows a more gradual transition between top-hat profile and Gaussian profile.

$$c(x,y,z) = \frac{Q}{\pi U_w \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} e^{-\frac{z^2}{2\sigma_z^2}} \tag{16}$$

At X = X_e, the virtual point-source approach is adopted to derive the concentration downwind to X=X_e from that upwind of X=X_e:

1. Calculate dispersion coefficients at X = X_e using Equation (3) and Equation (6) valid for X< X_e: $\sigma_y = \sigma_y(X_e - L_x + X_{vy})$, $\sigma_z = \sigma_z(X_e - L_x + X_{vz})$
2. Calculate downwind distances X_{vy}, X_{vz} for virtual source by imposing continuity at X = X_e and using Equation (2) and Equation (6) valid for X> X_e:

$$X_{vy} = \{\sigma_y/[a(t_{av}/600)^{0.2}]\}^{1/b},\ \ X_{vz} = \{\sigma_z/c'\}^{1/d'}$$

3. Calculate concentration c(x,y,z) for X > X_e from Equation (1) with h=0, using the far-field formulas (2), (6) for setting $\sigma_y = \sigma_y(X - X_e + X_{vy})$, $\sigma_z = \sigma_z(X - X_e + X_{vz})$:

$$c(x,y,z) = \frac{Q}{\pi U_w \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} e^{-\frac{z^2}{2\sigma_z^2}} \tag{17}$$

Downwind of recirculation zone (no presence of linear Gaussian dispersion only: L_x>X_e)

Note that the above formulation is applicable for X_e>L_x only, i.e. if the point of near- to far-field transition lies downwind to the edge of the lee. In case of X_e<L_x, only one transition occurs and the virtual point-source approach needs only to be applied once. In this case

1. Set at X= L_x: $\sigma_y = L_y/1.25$, $\sigma_z = L_z/1.25$
2. Calculate virtual-source downwind distances:

$$X_{vy} = \{\sigma_y/[a(t_{av}/600)^{0.2}]\}^{1/b},\ \ X_{vz} = \{\sigma_z/c'\}^{1/d'}$$

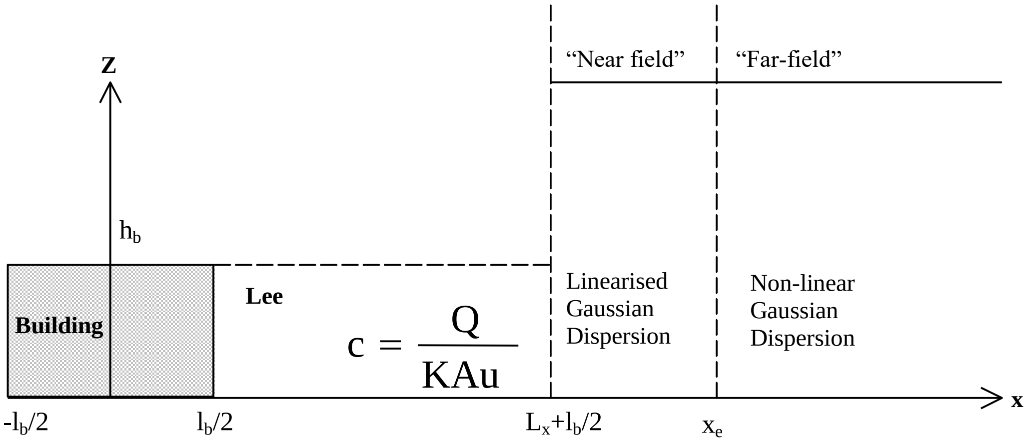
3. Calculate concentration c(x,y,z) for X > X_e from Equation (1) with h=0, using the far-field formulas (2) and (6) for setting $\sigma_y = \sigma_y(X - L_x + X_{vy})$ and $\sigma_z = \sigma_z(X - L_x + X_{vz})$:

$$c(x,y,z) = \frac{Q}{\pi U_w \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y^2}} e^{-\frac{z^2}{2\sigma_z^2}} \tag{18}$$

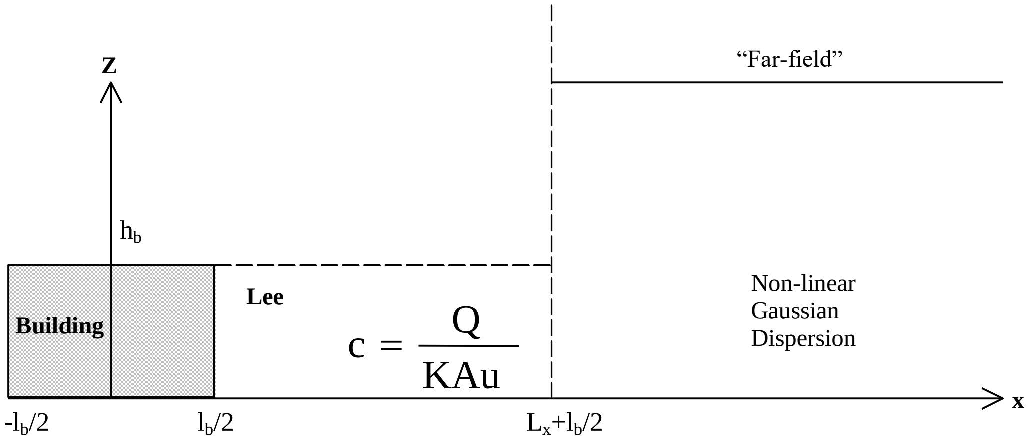
Note that at the downwind edge of the lee, X = L_x, the Gaussian formulas [Equation (18) or (16)] yields for the maximum concentration [y=0, z=0,]

$$c\left(\frac{l_b}{2} + L_x, 0, 0\right) = \frac{Q}{\pi U_w \frac{L_y}{1.25} \frac{L_z}{1.25}} \approx \frac{Q}{2 U_w L_y L_z}$$

which is consistent with the building-wake concentration c =Q/[KAU_w] provided that KA = 2 $L_y L_z$.



(a) Case of presence of linear Gaussian dispersion ($L_x<X_e$, or $L_x+½l_b<x_e$)



(b) Case of no presence of linear Gaussian dispersion ($L_x>X_e$, or $L_x+½l_b>x_e$)

Figure 3. The continuous SDI model for roof/lee releases.
The downwind dispersion is split into three zones ($X = x- l_b/2$ = downwind distance from building) :
(1) uniform concentration $c=Q/KAu$ along recirculation zone ($½l_b<x<L_x+½l_b$; or equivalent $0<X<L_x$)
(2) near-field linearised Gaussian dispersion ($L_x+½l_b <x<x_e$; or $L_x<X<X_e$; present for $L_x<X_e$ only)
(3) far-field non-linear Gaussian dispersion ($x>x_e$; or $X>X_e$)

2.2.2 Instantaneous release (including BWM extension of SDI)

Section 2.3.2 in the SDI report[iii] discusses the method adopted in the TNO short-distance emission model SDI in case of an instantaneous release from a roof of the building or within the recirculation zone downwind of the building. The model reported in this section contains a description of this SDI model, including a description and discussion of the further extensions applied to the BWM model.

The SDI model for instantaneous releases is summarised in Figure 4. The downwind dispersion is split as follows:

(a) Initially (for time < residence time t_{res}) the instantaneous cloud remains in the building wake and an uniform concentration within the recirculation zone is assumed ($½l_b<x<L_x+½l_b$; $0<X<L_x$)
(b) At time $t=t_{res}$ the cloud is approximated by an equivalent instantaneous Gaussian cloud
(c) For larger times ($t>t_{res}$), the cloud disperses in the downwind direction

The calculation of the dispersion described below.

<u>In recirculation zone ($0<X<L_x$)</u>

A homogeneous distribution of material in the recirculation volume is assumed

$$c(x,y,z,t) \quad = \frac{m_c}{K\,L_x A} = \frac{m_c}{L_x(2L_y)L_z}, \quad \text{inside rec. zone (no other buildings), for } t<t_{res} \qquad \textbf{(19)}$$

For X< L_x, the above uniform maximum concentration is assumed within the recirculation zone ($|y| < L_y$, $z < L_z$) and a zero concentration outside. The above maximum concentration is assumed for the times t less than the residence time t_{res} of the instantaneous plume into the cloud. Note that the above formula is applicable if no building is present in the recirculation zone with building width larger than the building causing the recirculation.[8]

Compared to the original SDI model, the following extensions are adopted to the BWM model:

1. The SDI model adopts K=1 always ($2L_yL_z$ = KA = A), which is inconsistent with the assumption K=0.2 quoted in the Dutch QRA CPR-15/2 method[ii] (see also 0). Duijm and Webber[xix] quote the recommendation K=0.5 from Fackrell and Pearce[xiv]. Note that the recommended values of K for instantaneous releases appear to be different to those for continuous releases (see Section 4)!

2. The SDI model provides a value for the maximum lee concentration only, and does not provide information on the residence time t_{res}. The BWM adopts the correlation by Fackrell and Pearce[xiv],

$$t_{res} \quad = \quad \frac{h_b}{U_w}\;\frac{11\left(\dfrac{b_b}{h_b}\right)^{1.5}}{1+0.6\left(\dfrac{b_b}{h_b}\right)^{1.5}} \qquad \textbf{(20)}$$

   The above correlation is stated by Duijm and Webber[xix] to agree with experimental data within 20% for $b_b/h_b<7$ and $0.05<l_b/h_b<7$. Mavroidis et al.[xv] also confirmed good agreement of this formula with experimental data. Note that the residence time is in the literature defined as the time it takes for the concentration to decay by '1/e' of its original value. In the BWM model, it is used in a simplified manner to define the time that the instantaneous cloud remains in the building wake.

3. For a very large release rate m_c, Equation (19) may result in a larger than 100% concentration. This means that the instantaneous source will fill more than the building wake. This is not allowed in the building wake model, and the user is recommended to run instead the UDM model.

8 The SDI report also considers this case. Let X_b be the building distance ($X_b < L_x$). An extra correction is needed for the concentration inside the recirculation zone ($t<t_{res}$) if the building width is larger than the width b_b of the building causing the recirculation: $c(x,y,z,t) = [L_x/X_b]\,[m_c/(KL_xA)] = m_c/[KX_bA]$. This extra correction is not included in BWM at this stage.

Downwind of recirculation zone

The formulation for the SDI model downwind of the recirculation zone is not fully described in the SDI report, and several provisional assumptions are adopted below[9].

For $t < t_{res}$, concentrations outside the building wake are zero and concentrations inside the building wake are as given above. Only after time $t = t_{res}$ the cloud is considered to move in the downwind direction. At time $t=t_{res}$, the cloud centre is chosen at the middle of the building wake, i.e. $x_{cld}(t_{res}) = ½ (l_b+L_x)$ or $X_{cld}(t_{res}) = ½ L_x$. Here $x_{cld} = X_{cld}+½l_b$ is the downwind distance of the centre of the cloud from the centre of the building, and X_{cld} the downwind distance from the downwind edge of the building.

The virtual point-source approach from Section 3.7 of the TNO yellow book[v] is adopted to match at time $t=t_{res}$ the 'recirculation area plume' with an equivalent instantaneous Gaussian plume. Thus the dispersion coefficients of the new instantaneous source area are found.

After time $t=t_{res}$, the instantaneous cloud will move in the downwind direction with a speed U_w. Thus the position of the cloud centre is given by

$$X_{cld}(t) = \frac{L_x}{2} + U_w(t - t_{res}) \qquad \text{for } t>t_{res} \tag{21}$$

Linearised Gaussian dispersion is included as for the continuous SDI model. Unlike the original SDI model where no time averaging was adopted ($t_{av}= t_{av}^{ins}$ =18.75s), the BWM model allows the option of time averaging.

Downwind of recirculation zone (case of presence of linear Gaussian dispersion: $X_e>L_x/2$)

Linearised Gaussian dispersion is adopted for $L_x/2<X_{cld}<X_e$ and non-linear Gaussian dispersion is adopted for $X_{cld}>X_e$.

The algorithm for determining the concentration for $L_x<X_{cld}<X_e$ is as follows

1. Set source dimensions (at time $t=t_{res}$) equal to lee dimensions: length L_x, half-width L_y, height L_z
2. Set dispersion coefficients at $X_{cld}= L_x/2$: $\sigma_x=L_x/2.50$, $\sigma_y=L_y/1.25$, $\sigma_z=L_z/1.25$[10]
3. Calculate downwind distances for virtual source X_{vx}, X_{vy}, X_{vz}: set X_{vx}, X_{vy}, X_{vz} such that $\sigma_x(X_{vx})= L_x/2.50$, $\sigma_y(X_{vy})= L_y/1.25$, $\sigma_z(X_{vz})= L_z/1.25$ and with $\sigma_y(X)$, $\sigma_z(X)$ far-field formulas valid for $X<X_e$ [Equations (3) and (6), with $t_{av}=t_{av}^{ins}$]

   $X_{vx} = \sigma_x/0.13 = L_x/[2.50*0.13]$

   $X_{vy} = \sigma_y/[a(t_{av}^{ins}/600)^{0.2} X_e^{b-1}] = L_y /[1.25a(t_{av}^{ins}/600)^{0.2} X_e^{b-1}]$

   $X_{vz} = \{\sigma_z/c'\}^{1/d'} = \{L_z /[1.25c']\}^{1/d'}$

4. Calculate the concentration $c(x,y,z,t)$ for $L_x/2<X_{cld}(t)<X_e$ from Equation (13) with h=0 and using $\sigma_x = \sigma_x(X_{cld}-½L_x+X_{vx})$, $\sigma_y = \sigma_y(X_{cld}-½L_x+X_{vy})$ and $\sigma_z=\sigma_z(X_{cld}-½L_x+X_{vz})$,

$$c(x, y, z, t) = \frac{2\,m_c}{(2\pi)^{3/2}\sigma_{xi}\sigma_{yi}\sigma_{zi}} e^{-\frac{(X - X_{cld}(t))^2}{2\sigma_{xi}^2}} e^{-\frac{y^2}{2\sigma_{yi}^2}} e^{-\frac{z^2}{2\sigma_{zi}^2}} \qquad \text{for } ½L_x<X_{cld}(t)<X_e \tag{22}$$

$$X_{cld}(t) = \frac{L_x}{2} + U_w(t - t_{res})$$

At $X = X_e$, the virtual point-source approach is adopted to derive the concentration downwind to $X=X_e$ from that upwind of $X=X_e$:

1. Calculate dispersion coefficients at $X = X_e$ using Equation (3) and Equation (6) valid for $X_{cld} < X_e$: $\sigma_x = 0.13(X_e - L_x/2+X_{vx})$ $\sigma_y = \sigma_y(X_e - L_x/2+X_{vy})$, $\sigma_z = \sigma_z(X_e - L_x/2+X_{vz})$

[9] Following trial runs of the SDI code, dispersion results downwind of the building wake did not appear to be affected by the building wake at all (e.g. possibly significant increase of concentration for distances downwind of the wake). Also no specific example is provided in the SDI report itself for instantaneous releases within the building wake.

[10] Note that this converts at time $t = t_{res}$, the top-hat profile (uniform concentration in lee) to an equivalent Gaussian profile.

