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PREDICTING MAXIMUM BUILDING SURFACE CONCENTRATIONS FROM NEARBY POINT SOURCE EMISSIONS

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ABSTRACT

In most air pollution problems it is often the case that either the source or the receptor (or both) will be near buildings. In this paper we consider the building surface concentration and, by implication, the concentration in any air intakes located there as a result of (i) upwind sources, (ii) surface sources, (iii) downwind sources in the near wake recirculating region, and (iv) short roof-mounted stacks.

A qualitative description of the relevant dispersion mechanisms is first given and then some semianalytical and experimental results are presented.

Simple methods of estimating reasonable upper bounds to the surface concentrations are suggested.

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NOMENCLATURE

A_w - surface area of wake recirculation region, m^2

A - projected building frontal area, m^2

B_o, B_1, B_2, B_3 - empirical constants

C_M - maximum building surface concentration at a fixed distance r from the source, kg/m^3

C_{MAX} - global maximum concentration at the roof plane from a stack on the roof, kg/m^3

C_e - contaminant concentration in the gas at the source, kg/m^3

C_w - spatially averaged near wake concentration, kg/m^3

C_r - roof level concentration from a stack of height h_s above the roof, kg/m^3

C_{ro} - roof level concentration for zero stack height with same release conditions, kg/m^3

D_s - smaller of building height or width, m

D_L - larger of building height or width, m

h_s - stack height above roof level, m

Δh - plume rise above stack exit, m

H - building height, m

i_C - RMS intensity of isotropic turbulence

K_e - normalized concentration at source, see (15)

L - $\sqrt{A}$ length scale for flow and diffusion, m

m_w - mass transfer rate across recirculating wake boundary, kg/s

q_e - volume flow from source m^3/s

Q - mass release rate of contaminant, kg/s

Q' - mass release rate per unit length of line source kg/sm

r - shortest distance between source and building receptor measured along the surface, m

R	-	length scale for flow and diffusion, see (1), m
t_d	-	wake ventilation time constant, s
U	-	time average windspeed, m/s
U_s	-	windspeed at the point of emission, m/s
U_∞	-	uniform windspeed far upwind from an obstacle, m/s
U_c	-	mean plume convection velocity through plume crosswind section, m/s
U_{avg}	-	mean convection velocity between source and building, m/s
U_H	-	windspeed at roof level for upwind of the building, m/s
V_e	-	exit velocity from a surface vent, m/s
V_w	-	volume of the wake recirculation region, m^3
W	-	width of the upwind building face, m
x_s	-	distance from upwind building face to upwind source position
x_R	-	distance from the downwind building face to the reattachment point of the near wake recirculation region
z_o	-	roughness length, m

GREEK SYMBOLS

α	-	entrainment constant for recirculation region
σ	-	plume spread normal to trajectory in isotropic turbulence, m
σ_y	-	crosswind plume spread, m
σ_z	-	vertical plume spread, m
ρ	-	density of ambient air, kg/m^3
ρ_e	-	density of emission gas at the source, kg/m^3

1.0 SCOPE OF THE STUDY

While the maximum ground-level concentration from a pollution source may only rarely effect humans, the concentration on the surface of the building is far more likely to affect people by being injested into building air intakes, through open windows, or by direct contact with people leaving or entering the building. The fundamental question that a designer must answer is whether an unacceptable high level of concentration is likely to exist on a building surface from a particular emission source. What is required to answer this question is a set of simple explicit computational methods that set reasonable upper bounds on building surface concentrations. The objective of the present study is to review existing theoretical models and experimental data to determine these required design procedures.

Only surface concentrations on isolated buildings caused by point sources of contaminant will be considered. Four different situations will be examined:

1. Plume impingement from a source upwind of the building.
2. Sources from surface vents on the building.
3. Downwind sources in the near wake recirculation region.
4. Sources from short roof mounted stacks on the building.

Emissions from roof mounted stacks also qualify as a source on the building, but because they are designed specifically to avoid building surface concentrations, stacks will be considered separately from surface vents.

1(a) Computational Models

The computational methods that we seek should be physically realistic, and exhibit the effects of the relevant variables such as wind speed, source strength, distance, and building size in a dimensionally consistent way. However, the experimental data correlations used to develop models typically has an uncertainty factor of two to five for concentration. This is due mostly to the sensitivity of receptor concentration to small shifts in the trajectory from a point source. The error in predicting local concentration may be a factor of ten or more when the influence of nearby structures and local terrain irregularities are included. With this level of uncertainty, it is not necessary to develop complicated models for the interaction of the building with the surrounding flow, and simple diffusion models will usually be sufficient for design purposes.

The time over which concentration measurements are averaged is also an important factor. All the data used to support the predictions in this study are from wind-tunnel simulations, or short-term full-scale measurements, both of which exclude the slow variations in crosswind turbulence that are perceived as wind direction shifts in the full-scale. Thus, the concentrations predicted will represent averaging times in the full-scale from about one to ten minutes, and can probably be considered as typical of three-minute averages.

If must be emphasized that the purpose of this study is not to provide a comprehensive review of all previous work, but rather to develop proven design methods for evaluating building surface concentrations. For recent literature reviews the reader may refer to Meroney (19) and Hosker (9).

1(b) Flow Patterns over Buildings

Figure 1 shows the divergence of streamlines caused by the flow deceleration as is approaches the upwind face of a building, the subsequent vortex formation and flow separation from sharp upwind edges, followed by reattachment if the building is sufficiently long in the flow direction. The complex surface flow patterns shown in Figure 2 were determined using flow visualization in a water channel with a turbulent flow approaching the model buildings. These patterns are caused by the effect of the ground plane and the variation of wind speed with height in the approach flow. With wind perpendicular to the upwind face, the surface flow pattern in Figure 2 suggests a stagnation point on the rear face about one-third of the building height up from the ground plane. This observation is consistent with the descriptions by Peterka, Meroney, and Kothari (22) who discuss how the conventional notion of a single closed near-wake recirculation bubble is probably not realistic due to the influence of the ground plane and upwind velocity profile. Indeed for a three-dimensional object, pollutants may enter and escape the separation cavity by convection through interaction with horseshoe vortex circulations near the ground, steady arch-shaped vortex circulations behind the building, and intermittant "washing out" of the cavity by large turbulent gusts. However, we will see later that the concept of a closed recirculation volume in which wake contaminants are trapped will be a convenient model of diffusion from downwind sources. It is easy to see from the flow patterns in Figure 2 how uncertainty factors of two to five in concentration can be induced by a shift in plume trajectory. There are three basic receptor-source conditions:

1. The plume from the source to the receptor is always in the same unseparated flow.

2. The plume is emitted from and the receptor is located in a recirculation zone.

3. The plume passes through a recirculation zone but either the source or receptor or both are in unseparated flow.

Each of these situations might be expected to produce different rates of plume diffusion.

1(c) Length Scales for Flow and Diffusion

For a plume passing over a building several turbulence scales can be identified. The first set of these are the turbulence scales in the approach flow, which influence plume dispersion for sources upwind of the building. However, once the flow begins to interact with the building, it is the building itself that determines turbulence scales caused by flow separation patterns around it. The simplest length scale L for flow around a building, is formed from the projected frontal area $L = \sqrt{A}$. However, this approach is not realistic for long slender structures where most of the flow passes around the smallest dimension, making this the dominant scale length. Wilson (34) found that the roof recirculation zone and the wake above the roof had a length scale

$$R = D_s^{0.67} D_L^{0.33} \tag{1}$$

which is dominated by the smallest building dimension D_s. However, for buildings with aspect ratios of 5:1 or less, the two length scales L and R will differ by less than 30 percent. Keeping in mind the high levels of uncertainty in concentration, the simpler form for the length scale L will be used here. However, for long slender structures the length scale R is more appropriate and the reader may make this substitution of R^2 for A whenever necessary.

2.0 PLUME IMPINGEMENT FROM UPWIND SOURCES

As a plume approaches a building its spreading rate will increase due to streamline divergence as the flow decelerates approaching the stagnation point on the upwind face of the building. This increased spreading, accompanied by a decreased plume advection velocity is shown schematically in Figure 3. Lucas (18) suggested, without much theoretical or experimental justification, that the building surface concentration will be approximately equal to the concentration at the same point in space in an undisturbed plume. The recent experimental and theoretical study of Britter and Hunt (1) showed that when the plume centerline impinges directly on a building, the building surface concentration will always be less than the maximum concentration on the undisturbed centerline.

Simply, this may be explained as a result of a lower average convection velocity in the presence of a building while the rms turbulent velocities remain constant. A line source impinging on a two-dimensional obstacle reduces the concentration very little. Elaborate and rigorous analyses which include sources off and on the stagnation line may be found in the review by Hunt, Britter and Puttock (11), in Puttock and Hunt (29), and Britter and Hunt (1).

The prediction that the maximum surface concentration will always be less than the axial concentration in the undisturbed plume is confirmed by the experimental results shown in Figures 4 and 5. All of these experiments were carried out with a two-dimensional cylinder suspended without a ground plane in grid generated turbulence. In this case flow symmetry makes the cylinder radius, a, the appropriate length scale for normalizing distance. Figure 4 confirms that the maximum surface concentration from a point source on the stagnation line of a circular cylinder is always less than that measured in the undisturbed flow with the obstacle removed. The data also shows that the source must be very close to the obstacle, at about $x_s/a < 2$ for the surface concentration to be significantly less than the undisturbed plume axis concentration. The measurements in Figure 5 for a line source on the stagnation line of a two-dimenstional cylinder also confirmed the prediction that the reductions in concentration will be less than those for point source. For both point and line sources located off the stagnation line, Puttock (24) and Britter and Hunt (1) observed that the maximum surface concentration was also reduced below the maximum axial concentration, but was located near the edge of the cylinder rather than on the stagnation line.

Wilson and Netterville (36) measured the building surface concentration around a rectangular model building in a simulated atmospheric boundary layer. The source was located at roof level about 4.6 building heights upwind. Using the projected frontal area to form a length scale, the source was located at $x_s/\sqrt{A} = 5.7$ for the upwind face normal to the wind, and $x_s/\sqrt{A} = 4.0$ for the building at 45° to the wind. These measurements are summarized in Figures 6 and 7, using the concentration at the position of the upwind roof edge in the undisturbed plume as a normalizing value. Within the experimental uncertainty of about 5 percent, the maximum building surface concentration was found to be identical to the concentration on the undisturbed plume axis, in agreement with the observations at similar x_s/a values shown in Figures 4 and 5.

Caldwell and Goldie-Scott (1976, unpublished) measured the concentration on the face of a rectangular block with the height twice the width and four times the depth. Their data with a ground plane and highly turbulent and sheared approach flow confirmed the observations of Wilson and Netterville (36). Their experiments showed that maximum concentration on the building surface was equal to the axial concentration in the undisturbed plume, within an experimental uncertainty of 10 percent.

The increased plume spreading shown in Figure 3, and predicted by the simple analysis, is also readily apparent in the measurements in Figures 6 and 7. As the plume is decelerated in the flow approaching the building, the diverging streamlines cause the concentration to remain high over a larger area than in the undisturbed plume. Because the mass flux through any cross section of the plume remains constant, the lower velocity and approximately unchanged centreline concentration requires higher concentrations to occur in the outer edges of the plume, as shown is Figures 6 and 7. Thus, although the maximum concentration on the building surface is the same as that in the undisturbed plume, the area covered by this maximum concentration is much larger, indicating a proportionately larger risk of exposure when a building is present.

2(a) Design Procedure for Plume Impingement

The experimental data and theoretical arguments show that Lucas (18) was essentially correct in assuming that the maximum surface concentration on the building is equal to the maximum concentration in the undisturbed plume at the same downwind location. For design purposes it is suggested that a conservative estimate of the concentration on the building surface from an impinging plume be taken as uniform and equal to the maximum undisturbed plume concentration intercepted by the projected frontal area, A, of the building.

For groups of buildings, an upper limit to the surface concentration will be the undisturbed plume maximum intercepted by the building closest to the plume axis. The effect of upwind and downwind buildings and terrain irregularities can only be determined with any certainty by performing a wind-tunnel model study.

