Waste Management and
Environmental Technology

WSRC-RP-95-89

VERIFICATION OF VENTSAR

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Technical Reviewer

January 1995

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

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Key Words
Source Terms
Atmospheric Dispersion
Building Wake Effects

Retention: Lifetime

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ABSTRACT

VENTSAR is a computer model that will analyze flow patterns of pollutants on or near buildings. Plume rise may be considered. Verification of VENTSAR is complete and the methodology is discussed in detail within this report. Hand calculations were performed to ensure proper application of methodologies.

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VERIFICATION OF VENTSAR

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1.0 INTRODUCTION

The VENTSAR code is an upgraded and improved version of the VENTX code (Smith and Weber, 1983), which estimates concentrations on or near a building from a release at a nearby location. The code calculates the concentrations either for a given meteorological exceedance probability or for a given stability and wind speed combination. A single building can be modeled which lies in the path of the plume, or a penthouse can be added to the top of the building. Plume rise may also be considered. Release types can be either chemical or radioactive. Downwind concentrations are determined at user-specified incremental distances.

This verification report was prepared to demonstrate that VENTSAR is properly executing all algorithms and transferring data. Hand calculations were also performed to ensure proper application of methodologies.

2.0 CODE ORGANIZATION

The code is set up so that the bulk of the work concerning the plume rise and building wake effects is done within the main program; however subroutines are called for other calculations. Figure 1 shows the layout of the subroutines used within VENTSAR; a brief description of each of the subroutines follows.

INPUT This subroutine reads the user input, checks the input for validity, and echoes it for the output. Unit conversions are also done as needed. The DRAW subroutines depicts the building dimension as a printer sketch in part of the output.

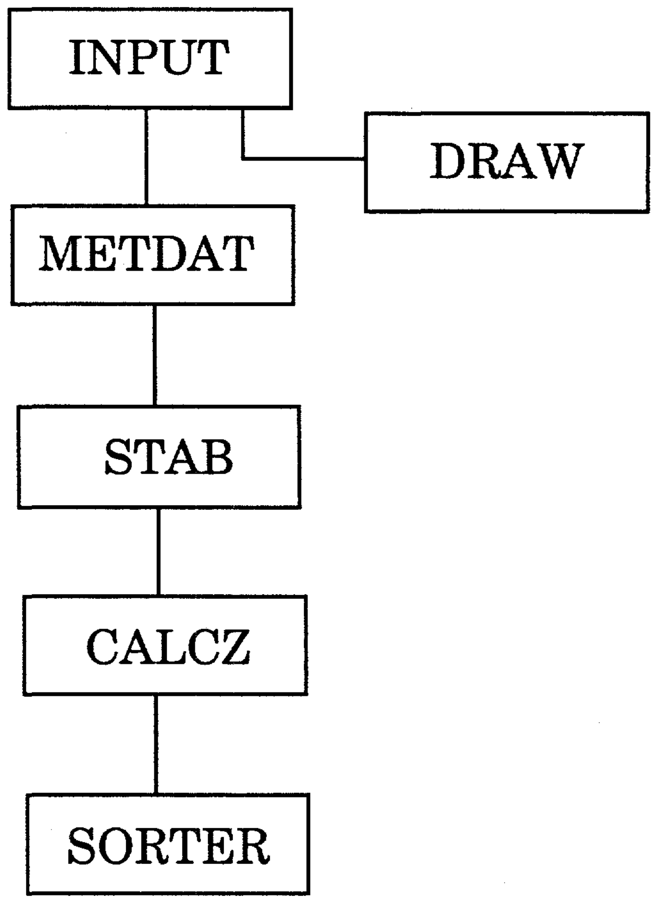
METDAT This subroutine reads the meteorological frequency distribution of the tower that is closest to the release point, if needed. The wind speeds are also read from this subroutine. The meteorological frequency distribution is echoed as part of the output.

STAB This subroutine determines the horizontal and vertical diffusion coefficients used to determine the relative air concentrations.

CALCZ Determines the height of the plume based on the turbulence zones created by the building.

SORTER Ranks the relative air concentrations to determine the given probability value. The associated wind speed and stability class are also maintained.

Figure 1. Subroutine Layout



3.0 THEORETICAL MODELS

This section discusses the theoretical models and data files that are employed within VENTSAR.

3.1 Gaussian Plume Model

The pollutant dispersion calculations in the VENTSAR code are based on a reflecting Gaussian plume model (Pasquill, 1961). Along the plume centerline, the dispersion factor or relative air concentration, defined as the ratio of the pollutant concentration χ (kg/m^3 or Ci/m^3) to the source strength Q (kg/sec or Ci/sec), is given by the equation:

$$\frac{\chi}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U_S}\left[e^{-\left(\frac{(z-h_e)^2}{2\sigma_z^2}\right)} + e^{-\left(\frac{(z+h_e)^2}{2\sigma_z^2}\right)}\right] \quad (1)$$

where:

χ/Q	the dispersion factor, (sec/m^3);
z	height above the ground surface, (m);
h_e	effective release height, (m);
U_S	wind speed at the release height, (m/sec);
σ_y	the standard deviation of the concentration distribution in the horizontal cross-plume direction, (m); and
σ_z	the standard deviation of the concentration distribution in the vertical direction, (m).

Annual averaged values of χ/Q are calculated as:

$$annual\,(\chi/Q) = \sum P_i \left(\frac{\chi}{Q}\right)_i \quad (2)$$

where

$(\chi/Q)_i$ the value calculated for a specific meteorological condition, and

P_i the probability of that particular meteorological condition occurring within a five-year time period.

3.1.1 Meteorological Data Files

Meteorological data files for use with VENTSAR exist for the following areas onsite: A, C, D, F, H, K, and P. The meteorological data are obtained from hourly averages of measurements made at 1.5 seconds intervals. The files contain joint frequency distributions and reciprocal average wind velocities categorized by wind direction, speed, and stability class. Reciprocal average wind speeds are utilized since air concentration is inversely proportional to wind speed. Table 1 provides wind speed category definitions. Validation of the meteorological data are the responsibility of the Environmental Transport Group. See Parker (1992) and Weber (1993) for more details on the wind statistics obtained from the SRS area meteorological towers.

Table 1. Wind Speed Category Ranges

Speed Category	Range (m/sec)
1	$0<U\leq2$
2	$2<U\leq4$
3	$4<U\leq6$
4	$6<U\leq8$
5	$8<U\leq12$
6	$U\geq12$

Atmospheric stability is classified by standard deviations of the lateral or azimuthal wind direction. Area meteorological towers contain instrumentation at 61 m (200 ft) which measures horizontal (azimuth) and vertical (elevation) wind direction as well as direct measurements of turbulence, expressed as standard deviations of fluctuations about mean azimuth (noted either as σ_a or σ_θ) and elevation (σ_e) angles.

For calculational purposes within the program, an assumed average value of σ_θ is chosen for the atmospheric stability class of interest as shown in Garrett and Hoel (1982). Ranges for σ_θ and the values that are used within VENTSAR are shown in Table 2.

Table 2. Classification of Atmospheric Stability

Pasquill Category	Range for σ_θ (degrees)	σ_θ Used in VENTSAR (degrees)
A	$23\leq\sigma_\theta$	27.5
B	$18\leq\sigma_\theta<23$	22.5
C	$13\leq\sigma_\theta<18$	17.5
D	$8\leq\sigma_\theta<13$	12.5
E	$4\leq\sigma_\theta<8$	7.5
F	$2\leq\sigma_\theta<4$	3.75
G	$\sigma_\theta<2$	2.00

3.1.2 Pasquill-Briggs Dispersion Coefficients

The lateral and vertical dispersion coefficients within VENTSAR are those derived by Pasquill (1976) and Briggs (1973), respectively. The equation representing Pasquill's lateral dispersion coefficients is shown below:

$$\sigma_y = \sigma_\theta X f(X) \tag{3}$$

where

σ_θ standard deviation of lateral wind direction, (radians). See Table 2.

X downwind distance (km), and

$f(X)$ function of distance, X in kilometers, as discussed below.

Pasquill developed formulations for $f(X)$ with a table of values for distances less than 10 km and the following equation for distances greater than 10 km:

$$f(X) = 0.33\left[\frac{10}{X}\right]^{0.5} \tag{4}$$

For distances less than 10 km, the following equation was derived from the table of values with X in kilometers:

$$f(x) = \frac{1}{1+0.031(1000X)^{0.46}} \tag{5}$$

Pasquill (1976) gave a detailed description on how the coefficients were developed using data from experiments at various sites.