2. Calculate downwind distances X_{vx},X_{vy}, X_{vz} for virtual source by imposing continuity at X = X_e and using Equation (2) and Equation (6) valid for X> X_e (with t_{av}=t_{av}^{ins}):

$X_{vx} = \sigma_x/0.13$, $X_{vy} = \{\sigma_y/[a(t_{av}^{ins}/600)^{0.2}]\}^{1/b}$, $X_{vz} = \{\sigma_z^{ins}/c'\}^{1/d'}$

3. Calculate the concentration c(x,y,z,t) for time $X_{cld}(t)>X_e$ from Equation (13) with h=0 and using $\sigma_x = \sigma_x(X_{cld}-½L_x+X_{vx})$, $\sigma_y = \sigma_y(X_{cld}-½L_x+X_{vy})$ and $\sigma_z=\sigma_z(X_{cld}-½L_x+X_{vz})$,

$$c(x,y,z,t) = \frac{2\,m_c}{(2\pi)^{3/2}\sigma_{xi}\sigma_{yi}\sigma_{zi}} e^{-\frac{(X-X_{cld}(t))^2}{2\sigma_{xi}^2}} e^{-\frac{y^2}{2\sigma_{yi}^2}} e^{-\frac{z^2}{2\sigma_{zi}^2}} \quad \text{for } X_{cld}(t)>X_e \qquad (23)$$

$$X_{cld}(t) = \frac{L_x}{2} + U_w(t-t_{res})$$

<u>Downwind of recirculation zone (no presence of linear Gaussian dispersion: $X_e<L_x/2$)</u>

Note that the above formulation is applicable for $X_e>L_x/2$ only. In case of $X_e<L_x/2$, only one transition occurs and the virtual point-source approach needs only to be applied once. In this case the algorithm is as follows:

1. Set source dimensions (at time $t=t_{res}$) equal to lee dimensions: length L_x, half-width L_y, height L_z
2. Set dispersion coefficients at X= L_x: $\sigma_x=L_x/2.50$, $\sigma_y=L_y/1.25$, $\sigma_z=L_z/1.25$
3. Calculate downwind distances for virtual source X_{vx}, X_{vy}, X_{vz}: set X_{vx}, X_{vy}, X_{vz} such that $\sigma_x(X_{vx})= L_x/2.50$, $\sigma_y(X_{vy})= L_y/1.25$, $\sigma_z(X_{vz})= L_z/1.25$ and with $\sigma_y(X)$, $\sigma_z(X)$ far-field formulas [Equations (2) and (6), with t_{av}=t_{av}^{ins}]

   $X_{vx} = \sigma_x/0.13 = L_x/[2.50*0.13]$

   $X_{vy} = \{\sigma_y/[(t_{av}^{ins}/600)^{0.2}]\, a\}^{1/b} = \{L_y/[1.25*0.5*a]\}^{1/b}$

   $X_{vz} = \{\sigma_z/c'\}^{1/d'} = \{L_z/[1.25c']\}^{1/d'}$

4. Calculate the concentration c(x,y,z,t) for time $t>t_{res}$ from Equation (13) with h=0 and using $\sigma_x = \sigma_x(X_{cld}-½L_x+X_{vx})$, $\sigma_y = \sigma_y(X_{cld}-½L_x+X_{vy})$ and $\sigma_z=\sigma_z(X_{cld}-½L_x+X_{vz})$,

$$c(x,y,z,t) = \frac{2\,m_c}{(2\pi)^{3/2}\sigma_{xi}\sigma_{yi}\sigma_{zi}} e^{-\frac{(X-X_{cld}(t))^2}{2\sigma_{xi}^2}} e^{-\frac{y^2}{2\sigma_{yi}^2}} e^{-\frac{z^2}{2\sigma_{zi}^2}} \quad \text{for } t>t_{res} \qquad (24)$$

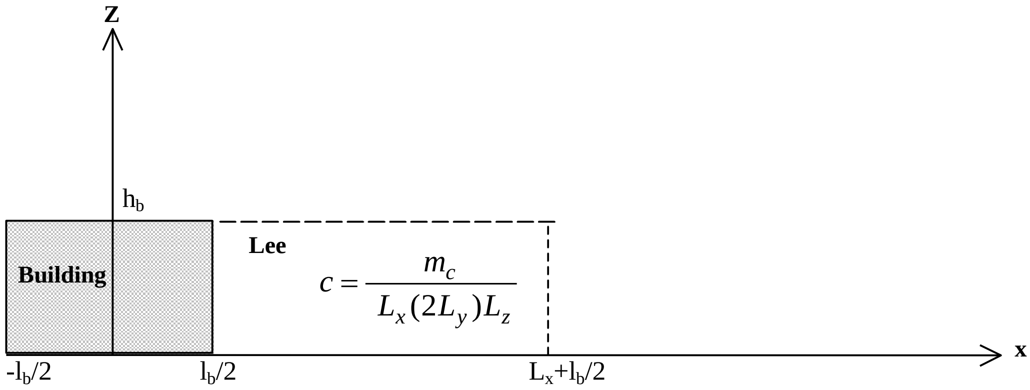
$$X_{cld}(t) = \frac{L_x}{2} + U_w(t-t_{res})$$

Note that at time t = t_{res}, the above formula (24) yields for the concentration at the centre of the cloud $X=X_{cld}(t_{res})= ½\,L_x$, y=0, z=0,

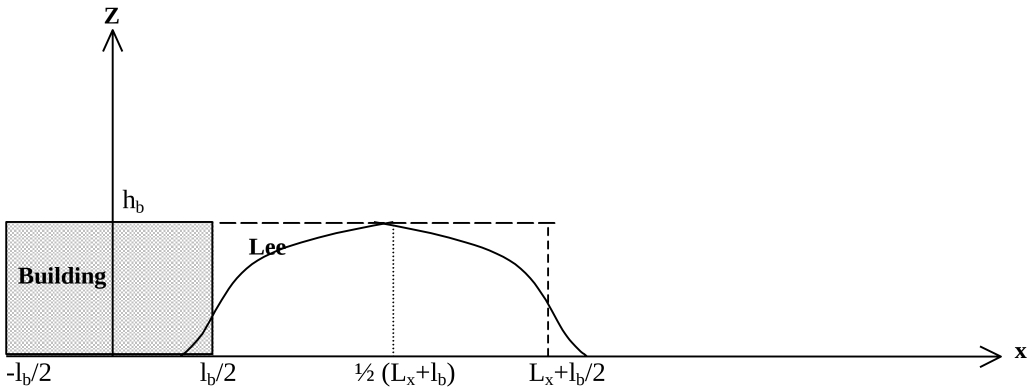
$$c(\frac{L_x}{2},0,0,t_{res}) = \frac{2m_c}{(2\pi)^{3/2}\frac{L_x}{2.50}\frac{L_y}{1.25}\frac{L_z}{1.25}} \approx \frac{m_c}{2L_xL_yL_z}$$

which is consistent with the building-wake concentration for time t < t_{res} (see Equation (19). Thus the maximum cloud concentration is indeed continuous at time t_{res}. Note however that there will be a discontinuity of the maximum concentration (over all times) at the downwind edge of the building wake, X = L_x.[11]

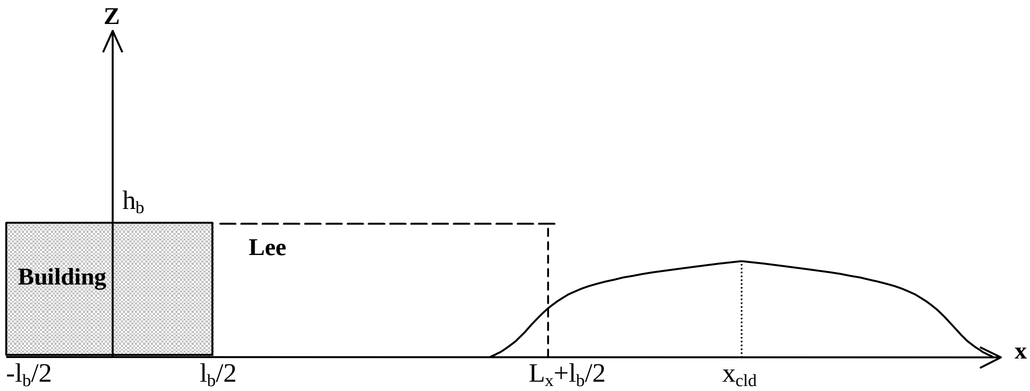
[11] Note that the alternative choice $X_{cld}(t_{res})= L_x$ instead of $X_{cld}(t_{res})= ½\,L_x$, would lead to a continuous maximum concentration (over all times) at X = L_x, but to a weird unrealistic sudden increase of the maximum cloud concentration (at a given time, over all distances) at time t = t_{res}. Therefore the choice $x_{cld}(t_{res})= ½\,L_x$ is applied in the BWM.



(a) time $t < t_{res}$: cloud in lee (uniform building wake concentration; t_{res} = residence time)



(b) time $t = t_{res}$: virtual source - match cloud with equivalent instantaneous Gaussian cloud



(c) time $t > t_{res}$: Gaussian cloud moves downwind [cloud centre at $x_{cld} = ½ L_x + U_w(t-t_{res})$]

Figure 4. The instantaneous SDI model for roof/lee releases.

2.2.3 Choice of continuous versus instantaneous sources

Section 2.4 in the SDI report[iii] discusses the choice of continuous versus instantaneous sources.

<u>Evaluation of total released mass</u>

In reality, most sources will be time-varying sources instead of continuous or instantaneous sources. The release is assumed to start at time t=0 and end at $t=t_{dur}$, where t_{dur} is the release duration. The total released mass m_c (kg) is then found by means of integration of the source strength $Q(t) = dm_c/dt$ between the start time and the end time,

$$m_c = \int_0^{t_{dur}} Q(t)\, dt \qquad (25)$$

If there is no clear start and end time, the start and end time could be chosen as those corresponding to that of 10% of the maximum source strength. For a finite-duration source of duration t_{dur} and uniform strength Q, the released mass equals $m_c = t_{dur}Q$.

<u>Criterion of continuous versus instantaneous source</u>

Using Equation (15), it follows that for a continuous release the total mass m_{lee} (kg) in the recirculation zone equals

$$m_{lee} = V_{lee} c_{lee} = \left\{ L_x (2L_y) L_z \right\} \left\{ \frac{Q}{KAU_w} \right\} = \frac{L_x\, Q}{K\, U_w} \qquad (26)$$

where $V_{lee} = L_x (2L_y) L_z = L_x A$[12] is the volume and C_{lee} the concentration within the recirculation zone. For a finite-duration release with uniform release rate Q and duration t_{dur}, the total released mass $m_c = t_{dur}Q$ must be larger than m_{lee} in order for the above formula to apply. Thus the following criterion is applied in SDI for modelling of the recirculation zone[13]:

$$\begin{aligned} t_{dur} &\geq \frac{L_x}{U_w} \quad \Rightarrow \quad \text{continuous SDI model} \\ t_{dur} &< \frac{L_x}{U_w} \quad \Rightarrow \quad \text{instantaneous SDI model} \end{aligned} \qquad (27)$$

For modelling of dispersion for distances downwind of the recirculation zone, the TNO yellow book[v] provided the following recommendations:

$$\begin{aligned} X &\leq 1.8\, U_w\, t_{dur} \quad \Rightarrow \quad \text{continuous Gausian model} \\ X &\geq 18\, U_w\, t_{dur} \quad \Rightarrow \quad \text{instantaneous Gaussian model} \\ 1.8\, U_w\, t_{dur} &< X < 18\, U_w\, t_{dur} \quad \Rightarrow \quad \text{interpolation} \end{aligned} \qquad (28)$$

Note that the above is NOT currently applied in the BWM. Instead a warning is given for $X > 1.8\, U_w t_{dur}$, with the advice to run the instantaneous UDM model (no effect of building wakes) particularly for estimate of concentrations for distances $X > 18U_w t_{dur}$.

Note that no time averaging is applied within the recirculation zone. In the original SDI model, downwind of the recirculation zone the averaging time = $\min\{t_{av},t_{dur}\}$ was applied. However the BWM applies as default option the actual averaging time t_{av}.

Note that the SDI model described above is very approximate. The stochastical process for dispersion (turbulent atmospheric boundary layer) will result in time-average concentrations, of which an ensemble average is taken. Therefore considerable deviations of average may occur (also caused by model inaccuracies). The uncertainty will increase with smaller times t and smaller downwind distance x (less effect of distance/time averaging).

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12 Note that this only applies if mass conservation is assumed (see footnote 4). Note the SDI report adopts the different criterion $t_{dur} \geq 3h_b/KU_w$, since it assumes $L_x=3h_b$, $L_y= ½b_b$, $L_z=h_b$, $A=2h_b b_b$ (i.e. mass conservation only applies for the SDI criterion if K=1).

13 Note that this is somewhat comparable with the UDM quasi-instantaneous transition, which can be applied for a finite-duration release with an uniform rate. This involves a transition from a continuous into an instantaneous cloud, if the cloud width becomes sufficiently large relative to the length

2.3 Release from chimney at top of building (Dutch National Model)

In the case of a release from a chimney at the top of the building, the plume will not be affected by the building wake for large chimney heights, and only partly affected for intermediate chimney heights (stack downwash; modified Gaussian plume model). This is described in detail by a building-wake extension[vii,xvi] of the Dutch National Model[viii] for passive air pollution. This section describes the major steps in the corresponding 'building-wake algorithm'.

2.3.1 Geometry, co-ordinates and notation

Downwind of the building with length l_b, width b_b, height h_b, a recirculation zone is assumed to exist with length L_x and area A:

$$L_x = 3\delta = 3\min(h_b,b_b)$$

Here the area A is the frontal area of the building (projecting on a plane perpendicular to the wind direction. The Dutch National Model recommends to adopt the smallest, worst-case value of $A = h_b b_b$.

The stack (chimney) is located at the centre at the top of the building. The stack has a height h_s (m), a top-inside diameter d_s (m), vertical exit velocity v_s (m/s). Further release data at the stack are the smoke temperature T_{pol} (K) and the smoke release rate Q (kg/s). The exit velocity v_s is calculated from the following expression for the release rate Q

$$Q = \left\{\frac{1}{4}\pi\, d_s^2\right\} v_s \rho_{pol}(P_a, T_{pol}) \qquad (29)$$

Here the pollutant density ρ_{pol} is set as function of the ambient pressure P_a (= exit pressure) and the exit temperature T_{pol}; see Appendix A for details on the adopted thermodynamics.

Cartesian co-ordinates x,y,z correspond with the downwind distance from the stack, the crosswind distance from the stack, and the vertical distance from the ground. Thus the stack corresponds with $\underline{x}=[0,0,h_s]$, and the centre of the re-circulation zone with $\underline{x}=[x^*,0,0]$ with $x^* = 0.5\,(l_b+L_x)$.

Required ambient data are the stability class, the wind speed at chimney height u_{as}, the temperature T_a, and the ambient pressure P_a. Also required is the surface roughness length z_R and the averaging time t_{av}.

2.3.2 Stack-tip downwash

Stack-tip downwash is due to the regions of low pressure that form in the recirculation region. If the pollutant leaving the stack does not clear the stack sufficiently, then part of the bottom of the plume may be 'caught' by the recirculating flow and will be lowered somewhat. A mean correction to the stack height h_s (m) is applied that has been suggested by Briggs[xvii,14],

$$h_s = \max\left[h_b\,,\, h_s - 2\,d_s \max\{0, 1.5 - \frac{v_s}{u_{as}}\}\right] \qquad (30)$$

Note that the maximum correction is 3 d_s. For large exit velocities ($S_s = v_s/u_{as} > 1.5$) no correction is applied. For small exit velocities ($S_s = v_s/u_{as} < 1.5$), the exit velocity v_s is reset to 0 following the above correction [v_s=0, if $S_s = v_s/u_{as} < 1.5$]. Note that for a roof release ($h_s = h_b$) no correction is applied.

2.3.3 Plume rise

<u>Plume rise after chimney release and before correction for building-wake effects</u>

The plume height h(x) equals $h(x) = h_s + \Delta H(x)$. Prior to the correction for building-wake influence, the vertical plume rise $\Delta H(x)$ is set using the EPA-ISC plume rise formula. This formula is selected based on comparison of a range of plume-rise formulae against wind-tunnel data; see Chapters 5,7 and Appendix A in Baars and Melle[xvi]. See also Briggs[xviii] for a review of plume-rise formulae. This includes a formula for plume rise in a cross wind, in case of jet (momentum-dominated), a hot plume (buoyancy-dominated) and a 'transition' plume.

[14] JUSTIFY. This stack-downwash correction will only be valid for narrow stacks. This is however currently not checked by the building wake model.

The EPA-ISC formula is based on the generalised Briggs plume-rise equations. In the case of stack-tip downwash ($S_s = v_s/u_{as}<1.5$), the plume-rise formula applicable for buoyant plumes is adopted for the plume rise $\Delta H(x)$ as function of downwind distance[15],

$$\Delta H(x) = \left\{ 36.2 \frac{Q_H x^2}{u^3} \right\}^{1/3} \quad , \quad \text{if } S_s < 1.5 \tag{31}$$

Otherwise the more general 'transition' formula is adopted,

$$\Delta H(x) = \left\{ \frac{3}{4} \frac{T_a}{T_s} \left[\frac{d_s\, S_s^2}{1+0.33 S_s} \right]^2 x + 36.2 \frac{Q_H x^2}{u^3} \right\}^{1/3} \quad , \quad \text{if } S_s > 1.5 \tag{32}$$

In the above equations the plume heat content Q_H is defined in Megawatts, and is given by (see Equation 6.1 in Baars and Melle[xvi]) [16]

$$Q_H = 10^{-6} C_{pa} \frac{273}{T_{pol}} \left(T_{pol} - T_a \right) \rho_a \frac{\pi}{4} d_s^2 v_s = 0.29 \left(1 - \frac{T_a}{T_{pol}} \right) Q \tag{33}$$

Correction for building-wake effects

The distance x" at which the plume height is potentially corrected for building-wake effects must be must be upwind of the middle of the re-circulation zone $x = x^*$. The following formula is adopted (with Q_H in MW, d_s in m and v_s in m/s)

$$x'' = \min(x', x^*) \tag{34}$$

with x' defined by

$$\begin{aligned} x' &= 284\, Q_H^{0.4}, && \text{if } Q_H > \max\{6, 0.0016 (d_s v_s)^{1.67}\} \\ x' &= 190\, Q_H^{0.63}, && \text{if } 0.0084 (d_s v_s)^{1.33} < Q_H < 6 \\ x' &= 4 d_s \{ S_s + 6 + \frac{9}{S_s} \}, && \text{if } 6 < Q_H < 0.0016 (d_s v_s)^{1.67} \text{ or } Q_H < \min\{6,\ 0.0084 (d_s v_s)^{1.33}\} \end{aligned} \tag{35}$$

In the above three relations, the first relation refers to the downwind distance x' of plume rise for a hot plume (buoyancy dominated), the third that for a high-momentum or cold plume (momentum dominated), and the second to that for an intermediate plume.