3.0 SURFACE VENT SOURCES ON THE BUILDING

The complex flow patterns shown in Figure 2 and discussed by Peterka et al. (22) make it virtually impossible to predict the detailed trajectory of the plume from a surface release. Wind-tunnel model studies are required to determine the effect of building orientation and vent location. Halitsky (7, 8) was the first to carry out a systematic study of the effect of vent and receptor location for various shapes and orientations. Using a nonturbulent uniform approach flow his measurements show the effect on diffusion of building turbulence alone. Later studies by Wilson (38, 39) and Li and Meroney (16, 17) used a simulated turbulent atmospheric boundary layer with a vertical velocity power of 0.23 and 0.19 respectively as the approach flow. The combination of atmospheric and building-generated turbulence caused increased diffusion which produced surface concentrations about a factor of three less than those observed by Halitsky. Wilson's data with a low source momentum ratio $\sqrt{\rho_e/\rho}\ V_e/U_H = 0.11$ and Li and Meroney's data with a value of 0.07 are characteristic of surface vents with louvers or rain caps that produce little momentum rise of the source jet.

All of these studied present concentration isopleths for various building shapes and vent locations. These diffusion measurements confirm what is apparent from Figure 2: that surface flow patterns isolate the upper two-thirds of a structure from the lower one-third. This suggests that good design practice should be to locate vents in the upper portion of the structure and intakes in the lower portion.

3(a) Predicting Maximum Concentration

From a designer's point of view, the most useful piece of information is the maximum concentration expected at a fixed receptor from a given source location. This will occur for the specific wind direction where the complex surface flow patterns cause the maximum concentration on the plume axis to pass over the receptor.

As the simplest model of this process, consider a Gaussian plume is isotropic turbulence where $\sigma = \sigma_y = \sigma_z$, with image source reflection which doubles surface concentration. The maximum C_M on the plume axis is given by

$$C_M = \frac{Q}{\pi U_c \sigma^2} \quad (2)$$

Receptors on the building should be close enough to the source for plume spread σ to be a linear function of travel time. Taking the travel time as r/U_C, where r is the shortest distance along the building surface between the source and receptor

$$\sigma \simeq i_C r \quad (3)$$

where i_C, is the turbulence intensity normal to the plume axis, formed using the local mean convection velocity U_C. Using the approach wind speed U_H at building roof height as the scaling velocity, (2) and (3) combine to produce

$$\frac{C_M\ U_H\ r^2}{Q} \simeq \frac{U_H}{U_C}\ \frac{1}{\pi\ i_C^2} \qquad (4)$$

Wilson (38, 39) found that the combination of variables on the right side of (4) was a constant, B_o, for most source and receptor locations, so that

$$\frac{C_M\ U_H\ r^2}{Q} = B_o \qquad (5)$$

While the changes in U_C and i_C should compensate, with U_C low and i_C high in wake recirculation regions, and the reverse in unseparated flow, it is none the less remarkable that the product $U_C i_C^2$ remains virtually constant, leading to (5).

The data in Figures 8 to 12 are presented in terms of the dilution factor C/C_e, using the concentration C_e of contaminant in the vented gas at the source. Using $Q = C_e q_e$, (5) can be rearranged in the form of the minimum dilution C_e/C_M,

$$\frac{C_e}{C_M} = \frac{K_e\ r^2}{B_o A} \qquad (6)$$

where

$$K_e = \frac{C_e\ U_H\ A}{q_e} \qquad (7)$$

Note that the diffusion length scale $L = \sqrt{A}$ is not a parameter in (5), and cancels from (6) and (7). This is because L affects only the length scale of turbulence, which is not a factor close to the source where σ depends only on the turbulence intensity i_c, and distance r.

The data for roof, side and rear vents summarized in Figures 8, 9 and 10, produce the same constant $B_o = 9.0$ for the minimum dilution (or maximum surface concentration). The data for sources on the upwind face of the building, summarized in Figure 11, do not follow this simple correlation. Wilson (38) found that higher upwind face concentrations were for sources on the lower one-third of the building upwind face, and receptors on the lower one-third of the building sides. One plausible explanation for these higher concentrations is that emissions on the lower one-third of the upwind face are trapped in the upwind vortex system and carried by it around the sides of the building with less dilution. These higher concentrations could be accounted for by changing the constant in (5) to $B_o \simeq 30$.

Orientation of the building to the approach wind strongly affects building surface concentrations. Li and Meroney (16) found that the roof vortices found at orientations of 45° resulted in much higher surface concentrations near the ground as noted by comparing Figures 12 and 13. One can adjust for this fact by defining a new constant B_o as $B_o' = B_o(1 + 4\theta/\pi)$ where θ is the approach angle in radians.

Because a point source model was used for plume diffusion, it unrealistically predicts $C_M > C_e$, the contaminant concentration in the vented gas. In fact, the experiments showed that for distances greater than a few source diameters from the vent, the back and forth meandering of the plume caused high intermittency which led to average concentrations that were always less the 10 percent of the vent gas contaminant concentration C_e.

It is interesting to see what plume turbulence intensities are implied by the observed values of B_o. Comparing (4) and (5)

$$B_o = \left(\frac{U_H}{U_c}\right)\frac{1}{\pi\, i_C^2} \tag{8}$$

For roof vents $B_o = 9.0$, and taking $U_H/U_c \simeq 1.0$ this implies $i_C \simeq 0.19$. Using Drivas and Shair's (3) estimate of $U_H/U_c \simeq 6.0 \pm 3.0$ in the near wake, rear vents with $B_o = 9.0$ implies $i_C \simeq 0.46$. Both these estimates for turbulence intensity seem reasonable, increasing our confidence in (5).

3(b) Design Procedure for Building Surface Sources

Using the previous results, a conservative but realistic procedure for estimating the maximum building surface concentration at a distance r from a surface vent is:

1. When the receptor is closer than three source diameters to the vent assume $C_M \simeq C_e$, the vent gas contaminant concentration.
2. When r is greater than three source diameters from the vent, assume plume "flapping" produces at least a factor of ten dilution so the $C_M \leqq 0.1\ C_e$.
3. Keeping constraints 1 and 2 in mind, use (5) with $B_o = 9.0$ or $(9.0 + 36.0\theta/\pi)$ to compute C_M, unless both the source and receptor are on the lower third of the same or adjacent walls, in which case use $B_o = 30$.

4.0 SOURCES IN THE NEAR WAKE RECIRCULATION REGION

Immediately downstream of the building the flow recirculates, with streamlines pointing upwind at ground level for about two to six building heights downwind from the rear face. Hosker (9) correlating the experimental data of several wind-tunnel studies found the distance X_r from the downwind face to the point of reattachment

$$X_R = \frac{1.75\ WH}{H + 0.25W} \tag{9}$$

Virtually all the data used in this correlation were for buildings with $W \geq H$. For this case the correlation may be approximated within ± 15 percent by the simpler form

$$X_R \simeq 1.6A \tag{10}$$

over the practical range $1 \leq W/H \leq 15$. The gases from sources released in this region will be carried upwind to produce contamination of the building surface. The very high turbulence intensity in the near wake, combined with the flow recirculation there, cause the plume from the source to be mixed to a uniform concentration after traveling a short distance. Most wake recirculation models, such as those of Gifford (5), and Vincent (33) assume a uniform concentration across the entire near wake region.

However, the studies of Wilson (38) and Kothari, Meroney and Peterka (14) show that an emission from the rear face of a building into the recirculating region produces a diffusing plume for considerable distance from the source. This spatially varying concentration is shown in Figure 14 for release from the center of the downwind building face. Kothari et al. (14) measured the plume as it traversed through the cavity and downwind. The perturbation method discussed in Peterka, Meroney and Kothari (22) effectively predicts plume concentrations after the gases leave the immediate wake/cavity region. The maximum concentration found by Wilson is shown in Figure 10 to follow (5), the same decay law for releases on roof and other building surfaces. What is required then is a composite diffusion model for near wake releases which accounts for self-entrainment of the plume far from the source, but which allows the plume near the source to diffuse as any other surface release.

4(a) Wake Ventilation Model

Let us first examine the asymptotic case where the receptor is far enough from the source that the plume is dominated by self-entrainment, and has a uniform concentration through this region of the wake. Gifford (5) proposed a diffusion model aimed essentially at predicting concentrations downwind of the near wake. This model was the first to suggest that the projected frontal area A was the appropriate diffusion length scale of a near wake, and proposed the often quoted range of uniform wake concentrations $0.5 \leq C_w U_H A/Q \leq 2.0$. Reviewing more recent data Gifford (4) proposed that the upper limit of 2.0 is probably the most reasonable choice.

Vincent (32, 33) characterized the wake diffusion by the time constant t_d for the decay rate of the spatially averaged near wake concentration. The advantage of this approach seems to be that a suitably normalized wake ventilation time constant is less dependent on building geometry than the concentration itself. Vincent (32) carried out specific studies where the angle of building incidence to the wind was changed to clearly demonstrate that the building projected frontal area A is the appropriate scaling factor for the ventilation time constant.

$$\frac{t_d\ U_H}{\sqrt{A}} = B_1 \tag{11}$$

where, for a surface mounted cube at various angles of incidence and varying approach flow turbulence $B_1 = 6.8 \pm 1.5$ with the lower value corresponding to higher freestream turbulence levels. Full-scale experiments of Drivas and Shair (3) for a ground level source in the recirculation region behind a building 12 m high and 64 m wide gave a time constant of $t_d = 60$ s for a wind speed of $U_H \simeq 2.5$ m/s. This result corresponds to $B_2 \simeq 5.4$ which agrees very well with the high approach flow turbulence range of Vincent's wind-tunnel data.

Following Fackrell and Robins (28), the time constant can be related to the uniform wake concentration by modeling the recirculation zone as a closed cavity with a surface area A_w. The mass flux m_w across this wake boundary is expressed in terms of an entrainment constant α

$$m_w = U_H \alpha A_w (C_w - C_\infty) \tag{12}$$

Taking the approach flow concentration $C_\infty = 0$ a mass balance for a source emission rate Q into the wake gives

$$\frac{dC_w}{dt} = \frac{Q - \alpha U_H A_w C_w}{V_w} \tag{13}$$

where V_w is the effective wake volume occupied by the uniform concentration C_w. The steady state solution of (11) when $\frac{dC_w}{dt} = 0$ is

$$C_w = \frac{Q}{\alpha A_w U_H} \tag{14}$$

and the decay time constant for a suddenly stopped source is

$$t_d = \frac{V_w}{\alpha A_w U_H} \tag{15}$$

Using (11) in (15) we find

$$\alpha A_w = \frac{V_w}{b_1 \sqrt{A}} \tag{16}$$

and combining this with (14) yields

$$\frac{C_w U_H A}{Q} = B_1 \frac{A^{3/2}}{V_w} \tag{17}$$

For a building that is not too wide, say $W/H \lesssim 4$ the uniform concentration C_w should occupy the entire wake volume, which we assume scales with projected frontal area A

$$V_w = B_2 A^{3/2} \tag{18}$$

If the effective wake volume is approximated as $V_w \simeq AX_R$, then (10) implies $B_2 \simeq 1.6$. Because the wake recirculation region is not really a closed volume, some of the source emission will be "pumped " out of the near wake by the unsteady fluctuations of wake reattachment. This will make the effective mixing volume larger, increasing B_2 so that $1.5 \leq B_2 \leq 3.0$ is a reasonable expected range. Combining (17) and (18) and defining $B_3 = B_1/B_2$

$$\frac{C_w U_H A}{Q} = B_3 \tag{19}$$

where from the range of values for B_1 and B_2 we expect $1.75 < B_3 < 5.5$. It is interesting to note that neither the entrainment constant α or the surface area A_w of the wake recirculation appear in this final equation for concentration. Using the mean value for B_3, the suggested design equation for the uniform wake concentration is

$$\frac{C_w U_H A}{Q} = 3.0 \pm 2.0 \tag{20}$$

How does this compare to other estimates of B_3? Using the full-scale data of Drivas and Shair (3) to evaluate wake volume with their observed reattachment three building heights downwind, and their value of $B_1 = 5.4$, we find $B_3 \simeq 4.0$. Halitsky (7) and Meroney and Yang (20) both find for the near wake the constant $B_3 \simeq 1.0$. Later full-scale data for release near a group of nuclear reactor buildings, Halitsky (6) shows that close to the source $x < 100$ m, $B_3 \simeq 2.0$ is in agreement with Gifford's (4) suggested value. Wind-tunnel data of Robins and Castro (26, 27) produce values of B_3 ranging from about 1.0 to 3.0 for releases from the building surface and ground level receptors in the near wake for $r/\sqrt{A} \geq 1.5$. Kothari, Meroney and Peterka (14) measured near wake concentrations behind a variety of cylindrical, cubical and hemispherical shaped model buildings for releases from flush roof vents. Maximum vlaues of B_3 varied from 0.5 to 2.0 in the near wake for $r/\sqrt{A} \geq 1.0$. These values are probably reasonable for our situation of interest, where source and receptor positions are reversed.