The vertical diffusion coefficients defined by Briggs (1973) and then refined by Briggs and published in Hanna (1982) for open-country conditions are represented in Table 3 as a function of Pasquill's atmospheric stability classes. For these equations the units of X should be meters.

Table 3. Brigg's Vertical Diffusion Coefficient Formulas

Pasquill Stability Category	σ_z (X in meters)
A	$0.20X$
B	$0.12X$
C	$0.08X(1 + 0.0002X)^{-0.5}$
D	$0.06X(1 + 0.0015X)^{-0.5}$
E	$0.03X(1 + 0.0003X)^{-1}$
F	$0.02X(1 + 0.0003X)^{-1}$
G	$0.01X(1 + 0.0003X)^{-1}$

3.2 Plume Rise

Plume rise models are based on fundamental laws of fluid mechanics, conservation of mass, potential density, and momentum. The quantities across the plume are referred to as "top-hat" meaning that discontinuities in temperature, speed and etc. are assumed at the plume boundary. Therefore, for the models employed here, constant values are assumed inside the plume, and another constant value outside of the plume. VENTSAR considers plume rise due to both buoyancy and momentum effects.

Several different mechanisms can increase or decrease the height of the plume at downwind distances. Plume rise due to momentum and buoyancy effects can increase the height of the plume while downwash can decrease the height of the plume. The effective plume height at a given distance, X, downwind is:

$$h(X) = h_s - \Delta h_D + \Delta h_B(X) + \Delta h_M(X) \tag{6}$$

where

h_S initial height of the source,

Δh_D source height change due to downwash,

Δh_B source height change due to buoyancy effects, and

Δh_M source height change due to momentum effects.

3.2.1 Downwash

Downwash occurs when the plume is drawn downward due to low pressure in the wake of the stack. Downwash will *not* occur if the velocity of the effluent (W_e,) is a significantly greater than the crosswind velocity (U). Downwash is generally recognized to occur when W_e/U is less than 1.5 (Briggs, 1973). When the ratio is less than 1.5 the following equation is applied to determine the effects of downwash (Hanna, 1982):

$$\Delta h_D = 2\left(\frac{W_e}{U} - 1.5\right)D \tag{7}$$

where

D the internal stack diameter (m),

W_e effluent velocity (m/s), and

U crosswind velocity (m/s).

Recent work by Snyder (1991) suggests that downwash seldom has consequences due to the fact that conditions are typically associated with small diameters, and the change in stack height due to downwash is only of a few diameters. Snyder states that " serious downwash will occur only for sources with: WD<0.5(60,000)(0.15cm^{2}s^{-1})~0.5 m^{2}s^{-1}."

3.2.2 Buoyancy Effects

For most plumes, the primary contributor to rise is buoyancy which results from density differences between the effluent and the atmosphere. (Briggs, 1984) The initial buoyancy flux for a plume is determined by (Hanna, 1982):

$$F_o = g(DRHO)(CMS) \tag{8}$$

where

F_o buoyancy flux (m^4/s^3)

g acceleration due to gravity (9.8 m/s^2),

CMS volume flux at the stack exit (m^3/s), and

$DRHO$ density ratio (unitless), defined below.

Plumes are considered dense when the density ratio, *DRHO*, is greater than zero (Meroney, 1982a). *DRHO* is determined using the following equation:

$$DRHO = 1 - \frac{MW_a T_e}{MW_e T_a} \tag{9}$$

where

MW_e molecular weight of the effluent,

MW_a molecular weight of the air (28.9),

T_e temperature of effluent (K), and

T_a temperature of air (K).

The Froude number (*Fr*) is used to represent the ratio of inertial forces to buoyancy forces (Snyder, 1972). If DRHO≤0, the plume is lighter than air and the Froude number is not determined. The plume falls to the ground close to the source when the Froude number is less than 7.7 (Meroney, 1982a).

$$Fr = \frac{U}{\sqrt{g * DRHO * D}} \tag{10}$$

where

Fr Froude number, unitless,

U wind speed, m/s, and

D plume exit diameter, m.

For the vertical motion of the plume, the environmental stability parameter, *S*, plays an important role for unstable conditions. *The stability parameter is set to unity for all classes except E, F and G where*

$$S = \frac{g * \frac{\partial T_a}{\partial z}}{T_a} \tag{11}$$

where

S stability parameter, s^{-2}, and

$\frac{\partial T_e}{\partial z}$ = 0.02 for E, 0.03 for F, and 0.04 °C/100 m for G stability (Hanna, 1982).

For use within the code we will redefine the stability parameter as:

$$SP = \sqrt{S} \tag{12}$$

Now that many of the initializing parameters have been determined the increase in plume height due to buoyancy can be calculated. For unstable to neutral conditions buoyancy is limited to a distance *XSTR* from the source using the following formulations (Briggs, 1971):

For $F_o > 55\ m^4/s^3$

$$XSTR = 120.7 F_o^{0.4} (m) \tag{13}$$

For $F_o \leq 55\ m^4/s^3$

$$XSTR = 49.0 F_o^{0.625} (m) \tag{14}$$

Using the above determined distances, the increase in plume height due to buoyancy effects for unstable to neutral conditions where $X<XSTR$ is determined using the following equation (Briggs, 1969):

$$\Delta h_B = 1.6\frac{F_o^{1/3}X^{2/3}}{U} \tag{15}$$

For distances greater than *XSTR*, the same equation is used, except X is set to a constant value of *XSTR*.

For stability classes E, F and G with calm winds (given below) the increase in plume height is determined by the following (Briggs, 1969):

$$\Delta h_B = 5.0\left[\frac{F_o}{SP^3}\right]^{1/4} \tag{16}$$

For stability classes E, F and G with the wind speed greater than the calm wind speed, and for distances greater than $XTST=2.07U/SP$ then buoyancy is less dominating and the increase in plume height is given by the following (Hanna, 1982):

$$\Delta h_B = 2.6\left[\frac{F_o}{(U)SP^2}\right]^{1/3} \tag{17}$$

For distances less than *XTST,* Equation 15 is applied.

By setting equations 16 and 17 equal and solving for U, calm winds are given by the following relationship: $U< 0.141*(F_o*SP)^{0.25}$ m/s.

3.2.3 Momentum Effects

Plume rise may also occur because the initial vertical velocity of the effluent is great enough to elevate the plume. Plume rise due to momentum effects near the source for unstable to neutral weather conditions (Stability Classes A-D) is determined by the following equation (Briggs, 1976):

$$\Delta h_M = \left[\frac{3\pi}{4\beta^2}\right]^{1/3}\left[\frac{DW_eM_o}{U}\right]^{2/3}X^{1/3} \tag{18}$$

where

β $=0.4+1.2U/W_e$, (unitless),

U wind speed, m/s,

W_e effluent velocity, m/s,

D diameter of the stack, m,

M_o measure of relative density of effluent plume to that of air:

$$M_0 = \left[\frac{M_e T_a}{M_a T_e}\right]^{1/2} \tag{19}$$

X downwind distance, m.

For ease in calculation within the program the equation is rewritten as

$$\Delta h_M = \left[B1 * X * DHMOM^2\right]^{1/3} \tag{20}$$

where

$$B1 = \frac{0.75 * \pi}{(0.4 + 1.2U/W_e)^2} \tag{21}$$

$$DHMOM = D * \frac{W_e}{U} M_o \tag{22}$$

with all terms previously defined.