The plume height H^* at x = x" prior to correction equals

$$H^* = h_s + \Delta H(x'') \tag{36}$$

The minimum height H_{min} is a correction to the height H^* at x"[17] to include the effect of lowering of the height due to the building–wake effect. The value of H_{min} is given in Table 2 as function of $\lambda=(H^*-h_b)/\delta$ and is based on the TNO wind-tunnel results:

- For $\lambda>1.5$ (very high plume), no effects of the building wake occur and no correction takes place.
- For $\lambda<0.2$ (plume below building height), the plume is fully ($\lambda<0$) or partly ($0<\lambda<0.2$) taken up by the recirculation zone and $H_{min} = h_b - 0.4\delta$.

[15] The chimney model assumes an uniform wind speed $u = u_{as}$ throughout the model.

[16] JUSTIFY. The TNO equation 6.1 adopts the air density ρ_a = 1.30 kg/m^3 at 273K and the specific heat of air C_{pa} = 1045 J/kg/K. More correct seems to be to use the equation $Q_H = 10^{-6} C_p^{pol} (T_{pol}-T_a) Q$ with C_p^{pol} being the specific heat of the pollutant at the release temperature. However, in the current BWM model the factor 0.29 is maintained to maintain compatibility with the TNO model.

[17] The building-wake extension report refers to H_{min} at height x*. This seems to be not logical in case of x"=min(x',x*)<x*. Therefore H_{min} is taken to be the height at x"

- For $0.2<\lambda<1.5$, the plume is lowered by the building wake but not taken up by the wake. The lowering of the plume height is derived by linear interpolation from the above two values at $\lambda=0.2$ and $\lambda=1.5$.

Plume rise downwind of correction for building-wake effects

After applying the correction for lowering of the plume due to the building influence, further plume rise due to momentum is assumed not to take place. However further rise due to buoyancy (plume heat content) may need to be taken into account downwind of x" if x''=min(x',x*)=x* (x*<x'). In the latter case the location x' for the final maximum plume height following the correction at x" is first recalculated from Equation (35) with zero impulse effects,[18]

$$
\begin{aligned}
x' &= 284\, Q_H^{\,0.4} \;, \quad if\;\; Q_H > 6\, MW \;\; and\; no\; stable\; conditions \\
&= 190\, Q_H^{\,0.4} \;, \quad if\;\; Q_H < 6\, MW \;\; and\; no\; stable\; conditions \\
&= 89\;\, u \;, \qquad\quad if\;\; stable\; conditions
\end{aligned}
\qquad (37)
$$

and further plume rise is set from Equation (31).

Thus following the above the following formula applies for plume rise downwind of the correction for building-wake effects[19,20],

$$
\begin{aligned}
h(x) &= H^* , && for\; x'' < x < \tfrac{1}{2} l_b \;, && if\;\; x'' < x^* \\
&= H_{\min} , && for\; \max(\tfrac{1}{2} l_b , x'') < x \;, && if\;\; x'' < x^* \\
&= H_{\min} + \left\{ 36.2 \frac{Q_H}{u^3} \right\}^{1/3} \left[x^{2/3} - (x'')^{2/3} \right] , && for\; x'' < x < \max(x', x'') \;, && if\;\; x'' = x^* \\
&= H_{\min} + \left\{ 36.2 \frac{Q_H}{u^3} \right\}^{1/3} \left[(\max(x', x''))^{2/3} - (x'')^{2/3} \right] , && for\; x > \max(x', x'') \;, && if\;\; x'' = x^*
\end{aligned}
\qquad (38)
$$

2.3.4 Plume concentration

The calculation procedure for the plume concentrations is summarised in Table 2 for different values of $\lambda = (H^*-h_b)/\delta$ [X is defined as distance downwind of building = x – $l_b/2$]. First the lee concentration (0< X < 3δ) and the concentration for $X/\delta >$ 10 are set from Table 2. Subsequently the ground-level concentration for $3 < X/\delta < 10$ is set by means of linear interpolation.[21]

For each of the different cases, the following is carried out.

- case of no building influence (λ>1.5). The concentration c(x,y,z) is found from the Gaussian Equation (1) where the plume height h = $h_{n.m.}(x)$. Here $h_{n.m.}(x) = h_s+\Delta H(x)$ with $\Delta H(x)$ based on Equation (31) for $v_s/u_{as}<1.5$, or based on Equation (32) for $v_s/u_{as}>1.5$. Moreover the dispersion coefficients are defined by the Pasquill-Gifford formulas defined by Equation (2), with σ_y and σ_z values according to the National Model.
- no take-up but only lowering of plume axis ($0.2<\lambda<1.5$). Set plume height (including correction) as defined in Section 2.3.3. Set concentration c from Equation 1 with the dispersion coefficients given by the Pasquill-Gifford formulas.
- full take up of the plume in the recirculation zone ($\lambda<0$). The corrected plume height is given by $h(x) = h_b - 0.4\delta$ for x >x". The concentration is given by:
  - for $X<3\delta$: c(x,y,z) = Q/(KAu) within zone, and c(x,y,z)=0 outside zone

---

[18] JUSTIFY. Old PLUIMPLUS documentation quotes $x'=2.1u\, s^{-1/2}=89$ u, with s =5.6x10^{-4}. Note that Equations (35) and (37) are not consistent for stable conditions!

[19] In BWM, this formula for additional buoyant rise is assumed to be applicable for $0.2<\lambda<1.5$ only. For $\lambda<0.2$ (partly or fully taken up by plume) no additional plume rise is assumed to occur. For $\lambda>0.5$, the original plume rise formula (31) is adopted until x = x', with x' defined by Equation (35).

[20] In case of partial or complete lee take-up, this formula for the height is not used for the calculations of the top-hat concentration along the building wake.

[21] In BWM, the concentration c(x,y,z) is set for $3 < X/\delta < 10$ by means of linear interpolation of the values of c_{max}, σ_y, σ_z at X/δ =3 and X/δ =10.

- for $X>10\delta$: use Gaussian plume equation c(x,y,z) with height h(x) and $\sigma_z = \sigma_z(NM) + \delta/2.36$ and $\sigma_y = \sigma_y(NM) + \delta/2.83$[22]
- for $3\delta < X < 10\delta$, interpolate: $c(x,y,z) = c(3\delta+l_b/2,y,z)\,[(10\delta-X) / (10\delta-3\delta)] + c(10\delta+l_b/2,y,z)\,[(X-3\delta) / (10\delta-3\delta)]$

- partly taken up ($0<\lambda<0.2$). A fraction of $(1-5\lambda)$ of the plume will be taken up by the recirculation zone. The corrected plume height is given by $h(x) = h_b - 0.4\delta$ for x >x". The concentration is given by:
  - for $X < 3\delta$: $c(x,y,z) = (1-5\lambda)Q / (KAu)$ within zone[23]
  - for $X > 10\delta$: use Gaussian plume equation c(x,y,z) with full rate Q, height h(x) and $\sigma_z = \sigma_z(NM) + \delta(1-5\lambda) / 2.36$ and $\sigma_y = \sigma_y(NM)$ [22]
  - for $3\delta < X < 10\delta$: interpolate, $c(x,y,z) = c(3\delta+l_b/2,y,z)\,[(10\delta-X) / (10\delta-3\delta)] + c(10\delta+l_b/2,y,z)\,[(X-3\delta) / (10\delta-3\delta)]$

Table 2. Summary of height and concentration calculations

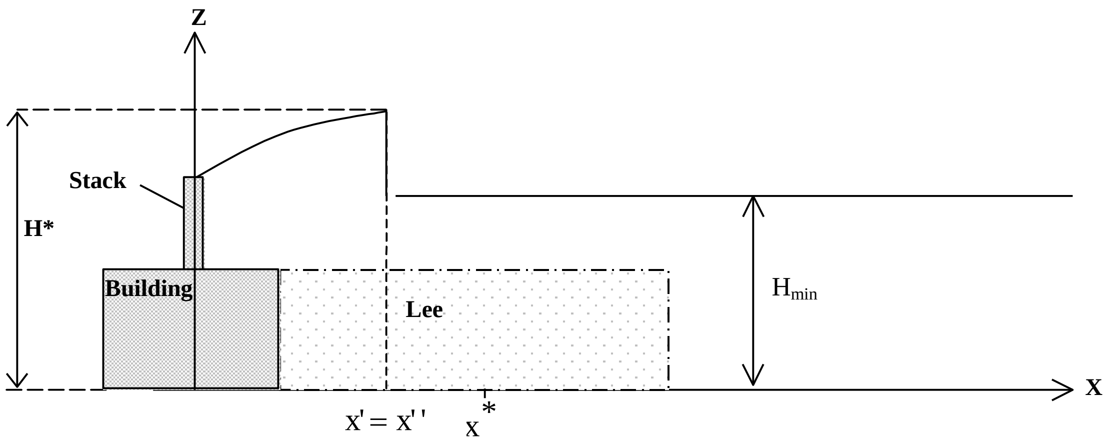
$\lambda=(H^*-h_b)/\delta$	*corrected plume-axis height H_{min} at x"*	*concentration (in lee; $0<X/\delta<3$)*	*concentration (interm. Region; $3<X/\delta<10$)*	*concentration (far away; $X/\delta>10$)*
$\lambda>1.5$	H^*	c=0 [no lee take up]	-	N.M. Gaussian equation with no wake effect on height h (see Section 2.3.3)
$0.2<\lambda<1.5$	$H^* - \delta\,(0.69-0.46\lambda)$	c=0 [no lee take up]	use lowered height	use lowered height
$0<\lambda<0.2$	$h_b - 0.4\delta$	$c=Q(1-5\lambda)/(KAu)$ [partly taken up]	interpolate concentration	$h = h_b - 0.4\delta$, $\sigma_z=\sigma_z(NM) + \delta(1-5\lambda)/2.36$, unchanged σ_y
$\lambda<0$	$h_b - 0.4\delta$	c= Q/(KAu) [fully taken up]	interpolate concentration c(x,y,z;H)	$h = h_b - 0.4\delta$, $\sigma_z = \sigma_z(NM) + \delta/2.36$, $\sigma_y = \sigma_y(NM) + \delta/2.83$[24]
roof/lee release (SDI)	n.a.	c=Q/KAu [fully taken up] for $x<3h_b$	virtual source technique up to 100 m	virtual source technique

[22] JUSTIFY. Note that this formula does not provide continuous transition at $\lambda=0$ for σ_y. Better to use $\sigma_y = \sigma_y + \delta(1-5\lambda)/2.83$, which would ensure continuity and be consistent with the σ_z formula

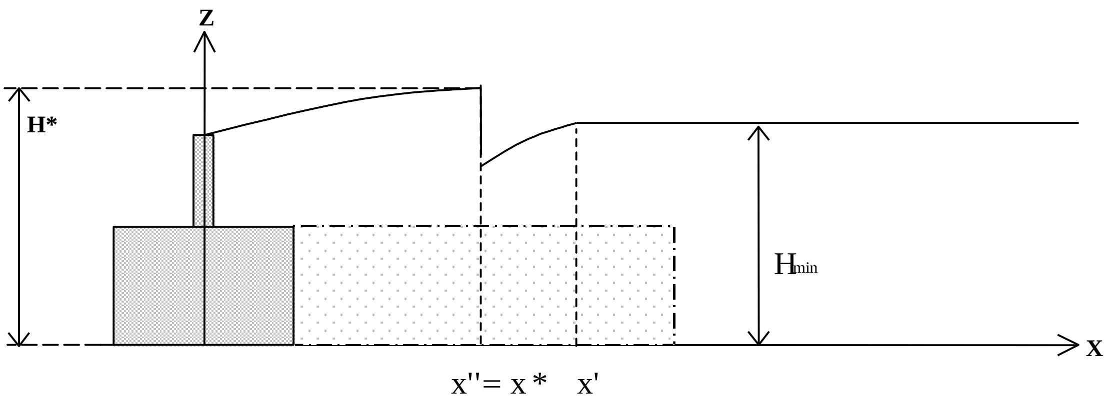
[23] JUSTIFY. In future to include as separate Gaussian plume, part of cloud not taken up by lee (fraction 5λ) and to sum the contributions for both plumes.

[24] Note that the original National Model assumed $\sigma_z = \sigma_z + h_b/2.36$, $\sigma_y = \sigma_y + b_b/2.83$ for $\lambda<0$ and $X/\delta>10$, which however resulted in a discontinuity at $\lambda=0$. Therefore this has been changed.

The correction of the plume height for building-wake effects is summarised in Figure 5.



(a) x' = x'' < x*



(b) x'' = x* < x'

Figure 5. **The National Model (N.M.) for chimney releases.**
Correction for building-wake effects at x = x'' of plume height h(x) from maximum height H^* to minimum height H_{min}; x' = distance for final maximum plume height without building-wake effects (plume rise because of buoyancy or momentum); x^* = distance for middle of building wake (re-circulation zone)

2.4 The building-wake model BWM for lee/roof and chimney releases

The SDI building-wake-dispersion model for a roof/lee release has been described in Section 2.2, and the Dutch National model for a chimney release has been described in Section 2.3. Both of these models have been implemented into a new building-wake-dispersion program called BWM.

This section describes the parameters and assumptions adopted by the BWM model.

2.4.1 Model parameters

In the BWM program, the model assumptions can be varied by means of a number of model parameters. One of these parameters allows the user to define the 'model type', which give the following options for the default assumptions to be adopted:

- assumptions corresponding to the original TNO SDI model[iii] and the TNO Dutch National Model[vii]
- worst-case assumptions. These are recommended to be used as part of a consequence analysis in the program PHAST, and are therefore chosen as the default option in PHAST.
- best-estimate assumptions. These are recommended to be used as part of a risk analysis in the program SAFETI, and are therefore chosen as the default option in SAFETI.

Note that further modifications to the model assumptions may need to be applied in the future (e.g. as part of possible additional verification).

Table 3 lists the parameters that enable the user to vary the model assumptions in BWM. The parameters respectively define:

- release type: 1 - roof/lee release (SDI model), 2 - chimney release (N.M. model). Note that this is not a parameter, but is an required input data. The SDI model is more appropriate for safety cases (10 minutes averaging time), while the N.M. model is more applicable for air pollution (60 minutes averaging time)
- model type: 1 - original TNO model, 2 - recommended worst-case PHAST model, 3 - recommended best-estimate SAFETI model
- lee dimensions: length L_x, half-width L_y, and height L_z . Note that these are expressed in terms of building length l_b, width b_b, and height h_b [$\delta = \min(h_b,b_b)$]
- factor K for building-wake concentration c = Q / (KAu) [recommended to be user-specified for SAFETI]

DNV

Table 3. Model assumptions (default parameter values - continuous)
{the six columns in the table correspond to all combinations of release types [roof/lee (SDI), or chimney NM] and model types [original (TNO), worst-case (wc) or best-estimate (be)]}

parameter	original TNO assumptions		worst-case assumptions		best-estimate assumptions	
	SDI	**NM**	**SDI**	**NM**[25]	**SDI**	**NM**[25]
roof/lee or chimney	1	2	1	2	1	2
model type	1	1	2	2	3	3
lee length L_x	3 h_b	3 δ	Fackrell	3 δ	Fackrell	3 δ
lee half-width L_y[26]	0.5 K b_b[27]	0.5 K b_b	0.5 b_b	0.5 K b_b	0.5 b_b	0.5 K b_b
lee height L_z	h_b	h_b	K h_b	h_b	Kh_b	h_b
K[28]	0.2	0.2	0.2	0.2	1	1
near-field linear σ (x_e)	100m	-	100m	-	100m	-
NM change of σ	-	10δ	-	10δ	-	10δ
averaging time (t_{av} = user-specified)	min(t_{dur},t_{av}), cont. 18.75s, inst.	t_{av}	t_{av}	t_{av}	t_{av}	t_{av}

2.4.2 Model assumptions and model applicability

Ambient data

The model assumes uniform ambient data (wind speed, temperature, pressure, density), and this should be representative for the entire region of the dispersion. Currently these data are taken at the building height for a roof/lee release and at the stack height for a chimney release. Note that the original TNO models appear to adopt always the ambient data at the reference height of 10 meter.

Building-wake concentration: area

The model assumes for the building wake concentration c = Q/(K A u), where A is the frontal area of the building (projection on a plane perpendicular to the mean wind direction).

The area A = $b_b h_b$, with h_b the obstacle height and b_b the width of the building (projection on a horizontal line perpendicular to the mean wind direction). Let l_b be the building length along the wind direction, θ_b be the anti-clockwise angle between the wind-direction and the length-axis of the building [$0 \le |\theta_b| \le \pi/2$], L_b and B_b the building length and width ($B_b < L_b$), then

$$b_b = L_b \sin|\theta| + B_b \cos(\theta)$$
$$l_b = L_b \cos\theta + B_b \sin|\theta|$$

Thus $B_b h_b \le A = b_b h_b \le (L_b^2 + B_b^2)^{1/2} h_b$. The above derivation of ‘effective’ building dimensions for use in the building wake calculations is indicated in Figure 6.