Both Thompson and Lombardi (30) and Li and Meroney (17) for a release from a flush roof vent into the recirculation region found the maximum near wake ground level concentration occurs when the building is at 45° to the wind causing strong wake downwash. For this situation they found $B_3 \simeq 3.0 - 3.5$ at $r/\sqrt{A} \simeq 1.8 - 2.0$. Although this is not a true wake release the values are in agreement with (20).

However, it was pointed out that for a considerable distance near the source, the wake concentration follows (5), with concentration varying as distance r^{-2} (see Wilson (38)). Robins and Castro (26, 27) found releases from the rear face of a cube near the ground produced ground level near wake concentrations up to five times higher than a release near roof level. This observation also supports a non-homogeneous concentration model for sources released within the near wake. The uniform wake concentration C_w in (20) must be regarded as an asymptotic value observed far enough from the source for self-entrainment to dominate the plume. Equations (20) and (5) produce equal concentrations at $r/\sqrt{A} = 1.73$ and this is taken as the lower limit of distance at which (20) is valid.

All concentration estimates to this point assume mean concentrations averaged over a period of three to ten minutes. When an exhaust gas contains toxic, flammable, bacteriological and odorous material one is also interested in the concentrations instantaneous magnitude and associated probability distributions. Wilson (40) and Li and Meroney (17) have examined instantaneous concentration fluctuations in building wake regions. Near the ground centerline behind the model building upper limits to the peak-to-mean concnetration ratios are

$$(x_\rho/\bar{x})_{99\%} < 3.0,$$
$$(x_\rho/\bar{x})_{95\%} < 2.5, \text{ and} \tag{21}$$
$$(x_\rho/\bar{x})_{90\%} < 2.0$$

4(b) Design Procedure for Sources in Recirculating Wake

In the absence of a single theory to account for diffusion near the source as well as uniform wake concentrations far from the source:

1. For distances from the source measured along the building and/or along ground level of $r/\sqrt{A} \leq 1.73$ use (5) with $B_o = (9.0 + 36.0\ \theta/\pi)$
2. For distances $r/\sqrt{A} > 1.73$ use (19) with $B_3 = 3.0$.

These two equations are shown in Figure 10 for a surface release on the rear of the building and $\theta = 0°$.

5.0 SHORT STACKS ON FLAT ROOFED BUILDINGS

The basic purpose of a vent gas stack is to limit building surface concentration to safe levels. Because the present concern is for building surface concentrations, and not ground level concentrations far downwind of the building, a stack that meets the requirements for lower building surface concentration may simply shift the unacceptable concentration maximum to some downwind ground level location, although this will not concern us here. To determine the effect of the building wake on ground level concentration the reader is referred to the systematic studes of Snyder and Lawson (29), Huber and Snyder (10), Koga and Way (13), Kothari, Peterka, and Meroney (15), and to review by Hosker (9).

There are two situations of interest: predicting the effect of varying stack height on building surface concentrations, or specifying a stack of sufficient height so that the plume avoids all contact with building surfaces.

5(a) Effect of Stack Height on Roof Concentration

For flat roofed buildings it is possible to estimate the effect of stack height on concentrations at roof level receptors. Using the Gaussian plume model with stack height h_s above the flat roof, and plume rise Δh, the roof level concentration is

$$C_r = \frac{Q}{\pi U_c \sigma_y \sigma_z} \exp\left[- \frac{(h_s + \Delta h)^2}{2\sigma_z^2} - \frac{y^2}{2\sigma_y^2} \right] \tag{22}$$

Setting $h_s = 0$ this equation gives the concentration C_{ro} for a surface vent. The ratio of these two concentrations, assuming the convection velocity U_c and plume spread σ_y and σ_z are not a function of stack height is, for both on- and off-axis receptors,

$$\frac{C_r}{C_{ro}} = \exp\left[- \frac{(h_s^2 + 2h_s \ \Delta h)}{2\sigma_z^2} \right] \tag{23}$$

Wilson (35) carried out wind-tunnel measurements on 24 flat roofed building configurations each with 4 stack heights and a surface vent. The approach flow simulated a turbulent atmospheric boundary layer with a 0.23 power law velocity profile. Using (22) to correlate roof level concentrations, the vertical plume spread was found to be

$$\sigma_z = 0.21 \ R^{0.25} \ X^{0.75} \tag{24}$$

where R is the building length scale from (1). For a typical full-scale building 10 m high and 40 m wide, R = 15.8 m and $\sigma_z = 0.42 \ x^{0.75}$ m. This is about one-third higher than the spread $\sigma_z = 0.46 \ x^{0.68}$ recommended by Pasquill (21) for rough terrain, $z_o = 100$ cm.

Figure 15 shows the concentration reductions for one typical building configuration with wind perpendicular to the upwind face. The data correlation is satisfactory, considering that both on- and off-axis receptors are included, making the reductions very sensitive to small crosswind displacements of the plume axis with varying stack height.

Unfortunately, there are many situations where simple diffusion theory cannot be applied to short roof mounted stacks. Figure 16 shows one such case, with the wind at 45° to the building faces and the stack near the building edge close to the roof edge vortex system (see Figure 2). In this case there is almost no correlation between the stack height and reduction in surface concentration. The simple diffusion theory on which (22) is based is only reasonable if the stack does not lie in or near a roof edge vortex zone. As shown in Figure 2 these zones lie near the roof edges each with an included angle of about

20° from the upwind roof corner. Wilson (35) found evidence of these roof vortex patterns when the acute angle between the wind and any building face lay in the range from 30 to 60 degrees. Li and Meroney (16) also detected such vortex patterns at 22.5°.

Varying stack heights caused no consistent or predictable concentration reduction when the stack lay within a roof recirculation region, shown in Figure 1. Wilson (34) found that this recirculation zone had its maximum dimensions when the wind direction was perpendicular to the upwind face. The height and the attachment length of this recirculation cavity was found by flow visualization to be

$$H_c = 0.22R$$
$$X_c = 0.5R \qquad (25)$$
$$L_c = 0.9R$$

For typical buildings H_c from (24) agrees well with the U.S.E.P.A. (31) recommendation that $H_c = 0.5\ D_s$. By determining the extent of the roof recirculation region and roof edge vortices, the stack can be located to provide maximum benefit from its height. As pointed out by Wilson (34), and Robins and Fackrell (28), the best location for a stack is usually in the center of the roof where it is most likely to avoid these problems. When a stack must be located in a recirculation or vortex zone it should be considered as a surface vent, or made high enough for the plume to completely avoid the building.

5(b) Stack Design to Avoid Building Interaction

To avoid excessive building surface concentrations, the simplest method is to select a stack height so the plume will not contact any building surface. This is a much less stringent requirement than avoiding all interaction with downwind building wake, which led to the

2.5 H rule for building stacks, see for example Snyder and Lawson (29). Wilson (34) proposed a graphical design procedure based on flow visualization studies over flat roofed buildings. Essentially, the procedure consists of using Figure 1 and (32) to construct the flow recirculation cavity on the upwind edge of the roof. Then, a high turbulence zone boundary is constructed with a downwind slope of 1:10 from the top of this recirculation cavity. Where this boundary crosses the downwind roof edge, the edge of the plume, taken at a 1:5 slope, is projected back upwind over the building. All stack heights should be located above this plume edge boundary to avoid high surface concentrations on the roof. Alternate procedures are suggested by Wilson (34) to account for multilevel roofs and more complex building shapes.

5(c) Entrainment of Stack PLumes into the Recirculating Wake

Even when the stack is designed so that the plume clears the downwind edge of the roof, it may become entrained in the wake recirculation and cause high concentrations on the downwind wall of the building. Puttock and Hunt (25) developed an analytical model for sources outside the wake recirculation region which predicts that a uniform concentration will exist within the wake due to entrainment across the boundary of the recirculation region. Moreover, this uniform wake concentration c_W is approximately equal to the average concentration over the surface of the recirculation region. These predictions were confirmed by the experiments of Puttock (24), for sources passing over a two-dimensional cylinder and being entrained in the near wake.

If we approximate the wake boundary as a horizontal plane extending downwind from roof level, these results indicate that an upper bound on concentration, both on the roof and within the recirculation cavity, is simply the global maximum concentration at the roof plane. For a Gaussian plume with surface reflection and vertical and crosswind spreads proportional to one another, this global maximum is simply

$$C_{MAX} \simeq \frac{Q}{\pi\ U_H\ e^{1.0}\ (h + \Delta h)^2}\left(\frac{\sigma_z}{\sigma_y}\right) \tag{26}$$

Taking $\sigma_y/\sigma_z \simeq 1.25$ this upper bound becomes

$$\frac{C_{MAX}\ U_H\ (h_s + \Delta h)^2}{Q} \simeq 0.1 \tag{27}$$

This upper bound is perhaps the simplest method for specifying the height of short roof mounted stacks. If (27) predicts what appears to be an excessively high stack, then wind-tunnel model studies may be required for a refined design.

6.0 CONCLUSIONS

In the preceding sections recent wind-tunnel studies and a few full-scale tests have been used to develop design procedures for predicting building surface concentrations. In each case, an attempt has been made to provide conservative but realistic design equations for sources upwind, on the building surface, and in the recirculating wake. The most important result of this review was that a suitably modified simple Gaussian plume theory could be used to describe much of the complex interaction between a plume and a building. For simple building shapes, only a few equations are required to define all the important situations. It is only in the area of stack design that some difficulty arises in accounting for the effects of building recirculation zones and roof edge vortices on surface concentrations. However, these problems can be largely avoided by making the stack high enough to avoid significant interaction with the building.

Up to the present, the design of short stacks on buildings, and the estimation of building surface concentration has been largely by guess work, or by laborious and expensive model studies. The experimental data correlations and simple theoretical models in this paper should allow estimates to be made of surface concentrations in many situations. It is only when such simple estimating procedures are available that these concentrations will be considered in routine design calculations.