The above equation is applicable for all distances less than XTEST where

$$XTEST = \frac{27.0\,DHMOM}{B1} \tag{23}$$

For distances where X≥XTEST the increase in plume height due to momentum effects is given by the following equation (Briggs, 1969):

$$\Delta h_M = 3DHMOM \tag{24}$$

For stable weather conditions (Stability Classes E, F, and G) the change in plume height due to momentum effects is equal to the minimum of the following two equations (Briggs, 1969):

$$\Delta h_M = 4.0\sqrt{\frac{DHMOM * U}{2SP}} \tag{25}$$

$$\Delta h_M = 1.5\left(\frac{DHMOM^2 U}{4SP}\right)^{1/3} \tag{26}$$

3.3 Building Wake Effects

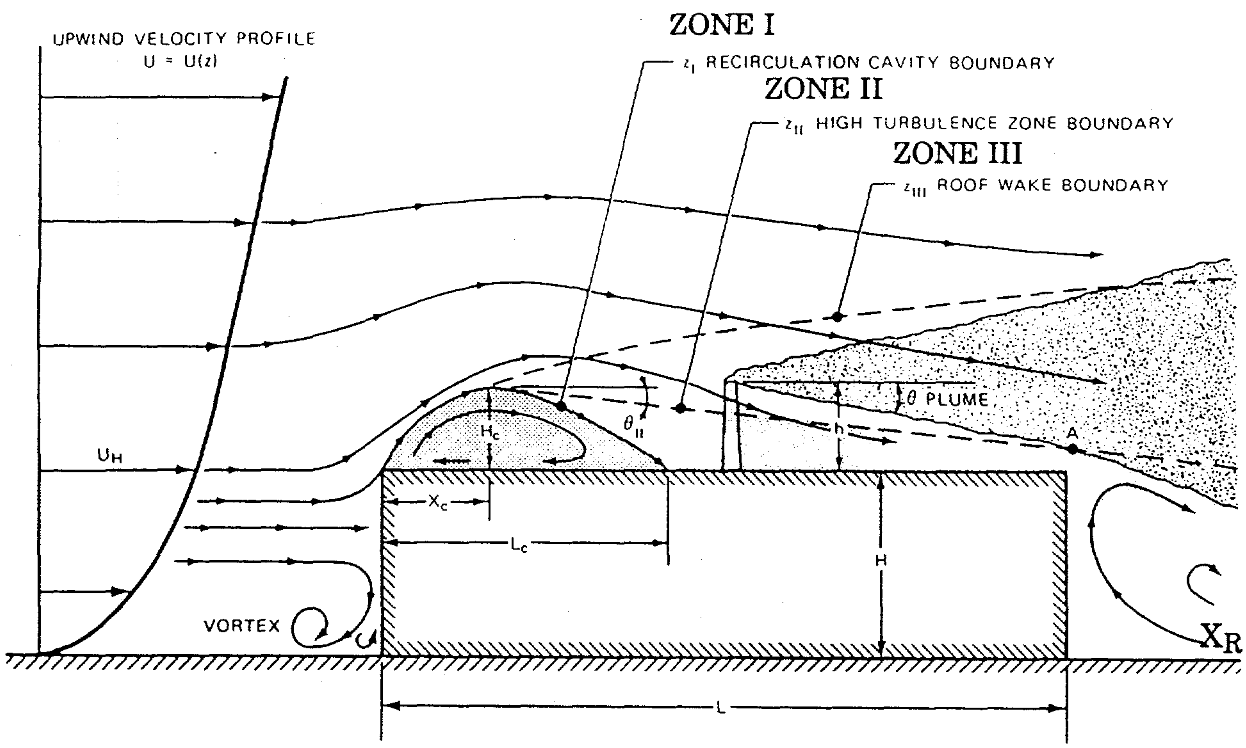
An exact mathematical solution to the plume interaction with air flow does not exist. However, a great deal of useful quantitative information has been obtained using wind-tunnel simulations of flow around model buildings, and a limited number of measurements around full-scale buildings of relatively simple geometry. Semi-empirical models consolidating these simulations and experiments are available for estimating pollutant concentrations around buildings. A summary of the methods available for determining flow patterns and pollutant concentrations near buildings with a simple block-like structure has been prepared by Hanna (1982).

Wind passing over and around buildings creates a complicated dispersion pattern. A recirculation cavity and zones of high turbulence are created on the building roof with a roof cavity region produced downwind of the structure. These regions may trap effluent material and produce high ground- or roof-level concentrations. Models that neglect turbulence effects near structures will usually underestimate pollutant concentrations on building roofs or near buildings. Since air-intake vents may be located on building roofs or near the ground downwind of a release source, an estimation of pollutant concentrations on or near a structure is important in determining expected pollutant levels. Therefore, a methodology was adapted to determine the effect of plume interaction with the air-flow pattern around buildings. This provides a useful tool for determining heights of new stacks so that acceptable pollutant levels near the source and downwind buildings can be assured.

Figure 2 (Wilson, 1979) shows a cross-section of the flow over a building with the wind perpendicular to the face of the building. The recirculation cavity (Zone I) is created due to the separation of the flow from the upwind edge of the roof. The flow recirculates and the turbulence levels are very high. Only if the roof is long enough will the flow reattach to the roof. The boundary of the high turbulence region (Zone II) is not precisely defined. Turbulence generated in the shear layers at the edge of the recirculation cavity result in accelerated diffusion to the roof level of any gases. Zone II is defined such that it also includes Zone I. The roof wake region (Zone III) is depicted in Figure 2 in an exaggerated form. This region's boundary is essentially straight and parallel with the flow. Gases that are released in this region will have some downwash and more rapid spreading than the gases above Zone III. Zone III also includes Zones I and II.

Analytical models have been associated with the regions discussed previously. Building effects are included in the model using the techniques presented by Wilson (1979). The dimensions of recirculation zones, high turbulence zones, and wake cavities associated with the building and any penthouse structure are determined based on building dimensions. If the plume is not over the building or the downwind wake cavity, the height above the ground, z, is set equal to zero to give ground-level concentrations.

Figure 2. Recirculation Zones for Building Wake Effects Calculations.



Various fluid modeling experiments have led to the development of models to predict the behavior of wind flow around buildings. The dimensional parameters describing the building of interest in VENTSAR are shown in Figure 3. These dimensions are consistent with the wind being perpendicular to the building face. When ratios of L/H (where L and H correspond to the length and height of the building or penthouse) are greater than one, reattachment of streamlines to the roof and sides is expected. This however, may not be the case if W/H is very large. The length the recirculation cavity zone (Zone I) extends from the upwind edge of the building is given by the following expression:

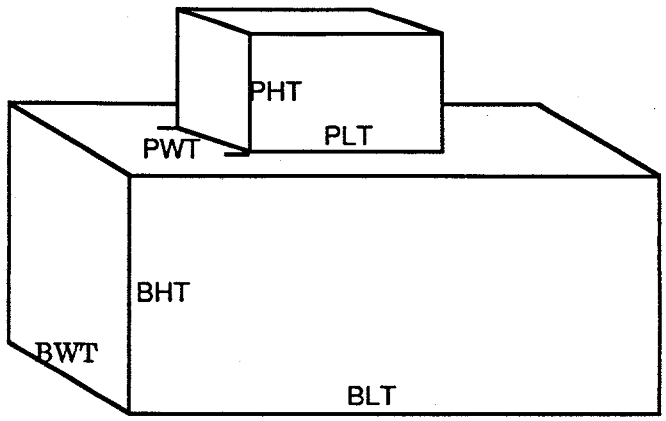
$$L_c \approx 0.9R \tag{27}$$

where

$$R \approx (B_{min})^{0.667}(B_{max})^{0.333} \tag{28}$$

where B_{min} is the smaller of H and W and B_{max} is the larger. The length of the cavity zone should be calculated for both the building and penthouse separately and then summed. All building dimension units are in meters.

Figure 3. Dimensions of Building and Penthouse used with VENTSAR



The maximum height of the recirculation zone (Zone I) is

$$H_c \approx 0.22R \tag{29}$$

and is assumed to occur at a distance of $R/2$ from the edge of the building. The length of the cavity zone is defined for both the building and the penthouse.

The distance beyond the building where plumes may be caught and mixed to the ground is called the wake cavity. The empirical formula for the length of the wake cavity is (Hanna, 1982):

$$X_r = \frac{A*W}{1+B(W/H)} \tag{30}$$

where

W the building width,

H the building height, and

A and B are discussed below.

Separate values for A and B are used depending on whether the flow reattaches to the roof and sides of the building. Cases of reattachment occur when L/H≥1. For this case

$$A = 1.75 \tag{31}$$

$$B = 0.25 \tag{32}$$

For cases where the flow does not reattach to the building

$$A = -2.0 + 0.37\left(\frac{L}{H}\right)^{0.33} \quad (33)$$

$$B = -0.15 + 0.305\left(\frac{L}{H}\right)^{0.33} \quad (34)$$

When the recirculation cavity does not reattach to the building roof, calculation of the effective release height is altered. Following Briggs, if the release height h' is less than the building height H, then the adjusted effective height is given by (Briggs, 1973):

$$h_{eff} = h' - 1.5D_{min} \quad (35)$$

where

h_{eff} the effective plume,

h' the release height adjusted by downwash and plume rise, and

D_{min} the smaller of the width and height of the building.