In absence of further information of the position of the building relative to the wind direction, the worst-case assumption of θ_b=0 is recommended. This results in the worst-case value of A = $B_b h_b$, with h_b the building height and B_b the building width. Moreover the length l_b is taken to be equal to L_b. If the user knows the wind-direction, he should specify the appropriate BWM input value for the angle θ_b.

25 The NM model has not changed now to ensure previous fit [δ = min(h_b,b_b) , Fackrell formula not used, L_z = h_b chosen]

26 Values L_y = 0.5 b_b, L_z = Kh_b ensure mass conservation with more realistic best-estimate values for concentration cross-wind profile at ground level (always advised for SAFETI; used as defaults for PHAST). Values L_y = 0.5 K b_b, L_z = h_b ensure mass conservation with more realistic values for concentration profile through vertical plane and plume centre-line (at zero cross-wind distance).

27 This value applied to ensure mass conservation, although the original SDI model actually uses 0.5 b_b

28 K depends on building dimensions and angle of wind with building. See Chapter 4 for an extensive discussion on this.

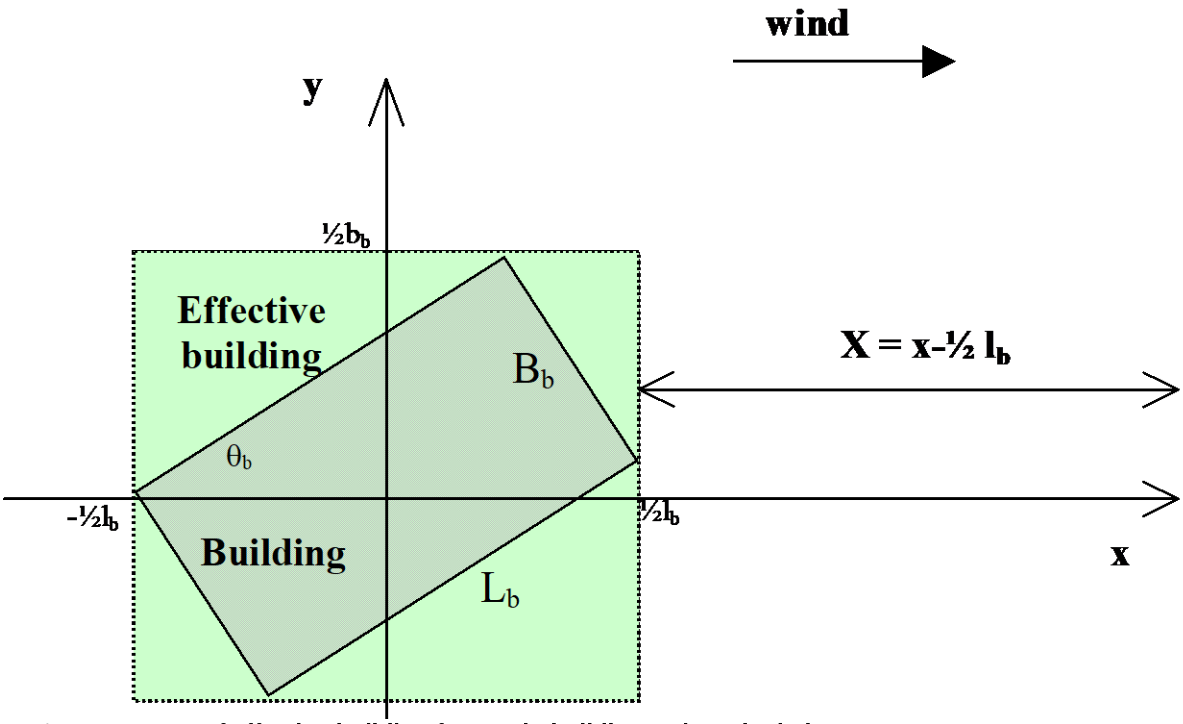


Figure 6. **Use of effective building for use in building wake calculations**
The dimensions of the effective building (height h_b, length l_b, width b_b) are derived from those of the original building (height h_b, length L_b, width B_b) and the cloud angle θ_b of the length-axis of the original building to the wind direction. Note that x=0, y=0 corresponds to the centre of the effective building, and $x = ½l_b$ with the downwind edge of the effective building. Thus $X = x-½\ l_b$ is the downwind distance of the downwind edge of the effective building.

Dimensions of recirculation zone

The length of the recirculation area is assumed to be $L_x = 3h_b$ in the original SDI model and $L_x = 3\delta = 3\ \min(h_b,b_b)$ in the original Dutch National Model (NM).

The alternative formula for the recirculation length recommended by Duijm and Webber[xix] is proposed. This is the Fackrell and Pearce formula $L_x = 1.8b_b\ /\ [\ (l_b/h_b)^{0.3}\ (1+0.24b_b/h_b)]$ to give a fit within 20% from experimental data for $0.3 < l_b/h_b < 3$. For $l_b/h_b < 0.3$ the value for 0.3 is adopted, while for $l_b/h_b > 3$ that for 3 is adopted.

For a cubic building ($h_b = l_b = b_b = \delta$) this leads to $L_x = (1.8/1.24)\delta\ \cong 1.5\delta$ which is a factor 2 as small as the N.M. value! The new formula is proposed for the SDI model, but the old N.M. formula is applied at this stage to ensure previous fit. Note that the new formula may be invalid outside the range $0.3 < l_b/h_b < 3$.

A uniform concentration $c = Q/[KAU_w]$ is assumed within the recirculation zone, and zero outside. Presuming the wind speed U_w also to apply inside the building wake (which may well be not appropriate), the mass flow Q through a vertical plane is conserved only, if $KA = Kh_bb_b$ instead of A is considered to be the cross-section area of the recirculation zone. Thus $Kh_bb_b = 2\ L_yL_z$. If the latter condition is not satisfied, continuity of maximum concentration does not apply at the downwind edge of the lee (between the building-wake concentration and the Gaussian profile). Thus the default formula for the recirculation height L_z is found by imposing mass conservation, i.e. $L_z = (K\ h_b\ b_b)\ /\ (2\ L_y)$.

Note that the worst-case value of the area is always assumed for the area A, i.e. the minimum value $A= b_bh_b$ [note that the maximum value equals $A = h_b\ (b_b^2 + l_b^2)^{1/2}$].

See Section 4 for a further discussion of the above.

Dispersion coefficients

There seems to be no justification for near-field linearisation of dispersion coefficients in SDI model (up to x_e =100 m). This would also remove an inconsistency between the SDI and NM models. Thus the SDI model would apply the virtual source technique for transitions downwind of the lee and at not anymore at x_e =100m. However it is envisaged that this has little effect on the results, and x_e=100m is maintained.

Note that the NM model applies possible adjustment of σ_y and σ_z at x = x_e=10δ. This adjustment includes discontinuities at λ=0, 0.2 [$\lambda = (H^*-h_b) / \delta$]. In future this may be improved by, for example, using the SDI virtual-source technique to obtain smooth concentrations without discontinuities.

Corrections to the original Dutch National model

Some corrections to the original N.M. documentation have been made to the N.M. model implemented in BWM (for all cases):

- In N.M. model, H_{min} is defined to be the corrected height at x", and not at x* as stated in the N.M. documentation [x" = min(x',x*)].
- In case of no wake effect (λ > 1.5), use EPA-ISC formula always. Thus no interpolation is needed of height or concentration (as stated in Table in N.M. report).
- In case of no lee take-up but lowering of plume (0.2 < λ < 1.5), use EPA-ISC formula including momentum before correction (at x") and excluding momentum after correction (until reset x'); thus again no interpolation of height or concentration is needed (as stated in table in N.M. report)
- In case of N.M. partial take-up of plume by lee (0 < λ < 0.2), a fraction fr of the release rate Q is taken up. Thus there is strictly speaking also a need to add the additional second contribution (1-fr) Q of the plume not taken up, [what height to use for this second plume (use H*)?]. Since this is expected not to have much effect on the ground level concentrations and because of model uncertainties, it has been decided not to include this at this stage. As a result a warning is produced by the building wake model in the case of partial take up.

Heavy-gas effects

No heavy-gas effects are taken into account and the theory to predict the concentration in the recirculation zone is simplistic. Heavy-gas effects may be particularly relevant in case of the release from a stack without full take up of the plume by the lee.

In case of full take-up by the lee, the gas would be assumed to be uniformly mixed in the recirculation zone and heavy-gas effects would be considered to be less important (unless the plume is still heavy downwind of the lee). Note that Duijm and Webber indicate that the theory can be applied to dense gases for release in the concentration zone provided that the following criteria are met[xix,xx]:

$$\frac{g_0' \, q_o}{U_w^{\,3} \, h_b} < 0.004 \quad , \qquad \textit{for continuous releases} \qquad (39)$$

$$\sqrt{\frac{g_o' \, V_o^{\,1/3}}{U_w^{\,2}}} < \max\left[0.5, \frac{h_b}{V_o^{\,1/3}}\right] \; , \quad \textit{for instaneous releases}$$

where $g_o' = g\,(\rho_{pol}-\rho_a) / \rho_a$ is the reduced gravity at the source, U_w the wind speed at the obstacle height h_b, q_o the continuous release rate (m^3/s), and V_o the instantaneously released volume (m^3). If the above criterion is not satisfied, a warning is produced by BWM.

Thermodynamics and maximum concentrations

Ideal-gas thermodynamics is assumed in the BWM model, in order to evaluate the pollutant density and to carry out mole conversion.

Note that the passive-dispersion equation (1) is not valid for very small distances downwind of the source, for which it may lead to concentrations c larger than the pollutant density ρ_{pol}. Thus the BWM model applies as an upper limit for the concentration the pollutant density. This means that in case Equation (1) results into a value larger than ρ_{pol}, the concentration is reset to $c = \rho_{pol}$.

3 RESULTS

3.1 Steady release from roof or recirculation zone

Figure 7 includes BWM dispersion predictions corresponding to example 6 in the SDI report[iii]. This example corresponds to the steady-state release of a pollutant in the recirculation zone (or from the roof) downwind of a building with length l_b = 30 m, height h_b = 15 m and width b_b = 10 m. The dispersion takes place under very stable conditions (F2) and over urban terrain (z_R = 3 m). The concentration predictions correspond to a 10-minutes averaging time. Figure 7 includes results from 4 different types of runs:

- The solid line corresponds with a run (SDIVB6) corresponding to the assumptions in the SDI model of TNO. This means that the worst-case value of K=0.2 is assumed leading to maximum predictions for the building-wake concentration [see Equation (15)]. Moreover the recirculation width $2L_y$ is chosen to be equal to the building width b_b ($L_y = 0.5\ b_b = 5$ m) , which leads to discontinuity at the downwind edge of the recirculation zone $x = l_b/2 + 3h_b = 60$ m as previously observed[4]. Note that moreover total mass is not preserved!

  The concentration and dispersion predictions by this BWM run have been found in good agreement with the results reported for worked-out example 6 in the SDI report.[iii] Thus the BWM model is verified against fully worked-out hand calculations of concentrations in the building wake, the near-field (with linearised Gaussian dispersion) and the far field.

- The second and third runs correspond to continuous profiles assuming $L_y = 0.5Kb_b$, with K = 1.0 (SDIVB6C) and K = 0.2 (SDIVB6U), respectively. Moreover mass is conserved! The third run could be considered to be a truly worst-case condition.

- The final run fourth run (SDIVB6WC) corresponds to the recommended option of K = 0.2, $L_y = 0.5\ b_b$ in the BWM model. These options have been applied as default options. These lead to worst-case ground-level values for the maximum concentrations (more dense, thinner cloud), while at the same time ensuring conservation of mass and continuity at the downwind edge of the recirculation zone. Note that this implies $L_z = K\ h_b$. Thus it is chosen to have worst-case predictions for ground-level concentrations and not for concentrations at elevated height.

Figure 8 contains BWM dispersion predictions for the steady-state release of 24 kg/s of a pollutant from the roof downwind of a cubic building (height = 50 m). The dispersion takes place under neutral conditions (D6) and over urban terrain (z_R = 3 m). The release is from a chimney at roof height with diameter d_s = 2.5 m, exit velocity v_s = 3.75 m/s, release temperature T_s = 288K. The concentration predictions correspond to a 10-minutes averaging time. The ambient temperature T_a = 288K. The original TNO model assumptions have been applied (see TNO-SDI column in Table 3). Figure 8 contains results for the following runs:

- (SDI) The SDI model for release from the roof of the cubic building
- (NM) The Dutch National model for release from the stack at the roof of the building
- (SDINB) The SDI model in the absence of a building. Note that this corresponds to a ground-level point source at x = 0 m, with the Gaussian dispersion coefficients being linearised between x = 0 m and x = 100 m.
- (NMNB) The Gaussian dispersion model for a point-source at x = 0 m and at height h_b = 50 m [no linearisation]. The model corresponds to the Dutch National model prior to the building-wake extension.