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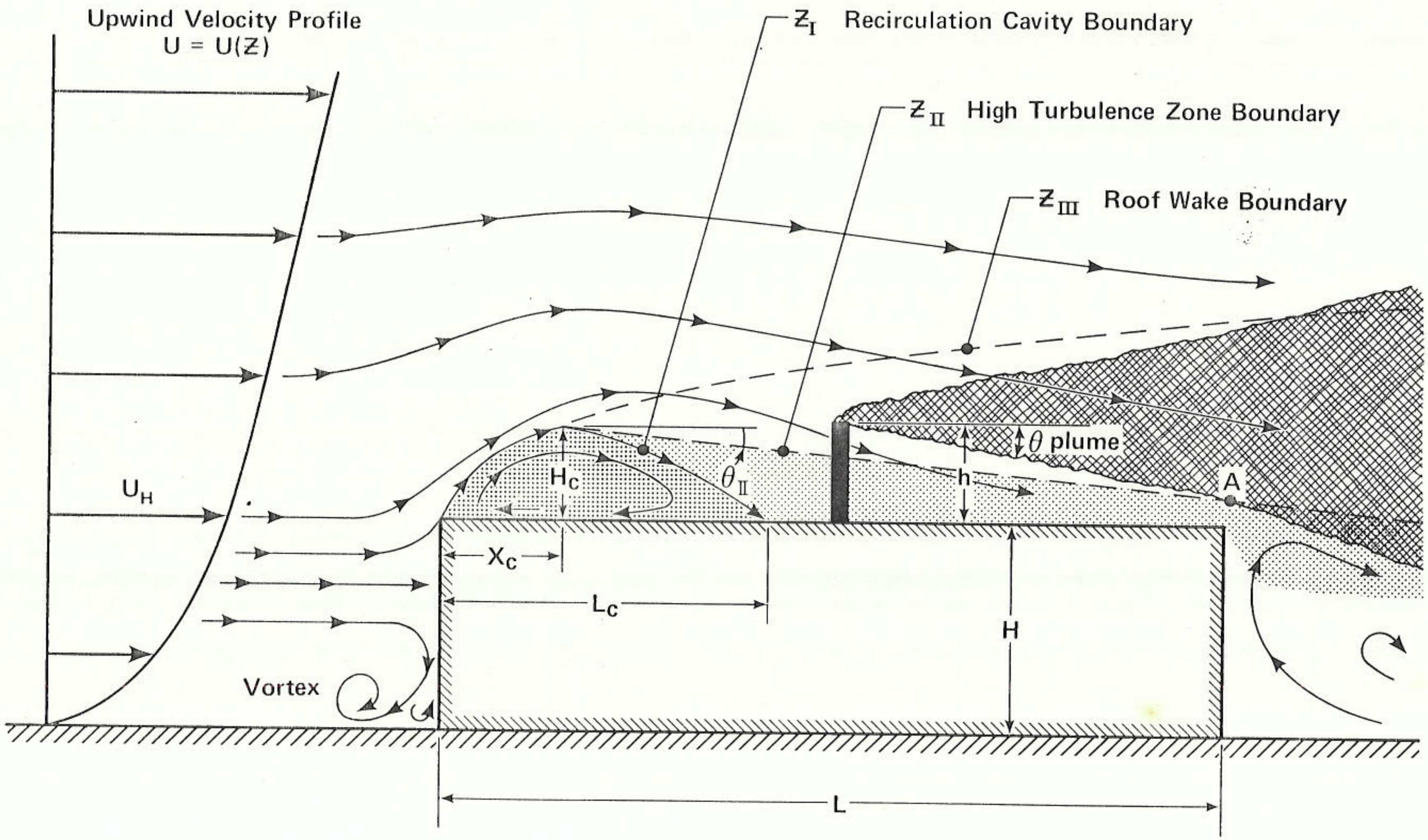
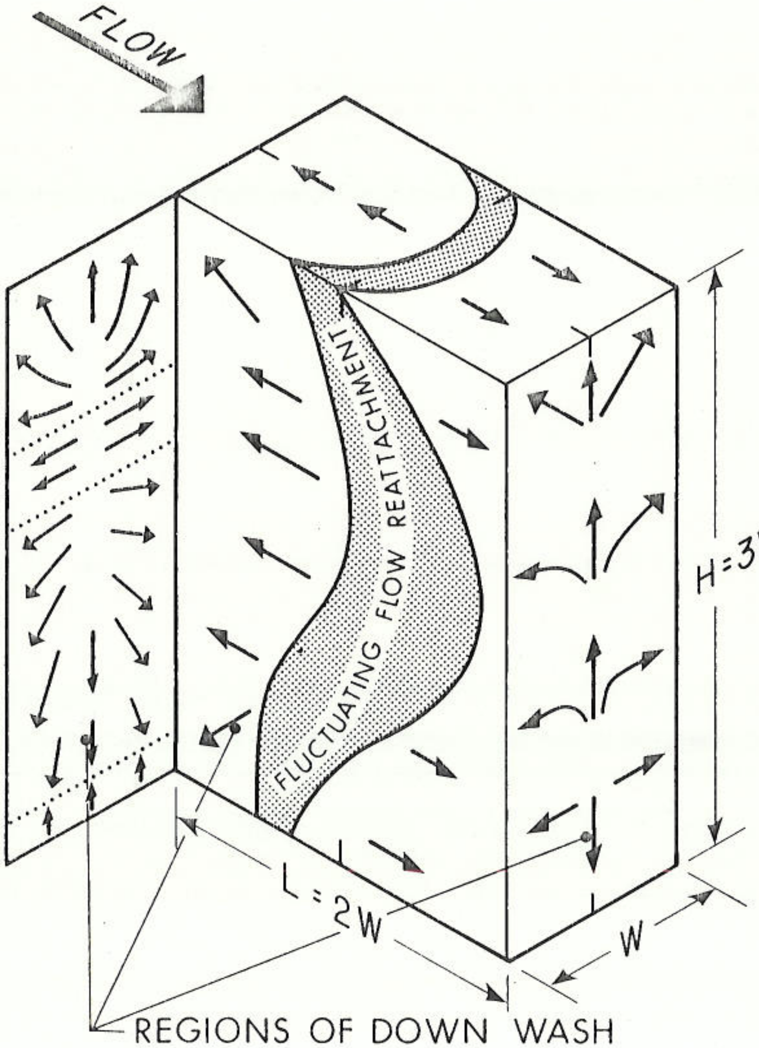
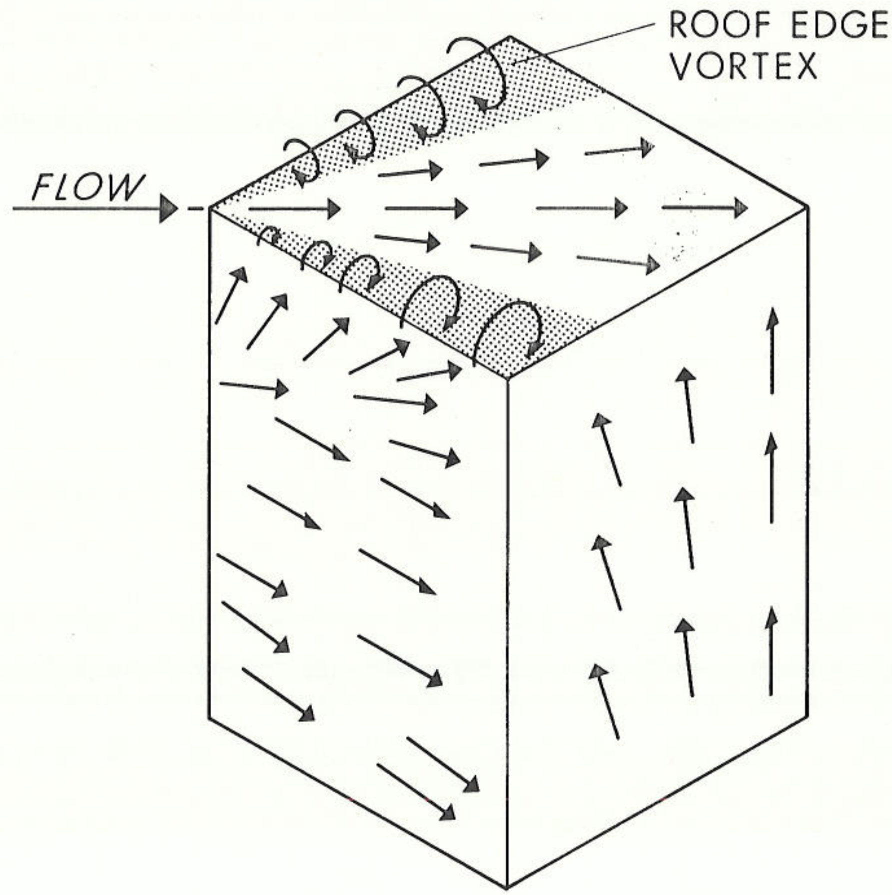
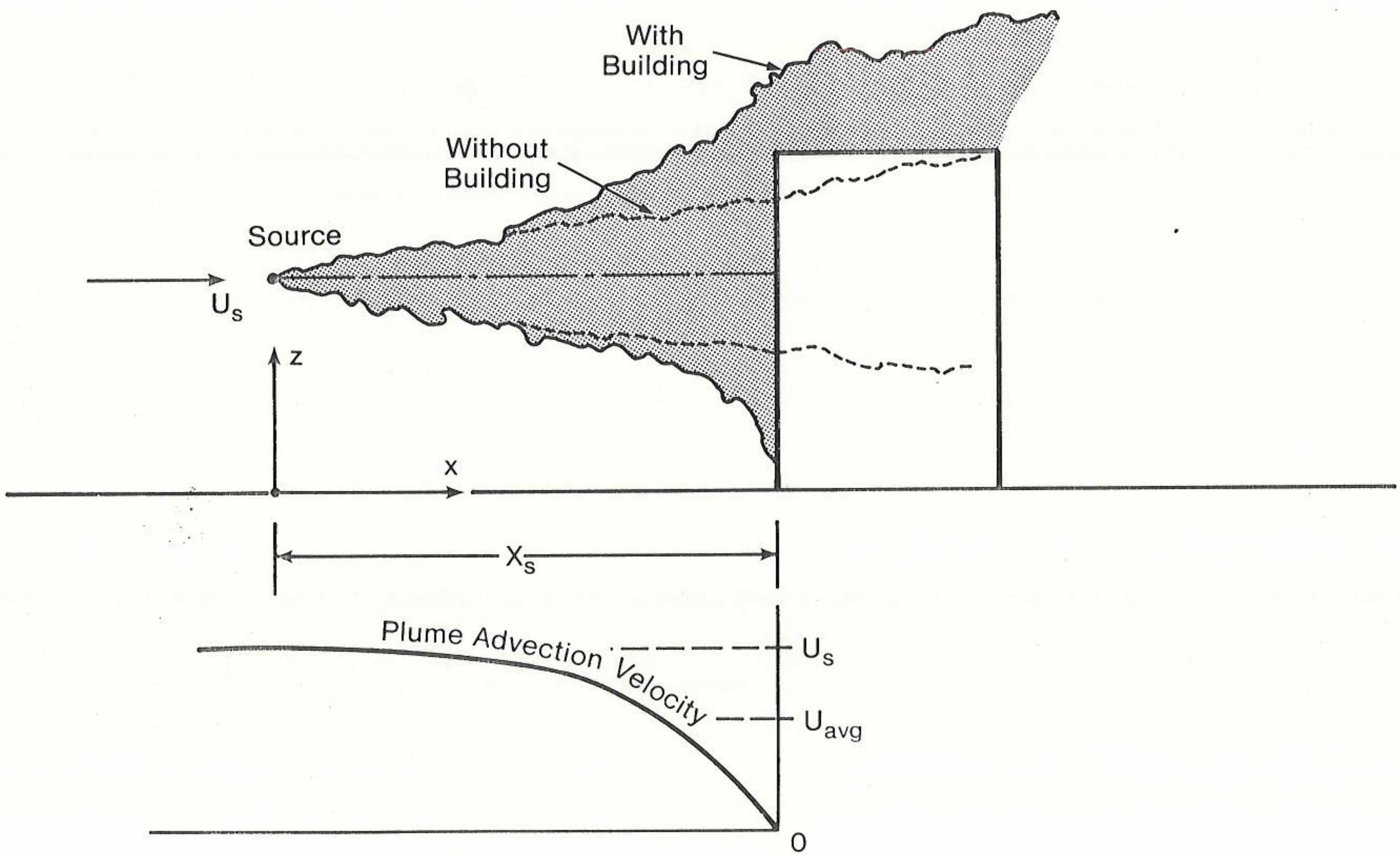
LIST OF FIGURES

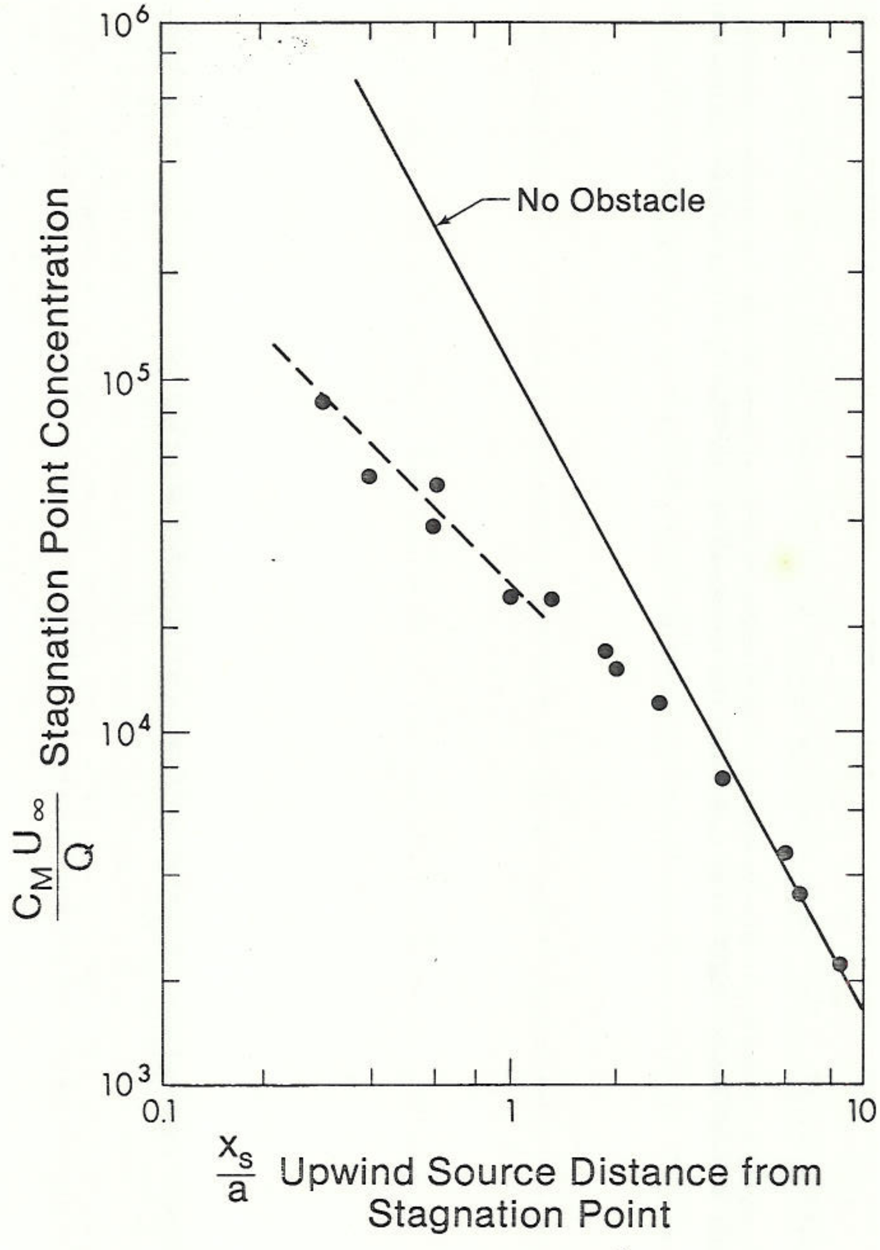


Upwind Velocity Profile
U = U(Z)
U_H
Vortex
Z_I Recirculation Cavity Boundary
Z_II High Turbulence Zone Boundary
Z_III Roof Wake Boundary
H_c
X_c
L_c
θ_II
θ plume
h
A
H
L