If the emission height at the building is such that $H < h' < H + 1.5\ D_{min}$, then the adjusted effective release height is:

$$h_{eff} = 2h' - (H + 1.5D_{min}) \quad (36)$$

If $h' \geq H + 1.5D_{min}$, the plume is out of the wake of the building and no effects from the building are seen, therefore, $h_{eff} = h'$.

When there is a change in elevation on the building roof, three separate flow regimes must be considered. Let X_s be the distance from the leading edge of the building to the step change in roof elevation. R_u and R_s are the scaling lengths given by Equation 28 for the building and penthouse upwind faces, respectively. The following three flow regimes can occur:

(i) $X_s < 0.5\ (R_u + R_s)$. The leading edge of the building is connected in a straight line to the top of the penthouse to form a recirculation cavity. Roof cavity heights and turbulence zone boundaries are calculated using $R = (R_u + R_s)$;

(ii) $0.5\ (R_u + R_s) < X_s < 2\ (R_u + R_s)$. The recirculation cavity height H_c and location X_c on the upwind portion of the roof are calculated using $R = R_u + R_s$. The top of this cavity region is joined in a straight line with the top of the penthouse to form a high turbulence zone. The cavity height on the penthouse roof and the downwind high turbulence zone boundary are then calculated using R_s as a scale length; or

(iii) $X_s > 2(R_u + R_s)$. The upwind roof and penthouse roof are treated as two separate buildings with scaling lengths R_u and R_s, respectively.

Using the R values determined above for a given point, the height of cavity Zone I is determined (Wilson, 1979).

For downwind distances less than 0.5R:

$$Z = 0.28R\left(\frac{X}{R}\right)^{1/3} \tag{37}$$

where

R determined above based on building dimensions, and

X downwind distance.

For downwind distance X where $0.5R<X\leq L$:

$$Z = 0.27R - 0.1X \tag{38}$$

For use within the code, the value of Z calculated above is added to the height of the building to determine the relative air concentration. Beyond the building Z=0.

When building wake effects are considered, adjustments must be made to the relative air concentration equation. Some fraction (f) of the effluent plume will be entrained into the wake cavity. For the model used in VENTSAR, this fraction is estimated as the ratio of χ/Q evaluated at the top of the cavity when it first forms to the value of χ/Q at the plume centerline. The material trapped within the wake cavity behaves as if it originates from an area source of building dimensions. Meroney (1982b) has shown that a simple expression useful for estimating pollutant concentrations within the cavity is:

$$\left(\frac{\chi}{Q}\right)_E = \frac{f}{HWU_s} \tag{39}$$

Equation 39 assumes that the effluent rapidly mixes in a uniform volume within the cavity. Turbulence within the wake cavity will produce a relatively constant pollutant concentration within this region. Experimental evidence indicates that this assumption will give conservative predictions of ground-level concentrations in most cases.

For distances beyond the wake cavity, surface χ/Q values will contain a component from the elevated plume $(\chi/Q)_E$ and from the area source of material trapped within the cavity $(\chi/Q)_T$. Following Hosker (1984), this is expressed as:

$$\frac{\chi}{Q} = (1-f)\left(\frac{\chi}{Q}\right)_E + f\left(\frac{\chi}{Q}\right)_T \qquad (40)$$

Meroney (1982b) proposed an empirical expression for $(\chi/Q)_T$ as:

$$\left(\frac{\chi}{Q}\right)_T = \left(\frac{\chi}{Q}\right)_0 \exp\left[-0.5\left(\frac{\chi}{Q}\right)_0 \pi HWU_s\left(\frac{h}{H}\right)^2\right] \qquad (41)$$

where:

$$\left(\frac{\chi}{Q}\right)_0 = \frac{1}{U_s\left(\pi\sigma_y\sigma_z + 0.5HW\right)} \qquad (42)$$

In Equation 42, σ_y and σ_z are evaluated using Pasquill and Briggs formulations with x equal to the distance from the start of the wake cavity. Initial values for σ_y and σ_z in Equation 42 are taken to be the minimum building cross-sectional dimensions.

4.0 VERIFICATION OF CALCULATIONS

Hand calculations were performed to ensure proper application of the previously discussed methodologies. First the building wake module and the plume rise module were tested independently and then together while setting the stability and wind speed to a constant value. The ranking of the 99.5% values was tested using a simple case with no building or plume rise.

4.1 Plume Rise Hand Calculations

Hand calculations were performed to demonstrate the plume rise module was performing correctly. Table 4 shows the input parameters that were used for the computer run to verify the plume rise module. Variables were chosen at random within the ranges of validity.

Table 5 shows the comparison of hand calculations to computer output for various downwind distances. Differences are slight and likely attributable to rounding errors. See Appendix A, Section 1 for the actual hand calculations.

Table 4. Input parameters for Plume Rise Verification.

Parameter	Input
Area or Release Location	A
English or Metric	M (metric)
Building Height	0.0 m
Building Width	0.0 m
Building Length	0.0 m
Penthouse Height	0.0 m
Penthouse Width	0.0 m
Penthouse Length	0.0 m
Penthouse Distance	0.0 m
Minimum Distance of Interest	10 m
Maximum Distance of Interest	1010 m
Compass Sector of Building Location	3
Distance of Vent from Roof Edge	-10.0
Vent Height	20.0 m
Radioactive Calculation?	No
Release Rate	0
Mole Fraction of Pollutant	1.8E-03
Vent Gas Flow Rate	50 m^3/s
Averaging Option	No
Wind Speed	6 m/s
Stability Class	4(D)
Vent Diameter	1.0 m
Vent Gas Molecular Weight	78.12
Vent Gas Air Temperature	40 C
Air Temperature	20 C
Four Vents?	no

Table 5. Hand Calculations for Plume Rise Verification

Downwind Distance (m)	Relative Air Concentration (s/m^3) VENTSAR	Relative Air Concentration (s/m^3) Hand Calculations	Percent Difference
10	0.00E+00	0.00E+00	0.0%
200	8.16E-17	8.18E-17	-0.2 %
1000	4.40E-07	4.40E-07	0.0 %

4.2 Building Wake Effects

Table 6 shows the input parameters that were used to verify the building wake effects module. Figure 4 shows a side view of the building and the places at which hand calculations were performed to verify the concentrations. These locations were selected to ensure all zones were considered.