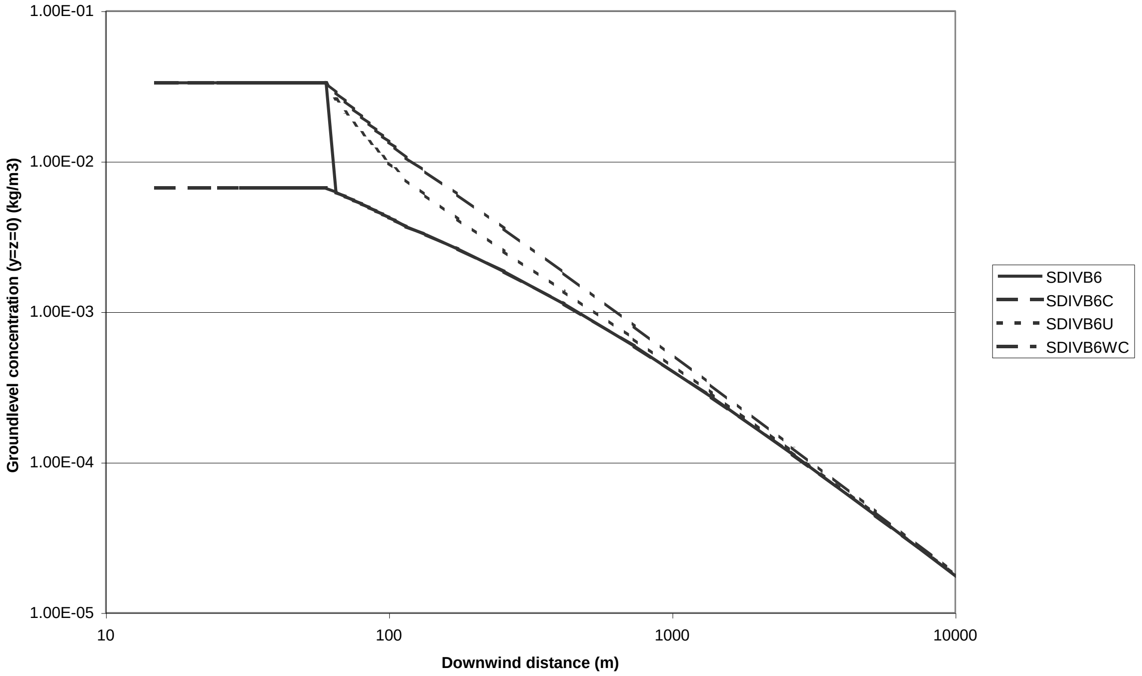


Figure 7 - (a) centre-line ground-level concentration

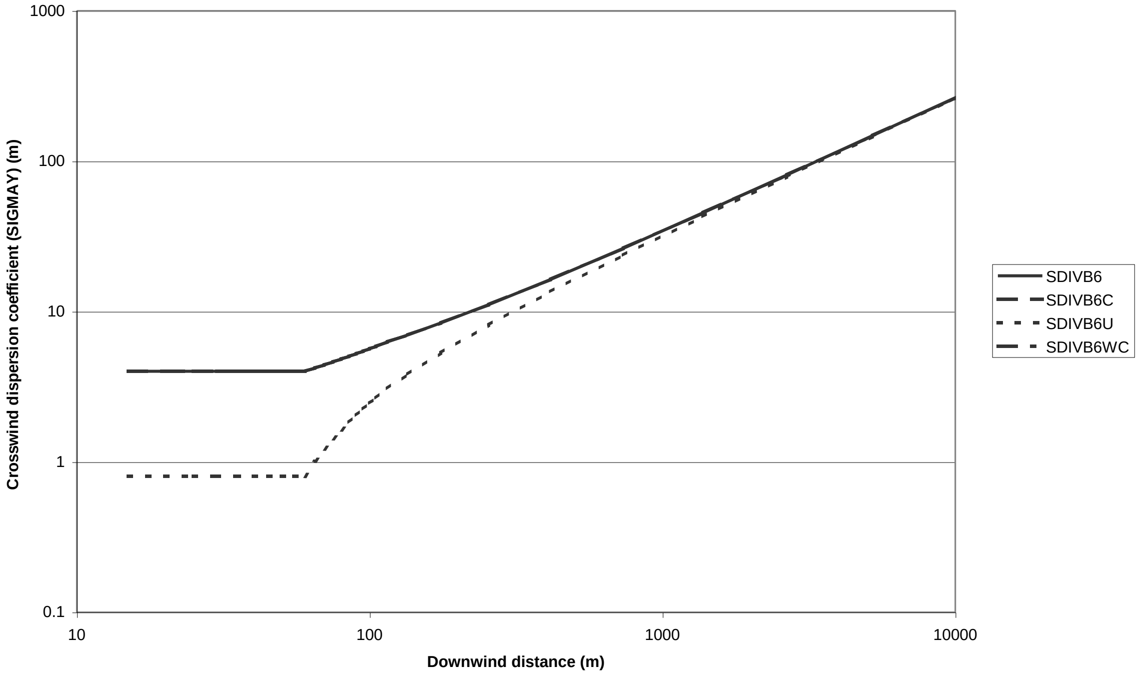
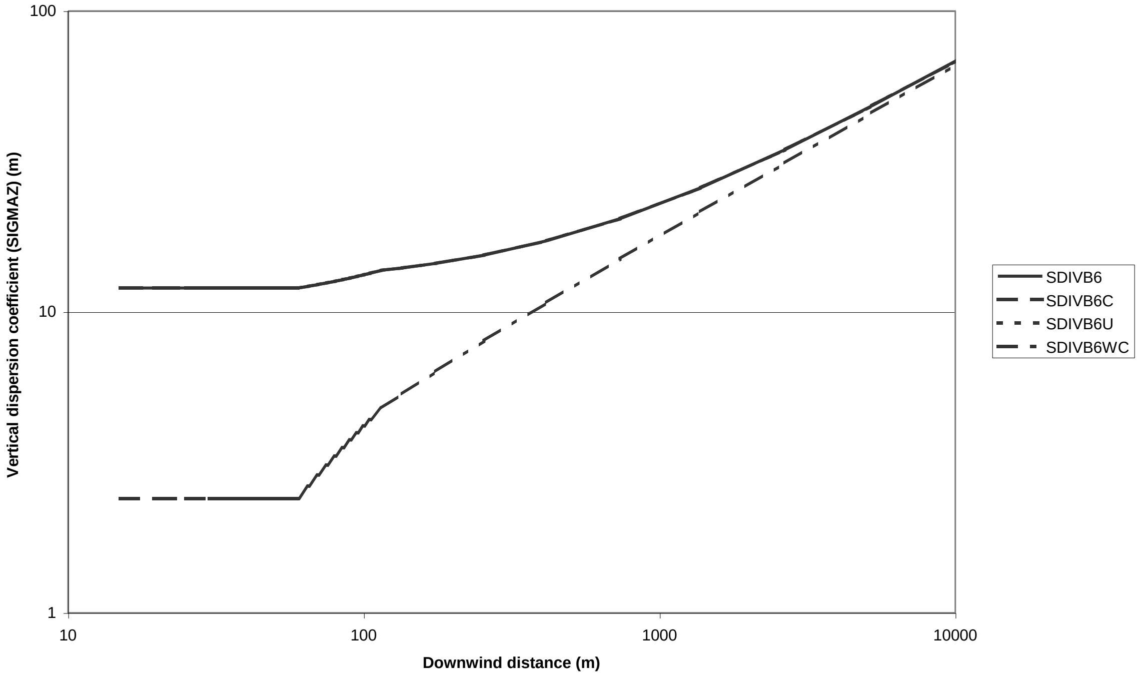


Figure 7 - (b) cross-wind dispersion coefficient

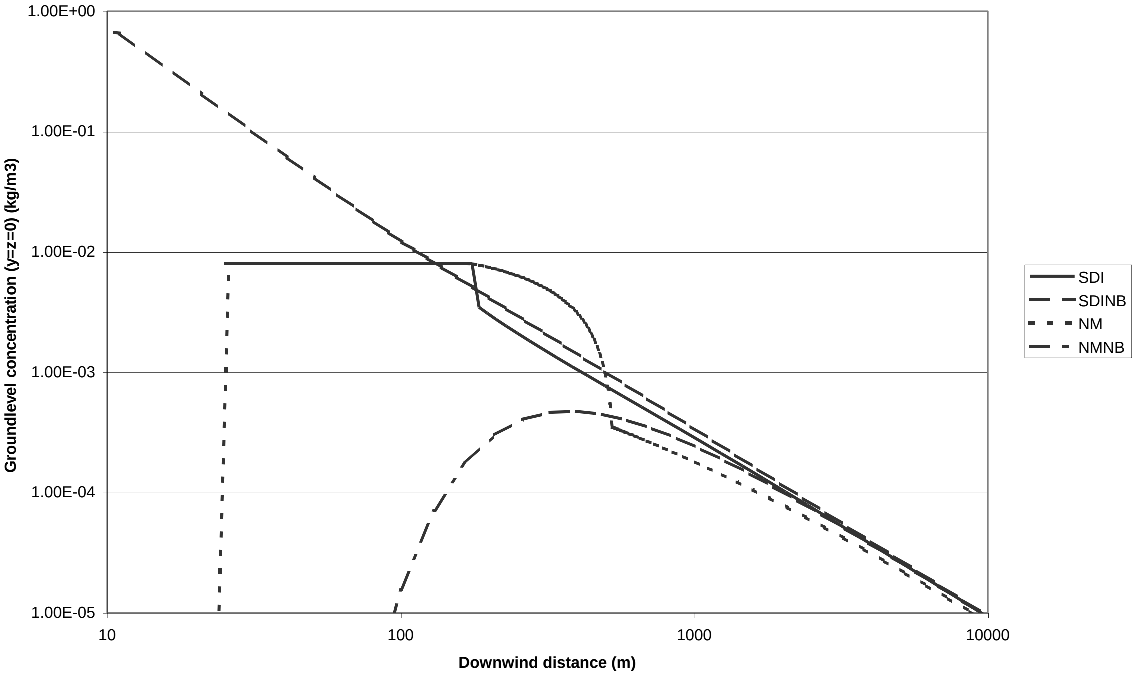


(c) vertical dispersion coefficient

Figure 7. BWM predictions for release in recirculation zone

Dispersion over urban terrain (z_R = 3 m) for pollutant release (2 kg/s) in recirculation zone downwind of building (length = 30 m, width = 10 m, height = 15 m) under very stable conditions (F2) [example 6 in SDI report]; runs shown are:

1. SDIVB6: K=0.2, L_y= ½b_b, L_z = h_b (assumptions as in SDI report: discontinuous c)
2. SDIVB6C: K=1, L_y= ½b_b, L_z = h_b (low continuous c, same σ_y and σ_z)
3. SDIVB6U: K=0.2, L_y= ½Kb_b, L_z = h_b (high continuous c, lower σ_z)
4. SDIVB6WC: K=0.2, L_y= ½b_b, L_z = Kh_b (high continuous c, lower σ_y)



(a) centre-line ground-level concentration

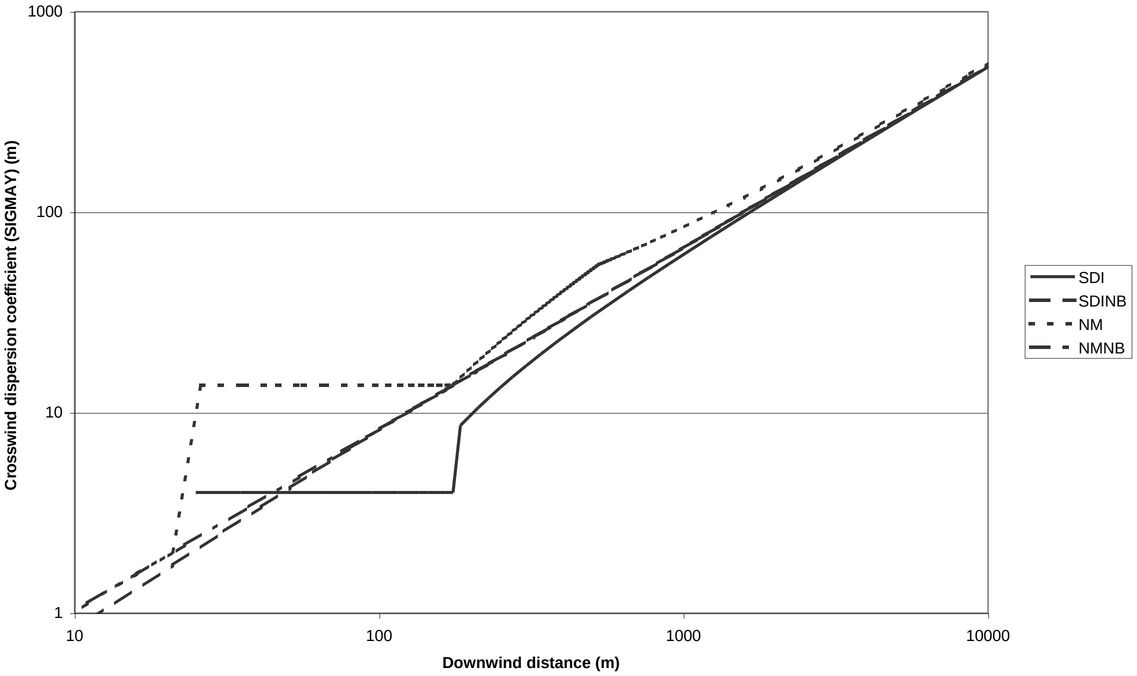
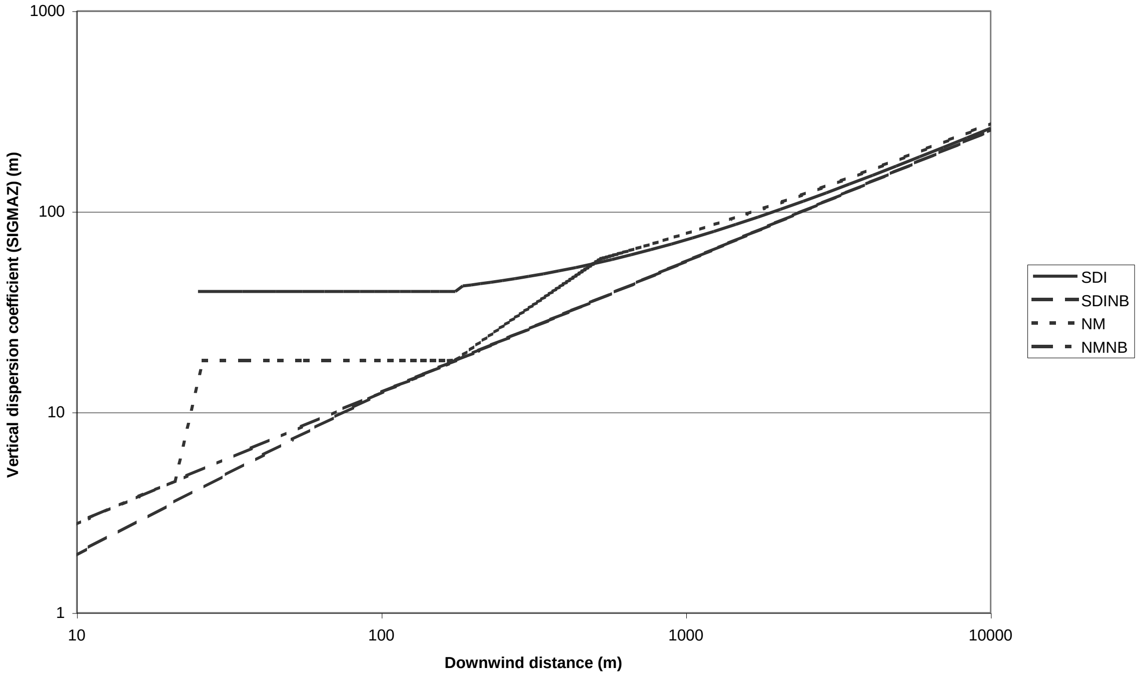


Figure 8 - (b) cross-wind dispersion coefficient



(c) vertical dispersion coefficient

Figure 8. **BWM predictions for release from roof of cubic building**

Dispersion over urban terrain (z_R = 3 m) for pollutant release (24 kg/s) in recirculation zone downwind of cubic building (height = 50 m) under neutral conditions (D6); BWM runs shown are:

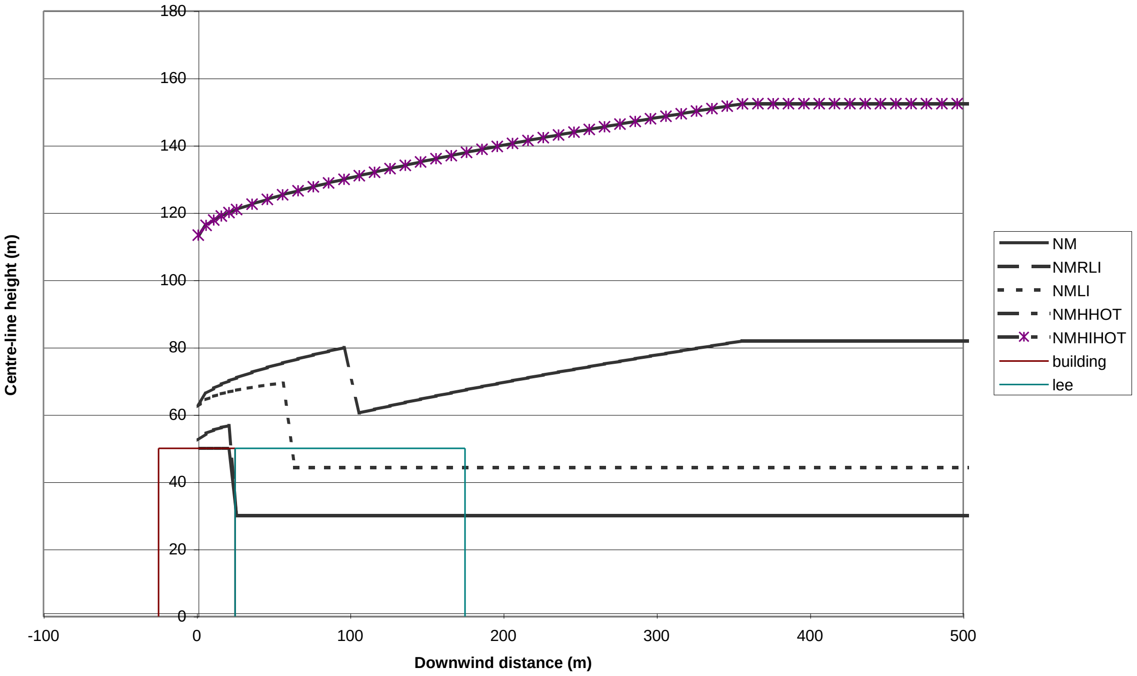
1. SDI: SDI model
2. SDINB: SDI model without buildings (linearised Gaussian model)
3. NM: Building extension of Dutch National Model
4. NMNB: SDI model without buildings (linearised Gaussian model)

3.2 Steady release from chimney

Figure 9 contains BWM dispersion predictions for the steady-state release of Q = 24 kg/s of a pollutant from a chimney downwind of a cubic building (height h_b = 50 m) The dispersion takes place under neutral conditions (D6) and over urban terrain (z_R = 3 m). The ambient temperature T_a = 288K. The concentration predictions correspond to a 10-minutes averaging time. The original TNO model assumptions have been applied (see TNO-NM column in Table 3).

The stack data have been varied in order to study the dispersion for a range of scenarios. (low or high impulse, low or high chimney, cold of hot plume. Figure 9 contains results for the following runs:

- The release of a low-impulse plume from a 'chimney' at roof height (h_s=h_b=50 m) with diameter d_s = 2.5 m, exit velocity v_s = 3.75 m/s, release temperature T_s = 288K. In this case stack-downwash takes place and the plume is fully taken up by the lee.
- The release of a higher impulse plume from a 'chimney' at roof height (d_s = 1.30 m; v_s = 15 m/s, h_s = 50 m, T_s = 288K). In this case stack-downwash does not take place and the plume is only partly taken up by the plume.
- The release of a plume from a higher chimney (d_s = 1.30 m; v_s = 15 m/s, h_s = 60 m, T_s = 288K). In this case the plume is not taken up by the plume, but the plume height is somewhat lowered.
- The release of a hot plume from the chimney (d_s = 1.30 m; v_s = 15 m/s, h_s = 60 m, T_s = 473K). In this case the plume is not taken up by the plume, but the plume height is somewhat (less) lowered. Note that after this building-wake correction for plume height the plume height further increases due to buoyancy.
- The release of a hot plume from a very high chimney (d_s = 1.30 m; v_s = 15 m/s, h_s = 110 m, T_s = 473K). In this case no building effects occur. The plume is not taken up by the plume, and the plume height is unaffected by the building wake.