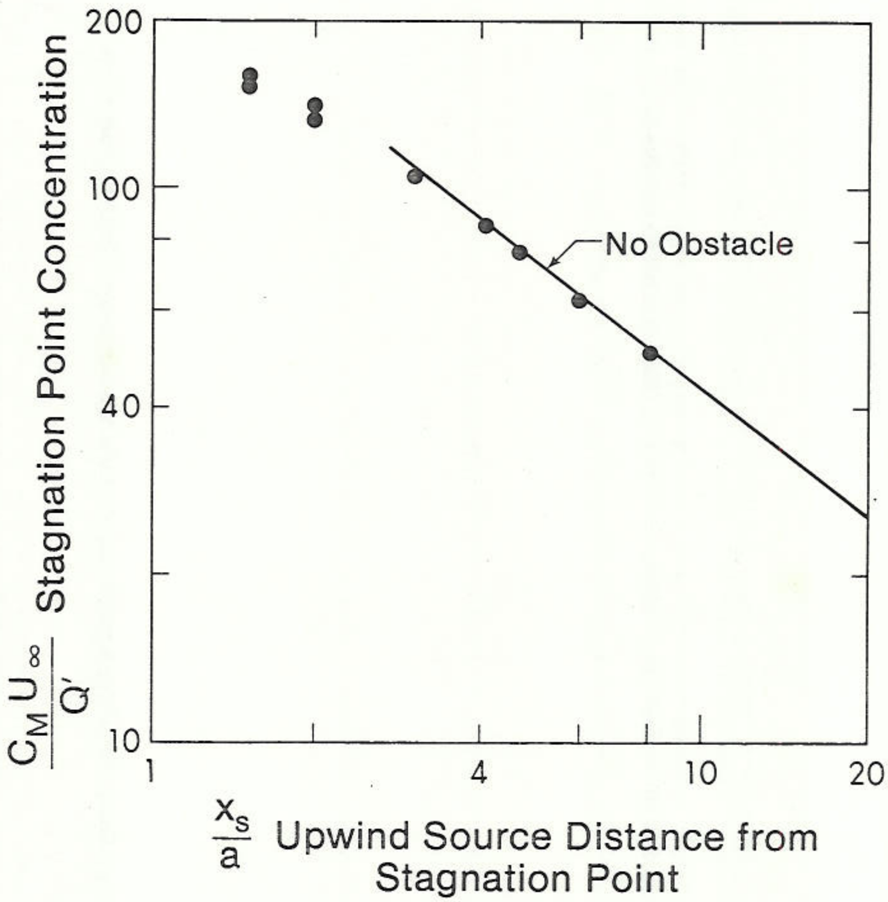

FLOW
FLUCTUATING FLOW REATTACHMENT
H=3W
L=2W
W
REGIONS OF DOWN WASH


ROOF EDGE
VORTEX
FLOW

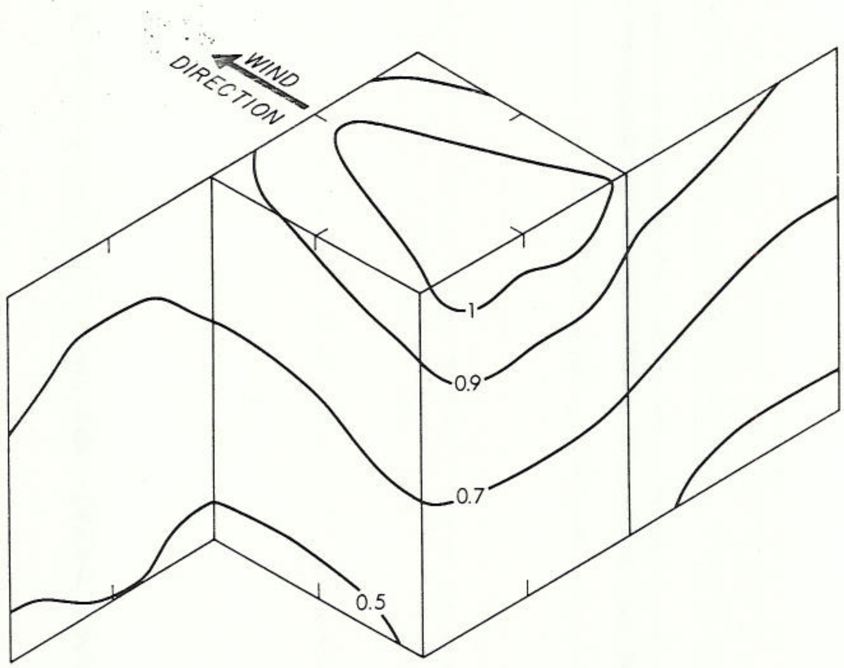

With
Building
Without
Building
Source
U_s
z
x
X_s
Plume Advection Velocity
U_s
U_avg
0

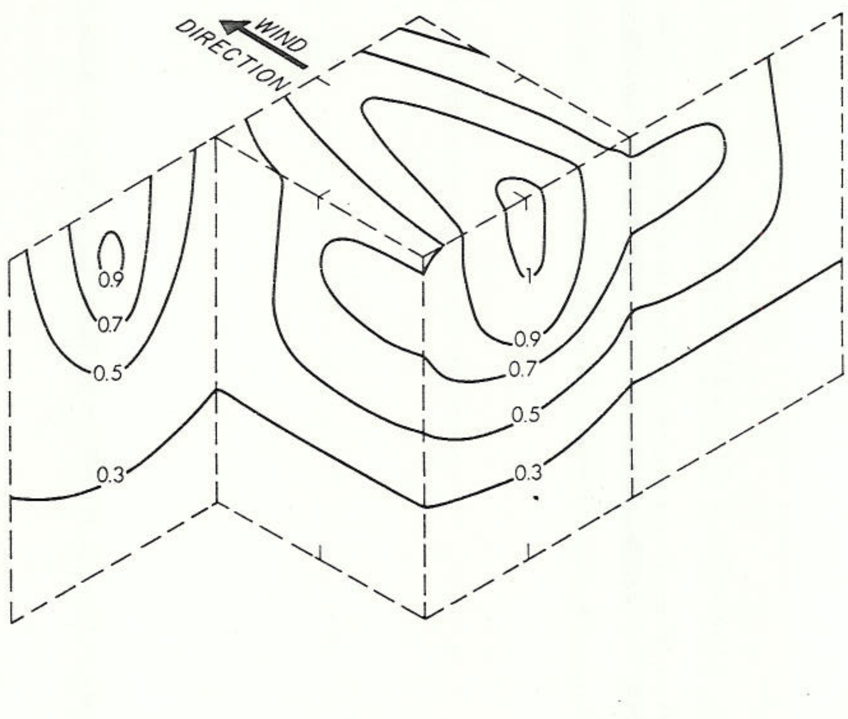


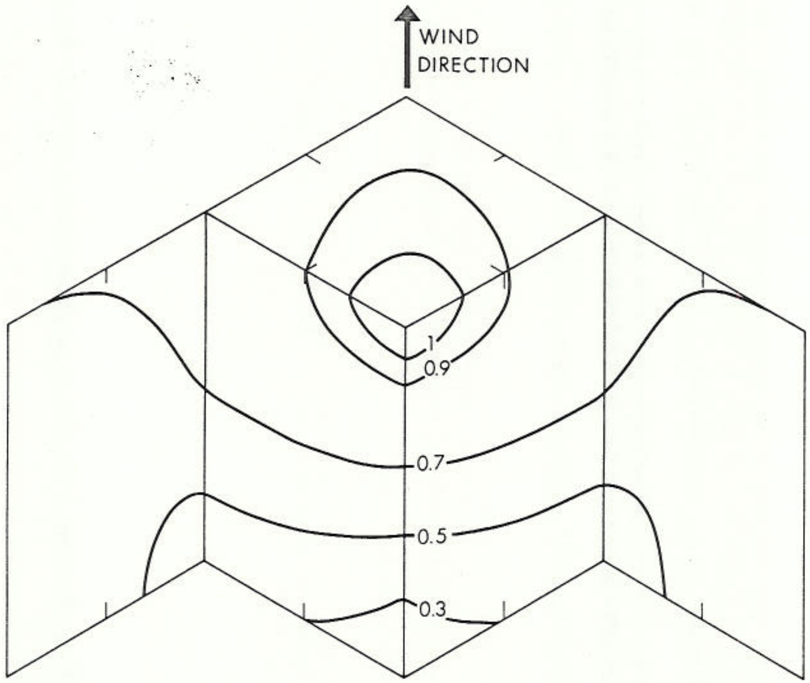
10^6
10^5
10^4
10^3
0.1
1
10
No Obstacle
$\frac{C_M U_\infty}{Q}$ Stagnation Point Concentration
$\frac{x_s}{a}$ Upwind Source Distance from Stagnation Point