Figure 4. Concentration locations for Building Wake Effects Verification

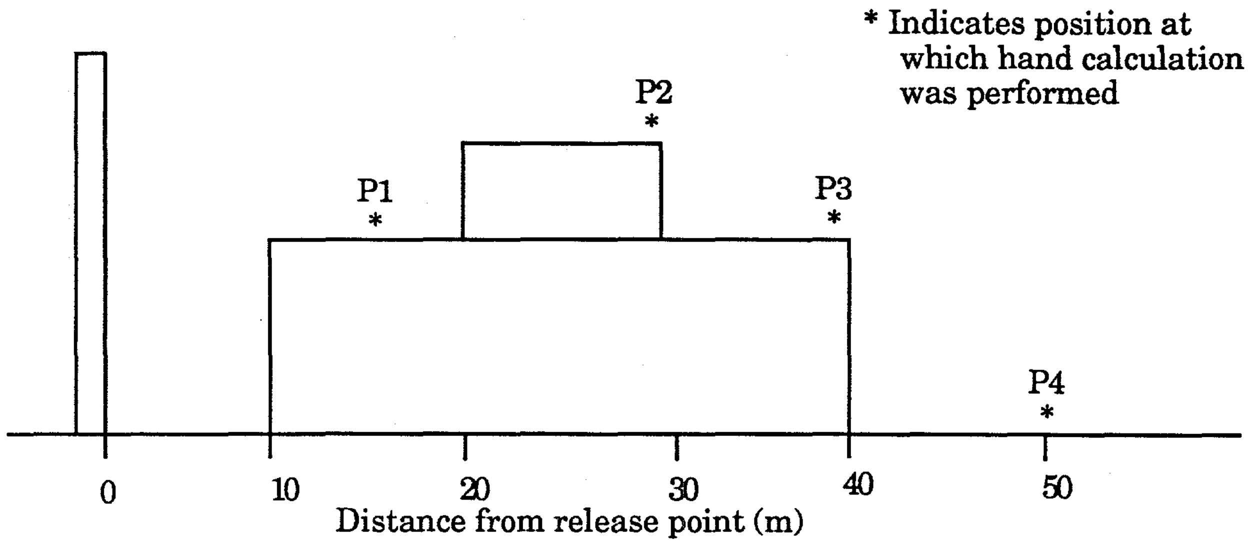


Table 6. Input parameters for Building Wake Effects Verification

Parameter	Input
Area or Release Location	K
English or Metric	M (metric)
Building Height	10.0 m
Building Width	20.0 m
Building Length	30.0 m
Penthouse Height	5.0 m
Penthouse Width	10.0 m
Penthouse Length	10.0 m
Penthouse Distance	10.0 m
Minimum Distance of Interest	10 m
Maximum Distance of Interest	1010 m
Compass Sector of Building Location	3
Distance of Vent from Roof Edge	-10.0
Vent Height	20.0 m
Radioactive Calculation?	Yes
Release Rate	1 Ci/min
Mole Fraction of Pollutant	0
Vent Gas Flow Rate	0
Averaging Option	No
Wind Speed	6 m/s
Stability Class	4 (D)
Vent Diameter	0.1 m
Vent Gas Molecular Weight	78.12
Vent Gas Temperature	0
Ambient Air Temperature	0
Four Vents?	no
Vent Height	20 m

Table 7 shows the results of the comparison. The differences are negligible. See Appendix A, Section 2 for the hand calculations.

Table 7. Hand Calculations for Building Wake Effects Verification

Downwind Distance (m) (Position)	Relative Air Concentration (s/m^3) VENTSAR	Relative Air Concentration (s/m^3) Hand Calculations	Percent Difference
15 (P1)	1.13E-14	1.13E-14	0.0%
30 (P2)	4.69E-05	4.69E-05	0.0 %
40 (P3)	3.16E-19	3.16E-19	0.0 %
50 (P4)	8.42E-14	8.42E-14	0.0 %

4.3 Plume Rise and Building Options Combined

A case with both a simple building and plume rise was analyzed. The input parameters for this comparison are shown in Table 8. The results of the hand calculations compared with the actual code output are shown in Table 9. The differences were 1% or less for all of the positions selected.

Table 8. Input parameters for Building Wake Effects and PR Verification

Parameter	Input
Area or Release Location	A
English or Metric	M (metric)
Building Height	10.0 m
Building Width	20.0 m
Building Length	30.0 m
Penthouse Height	0.0 m
Penthouse Width	0.0 m
Penthouse Length	0.0 m
Penthouse Distance	0.0 m
Minimum Distance of Interest	10 m
Maximum Distance of Interest	1010 m
Compass Sector of Building Location	3
Distance of Vent from Roof Edge	-10.0
Vent Height	0.0 m
Radioactive Calculation?	Yes
Release Rate	1 Ci/min
Mole Fraction of Pollutant	0
Vent Gas Flow Rate	0
Averaging Option	No
Wind Speed	4 m/s
Stability Class	3 (C)
Vent Diameter	1 m
Vent Gas Molecular Weight	78.12
Vent Gas Temperature	40 C
Ambient Air Temperature	20 C
Four Vents	no

Table 9. Hand Calculations for Building Wake Effects and PR Verification

Downwind Distance (m)	Relative Air Concentration (s/m^3) VENTSAR	Relative Air Concentration (s/m^3) Hand Calculations	Percent Difference
30	7.85E-73	7.90E-73	-0.6%
45	9.60E-69	9.70E-69	-1.0 %
100	9.82E-23	9.85E-23	-0.3 %
500	1.89E-07	1.89E-07	0.0 %

4.4 Averaging Option Hand Calculations

Verification of the averaging option within VENTSAR was accomplished by setting up a Microsoft EXCEL Spreadsheet that would calculate and sort the 42 separate X/Qs for a particular sector. Table 10 shows the input parameters for the calculation. Copies of the spreadsheets used to calculate the relative air concentrations are shown in Appendix A, Section 4.

Table 10. Input parameters for Averaging Option

Parameter	Input
Area	K
English or Metric	M (metric)
Building Height	0.0 m
Building Width	0.0 m
Building Length	0.0 m
Penthouse Height	0.0 m
Penthouse Width	0.0 m
Penthouse Length	0.0 m
Penthouse Distance	0.0 m
Minimum Distance of Interest	10 m
Maximum Distance of Interest	1010 m
Compass Sector of Building Location	1
Distance of Vent from Roof Edge	-10.0
Vent Height	20.0 m
Radioactive Calculation?	Yes
Release Rate	100 Ci/min
Mole Fraction of Pollutant	0
Averaging Option	Yes
Percentage	0.5%
Plume Rise	No
Vent Diameter	0.1 m
Vent Gas Molecular Weight	NA
Vent Gas Air Temperature	NA
Air Temperature	NA
Vent Gas Flow Rate	NA
Four Vents?	no

Table 11 shows the results of the hand calculation when compared to the VENTSAR output. No differences were found. Using the same EXCEL Spreadsheet the Annual Average X/Q values were also verified and the comparison of with actual code output is shown in Table 12.

Table 11. Hand Calculations for Averaging Option Verification

Downwind Distance (m)	Relative Air Concentration (s/m^3) VENTSAR	Relative Air Concentration (s/m^3) Hand Calculations	Percent Difference
200	1.74E-04	1.74E-04	0.0%
5000	8.58E-07	8.58E-07	0.0 %
10050	3.45E-07	3.45E-07	0.0 %

Table 12. Hand Calculations for Annual Average Concentration

Downwind Distance (m)	Annual Average Relative Air Concentration (s/m^3) VENTSAR	Annual Average Relative Air Concentration (s/m^3) Hand Calculations	Percent Difference
200	5.27E-06	5.27E-06	0.0%
5000	3.29E-08	3.29E-08	0.0 %
10050	1.45E-08	1.45E-08	0.0 %

5.0 CONCLUSIONS

VENTSAR has been verified and is operating as expected. All equations were verified to their original source and hand calculations were performed to ensure proper application of the methodologies. Test cases are performed semi-annually to ensure that VENTSAR continually operates as expected.

6.0 REFERENCES

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APPENDIX A. HAND CALCULATIONS

APPENDIX A. HAND CALCULATIONS

Independent calculations were performed to determine if VENTSAR was correctly applying the methodologies previously discussed. Calculations were done using an EXCEL Spreadsheet and by hand when necessary. VENTSAR input may be in English or Metric units. Regardless of which the user chooses, the calculations are done in metric after the necessary conversions are done. All of the conversions were verified and the problems that follow use metric units.

1.0 Plume Rise Options

The constants used in the plume rise equations were calculated using a Microsoft EXCEL spreadsheet. A copy of this spreadsheet is shown as Figure A1. For a downwind distance of 10 m the following calculations were performed using the parameters shown in Table 4.

Buoyancy Effects

From the Spreadsheet in Figure A1:

DRHO= 0.031

DELI= -0.065

F_o= 29.91 m^4/s^3

XSTR=409.80 m

Since the weather conditions are neutral (D stability) the value of the stability parameter, S, is one. Increase in release height due to buoyancy is:

$$\Delta h_B = 1.6\frac{F_o^{1/3}X^{2/3}}{U} = 1.6\frac{29.91^{1/3}10^{2/3}}{6} = 3.84m$$

Momentum Effects

From the EXCEL Spreadsheet shown in Figure A1:

B1 = 8.95

We=63.7 m/s

Mo=0.939

DHMOM=10.28 m

Figure A1. Constants for Plume Rise Calculation

		VENTSAR			
		Plume Rise Verification			
		Units			
Release Location	A				
(A,C,D, F, H, K, P, or O for other)	0				
Grid Coordinates Easting		ft			
Northing		ft			
Building Dimensions					
Building Height	0	m		bmin	0
Building Width	0	m		bmax	0
Building Length	0	m		ru	0
Penthouse Height	0	m		pmin	0
Penthouse Width	0	m		pmax	0
Penthouse Length	0	m		rs	0
Distance to Penthouse on Rooftop	0	m		r	0
(Negative indicates on roof)					
Minimum Distance of Interest	10	m		delx	5
Maximum Distance of Interest	1010	m			
Number of Increments	200			we	63.662031
Compass Sector of Building	1			b1	8.94976047
(1-N, 2-NNE, ...)				dhmon	10.2814263
Distance of Vent from Roof Edge	10	m		MO	0.93896252
(negative is upwind)					
Vent Height	20	m			
Radioactive Calculations(y or n)	n				
If yes Release Rate		Ci/yr			
If No Mole Fraction of Vent Gas	1.80E-03				
Vent Gas Flow Rate	50	m3/s			
Averaging Option (Y or N)	N			ta	293
If Yes Specify Probability Level				te	313
If No Wind speed at Vent Height	6	m		usii	6
Stability Class(1-7 to A-G)	D			deli	-0.0650052
Plume Rise(Y or N)				mwa	28.96
Vent Diameter	1	m		area	0.7853975
Gas Molecular Weight	78.12			we	63.662031
Vent Gas Temperature	40	C		mwe	29.048488
Ambient Air Temperature	20	C		drho	0.03051874
Use of Four Vent Heights (Y or N)	N			FRI	NA
Enter Minimum Height	20	m		fo	29.9083652
Increment Height	0	m		XSTR	409.794855

Using the above parameters, XTEST can be calculated as follows:

$$XTEST = \frac{27.0*DHMOM}{B1} = \frac{27.0*10.28}{8.95} = 31.01m$$

Since X is less than XTEST

$$\Delta h_m = \left(B1*X*DHMOM^2\right)^{1/3} = \left(8.95*10*10.28^2\right)^{1/3} = 21.15m$$

There is no downwash since W/U >1.5.

The effective change in plume height is

$$h(x) = h_s - \Delta h_D + \Delta h_B(x) + \Delta h_M(x)$$

$$h(x) = 20.0 - 0.00 + 3.84 + 21.15 = 44.99m$$

This number is in agreement with the effective plume height shown on the output.

From another EXCEL Spreadsheet the pollutant concentration is calculated to be 6.6E-174 s/m^3 which is assumed to be 0.00E+00 s/m^3.

The following hand calculation is for a downwind distance of X=200 m.

Using the same constants as above and since X<XSTR

$$\Delta h_B = 1.6\frac{F_o^{1/3}X^{2/3}}{U} = 1.6\frac{29.91^{1/3}200^{2/3}}{6} = 28.31m$$

For momentum effects, X>XTEST yielding

$$\Delta h_m = 3*DHMOM = 3*10.28 = 30.84m$$

$$h(x) = 20.0 - 0.00 + 28.31 + 30.84 = 79.15m$$

From an EXCEL Spreadsheet the pollutant concentration is 8.18E-17 s/m^3.

The following hand calculation is for a downwind distance of X=1000 m.

Since X>XSTR the same equation is used as above except X is replaced with the value of XSTR.

$$\Delta h_B = 1.6 \frac{F_o^{1/3} XSTR^{2/3}}{U}$$

$$\Delta h_B = 1.6 \frac{29.91^{1/3} 409.79^{2/3}}{6} = 45.67m$$

For momentum effects, X>XTEST yielding

$$\Delta h_m = 3 * DHMOM = 3 * 10.28 = 30.84m$$

$$h(x) = 20.0 - 0.00 + 45.67 + 30.84 = 96.51m$$

From an EXCEL Spreadsheet the pollutant concentration is 4.40E-07 s/m^3.

2.0 Building Wake Effects

The building wake effects will be verified using the input that was specified in Table 6 of the text.

For a downwind distance of 15 m, the length which the recirculation cavity zone extends from the upwind edge of the building is determined using the following expression:

$L_c \approx 0.9R$

where

$R \approx (B_{min})^{0.667}(B_{max})^{0.333}$

where B_{min} is the smaller of H and W and B_{max} is the larger.

For the building

$R_u \approx (10)^{0.667}(20)^{0.333}$

$R_u \approx 12.6$ m

For the penthouse

$R_s \approx (5)^{0.667}(10)^{0.333}$

$R_s \approx 6.3$ m

The total is 18.9 m.

Next a series of tests must be performed as shown in Section 3.3 to determine the correct characteristic length to use for the remainder of the equations. The variable X_s is equal to the length from the release point to the nearest edge of the building (10 m).

The conditions for this problem fell into the second set of criteria which are shown as follows.

(ii) $0.5\,(R_u + R_s) < X_s < 2\,(R_u + R_s)$.
$0.5(18.9)<10<2(18.9)$ is true therefore the recirculation cavity height H_c and location X_c on the upwind portion of the roof are calculated using $R = R_u + R_s$. The top of this cavity region is joined in a straight line with the top of the penthouse to form a high turbulence zone. The cavity height on the Penthouse roof and the downwind high turbulence zone boundary are then calculated using R_s as a scale length.

Since the position that has been chosen is on the upwind portion of the penthouse, R_{total} will be used to determine the cavity height and length as follows:

$H_c = 0.22R_{total}$	$X_c = 0.5R_{total}$
$H_c = 0.22*18.86\text{m}$	$X_c = 0.5*18.86\text{ m}$
$H_c = 4.15\text{ m}$	$X_c = 9.43\text{ m}$

The empirical formula for the length of the wake cavity is:

$$X_r = \frac{A * W}{1 + B\,(W/H)}$$

Two separate combinations of values for A and B are used depending on whether the flow reattaches to the roof and sides of the building. Cases of reattachment occur when the roof cavity length (L_c) is less than the length of the building.

Test to see if $0.9R_{total} < X_c$

$0.9 * 18.86 < 20$ is true.

For this case A = 1.75 and B = 0.25.

Using

$$X_r = \frac{1.75 * 20\text{ m}}{1 + 0.25\,(20/10)}$$

$X_r = 23.33$ m

Since $X_s < 0.5$ R

$$Z_{eff} = 0.28 * R * \left[\frac{X}{R}\right]^{0.333}$$

$$Z_{eff} = 0.28 * 18.86 \text{ m} * \left[\frac{5}{18.86}\right]^{0.333}$$

$Z_{eff} = 3.39$ m

$Z_{tot} = Z_{eff} + BHT = 3.39 \text{ m} + 10 \text{ m} = 13.39 \text{ m}$

Now to determine the relative air concentration

$$\frac{\chi}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U_s}\left[e^{-\left(\frac{(z-h_e)^2}{2\sigma_z^2}\right)} + e^{-\left(\frac{(z+h_e)^2}{2\sigma_z^2}\right)}\right]$$

For D stability 15 m downwind of release location

$$\sigma_y = \frac{\sigma_\theta x}{1 + 0.031(x)^{0.46}} \qquad \sigma_z = 0.06x(1 + 0.0015x)^{-0.5}$$

$$\sigma_y = \frac{0.218 * 15 \text{ m}}{1 + 0.031(15\ )^{0.46}} \qquad \sigma_z = 0.06 * 15 \text{ m}(1 + 0.0015 * 15)^{-0.5}$$

$\sigma_y = 2.954$ m $\qquad \sigma_z = 0.890$ m

$$\frac{\chi}{Q} = \frac{e^{-0.5((13.4-20)/0.89)^2} + e^{-0.5((13.4+20)/0.89)^2}}{2 * 3.14 * 2.954 \text{ m} * 0.890 \text{ m} * 6 \text{ m/s}} = 1.13\text{E-}14 \text{ s/m}^3$$

EXCEL Spreadsheets were set up to determine the relative air concentrations at the remaining distances. The calculations are performed in a similar manner but some of the tests resulted in different equations being used to arrive at the results.

3.0 Building Wake Effects and Plume Rise Verification

A simple building was analyzed along with the effects of plume rise for this hand calculation. Many of the parameters were determined using an EXCEL spreadsheet as shown in Figure A2. Determination of all other parameters follows:

Downwind Distance of 30 m.

Plume Rise

For plume rise due to buoyancy, using the parameters shown in Figure A2 and since Fo≤55 and X≤XSTR

$$\Delta h_B = 1.6\frac{F_o^{1/3}X^{2/3}}{U} = 1.6\frac{31.31^{1/3}30^{2/3}}{4} = 12.17\mathrm{m}$$

For plume rise due to momentum,

$$XTEST = \frac{27.0 * DHMOM}{B1} = \frac{27.0 * 15.4}{10.4} = 39.88\mathrm{m}$$

Since X is less than XTEST

$$\Delta h_m = \left(B1 * X * DHMOM^2\right)^{1/3} = \left(10.4 * 30 * 15.40^2\right)^{1/3} = 42.02m$$

For a ground level release with no downwash

$$\Delta h = 42.02 + 12.17 = 54.19m$$

Building Effects

Test to see if $0.9R_{total} < X_c$

$0.9 * 12.6 < 30$ is true.