(a) building geometry, lee geometry and plume height above ground

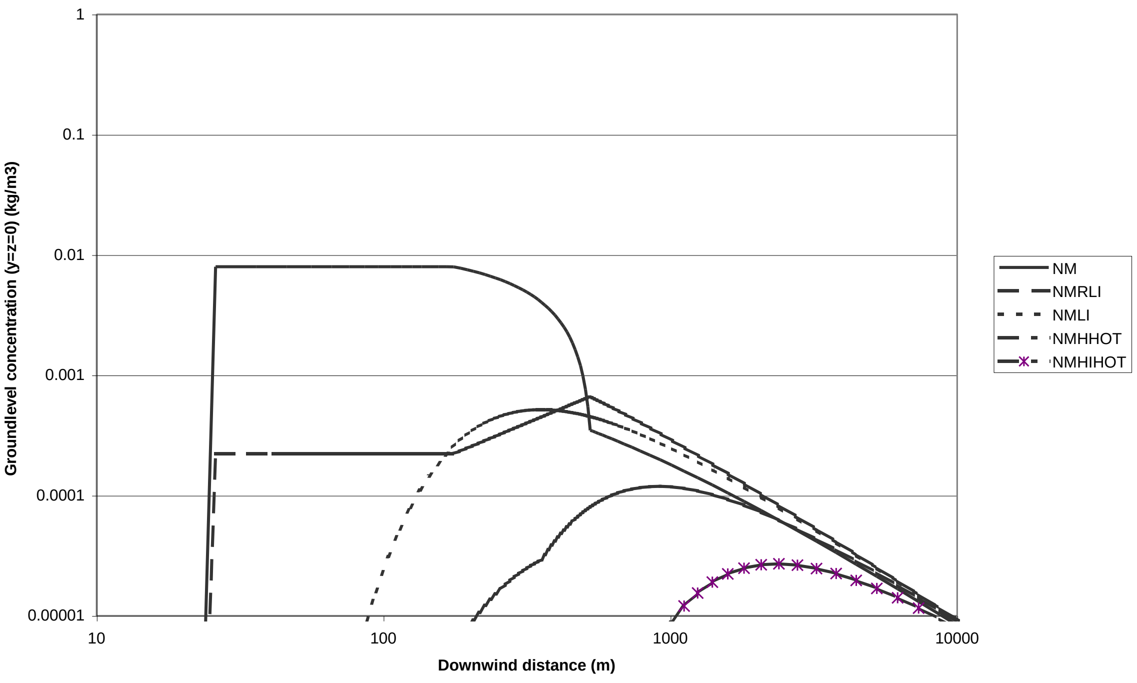
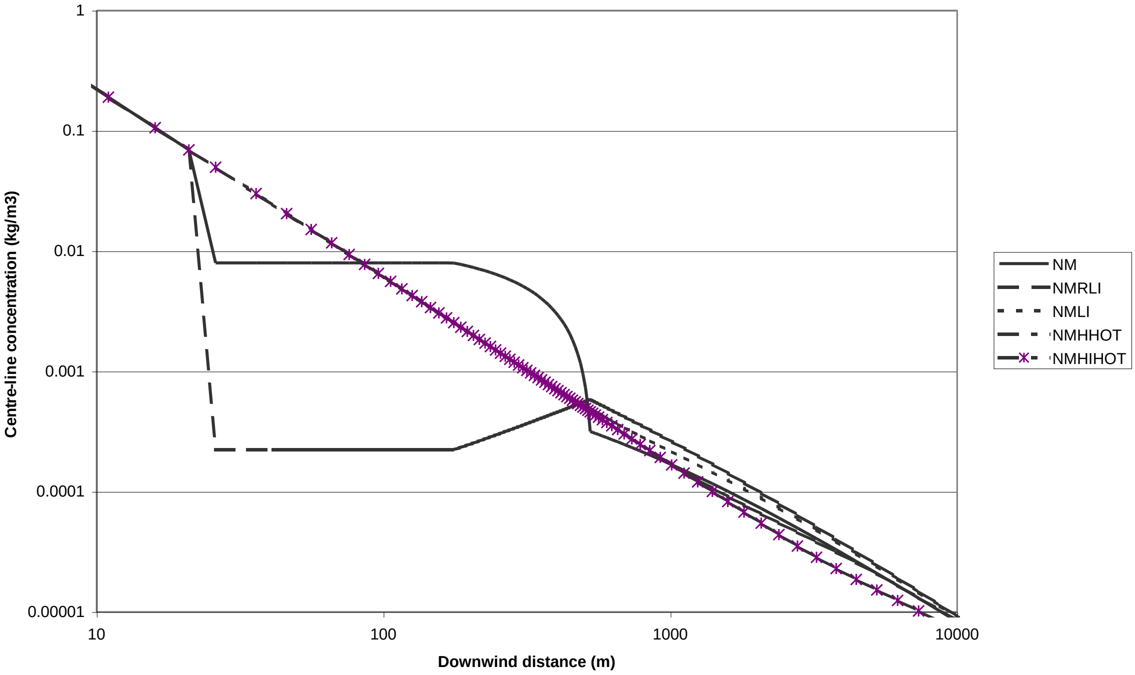


Figure 9– (b) centre-line ground-level concentration



(c) centre-line concentration

Figure 9. BWM predictions for release from chimney of cubic building (National Model)

BWM runs shown are:

(a) (NM) low-momentum plume from roof (d_s = 2.5 m, v_s = 3.75 m/s, h_s = 50 m, T_s = 288K)
(b) (NMRLI) plume from roof (d_s = 1.30 m, v_s = 15 m/s)
(c) (NMLI) plume from height h_s = 60 m
(d) (NMHHOT) hot plume from 60 m (T_s = 473K)
(e) (NMHIHOT) hot plume from 110 m (h_s = 110 m)

3.3 Finite-duration or instantaneous release from recirculation zone

Figure 10 contains BWM dispersion predictions for a finite-duration release of Q = 24 kg/s of a pollutant from the recirculation zone downwind of a cubic building (height h_b = 50 m) The dispersion takes place under neutral conditions (D6) and over urban terrain (z_R = 3 m). The concentration predictions correspond to a 10-minutes averaging time. The worst-case model assumptions have been applied (see wc-SDI column in Table 3).

BWM runs shown are for a range of durations t_{dur}:

1. t_{dur} = 600 seconds: continuous model (valid until 6505 m)
2. t_{dur} = 60 seconds: continuous model (valid until 673 m), note same results are obtained
3. t_{dur} = 13 seconds: continuous model (valid until 165 m), note same results are obtained
4. t_{dur} = 12 seconds: use of instantaneous model since $t_{dur} < L_x/U_w$ = 12.1s; note that the maximum lee concentration for the instantaneous model matches that of the instantaneous model at the transition time 12.1 seconds between the two models. It is seen however that for larger x the instantaneous model naturally leads to much smaller concentrations than that of the continuous model (based on infinite-duration assumption)
5. t_{dur} = 6 seconds: use of instantaneous model since $t_{dur} < L_x/U_w$ = 12.1s. The lower released mass now results in a lower lee concentration.

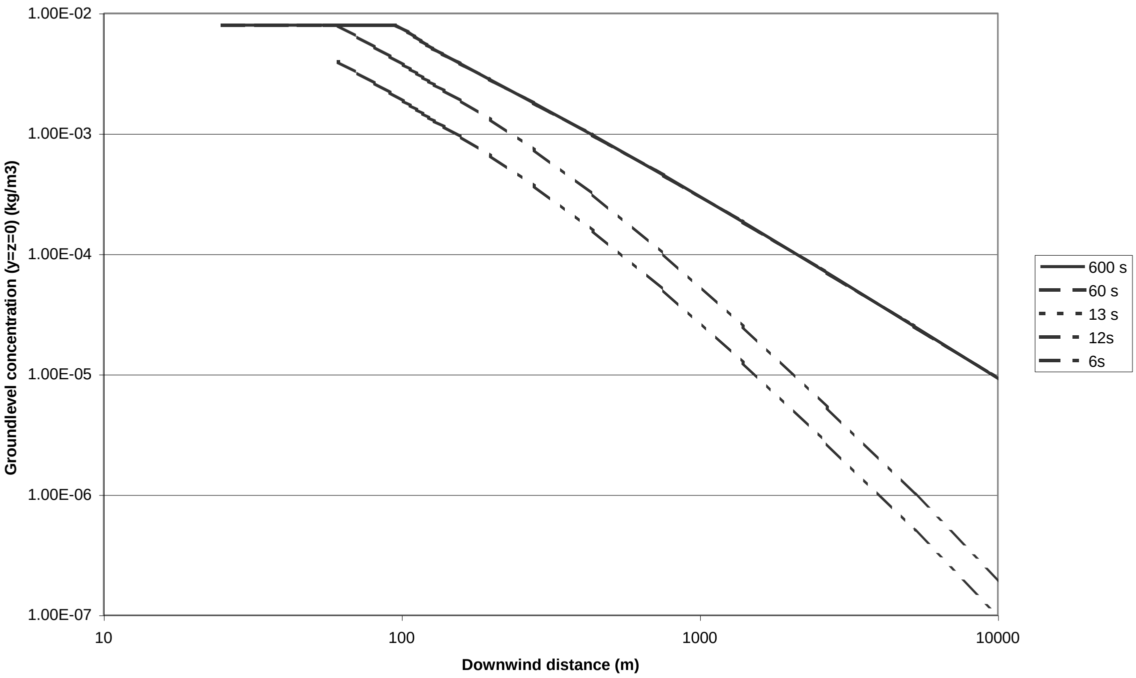


Figure 10. **BWM predictions for finite-duration release from recirculation zone (SDI model)**

4 FUTURE DEVELOPMENTS

A literature review has been carried out on building-wake modelling. As a result the following possible future extensions to the BWM model are considered.

Further adjustments of the SDI and N.M. models:

- The SDI model has been made unnecessarily complex by the near-field linearisation of the Gaussian dispersion coefficients (for x < 100 m). This linearisation may therefore be considered to be removed.

- The SDI model for finite-duration releases (see Sections 2.2.3 and 3.3), could be further improved in order to appropriately take into account the effects of along-wind diffusion. To this purpose the finite-duration correction as applied in the UDM model[xii] could be applied.

- The SDI model assumes always the plume height h = 0, while the N.M. model assumes the plume height $h = h_b - 0.4\delta$ in the case of full take-up of plume. Note that change in height downwind of lee is somewhat reflected in the SDI model by a virtual distance in σ_z. These inconsistencies between the two models could be removed.

- The current Dutch National Model (N.M. model) is rather ad hoc, and its formulation should be presented in dimensionally consistent terms. Its range of validity should be more clearly indicated (e.g. stack downwash correction is valid for narrow chimney diameters only)

- The several discontinuities for the N.M. model could be removed (smoothened). This may reduce the likelihood of problems in the calculation of risks by SAFETI from the BWM concentrations.

- In the N.M. model two different plume-rise formulas (Briggs) before height correction for wake effect (momentum + buoyancy) and after correction are applied (buoyancy only. Also two formulas are applied for the distance x' at which the final plume rise is calculated. A precise reference for this is not given in the N.M. documentation [Should both formulas not need to contain the different expression x'=89u for stable conditions?].

Building-wake concentration: K-factor

The model assumes for the building wake concentration c = Q/(K A u), where A is the frontal area of the building (projection on a plane perpendicular to the mean wind direction). The default value for K has been chosen to be the worst-case value of 0.2 as recommended by the SDI model. Note that this is very simplistic. The recommendations by the Dutch National Model[vii] are given in the table below:

Table 4. Values for the building-coefficient K (from Dutch National Model)[vii]

Source location	*Value for K*
source at top of middle of cubic building	1 (90°) 0.2 (45°)
buildings – in general	0.5 with uncertainty of factor 2 (0.25<K<1) 1 for annual averaged concentrations
sources near downwind obstacle face and concentrations on centre-line	0.5 ($l_b < h_b < b_b$) 0.3 ($l_b = 2h_b$) 4 ($l_b = 4h_b$)
tower-flat $l_b=b_b=h_b/3$	2 (90°) 1 (45°)
source downwind long, wide building	0.3 (90° and 45°)

Note that for buildings in general, a best-estimate value of K = 1 is to be recommended from the above table.

Note that the above table does not give values of K for a complete range of θ, b_b, l_b, h_b. Therefore reference is made to HSE-sponsored work by Atkins, who have carried out a rather detailed study of the dispersion near buildings:

- Phase I of this work included a literature review[xxi] (experimental data, simple models, CFD models). Sections 4.2, 4.3 of Reference [xxi] include an overview of simple models for wake concentration in case of both passive and non-passive releases, respectively [including the Dutch National Model].

- Phase II of this work included an in-depth study of CFD modelling to dispersion around buildings (including validation)[xxii], and further work on simple modelling[xxiii]. The study focussed upon particular applications of wake modelling:

    - o Models for normal wind incidence; near-wake recirculation model assuming uniform concentration, recommended by UK Atmospheric Dispersion Model Working Group, with more specific expression for

K and area of effective source. Effective source may then be used as an input to an area source Gaussian plume model or even a dense gas dispersion model. Also source width/height may be used (as in TNO SDI model) to define a virtual source primarily relating to non-normal wind incidence and the effects of high density on the concentration.

- For non-normal wind incidence, same formulas may be used using 'effective building dimensions'. Further improvement would be to use area as function of width/height aspect ratio and wind-incidence angle, i.e. $A = A(b/h,\theta)$. Parametric studies using CFD modelling could provide this type of formula. Effect of θ has significant effect for large aspect ratios only.

Duijm and Webber[xix] discuss dispersion in presence of buildings, distinction between source upwind of obstacle, release in circulation zone.

Following the above, it is recommended to further investigate the above and possible additional literature in order to be able to provide a best-estimate formula $K = K(\theta,b_b,l_b,h_b)$ valid for the entire range of θ,b_b,l_b,h_b.

Dispersion coefficients

The values for the dispersion coefficients quoted in Section 2.1.1 are based on those of the old 1992 TNO yellow book[v]. It could be considered to implement more recent formulations for the evaluation of the dispersion coefficients. Sections 4.3.3 and 4.5.3 in new 1997 TNO yellow book[vi] contain a number of alternative formulas for the above dispersion coefficients. Even more recently, Dave Wilson[xxiv] suggested some improvements. Note that the above work is recommended to be carried out, after completion of a similar exercise for the UDM model.

Variable ambient data

The model now assumes uniform ambient data (wind speed, temperature, pressure, density), and this should be representative for the entire region of the dispersion. Currently these data are taken at the building height for a roof/lee release and at the stack height for a chimney release. The model may be further extended to include a vertical velocity gradient.

Improved features from building-wake formulations in other models

Building-wake effects have already been included in a number of (passive) dispersion models, and further improved features may be included from these models:

- The EPA Industrial Source Complex dispersion model (ISC3)[xxv] is based on the straight-line, steady-state Gaussian plume equation. It is used for point source stack emissions, volume sources, area sources, and line sources. It applies a modified stack-tip downwash following Briggs[xvii]. It adopts building downwash methods of Schulman and Scire (1980)[xxvi] to set the reduced plume rise.
- The CERC model ADMS[xxvii] includes a specific buildings effect module, whereby the flow is split up into a near-wake region (Upwind, Recirculating, rest Around building) and the main wake (turbulent Wake, External to wake). It consists of the following subsequent steps:

  1. The complex of rectangular buildings is replaced with an equivalent single block.
  2. The flow field is set.
  3. The Hunt-Robins dispersion model is applied:
     (a) source in A, fraction entrained into R and then re-emitted as ground-level plume
     (b) source in R -> fully entrained, uniform concentration in R
     (c) stack downwash
     (d) matching downwind of W
     (e) plume rise module....

  A latest version of the ADMS version has been published by Robins and Apsley.[xxviii]

KEMA[x] has further improved the building-wake extension of the Dutch National Model[viii], which has resulted in a 'New Dutch National Model'[xi]. The BWM chimney model may be further compared/verified (and possibly updated) against the new Dutch National Model. The new model has been significantly changed compared to the old model. The main differences between the old and the new Dutch National Model appear to be as follows:

(a) the new model includes also includes the effects of roof recirculation flow, and assumes a modified wake geometry…

(b) the new model assumes a modified stack down-wash formulation

(c) the new model includes a modified plume width/depth calculation

(d) the plume rise formula in the new model includes variation of the wind speed in the vertical direction

(e) the new model includes a modified calculation of the lee take-up fraction of the plume

(f) the new model includes a modified building-wake concentration formula

(g) the new model sums contributions of the plume arising from both the wake and the residual plume (not taken up from the wake)

The resulting differences between the models are mainly caused by (a) higher wake concentrations except for case of tower, (b) effect of two plumes. For high chimneys, more equivalent results will be obtained (no wake effects, limited effect of variable wind speed).

Improved features from other work on dispersion over non-flat terrain

Schatzman et al.[xxix] described results of a wind-tunnel study for studying the effect of a single building on dispersion of a heavy-gas jet. This includes checks for concentration measured on building faces.