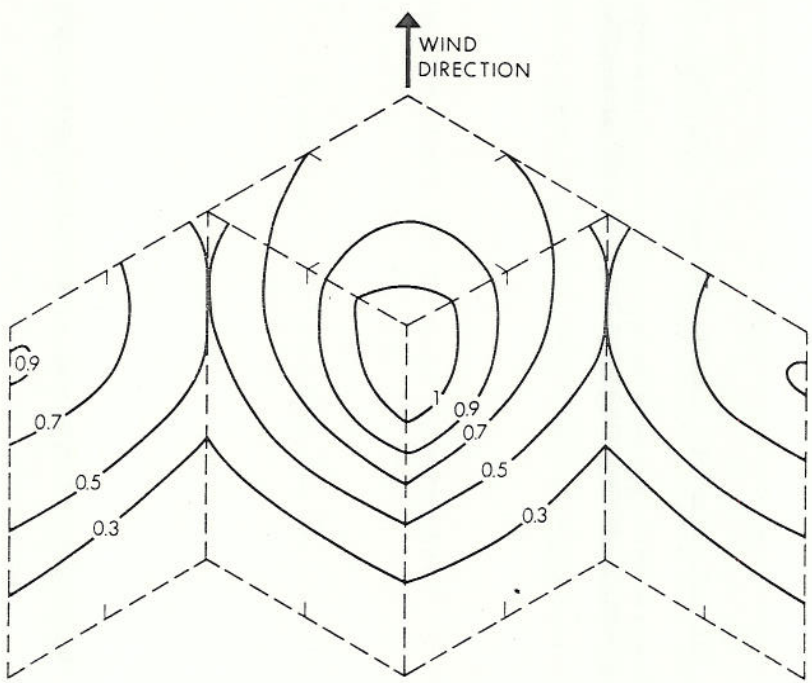


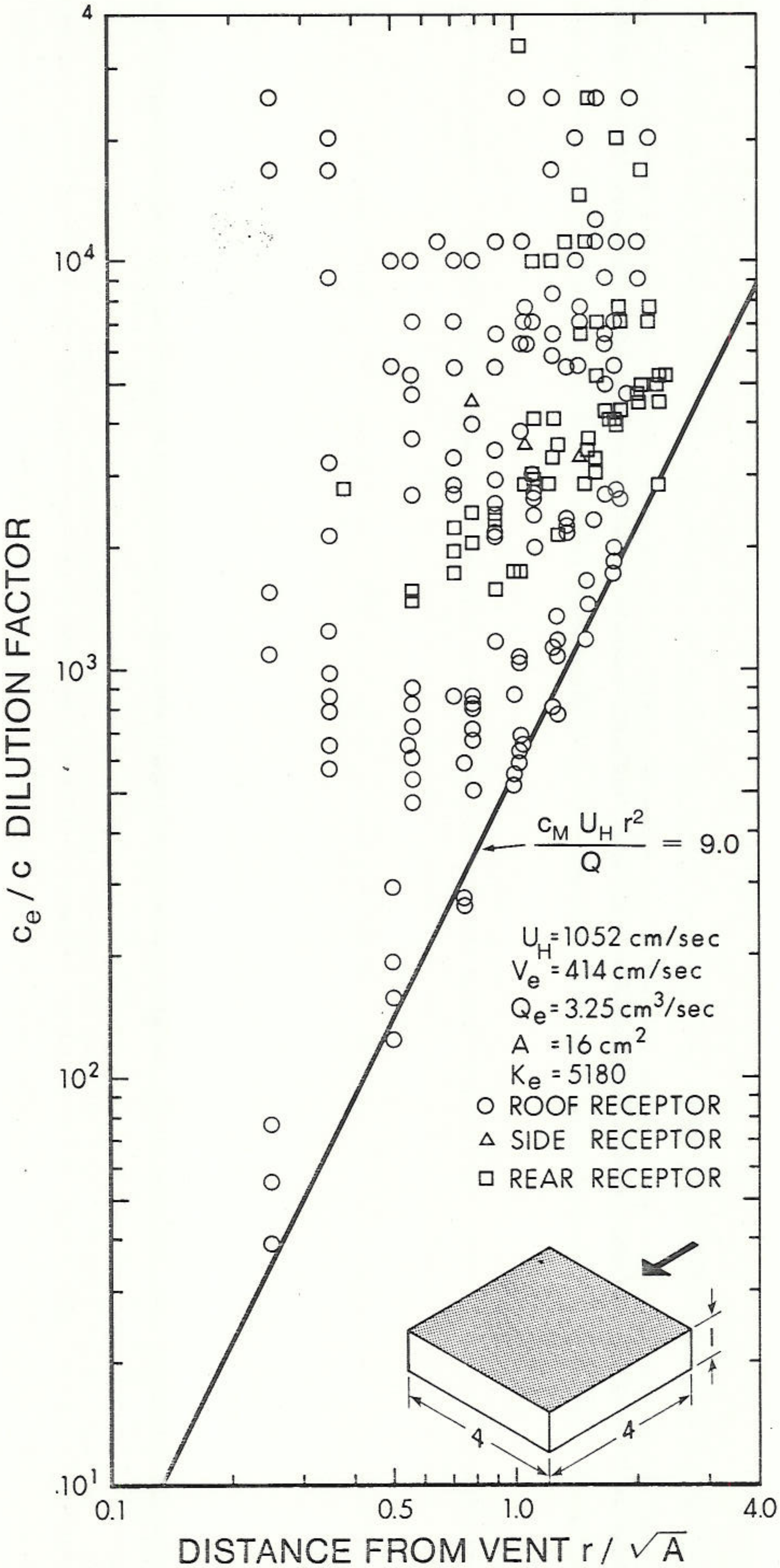
200
100
40
10
1
4
10
20
No Obstacle
$\frac{C_M U_\infty}{Q'}$ Stagnation Point Concentration
$\frac{x_s}{a}$ Upwind Source Distance from Stagnation Point