For this case A = 1.75 and B = 0.25.

Using

$$X_r = \frac{1.75 * 20\ \mathrm{m}}{1 + 0.25\ (20/10)}$$

$X_r = 23.33$ m

For downwind distances less than the length of the building:

$$Z = 0.27R - 0.1X$$

$$Z = 0.27 * 12.6 - 0.1 * 20 = 1.4\mathrm{m}$$

$Z = Z + BHT = 10.0 + 1.4 = 11.4$ m

Figure A2. Parameters for Wake Effects and Plume Rise Verification

		VENTSAR Verification			
		Units			
Release Location	A				
(A,C,D, F, H, K, P, or O for other)	0				
Grid Coordinates Easting		ft			
Northing		ft			
Building Dimensions					
Building Height	10	m		bmin	10
Building Width	20	m		bmax	20
Building Length	30	m		ru	12.5992105
Penthouse Height	0	m		pmin	0
Penthouse Width	0	m		pmax	0
Penthouse Length	0	m		rs	0
Distance to Penthouse on Rooftop	0	m		r	12.5992105
(Negative indicates on roof)					
Minimum Distance of Interest	10	m		delx	0.99009901
Maximum Distance of Interest	1010	m			
Number of Increments	100			we	63.662031
Compass Sector of Building	3			b1	10.4254732
(1-N, 2-NNE, ...)				dhmon	15.398632
Distance of Vent from Roof Edge	-10	m		MO	0.93610224
(negative is upwind)					
Vent Height	0	m			
Radioactive Calculations(y or n)					
If yes Release Rate	1	Ci/mi			
If No Mole Fraction of Vent Gas	0				
Vent Gas Flow Rate	0	m3/s			
Averaging Option (Y or N)	N			ta	293
If Yes Specify Probability Level				te	313
If No Wind speed at Vent Height	4	m		usii	4
Stability Class(1-7 to A-G)	C			deli	-0.0682594
Plume Rise(Y or N)				mwa	28.96
Vent Diameter	1	m		area	0.7853975
Gas Molecular Weight	78			we	63.662031
Vent Gas Temperature	40	C		mwe	28.96
Ambient Air Temperature	20	C		drho	0.03194888
Use of Four Vent Heights (Y or N)	Y			FRI	7.14856914
Enter Minimum Height	0	m		fo	31.3099042
Increment Height	0	m		XSTR	421.693752

Now to determine the relative air concentration

$$\frac{\chi}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U_S}\left[e^{-\left(\frac{(z-h_e)^2}{2\sigma_z^2}\right)} + e^{-\left(\frac{(z+h_e)^2}{2\sigma_z^2}\right)}\right]$$

For C stability 30 m downwind of release location

$$\sigma_y = \frac{\sigma_\theta x}{1 + 0.031(x)^{0.46}} \qquad \sigma_z = 0.06x(1 + 0.0002x)^{-0.5}$$

$$\sigma_y = \frac{0.305 * 30 \text{ m}}{1 + 0.031(30)^{0.46}} \qquad \sigma_z = 0.08 * 30 \text{ m}(1 + 0.0002 * 30)^{-0.5}$$

$$\sigma_y = 7.98 \text{ m} \qquad \sigma_z = 2.39 \text{ m}$$

$$\frac{\chi}{Q} = \frac{e^{-0.5((11.4-54.19)/2.39)^2} + e^{-0.5((11.4+54.19)/2.39)^2}}{2 * 3.14 * 2.39 \text{ m} * 7.98 \text{ m} * 4 \text{ m/s}} = 7.90\text{E-}73 \text{ s/m}^3$$

For a downwind distance of 45 m which is just beyond the building, the calculations are shown below.

For plume rise due to buoyancy, using the parameters shown in Figure A2 and since Fo≤55 and X≤XSTR

$$\Delta h_B = 1.6\frac{F_o^{1/3}X^{2/3}}{U} = 1.6\frac{31.31^{1/3}45^{2/3}}{4} = 15.95\text{m}$$

Since X>XTEST

$$\Delta h_m = 3 \times \text{DHMOM} = 3 \times 15.4 = 46.2\text{m}$$

$$\Delta h = 15.95\text{m} + 46.2\text{m} = 62.15\text{m}$$

Building Wake Effects

Since the point X is beyond the building, Z=0.

Now to determine the relative air concentration

$$\frac{\chi}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U_S}\left[e^{-\left(\frac{(z-h_e)^2}{2\sigma_z^2}\right)} + e^{-\left(\frac{(z+h_e)^2}{2\sigma_z^2}\right)}\right]$$

For C stability 45 m downwind of release location

$$\sigma_y = \frac{\sigma_\theta x}{1 + 0.031(x)^{0.46}} \qquad \sigma_z = 0.06x(1 + 0.0002x)^{-0.5}$$

$$\sigma_y = \frac{0.305 * 45 \text{ m}}{1 + 0.031(45)^{0.46}} \qquad \sigma_z = 0.08 * 45 \text{ m}(1 + 0.0002 * 45)^{-0.5}$$

$$\sigma_y = 11.66 \text{ m} \qquad \sigma_z = 3.58 \text{ m}$$

$$\frac{\chi}{Q} = \frac{e^{-0.5((62.15)/3.58)^2} + e^{-0.5((62.15)/3.58)^2}}{2 * 3.14 * 3.58 \text{ m} * 11.66 \text{ m} * 4 \text{ m/s}} = 9.70\text{E-}69 \text{ s/m}^3$$

For a downwind distance of 100 m.

For plume rise due to buoyancy, using the parameters shown in Figure A2 and since Fo≤55 and X≤XSTR

$$\Delta h_B = 1.6\frac{F_o^{1/3}X^{2/3}}{U} = 1.6\frac{31.31^{1/3}100^{2/3}}{4} = 27.16\text{m}$$

Since X>XTEST

$$\Delta h_m = 3 \times \text{DHMOM} = 3 \times 15.4 = 46.2\text{m}$$

$$\Delta h = 27.16\text{m} + 46.2\text{m} = 73.36\text{m}$$

Building Wake Effects

Since the point X is beyond the building, Z=0.

Now to determine the relative air concentration

$$\frac{\chi}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U_S}\left[e^{-\left(\frac{(z-h_e)^2}{2\sigma_z^2}\right)} + e^{-\left(\frac{(z+h_e)^2}{2\sigma_z^2}\right)}\right]$$

For C stability 100 m downwind of release location

$\sigma_y = \dfrac{\sigma_\theta\, x}{1 + 0.031(x)^{0.46}}$ $\sigma_z = 0.06x(1 + 0.0002x)^{-0.5}$

$\sigma_y = \dfrac{0.305 * 100 \text{ m}}{1 + 0.031(100)^{0.46}}$ $\sigma_z = 0.08 * 100 \text{ m}(1 + 0.0002 * 100)^{-0.5}$

$\sigma_y = 24.28$ m $\sigma_z = 7.92$ m

$$\frac{\chi}{Q} = \frac{e^{-0.5((73.36)/7.92)^2} + e^{-0.5((73.36)/7.92)^2}}{2 * 3.14 * 7.92 \text{ m} * 24.28 \text{ m} * 4 \text{ m/s}} = 9.85\text{E-}23 \text{ s/m}^3$$

For a downwind distance of 500 m.

For plume rise due to buoyancy, using the parameters shown in Figure A2 and since Fo≤55 and X≥XSTR

$$\Delta h_B = 1.6 \frac{F_o^{1/3} XSTR^{2/3}}{U} = 1.6 \frac{31.31^{1/3} 421.69^{2/3}}{4} = 70.90\text{m}$$

Since X>XTEST

$$\Delta h_m = 3 \times DHMOM = 3 \times 15.4 = 46.19m$$

$$\Delta h = 70.90m + 46.19m = 117.09m$$

Building Wake Effects

Since the point X is beyond the building, Z=0.