Webber et al.[xxx] suggest simple algorithms for the effects of buildings, which are claimed to be easily incorporated into almost any dispersion model (are included in DRIFT written by AEA for HSE). It also forms an ideal basis for incorporating the effects of obstacles into risk analysis. For a single fence, the simple model compares well with experiments by Rex Britter and Dave Hall. Subsequent speculative extension to finite-width building downwind to source (may go around obstacle, or over top, or completely engulf obstacle). Model used to compute effective source in the lee of the building. Not valid close to building. Comparison with (instantaneous) Thorney Island Trial 26 (cloud hits much higher building) and TNO wind-tunnel data by Duijm et al. (1994) [$H_b = L_b = 0.161$m, $W_b/H_b = 1, 3, 5$; circular pool (diameter=.107m) 0.241 upwind to front building; passive and dense releases].

TNO yellow book (draft version - 1995) states to include effects of obstacles for values of [min(h_b,b_b)]/[cloud height] larger than 0.5 - 1. Following Duijm and Webber (1994) recirculation zone may extend to 10h_b. Increased turbulence in wake results into a lower concentration downwind of recirculation than in absence of an obstacle. Nearer to obstacles no general trend but increases by factor of 2 have been reported.

In guidelines for use of vapour cloud-dispersion models (1996), model introduced for plume confinement by canyons, and concentration on building faces.

APPENDICES

Appendix A. BWM thermodynamics and properties

Evaluation of pollution density

The evaluation of the exit velocity for the chimney release requires evaluation of the pollutant density ρ_{pol} (kg/m^3) at the ambient pressure P_a and the release temperature T_{pol}; see Equation (29). The pollutant density equals the ratio of the pollutant molecular weight M_{pol} (kg/kmol) and the pollutant volume V_{pol} (m^3/kmol). Using the ideal-gas law it follows that

$$\rho_{pol}(T_s,P_a) = \frac{M_{pol}}{V_{pol}} = \frac{M_{pol}}{R\,T_{pol}/P_a} \quad (40)$$

where R is the gas-constant (R = 8314.3 J/K/kmol).

Evaluation of pollutant mole fraction and mixture temperature

The SDI and N.M. models both give predictions of concentration c (kg/m^3) and need further conversion to obtain the pollutant mole fraction y_{pol}. Using the ideal-gas law it can easily be shown that c is related to y_{pol} by

$$c(y_{pol};T_{mix},P_a) = \frac{pollutant\ weight\ /\ kmol\ of\ mixture}{mixture\ volume\ /\ kmol\ of\ mixture} = \frac{y_{pol}M_{pol}}{R\,T_{mix}/P_a} \quad (41)$$

Here the mixture temperature T_{mix} is found from energy conservation. This states that the total enthalpy of the individual compounds (wet air at temperature T_a, pollutant at temperature T_{pol}) before mixing, equals the enthalpy of the mixture (at temperature T_{mix}):

$$C_p^{wa}T_a(1-y_{pol}) + C_p^{pol}T_{pol}y_{pol} = \left[C_p^{wa}(1-y_{pol}) + C_p^{pol}y_{pol}\right]T_{mix} \quad (42)$$

where C_p^{wa} ,C_p^{pol} are the specific heats (J/K/kmol) of the wet air and pollutant, respectively.

The above two equations provide two equations for the two unknown variables y_{pol} and T_{mix}. Using the first equation to eliminate T_{mix} in the second equation can be shown to lead to the following square equation for $1/y_{pol}$:

$$\left\{\left(C_p^{wa} - C_p^{pol}\right)T_c\right\} + \left\{C_p^{pol}T_{pol} - C_p^{wa}\left[T_a + T_c\right]\right\}y_{pol}^{-1} + \left\{C_p^{wa}T_a\right\}y_{pol}^{-2} = 0 \quad (43)$$

where $T_c = M_{pol}P_a/(R\ c)$.

The solution to the above equation is as follows

$$y_{pol}^{-1} = \frac{1+T_{ca}-C_{pa}T_{pa}}{2} + \sqrt{\frac{1}{4}\left[1+T_{ca}-C_{pa}T_{pa}\right]^2 - [1-C_{pa}]T_{ca}} \quad (44)$$

where $T_{ca} = T_c/\ T_a$, $C_{pa} = C_p^{pol}/C_p^{wa}$, $T_{pa} = T_{pol}/T_a$.

Note that the above derivations are all based assuming an ideal-gas law, which is actually consistent with the simplicity of the BWM model. In BWM, the specific heat C_p^{wa} is approximated by the specific heat of air C_p^a = 1045 J/kg/K = 36.1 J/kmol/K (using molecular weight of air = M_a = 28.95 kg/kmol).

Evaluation of mixture density

The density ρ_{mix} (kg/m^3) of the mixture of pollutant (mole fraction y_{pol}) and air (mole fraction y_a = 1-y_{pol}) can now be evaluated at the ambient pressure P_a and the mixture temperature T_{mix}. This density equals the ratio of the mixture molecular weight M_{mix} (kg/kmol) and the mixture volume V_{mix} (m^3/kmol). Using the ideal-gas law it follows that

$$\rho_{mix}(T_{mix},P_a) = \frac{M_{mix}}{V_{mix}} = \frac{y_aM_a + y_{pol}M_{pol}}{R\,T_{mix}/P_a} \quad (45)$$

In a more general fashion it could be considered in the future to derive the above data from the MDE property system. This would involve the following properties: $\rho_{pol}(P_a,T_s)$, $y_{pol}(c;P_a,T_a, r_h)$, $\rho_{mix}(P_a,T_{mix})$ with use being made of the material property database to set specific heats and molecular weights of pollutant, dry air, and water in air.

Appendix B. Guidance on BWM input and output data

B.1 Input data

A list of the input data for the building wake model is given by Figure 11 and Figure 12. These data are split into the following categories:

1. Input data (always to be specified by the users); see Figure 11

   1.1. Release data

   1.1.1. Type of release. These select the type of model to be applied, i.e. roof/lee release (continuous or instantaneous SDI model) or chimney release (continuous National Model)

   1.1.2. Properties. The user normally specified the material name and its CAS number. If the CAS number is not defined, the user needs to specify pollutant specific heat C_p^{pol}, and pollutant molecular weight M_{pol} (kg/kmol). It is suggested to take the pollutant specific heat at the mean $(T_{pol}+T_a)/2$ of the pollutant temperature and the ambient temperature (as is done in case the CAS number is defined)

   1.1.3. Mass of released initial pollutant and (if present) initial air, release duration (not used for instantaneous release), and pollutant temperature

   1.1.4. Stack data (chimney only; not used for roof/lee release): height h_s above ground (m), top-inside diameter d_s (m)

   1.2. Ambient data: stability class, speed u_a^o at reference height z_o (m/s), temperature T_a^o (K) and pressure p_a^o (Pa) at reference height z_o^{Tp}, humidity

   1.3. Terrain data: surface roughness z_R (m)

   1.4. Concentration measurement: averaging time t_{av} (s)

   1.5. Building data: height h_b (m), length L_b (m), width B_b (m), clockwise angle between North and length axis of building, clockwise angle between North and wind direction. The effective building is calculated from these data, as illustrated in Figure 6. Note that in the case of a chimney release, the chimney is assumed to be located at the middle of the top of the effective building at x = 0. By specifying a different value of l_b this position could be changed, but this is not possible if the lee length depends on l_b (e.g. if the Fackrell formula is applied, which is the default assumption).

2. Parameters (input data to the changed by expert users only); see Figure 12

   2.1. Ambient data: specific heat, molecular weight, vertical wind profile $u_a(z)$ [1 - constant, 2 - power-law fit of logarithmic profile], cut-off height for power-law wind profile, vertical temperature/pressure profile (1 - constant, 2 - linear, 3 - log), mixing height flag (1 - yes, cloud rise is restrained by mixing layer, 2 - no, cloud rise is not restrained by mixing layer), height of mixing layer (=0: use hard-wired values in code). See the UDM theory manual for full details of the ambient profiles. Note that in BWM ambient data are taken to be at the building height for a roof/lee release and the stack height for a stack release. Thus change in ambient data is not taken into account if the plume rises or subsides.

   2.2. Model assumptions: model type, lee length L_x, lee half-width L_y, lee height L_z, K-factor, far-field distance X_e. Zero values for L_x, L_y, L_z, K, X_e indicate that default values are applied for the above parameters. Only expert users should specify non-default values, and also seek advice DNV. See Section 2.4 for further details. Note that advice in Section 4 may be used to set a more accurate value of the parameter K.

   2.3. Control of output steps: three input parameters are used to determine the step size for output of the BWM file: maximum size of initial fixed downwind step, Δx_{fix}, minimum number of fixed downwind steps along each model zone, n_{fix}, and factor for step increase after fixed steps, r_{size}

   - For the continuous SDI model, the 'model zones' from Figure 3 are
     (1) along wake (top-hat profile): first output distance is $x = l_b/2$ and output step size is $\Delta x = \min[\Delta x_{fix}, L_x/n_{fix}]$
     (2) zone of Gaussian linear dispersion: step size $\Delta x = \min[\Delta x_{fix},(x_e-L_x-½l_b)/n_{fix}]$
     (3) further downwind: increasing step size with $(\Delta x)_{new} = r_{size}\,(\Delta x)_{old}$
   - For the instantaneous SDI model, the 'model zones' from Figure 4 are
     (1) along wake during residence time (top-hat profile, uniform concentration): output distance is $x = ½l_b+½L_x$ and output times are 0, t_{res}
     (2) along wake after residence time (Gaussian profile): $\Delta x = \min[\Delta x_{fix}, L_x/n_{fix}]$ (initial output time t_{res})
     (3) zone of Gaussian linear dispersion: $\Delta x = \min[\Delta x_{fix},(x_e-L_x-½l_b)/n_{fix}]$
     (4) further downwind: increasing step size with $(\Delta x)_{new} = r_{size}\,(\Delta x)_{old}$
   - For the continuous chimney model, the 'model zones' from Figure 5are
     (1) upwind of wake: first output distance is x=0 and $\Delta x = \min[\Delta x_{fix}, ½l_b/n_{fix}]$
     (2) upwind of plume height correction: $\Delta x = \min[\Delta x_{fix},(x''-½\,l_b)\,/n_{fix}]$
     (3) upwind of final plume height (if present): $\Delta x = \min[\Delta x_{fix},(x'-x'')/n_{fix}]$

   2.4. Termination criterion:

   1. risk-based run; termination is based on material/result type:
      - if flammable, run stops when the maximum concentration at a downwind distance falls below the minimum concentration c_{min}

- if toxic, run stops when the maximum concentration falls below the concentration corresponding to the minimum probability of death p_{min}. For toxic mixtures, the toxic calculation method specifies whether to use the probit functions provided for the mixture, to use the most toxic component, or to combine doses from components. This calculation is also dependent on the parameter 'maximum release duration'.
- if both flammable and toxic, the run stops after both the minimum concentration c_{min} and the minimum probability of death p_{min} have passed
- if inert, risk-based run is not allowed

2. concentration and distance based run: run stops when both concentration is below c_{min} and maximum distance x_{max} have passed
3. distance-based run: run stops when maximum distance x_{max} has passed.
4. concentration based run: run stops when concentration is below c_{min}

Note that the run will be terminated earlier in case either the absolute maximum distance x_{max}^{abs} has been passed, or the maximum centre-line height h_{max} has been achieved. The run will also be terminated earlier if the maximum number of output steps n_{max} has been achieved.

	D	E	F	J	L	M	N	O	P
2	**Inputs**		**DNV BUILDING WAKE MODEL BWM**						
3	**Input**	**Description**	**Units**	**Dim**	**Limits**		**NM_cont**	**SDI_cont**	**SDI_inst**
4	**Index**			**2**	**Lower**	**Upper**			
14	**Release data**								
15		**Type of release**							
16	A	from roof/lee (1) or chimney (2)	-		1	2	2	1	1
17	A	continuous (2) or instantan. (1)	-		1	2	2		1
18		**Properties**							
19	N	Material name	-				METHANE		
20	5	Material CAS nr. (undefined=0)	-				74828		
21	A	Specific heat (if undefined CAS)	J/kg/K		0.001	10000	1100		
22	A	Mole weight (if undefined CAS)	kg/kmole		0.001	500	29		
23		**Mass rate and temperature**							
24	A	Pollutant mass	kg/s or kg		1.00E-06	1.00E+09	24		
25	A	Initial mass of air mixed in (must be 0 for chimney)	kg/s or kg		0	1.00E+09	0		
26	A	Duration	s		0.001	1.00E+08	3600		1
27	A	Pollutant temperature	K		1	1000	293.15		
28		**Stack data (chimney only)**							
29	A	Stack height	m		0	2000	50	0	0
30	A	Top-inside stack diameter	m		0	2.00E+02	2.5	0	0
31	**Ambient Data**								
32	A	Stability class (A,A/B,B,B/C,C,C/D,D,E,F,G=1,…10)	-		1	10	7		
33	A	Wind Speed	m/s		0.1	50	5		
34	A	Reference height for wind speed	m		0.1	100	10		
35	A	Temperature	K		200	350	293.15		
36	A	Pressure	N m-2		50000	120000	101325		
37	A	Reference height for temp./press.	m		0	100	0		
38	A	Humidity	fraction		0	1	0.7		
39	**Terrain data**								
40	A	Surface roughness length	m		1.00E-04	3	3		
41	**Averaging time**								
42	A	Averaging time	s		1	3600	600		
43	**Building data**								
44	A	Height	m		0.001	500	50		
45	A	Length	m		0.001	500	50		
46	A	Width	m		0.001	500	50		
47	A	Clockw. Angle N to length axis	degrees		0	180	0		
48	A	Clockw. angle N to wind-dir.	degrees		0	180	0		

Figure 11. Input data for building wake model BWM. Part I: input data always to be specified

The above input data are derived from the generic spreadsheet for the BWM. This first part of the input data should always be specified by the user (release data, ambient data, terrain data, averaging time, building data). For each input parameter a brief description of the meaning of the parameter is given, it unit, and its lower and upper limits. Column N contains a complete list of input data corresponding to an example of the (continuous) National Model. Columns O, P indicate those values that need to be changed to invoke the continuous SDI model and instantaneous SDI model, respectively.

	D	E	F	J	L	M	N	O	P
2	**Inputs**		**DNV BUILDING WAKE MODEL BWM**						
3	**Input**	**Description**	**Units**	**Dim**	**Limits**		**NM_cont**	**SDI_cont**	**SDI_inst**
4	**Index**			2	**Lower**	**Upper**			
49		**PARAMETERS (values to be changed by expert users only)**							
50	**Ambient Data**								
51	A	Specific heat	J/kg/K		800	1200	1004		
52	A	Molecular weight	kg/kmole		10	100	28.966		
53	A	wind profile (1-constant,2-power)	-		1	2	2		
54	A	cut-off height for power-law wind profile	m		0.1	1	1		
55	A	temperature/pressure profile (1-constant,2-linear,3-log)	-		1	3	3		
56	A	Mixing height flag (1-yes,2-no)	-		1	2	2		
57	A	Height of mixing layer [=0, use hard-wired values]	m		0	1000	0		
58	**Model assumptions**								
59	A	TNO (1), worst-case(2), best-est.(3)	-		1	3	3		
60	A	lee length [0: use default]	m		0	10000	0		
61	A	lee half-width [o: use default]	m		0	10000	0		
62	A	lee height [0: use default]	m		0	1000	0		
63	A	K-factor [0:def.]	-		0	5	0		
64	A	downwind distance after which to use normal Gaussian model (chimney only)	m		0	1000	0		
65	**Control of output: step size**								
66	A	Max. size init.fixed downw.step	m		0.1	100.0	10		
67	A	min. number fixed downw.steps along each model zone	-		1	1000	5		
68	A	Factor for step increase after fixed steps	-		1	10	1.2		
69	**Control of output: termination criterion**								
70	A	Termination criterion: 1 - min. prob. (toxic) and/or min. conc. (flammable), 2 - min.conc. and max.dist., 3 - max.dist., 4 - min.conc.	-		1	4	3		
71	A	minimum probability of death (toxic)	-		1.00E-10	1	1.00E-10		
72	A	minimum concentration	mole %		1.00E-10	10	1.00E-05		
73	A	maximum distance	m		10	100000	10000		
74	A	Absolute maximum distance	m		10	100000	50000		
75	A	Maximum plume height	m		1	10000	1000		
76	A	Material/result type (-2: inert, -1: toxic, 1: flammable, 0: both)			-2	1	0		
77	A	Toxic-load calculations flag for mixture (1 - mixture probit, 2 - most toxic probit, 3 - combination probit)			1	3	1		
78	A	Maximum duration for a release	s		0	1.00E+08	3600		
79	6	Maximum nr. of output steps	-		2	10000	100		

Figure 12. Input data for building wake model BWM. Part II: input parameters

The above input data are derived from the generic spreadsheet for the BWM. This second part of the input data correspond to the values of the input parameters (ambient data, model assumptions, control of output), which should be changed by expert users only. For each parameter a brief description of the meaning of the parameter is given, it unit, and its lower and upper limits. Column N contains a complete list of input data corresponding to an example of the (continuous) National Model. Columns O, P indicate those values that need to be changed to invoke the continuous SDI model and instantaneous SDI model, respectively.