WIND
DIRECTION
1
0.9
0.7
0.5

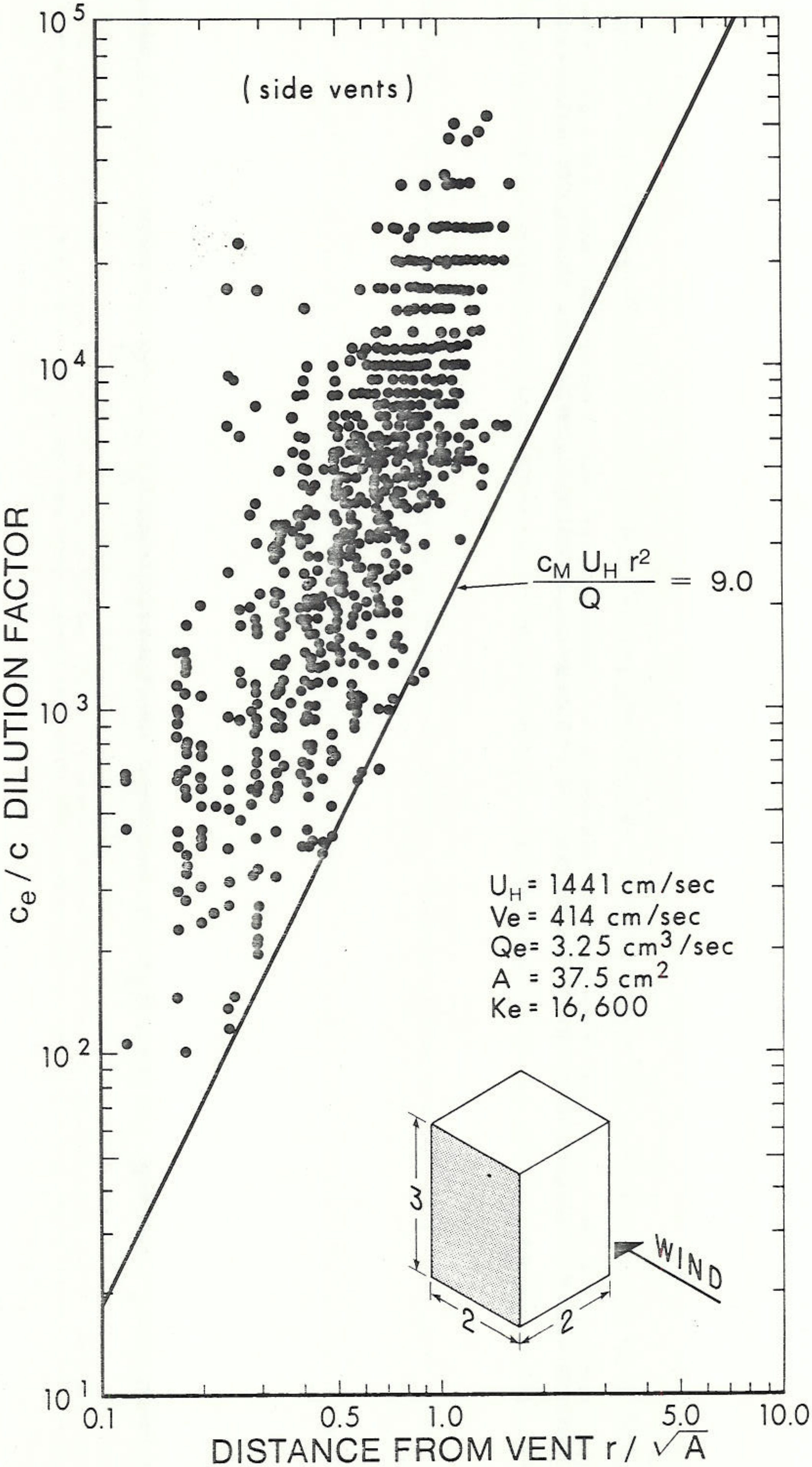

WIND
DIRECTION
0.9
0.7
0.5
0.3
1
0.9
0.7
0.5
0.3


WIND DIRECTION
1
0.9
0.7
0.5
0.3

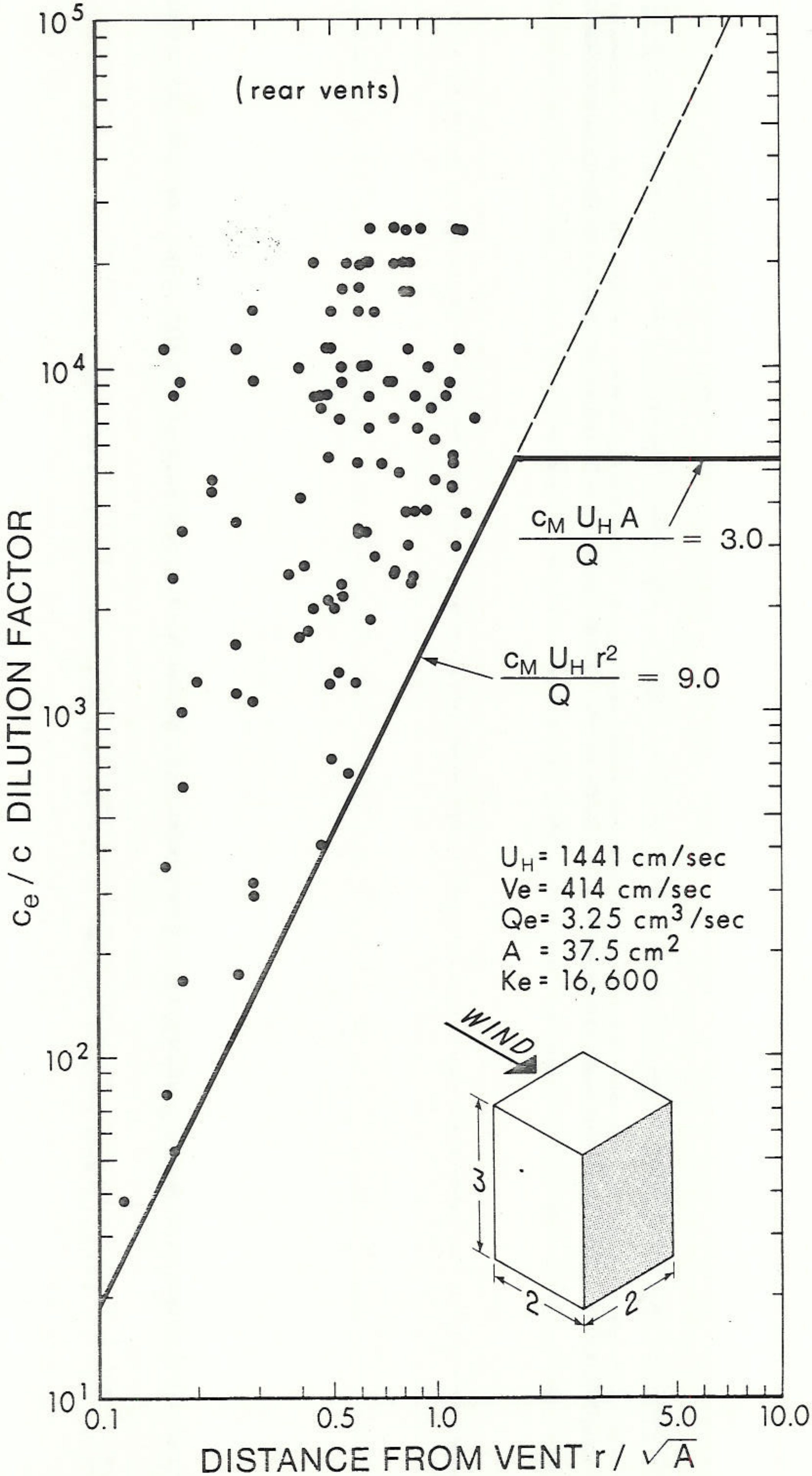

WIND DIRECTION
0.9
0.7
0.5
0.3
1
0.9
0.7
0.5
0.3



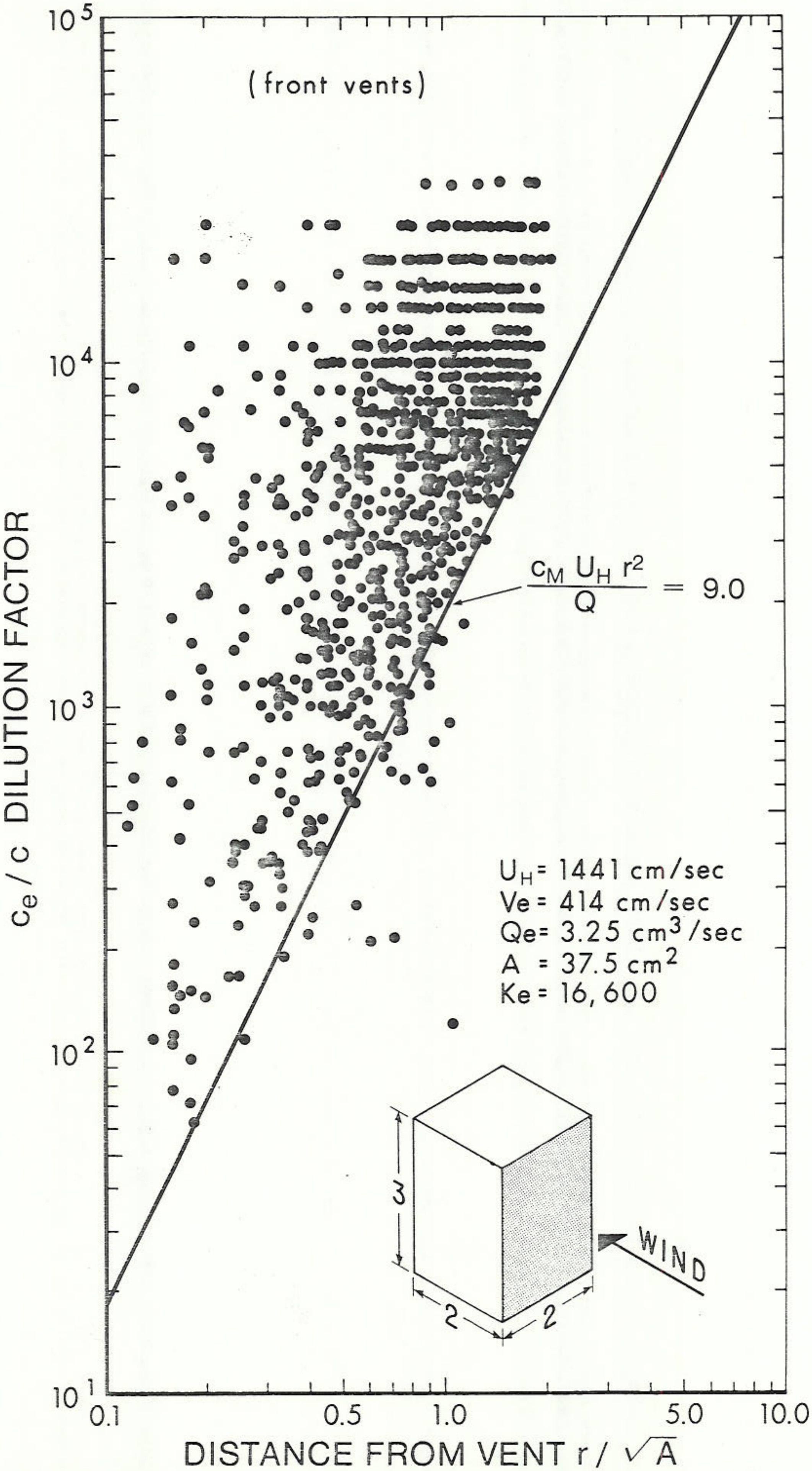
c_e / c DILUTION FACTOR
DISTANCE FROM VENT $r / \sqrt{A}$
$\frac{c_M U_H r^2}{Q} = 9.0$
$U_H = 1052$ cm/sec
$V_e = 414$ cm/sec
$Q_e = 3.25$ cm^3/sec
$A = 16$ cm^2
$K_e = 5180$
○ ROOF RECEPTOR
△ SIDE RECEPTOR
□ REAR RECEPTOR
0.1
0.5
1.0
4.0
10^1
10^2
10^3
10^4
4
4
1



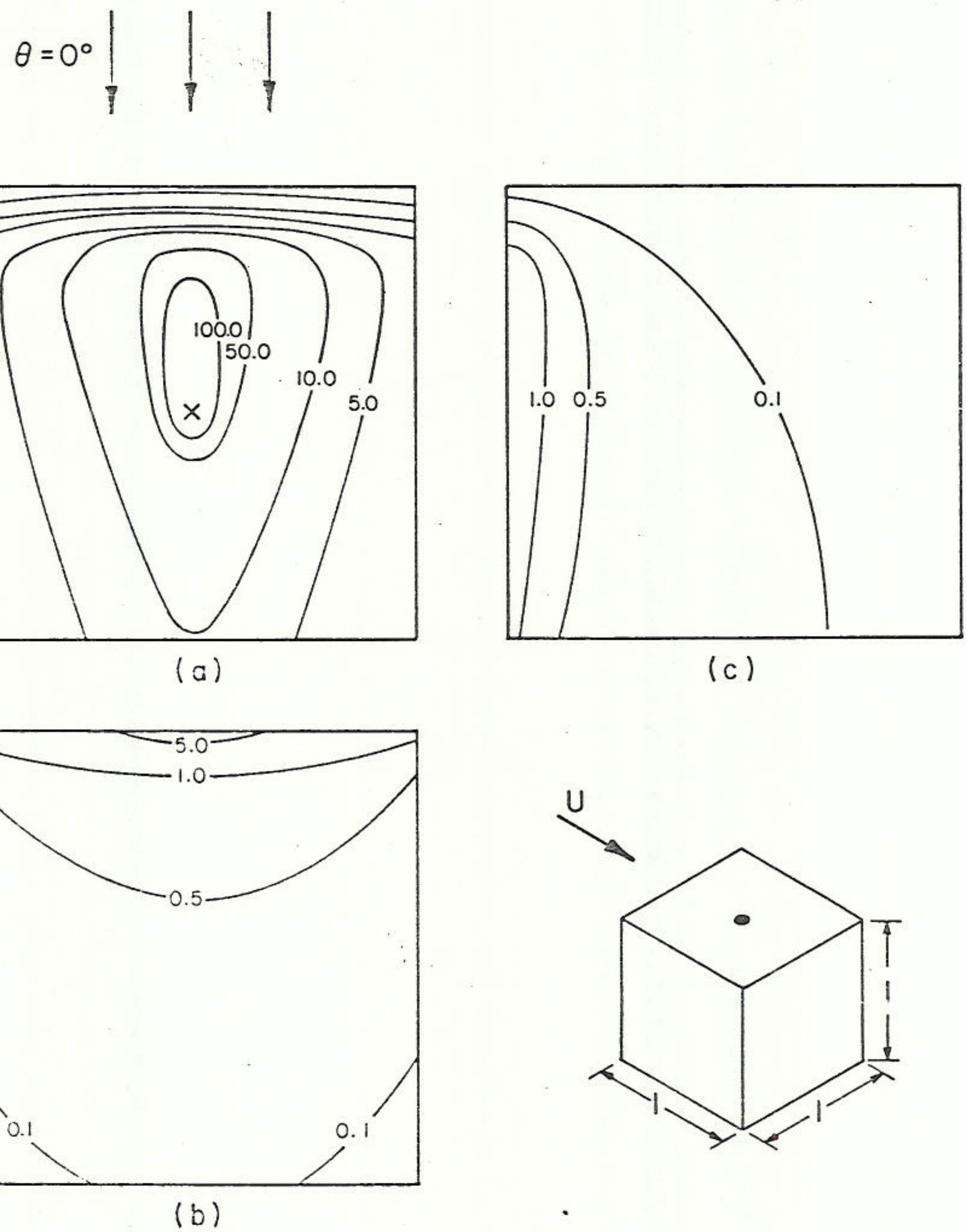
10^5
10^4
10^3
10^2
10^1
(side vents)
$\frac{c_M U_H r^2}{Q} = 9.0$
U_H = 1441 cm/sec
Ve = 414 cm/sec
Qe = 3.25 cm^3/sec
A = 37.5 cm^2
Ke = 16, 600
3
2
2
WIND
c_e / c DILUTION FACTOR
0.1
0.5
1.0
5.0
10.0
DISTANCE FROM VENT $r/\sqrt{A}$

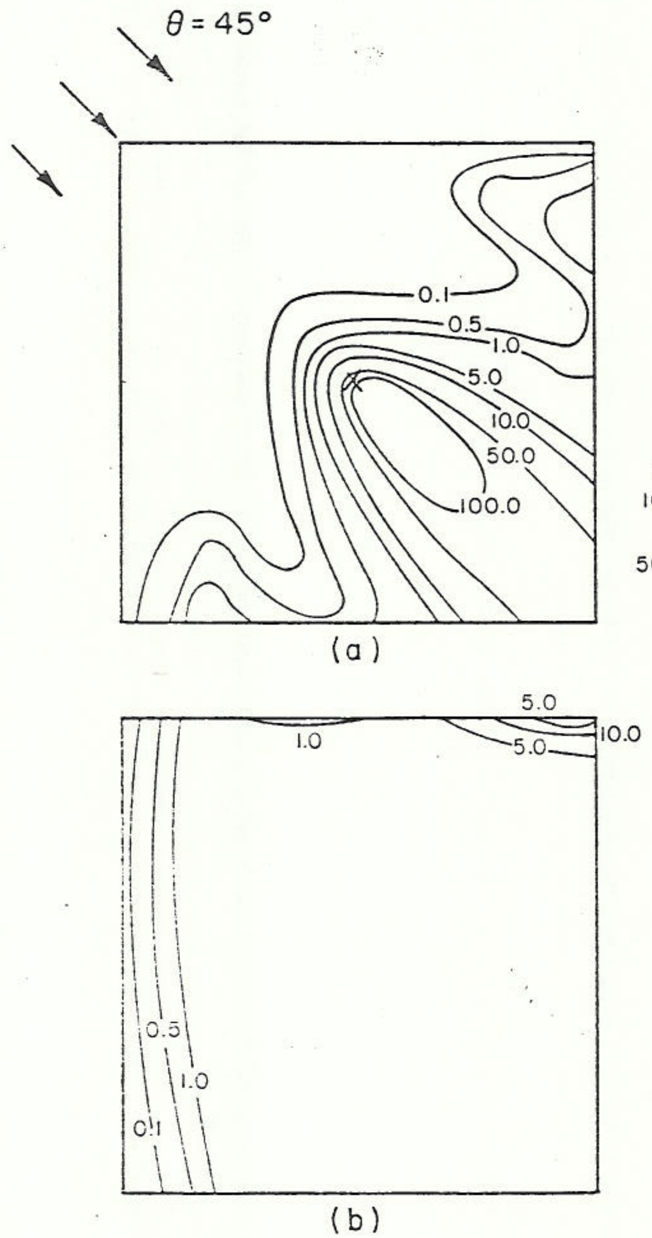


(rear vents)
10^5
10^4
10^3
10^2
10^1
c_e / c DILUTION FACTOR
$\frac{c_M U_H A}{Q} = 3.0$
$\frac{c_M U_H r^2}{Q} = 9.0$
U_H = 1441 cm/sec
Ve = 414 cm/sec
Qe = 3.25 cm^3/sec
A = 37.5 cm^2
Ke = 16,600
WIND
3
2
2
0.1
0.5
1.0
5.0
10.0
DISTANCE FROM VENT $r / \sqrt{A}$