Now to determine the relative air concentration

$$\frac{\chi}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U_S}\left[e^{-\left(\frac{(z-h_e)^2}{2\sigma_z^2}\right)} + e^{-\left(\frac{(z+h_e)^2}{2\sigma_z^2}\right)}\right]$$

For C stability 500 m downwind of release location

$\sigma_y = \dfrac{\sigma_\theta\, x}{1 + 0.031(x)^{0.46}}$ $\sigma_z = 0.06x(1 + 0.0002x)^{-0.5}$

$$\sigma_y = \frac{0.305 * 500\ m}{1 + 0.031(500)^{0.46}} \qquad \sigma_z = 0.08 * 500\ m(1 + 0.0002 * 500)^{-0.5}$$

$$\sigma_y = 99.13\ m \qquad \sigma_z = 38.13\ m$$

$$\frac{\chi}{Q} = \frac{e^{-0.5((117.09)/38.13)^2} + e^{-0.5((117.09)/38.13)^2}}{2 * 3.14 * 99.13\ m * 38.13\ m * 4\ m/s} = 1.89E\text{-}07\ s/m^3$$

4.0 Exceedance Probability Determination

Verification of the pollutant concentration exceedance probability calculations was performed by setting up a Microsoft EXCEL Spreadsheet. Table 10 of the text shows the input parameters that were used for the calculation.

The following sheets show the Spreadsheet used for the calculations. These calculations are for a downwind distance of 200 m. The first page shows the K Area meteorological data for certain sectors with the south sector appearing at the top of the first page. The second page shows the X/Q values that were determined for each of the 42 stability class and wind speed combinations along with their frequency of occurrence. The third page shows the ranking of these values in ascending order and the X/Q value for meteorological conditions not exceeded 99.5% of the time which is determined by interpolation.

The annual average concentration are also calculated on the third page in the last column. The frequency and relative air concentration are multiplied for each of the 42 combinations and the results are summed to determine the annual average which is shown at the bottom of the page.

Similar calculations were performed for the remaining distances.

K Area							
40925							
Wind	S			Observation Distribution			
Speed				Stability Category			
Category	A	B	C	D	E	F	G
1	100	20	10	9	0	0	1
2	268	95	42	23	15	2	2
3	242	53	35	50	33	12	2
4	80	12	14	23	15	4	0
5	9	1	3	5	0	0	0
6	0	0	0	0	0	0	0
Wind	SSW			Observation Distribution			
Speed				Stability Category			
Category	A	B	C	D	E	F	G
1	111	21	15	11	6	0	0
2	230	127	148	95	40	12	0
3	122	146	187	159	129	24	0
4	70	45	62	62	82	29	2
5	5	1	1	0	0	1	0
6	0	0	0	0	0	0	0
Wind	SW			Observation Distribution			
Speed				Stability Category			
Category	A	B	C	D	E	F	G
1	107	26	25	24	8	1	0
2	268	130	232	253	133	39	2
3	69	95	357	441	308	118	14
4	13	28	109	124	113	42	8
5	2	2	5	11	2	0	0
6	0	0	0	0	0	0	0
Wind	WSW			Observation Distribution			
Speed				Stability Category			
Category	A	B	C	D	E	F	G
1	123	14	16	13	2	1	0
2	326	162	296	247	149	21	0
3	90	141	410	507	420	120	12
4	8	15	106	186	92	60	6
5	0	0	10	16	0	0	1
6	0	0	0	0	0	0	0

DISTANCE (M)	200	South Sector			
SECTOR	STABILITY	WINDSPEED	X/Q	FREQUENCY	
1	1	1	8.9174E-05	0.00244349	2.179E-07
1	1	2	4.0563E-05	0.00654856	2.6563E-07
1	1	3	2.3167E-05	0.00591326	1.3699E-07
1	1	4	1.7076E-05	0.0019548	3.338E-08
1	1	5	1.2989E-05	0.00021991	2.8566E-09
1	1	6		0	0
1	2	1	0.00017743	0.0004887	8.6708E-08
1	2	2	7.8383E-05	0.00232132	1.8195E-07
1	2	3	4.8491E-05	0.00129505	6.2799E-08
1	2	4	3.5595E-05	0.00029322	1.0437E-08
1	2	5	2.7215E-05	2.4435E-05	6.65E-10
1	2	6		0	0
1	3	1	0.00029231	0.00024435	7.1425E-08
1	3	2	0.00015522	0.00102627	1.593E-07
1	3	3	9.3199E-05	0.00085522	7.9706E-08
1	3	4	6.8516E-05	0.00034209	2.3439E-08
1	3	5	4.7787E-05	7.3305E-05	3.503E-09
1	3	6		0	0
1	4	1	0.00075763	0.00021991	1.6661E-07
1	4	2	0.00031005	0.000562	1.7425E-07
1	4	3	0.00020117	0.00122175	2.4578E-07
1	4	4	0.00014365	0.000562	8.0731E-08
1	4	5	9.8683E-05	0.00012217	1.2057E-08
1	4	6		0	0
1	5	1		0	0
1	5	2	0.000839	0.00036652	3.0751E-07
1	5	3	0.00059659	0.00080635	4.8106E-07
1	5	4	0.00042316	0.00036652	1.551E-07
1	5	5		0	0
1	5	6		0	0
1	6	1		0	0
1	6	2	0.00272938	4.887E-05	1.3338E-07
1	6	3	0.00181959	0.00029322	5.3354E-07
1	6	4	0.00130945	9.774E-05	1.2799E-07
1	6	5		0	0
1	6	6		0	0
1	7	1	0.02662812	2.4435E-05	6.5066E-07
1	7	2	0.01084523	4.887E-05	5.3001E-07
1	7	3	0.00693911	4.887E-05	3.3911E-07
1	7	4	0	0	0
1	7	5		0	0
1	7	6		0	0
					5.2745E-06

Dist	200					
STAB	WS	X/Q	FREQUENCY	Cum Freq		
1	6		0	0		0
2	6		0	0		0
3	6		0	0		0
4	6		0	0		0
5	1		0	0		0
5	5		0	0		0
5	6		0	0		0
6	1		0	0		0
6	5		0	0		0
6	6		0	0		0
7	4		0	0		0
7	5		0	0		0
7	6		0	0		0
7	1	0.02662812	2.4435E-05	2.4435E-05		6.5066E-07
7	2	0.01084523	4.887E-05	7.3305E-05		5.3001E-07
7	3	0.00693911	4.887E-05	0.00012217		3.3911E-07
6	2	0.00272938	4.887E-05	0.00017104		1.3338E-07
6	3	0.00181959	0.00029322	0.00046426		5.3354E-07
6	4	0.00130945	9.774E-05	0.000562		1.2799E-07
5	2	0.000839	0.00036652	0.00092853		3.0751E-07
4	1	0.00075763	0.00021991	0.00114844		1.6661E-07
5	3	0.00059659	0.00080635	0.0019548		4.8106E-07
5	4	0.00042316	0.00036652	0.00232132		1.551E-07
4	2	0.00031005	0.000562	0.00288332		1.7425E-07
3	1	0.00029231	0.00024435	0.00312767		7.1425E-08
4	3	0.00020117	0.00122175	0.00434942		2.4578E-07
2	1	0.00017743	0.0004887	0.00483812	0.00017392	8.6708E-08
3	2	0.00015522	0.00102627	0.00586439		1.593E-07
4	4	0.00014365	0.000562	0.00642639		8.0731E-08
4	5	9.8683E-05	0.00012217	0.00654856		1.2057E-08
3	3	9.3199E-05	0.00085522	0.00740379		7.9706E-08
1	1	8.9174E-05	0.00244349	0.00984728		2.179E-07
2	2	7.8383E-05	0.00232132	0.0121686		1.8195E-07
3	4	6.8516E-05	0.00034209	0.01251069		2.3439E-08
2	3	4.8491E-05	0.00129505	0.01380574		6.2799E-08
3	5	4.7787E-05	7.3305E-05	0.01387905		3.503E-09
1	2	4.0563E-05	0.00654856	0.02042761		2.6563E-07
2	4	3.5595E-05	0.00029322	0.02072083		1.0437E-08
2	5	2.7215E-05	2.4435E-05	0.02074527		6.65E-10
1	3	2.3167E-05	0.00591326	0.02665852		1.3699E-07
1	4	1.7076E-05	0.0019548	0.02861332		3.338E-08
1	5	1.2989E-05	0.00021991	0.02883323		2.8566E-09
					Annual Ave	5.2745E-06

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