B.2 Model run and output data

Following initialisation of data, dispersion calculations are carried out as indicated in Table 2 and Chapter 2. First the plume height h = h(x) and subsequently the concentration and dispersion coefficients are calculated. The dispersion data are output as function of the downwind distance.

In the case of a release from the roof or within the recirculation zone, the continuous SDI model (see Section 2.2.1) or instantaneous SDI model (see Section 0) is adopted assuming all released pollutant taken up by recirculation zone, and an uniform lee concentration for $X<L_x$. In the case of a stack release, the extended National model (see Section 2.3) is followed.

The output data are listed by Figure 13. The output data are split into the following categories:

1. Effective building dimensions. These are calculated from data describing the actual building as indicated in Figure 6.

2. Lee data and model assumptions. See Section 2.4 for details of calculations. These define the data affecting the lee (lee dimensions, lee concentration, lee residence time (instantaneous SDI model only). It also defines the downwind distance, downwind of which the standard non-linear Gaussian dispersion model is adopted.

3. Output data for chimney release. These data are calculated in case of the Dutch National Model only. See Chapter 2 for details.

4. Dispersion data. See Chapter 2 for details of calculations. First the number of output steps are given. Subsequent for each output step, all data defining the full concentration profile are given. These include:

   - downwind distance x from the centre of the building
   - ground-level concentration c(x,0,0)
   - crosswind and vertical dispersion coefficients $\sigma_y(x)$, $\sigma_z(x)$
   - centre-line height h(x)
   - centre-line concentration c(x,o,h), kg/m^3, and centre-line mole fraction
   - centre-line temperature and centre-line cloud density
   - downwind dispersion coefficients $\sigma_x(x)$ [case of instantaneous SID model only]
   - time since start of release
   - profile type (2 - TNO Gaussian profile; 3 - top-hat profile)
   - cloud downwind radius, cloud crosswind radius and cloud vertical radius R_x, R_y, R_z in line with the UDM definitions of these data.
   - transition distance to passive (this has been added for the PHAST post-processor to deal with multiple averaging times)

	D	E	F	J	L	M	N	O	P
80	**Outputs**								
81	**Output**	**Description**	**Units**	**Dim**					
82	**Index**			**2**					
83		***ERROR STATUS***					***OK***	***OK***	***OK***
84	**Also output data on ASCII Output File and/or .TMP temporary results file**								
85	**Effective building dimensions**								
86	1	effective building length	m				50	50	50
87	2	effective building width	m				50	50	50
88	**Lee data and model assumptions**								
89	3	lee length	m				150	72.58064	72.58064
90	4	lee half-width	m				25	25	25
91	5	lee height	m				50	50	50
92	6	lee concentration	kg/m3				8.17E-04	9.78E-04	1.32E-04
93	7	lee residence time(inst.SDI only)	s				Undefined	Undefined	35.01785
94	8	K-factor	m				1	1	1
95	9	downwind distance after which to use normal Gaussian model	m				525	125	125
96	**Output data for chimney release**								
97	10	vertical exit velocity	m				7.373742	Undefined	Undefined
98	11	reduced release height	m				50	Undefined	Undefined
99	12	plume-correction parameter [full (<0), partial (0-0.2),lower(0.2-1.5), none(>1.5)]	-				3.29E-02	Undefined	Undefined
100	13	downwind distance for plume height correction	m				100	Undefined	Undefined
101	14	height before correction	m				51.6433	Undefined	Undefined
102	15	height after correction	m				30	Undefined	Undefined
103	16	downwind distance to achieve final plume height	m				100	Undefined	Undefined
104	**Dispersion data**								
105	17	Number of output steps	-				89	45	42
106	18	Downwind distance	m				Array	Array	Array
107	19	Groundlevel concentration (y=z=0)	kg/m3				Array	Array	Array
108	20	Crosswind dispersion coefficient (SIGMAY)	m				Array	Array	Array
109	21	Vertical dispersion coefficient (SIGMAZ)	m				Array	Array	Array
110	22	Centre-line height	m				Array	Array	Array
111	23	Centre-line concentration	kg/m3				Array	Array	Array
112	24	Centre-line mole fraction	-				Array	Array	Array
113	25	Centre-line temperature	K				Array	Array	Array
114	26	Centre-line cloud density	kg/m3				Array	Array	Array
115	27	Downwind dispersion coefficient (SIGMAX)	m				Array	Array	Array
116	28	Time	s				Array	Array	Array
117	29	Profile type (2-TNO,3-tophat)	-				Array	Array	Array
118	30	Cloud downwind radius - RADX	m				Array	Array	Array
119	31	Cloud crosswind radius - RADY	m				Array	Array	Array
120	32	Cloud vertical radius - RADZ	m				Array	Array	Array
121	33	Transition distance to passive	m				Array	Array	Array

Figure 13. Output data for building wake model BWM

The above output data are derived from the generic spreadsheet for the BWM. The values of the three runs in columns N,O,P correspond to the input values included in columns N,O,P of Figure 12. Output data for the dispersion array data are not included in this figure.

B.3 Detailed information on BWM errors and warnings

Below information on errors/warnings/messages are given, which can currently be produced by the BWM model.

Error messages

- 1 "Release results in %1%real% percent filling of wake; the UDM model should be applied instead (ignore wake)"

This message is given if the volume of the total initially released mixture (pollutant + initial air) in the building wake is such that it overfills the entire building wake. Therefore the building wake model is not applicable and the UDM model should be applied instead.

The volume fraction y_{lee} of the total initially released mixture (pollutant + initial air) in the building wake is given by

$$y_{lee} = \frac{c_{lee}}{\rho_{pol}} \frac{[M_{pol}/m_{pol}]+[M_{air}/m_{air}]}{[M_{pol}/m_{pol}]}$$

where c_{lee} is the building wake concentration (kg/m^3), ρ_{pol} the pollutant density at the mixture temperature corresponding to the concentration c_{lee} (kg/m^3), m_{pol}, m_{air} the molecular weight of pollutant and air (kg/kmole), and M_{pol}, M_{air} the release rates of pollutant and air (kg/s for continuous, kg for instantaneous). Thus the above message is given for $y_{lee} > 1$.

- 2 "Stack height of %1%Length%1 above ground is smaller than building height"

This message is given in case of a chimney release, if the specified stack height above the ground is smaller than the building height. The user should specify a stack height larger than or equal to the building height.

- 3 "Presence of initial air is not allowed for chimney release"

The current BWM formulation can at presently not cope with the initial presence of air in the case of a chimney release. The user can however specify by means of the property system as a pollutant to BWM a mixture, which contains air.

- 6 "Two-phase release, or liquid release (pollutant temperature is below boiling temperature of %1%Temperature%)"

The BWM model is applicable for a pure-vapour release only, and therefore the specified pollutant temperature must be always above the boiling temperature.

- 7 "Two-phase release, with liquid fraction %1%Real%, with added air. If an in-building release, try setting droplets trapped"

The BWM model is applicable for a pure-vapour release only. This error can occur for an in-building release where vapour condenses during expansion and the user has not selected 'droplets trapped' option.

- 8 "Chimney diameter %1%Length% is greater than the building length or the building width"

The chimney diameter cannot be greater than width or the length of the building. This message is given in case of a chimney release, if the specified chimney diameter is larger than the building length or building width. The user should specify a chimney diameter significantly smaller than the building length and building width, since e.g. otherwise the chimney may affect the building wake.

Warning messages

- 1003 "No mass conservation along lee: lee pollutant flow %1%Mass% different to pollutant release rate"

By default PHAST values for parameters are adopted for lee dimensions and K-factor, such that automatically mass conservation will apply. Therefore this message will only occur in case of user-defined values of one of the lee height, lee width and/or the K-factor. In case the user wishes to obtain worst-case values, no mass conservation (i.e. a too high mass) may be a wanted assumption. Otherwise the user should ensure 2 L_yL_z = K h_bb_b (continuous releases).

- 1005 "Heavy-gas effects (dense-gas factor %1real%1 exceeds criterion 1) may result in inaccurate concentrations"

This message is applied if heavy-gas effects are deemed to effect the BWM predictions. It is based on the Britter and McQuaid criterion as mentioned in the theory manual. Since BWM does not include heavy-gas effects, the BWM predictions may result in case of chimney releases in too high plumes and too low ground-level concentrations. For lee releases, the building wake concentration will be inaccurate.

- 1007 "Maximum number of output dispersion steps %1%integer% achieved. Dispersion calculations prematurely terminated"

This warning will be given if the maximum number of output dispersion steps is achieved, and the dispersion calculations will be prematurely terminated. To avoid this, the user could increase the parameter representing the maximum number of output dispersion steps.

Messages

- 2001 "Release too short to achieve steady-state wake; modelled as instantaneous (mass = %1%Mass%)"

This message is given if the release duration is too short for the steady-state building wake concentration to be achieved. As a result, the release is modelled as an equivalent instantaneous release (released mass = steady-state release rate * release duration)

- 2003 "Ambient data in BWM are taken at the building height (adopted wind speed = %1%Velocity%; no variation with height)"

This message is given in case of a roof/lee release, for which ambient data (velocity, temperature, pressure) are chosen to correspond to the actual ambient values at the building (roof) height. The ambient data are assumed to be uniform and no variation with height is taken into account.

- 2004 "Ambient data in BWM are taken at the stack height (adopted windspeed = %1%Velocity%; no variation with height)"

This message is given in case of a stack (chimney) release, for which ambient data (velocity, temperature, pressure) are chosen to correspond to the actual ambient values at the stack height (= release point). The ambient data are assumed to be uniform and no variation with height is taken into account.

- 2017 "Only fraction %1%real% taken up by lee. Remaining part of plume is not taken into account by BWM"

This warning will always be given in case of partial take-up of the plume by the lee [Dutch National Model, case of $0<\lambda<0.2$. This may result in too low concentrations, particularly for those above ground-level and for λ values more close to 0.2 (less of plume taken up by lee).

- 2018 "Beyond downwind distance %1%Length%1, predictions are conservative since duration is too short to ensure steady-state"

According to the SDI guideline, a finite-duration release with duration t_{dur}, can be modelled as continuous until a downwind distance of $X=1.8u_a t_{dur}$, where u_a is the ambient wind speed. The release should be modelled as instantaneous for distances above $X=18u_a t_{dur}$. For intermediate distances, $1.8u_a t_{dur}<X<18u_a t_{dur}$, interpolation should take place. See the theory manual for further details.

Appendix C. Dutch QRA CPR-15/2 regulatory method

This appendix summarises the Dutch QRA CPR-15/2 regulatory method for storage of hazardous materials, as described in the TNO report[ii]. The reader is referred to any further details to this report.

The VROM CPR-15/2 guideline states that QRA is required for storage of > 10 tonnes hazardous materials and with warehouse closer to build-up areas than indicated by VROM circular IBP 03892009. The TNO report describes a QRA method recommended by the VROM.

Problem

- exactly when QRA is needed (types of materials)
- protection levels (fire extinguish, fire detection, actions to prevent fire)
- risks for the environment - types of accidents:
  (1) release/ignition of flammable fuel: pool fire (radiation 16.5 kW/m^2 can occur up to 30 m distance), or cloud fire (pool evaporation -> dispersing gas cloud -> ignition above LFL -> cloud fire)
  (2) release of toxic liquids (evaporating)/powders due to failure of packing
  (3) warehouse fire with production of toxic combustion products.

Risk calculation for release of stored products.

Probabilities are taken into account of presence of product, packing failure, escalation (e.g. ignition, certain concentration pattern, etc.).Meteorology defined by wind speed, wind direction (use Dutch KNMI database of frequencies of closest weather station) and Pasquill Gifford stability class.

Release of toxic solid materials

Powders considered only, since other more coarse solids (e.g. grains) don't contribute to external risk. Release depends on package size [max. of 400 kg for very toxic materials, i.e. with LD_{50}(oral,cat) < 5 mg / kg].

Source strength = package contents * fraction active material (10-20% for pesticides, 100% for chemicals; use actual value) * fraction released content (normally take 10%) * fraction sufficiently small particles for dispersion and inhalation (<10μm; use actual value).

Because size<10μm, Gaussian dispersion may be assumed. In building wake area, max. concentration c (kg/m^3) from short-distance immission model, c = m / [K*B*H * 3H], with source strength m (kg), constant K (.2 for 45^o angle between wind and building width), building width B ⊥ wind direction, building height H.

The building wake area has a size of 0.2 of the building width, height H and a length of 3H. The building wake can be considered as an area source with a height. Concentrations in the environment can be set using the time-dependent Gaussian plume model from the yellow book.

The maximum doses can be set from the probit function $Pr = -A + \ln(C^2 t)$, with the constant A dependent on the toxicity LD_{50}, C the concentration (mg/m^3) and t the exposure time for inhalation.

For failure frequency only packing failure outside warehouse is relevant (during transport). Suggested failure frequencies are given for a number of cases. Probability of release of toxic solid from package = failure frequency (10^{-5} / package) * average number of packages treated.

For example, calculations are carried out of source strength, building wake concentration, Gaussian dispersion calculations, probit function, failure probability and individual risk.

Release of toxic liquid materials

Risks depends on toxicity and concentration. Concentration depends on source strength and meteorology. Source strength equals pool evaporation, which depends on pool area, ambient temperature (usually assume 15^{o}C), and vapour pressure of material (set from yellow book). External risk if toxicity of material is larger than LD/LC value at given vapour pressure (Table 3.2). Maximum package sizes given.

In building wake area, max. concentration c (kg/m^3) from short-distance immission model, c = m / [K*B*H * U], with U wind speed, constant K (.2 for 45^o angle between wind and building width), building width B (⊥ wind direction??), building height H. Subsequent dispersion calculations using semi-continuous Gaussian dispersion model (CPR-16). Use probit function from CPR-16.

Annual failure frequency for unpressurised storage / stationary tanks ($5*10^{-5}$ - $3*10^{-7}$), pressure vessels (10^{-6}). Factor 10 higher for mobile tanks/vessels. For drums 10^{-5}. Failure probability = frequency * number of package units.

Again example given.

Warehouse fire

Emission unburned toxic materials. Risk method (fire scenarios, duration, area, ventilation, combustion chemistry, burning velocity, source strength for combustion products and unburned toxic products, toxicity).

Source height equals height ventilation exits, assumed passive pollution, include effect of building wake. Set source dimensions and concentration as in Section 3.3. Use in dispersion model averaging times equal to exposure time to people in environment --> Probit functions --> ‘damage areas’.

Risk estimates, fire frequency and growth. Systems: automatic sprinklers / deluge / extinguishers, local fire brigade with dry deluge. Example given.

NOMENCLATURE

A	area of the effective building = frontal area of the original building (projection of the building on a plane perpendicular to the mean wind direction); $A = h_b b_b$
b_b	effective building width (projection of the building on a plane perpendicular to the mean wind direction), m
B_b	building width, m
c	concentration, kg of pollutant / m^3
C_{ZR}	correction factor to vertical dispersion coefficient for effect of surface roughness (-)
d_s	[stack release] stack diameter, m
h	centre-line height of plume, m
H_{min}	[stack release] plume height after correction of building-wake effects (at x = x''), m
H*	[stack release] plume height before correction of building-wake effects (at x = x''), m
h_b	building height, m
h_s	[stack release] stack height above ground, m
K	factor in formula $c = Q / KAU_w$ for building-wake concentration (-)
l_b	effective building length (projection of the building on a plane along the mean wind direction), m
L_b	building length, m
L_x	length of recirculation zone, m
L_y	half-width of recirculation zone, m
L_z	height of recirculation zone, m
m_c	total released mass, kg
Q	release rate for continuous release, kg of pollutant / s
Q_H	plume heat content, MW
t	time, s
t_{av}	averaging time for concentrations, s
u, U_w	wind speed, m/s
x	horizontal downwind distance from (effective) building centre, m
X	horizontal downwind distance from downwind edge of (effective) building, $X=x-b_b/2$
x'	distance at which the plume reaches its maximum height (plume rise because of buoyancy or momentum) without effects of recirculation zone, m
x''	distance at which the plume height is corrected for building-wake effects, m
x^*	distance for middle of building wake (re-circulation zone)
x_e, X_e	downwind distance from which to use the (non-linearised) Gaussian dispersion model ($X_e = x_e - b_b/2$ = distance from downwind edge of building), m
y	cross-wind distance, m [y=0 corresponds to building centre and plume centre-line]
z	vertical height above ground, m
z_R	surface roughness length, m

Greek letters

δ	minimum value [$=\min(h_b,b_b)$] of building height and width, m
θ_b	anti-clockwise angle between mean wind direction and length-axis of building
ΔH	plume rise from release height h_s (for chimney release), m
λ	dimensional factor used in chimney model to indicate the difference between the maximum plume height H* and the building height h_b, $\lambda = (H^*-h_b)/\delta$
σ_y	Gaussian cross-wind dispersion coefficient, m
σ_y	Gaussian vertical dispersion coefficient, m

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