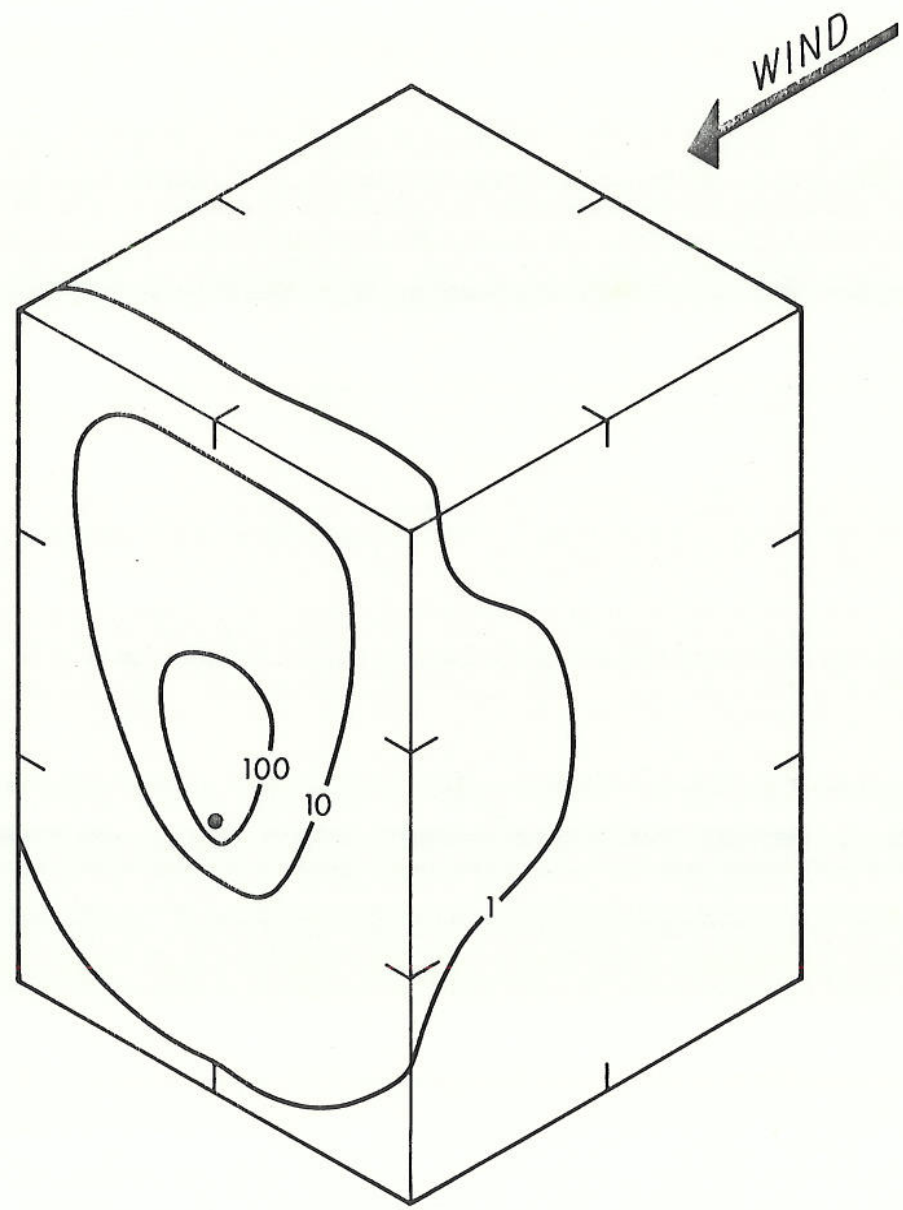


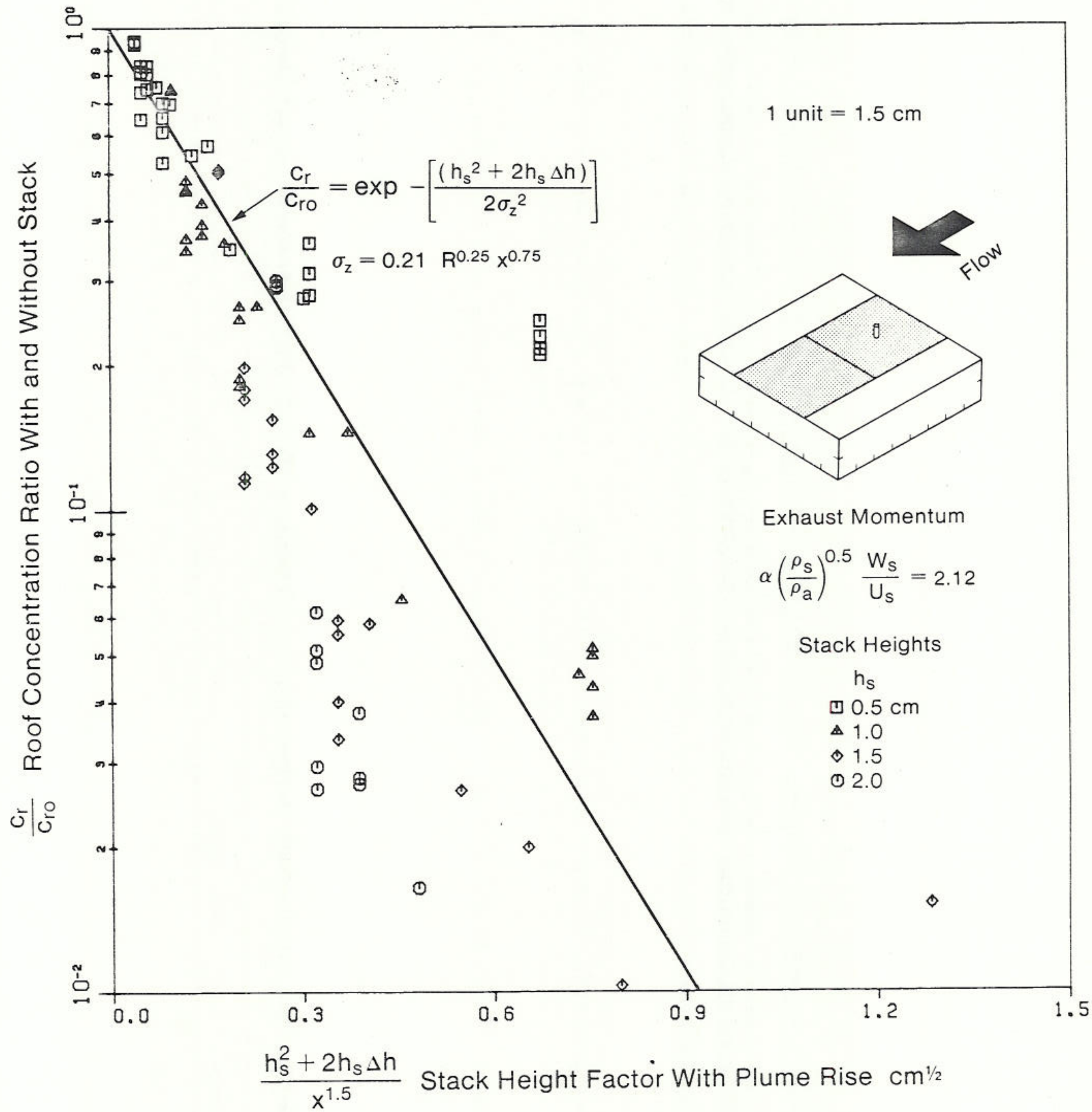
(front vents)
c_e / c DILUTION FACTOR
$\frac{c_M U_H r^2}{Q} = 9.0$
U_H = 1441 cm/sec
Ve = 414 cm/sec
Qe = 3.25 cm^3/sec
A = 37.5 cm^2
Ke = 16,600
3
2
2
WIND
10^5
10^4
10^3
10^2
10^1
0.1
0.5
1.0
5.0
10.0
DISTANCE FROM VENT $r / \sqrt{A}$

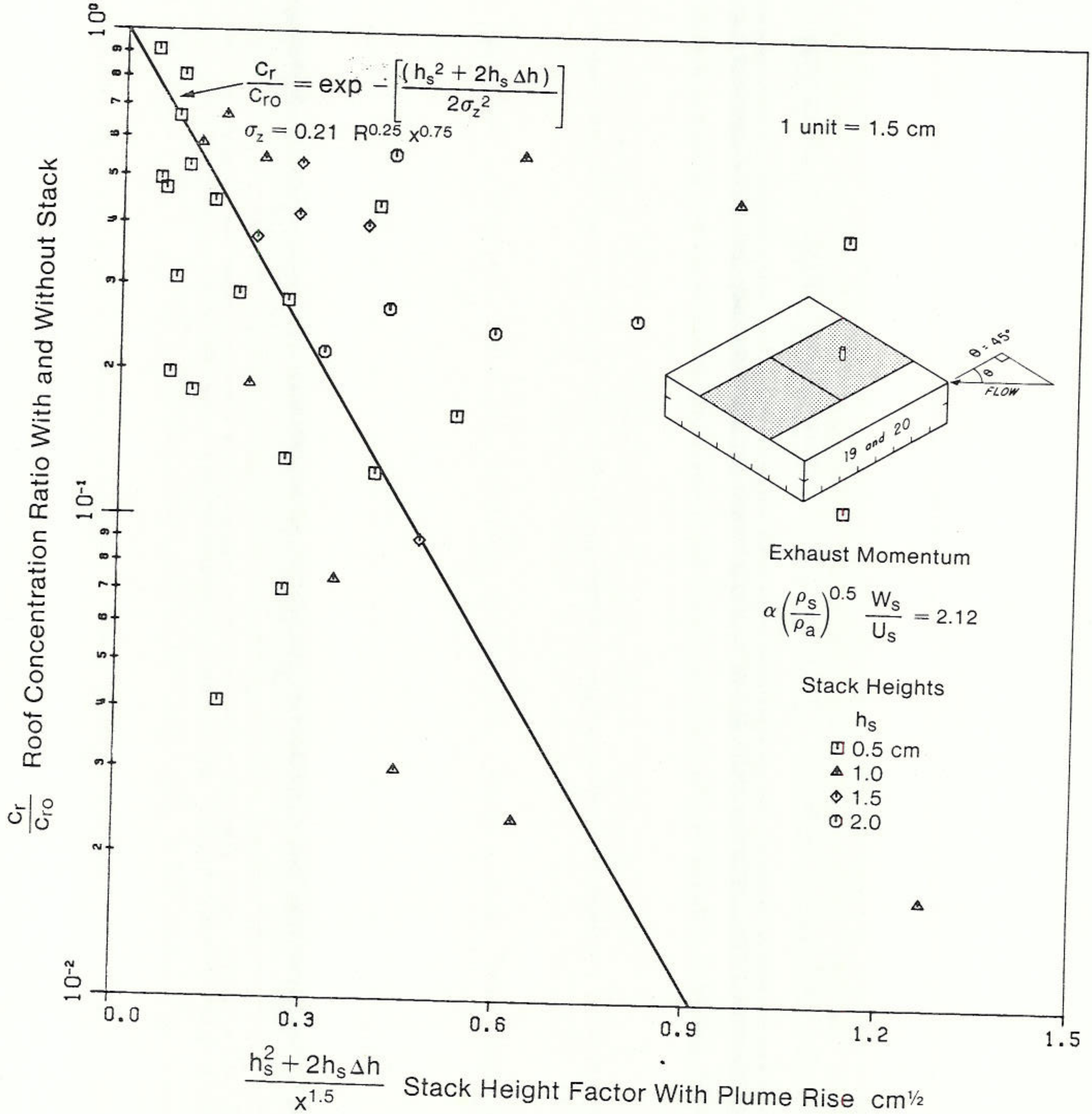

θ = 0°
100.0
50.0
10.0
5.0
(a)
1.0
0.5
0.1
(c)
5.0
1.0
0.5
0.1
0.1
(b)
U
1
1
1



θ = 45°
0.1
0.5
1.0
5.0
10.0
50.0
100.0
(a)
0.1
0.5
1.0
1.0
5.0
10.0
50.0
(c)
5.0
1.0
10.0
5.0
0.5
1.0
0.1
(b)
U
1
1


WIND
100
10
1


1 unit = 1.5 cm
$\frac{C_r}{C_{ro}} = \exp -\left[\frac{(h_s^2 + 2h_s\Delta h)}{2\sigma_z^2}\right]$
$\sigma_z = 0.21 \; R^{0.25} \, x^{0.75}$
Flow
Exhaust Momentum
$\alpha\left(\frac{\rho_s}{\rho_a}\right)^{0.5} \frac{W_s}{U_s} = 2.12$
Stack Heights
h_s
0.5 cm
1.0
1.5
2.0
$\frac{C_r}{C_{ro}}$ Roof Concentration Ratio With and Without Stack
$\frac{h_s^2 + 2h_s\Delta h}{x^{1.5}}$ Stack Height Factor With Plume Rise cm½
0.0
0.3
0.6
0.9
1.2
1.5
10^0
10^{-1}
10^{-2}



$\frac{C_r}{C_{ro}} = \exp -\left[\frac{(h_s^2 + 2h_s \Delta h)}{2\sigma_z^2}\right]$
$\sigma_z = 0.21 \ R^{0.25} \ x^{0.75}$
1 unit = 1.5 cm
θ = 45°
θ
FLOW
19 and 20
Exhaust Momentum
$\alpha \left(\frac{\rho_s}{\rho_a}\right)^{0.5} \frac{W_s}{U_s} = 2.12$
Stack Heights
h_s
0.5 cm
1.0
1.5
2.0
$\frac{C_r}{C_{ro}}$ Roof Concentration Ratio With and Without Stack
10^0
10^{-1}
10^{-2}
0.0
0.3
0.6
0.9
1.2
1.5
$\frac{h_s^2 + 2h_s \Delta h}{x^{1.5}}$ Stack Height Factor With Plume Rise $cm^{1/2}$