TABLE IV. INDOOR CONCENTRATIONS AND INDOOR/OUTDOOR RATIOS FOR IONIC SPECIES ASSOCIATED WITH FINE PARTICLES AT LUBBOCK DURING FEBRUARY 4-11 1982 (STANDARD) AND MARCH 4-11 1982 (ENERGY SAVING)

Status of Air Handling System	Ion	Concentration of Indoor Fine, ng/m^3	I/O, Fine
Standard[a]	$SO_4^=$	443	.08
Energy Saving[b]	$SO_4^=$	1600	.73
Standard	Cl^-	4	.4
Energy Saving	Cl^-	67	4.5
Standard	NO_3^-	37	-
Energy Saving	NO_3^-	292	2.5
Standard	Na^+	9	.13
Energy Saving	Na^+	60	1.9
Standard	NH_4^+	150	.05
Energy Saving	NH_4^+	430	.58
Standard	K^+	12	.75
Energy Saving	K^+	210	1.9
Standard	Ca^{++}	9	.12
Energy Saving	Ca^{++}	36	.08
Standard	Fine Particles	970	.09
Energy Saving	Fine Particles	6760	1.1

a) Fans on

b) Fans off

VENTILATION INTAKE AIR CONTAMINATION BY NEARBY EXHAUSTS

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Buildings with mechanical ventilation systems often place air intakes and exhausts close to each other to make the most efficient use of space. This is particularly true for direct air-to-air exchangers for exhaust heat recovery. The greatest hazards occur for exhausts on laboratories, hospitals and industrial buildings where concentrated emissions of solvents, toxic gases and pathogens are carried by the wind or their own momentum from exhaust to intakes. Tracer gas studies in wind tunnel simulations are reviewed, and correlated to show the contributions of exhaust jet plume rise, building induced turbulence, and large scale atmospheric turbulence on dilution between an exhaust and an intake. Measurements show that the two major factors that influence dilution are distance between exhaust and intake, and the ratio of exhaust jet velocity to windspeed. The location of the exhaust intake pair on the building is also important, with good design placing the intake on the lower third of the building and the exhaust on the upper two thirds. Flow visualization tests show the reason for this. A simple theory for exhaust to intake dilution is presented. The theory, which accounts for dilution close to the exhaust, is in good agreement with wind tunnel data, and with full scale tracer gas tests on large buildings. The implications for good design of closely spaced exhausts and intakes are discussed. It is shown that the fraction of recirculated exhaust in intake air can change by a factor of five with only minor changes in design, such as the removal of a rain cap.

Introduction

Indoor air quality depends on three factors: the emission rate of indoor air pollutants, the rate at which outdoor air is brought into the building, and the quality of this "fresh" air intake. In focusing our attention on indoor air quality we must keep in mind that "fresh" ventilation intake air can sometimes contain higher levels of contamination than the "dirty" indoor air it is replacing.

Buildings which are prime candidates for high levels of indoor air pollution are those with a low natural air infiltration rate. These include buildings with tightly sealed envelopes and with windows which are not (and often cannot) open. Most large buildings constructed in the last 20 years, and single family housing built in the last 10 years, fall in this category.

In large buildings ventilation intake air is brought by fans through the envelope at a few points and distributed within the interior. Some tight houses also make use of mechanical intakes and exhausts to maintain a sufficient ventilation rate. These mechanical systems tend to place their intake and exhaust locations in close proximity to minimize the lengths of ducts feeding the intake and exhaust fans. This is particularly true when air-to-air heat exchangers are used for energy recovery from exhaust.

In naturally ventilated buildings, where most air enters from a large number of widely separated leakage sites, there is little chance for exhaust to contaminate a significant fraction of this intake air. In contrast, the mechanically ventilated building shown in Figure 1 has a high probability of contaminating its air intake with some exhaust air, or worse still, with highly toxic gas from process vents. These vents present a particular hazard on hospitals, laboratories, and industrial buildings where the exhaust air may contain solvents, toxic gases or pathogenic organisms. In this study, wind tunnel and atmospheric data on diffusion near buildings will be reviewed to estimate the amount of dilution likely to occur between an exhaust location and an air intake. Design procedures to estimate this dilution will be outlined, and principles for locating intakes and exhausts to minimize cross contamination will be suggested.

Flow Patterns Over Buildings

"Where can I locate my air intake to prevent it from being contaminated by exhaust gases?" The answer to this question is that exhaust gases will almost always find a way to contaminate air intakes for some critical wind directions. Flow patterns over two high rise buildings measured by Wilson[1] using dye visualization in a water channel simulation are shown in Figure 2. The naturally increasing wind speed with height produces a pressure distribution on the building surface that causes complex upwash and downwash patterns on the upwind face. With the wind normal to this face the flow separates at the upwind edges and produces turbulent recirculation regions which carry emissions in the upwind direction. In oblique winds, strong roof edge vortices form. These can trap pollution and reduce exhaust to intake dilution.

Real buildings are always more complex in shape than those shown in Figure 2, and even the addition of a small rooftop penthouse[1] can drastically alter the flow patterns. The influence of nearby buildings also has a strong effect, and these factors make it almost impossible to accurately predict the trajectory of an exhaust plume as it passes over the building surface. In fact, we cannot even make the general statement that pollution is carried downwind.

Because all wind directions can occur over a period of weeks, it might seem impossible to suggest guidelines for locating intakes and exhausts on buildings. However, when Wilson[1] systematically examined flow patterns around both high and low rise buildings, it was found that there was little mixing between surface flows from the upper 2/3 of a building with those from the lower 1/3. This tendency is apparent in the flow patterns shown in Figure 2. From this we conclude that the first principle of good intake-exhaust design is to locate intakes on the lower 1/3 of buildings and exhausts on the upper 2/3, or vice-versa.

Some care must be exercised in applying this generalization for intake and exhaust locations. Traffic pollutants may contaminate intakes on the lower 1/3 of buildings in heavily built-up urban areas, and where loading docks and driveways are located. In deciding on the best location for intakes the designer often must make a compromise between avoiding pollution from ground level and rooftop sources.

Models for Predicting Exhaust-to-Intake Dilution

There are many windspeeds and directions for which a particular exhaust will cause no measurable contamination at an intake. However, there will always be one particular combination of windspeed and direction which results in the minimum dilution for a particular exhaust-intake pair.

An idealized model of this dilution process for a flush exhaust vent on a building surface is shown in Figure 3. Minimum dilution occurs when the highest concentration, on the exhaust plume centerline, passes over an intake. The three factors which contribute to this minimum dilution are: the initial entrainment and rise as the plume emerges from the exhaust and is bent over, turbulent diffusion with downwind distance, and stack height effects which move the plume trajectory away from the intake. With the exception of exhaust stacks designed to disperse highly toxic emissions, most exhausts are too close to the building surface to benefit much from the effect of stack height. Measurements of stack height effects are reported by Wilson and Winkel[6], and incorporated in design procedures in Wilson[1,7]. Here, we will only consider the two effects of initial and distance dilution.

i. Initial Dilution:

After an exhaust plume emerges from the vent outlet its jet momentum will carry it away from the building surface until it is bent over by the wind. The usual method of accounting for the effect of this plume rise is to predict the trajectory using semi-empirical equations. This rise height is then used to shift upward the effective source location in a dispersion model. While this approach is adequate far downwind from a stack, neither the plume rise equations nor atmospheric dispersion models give accurate estimates close to the source. The short exhaust-to-intake distances on a building can lead to errors of a factor of 10 to 100 in estimating intake contamination using plume rise and dispersion models developed for high isolated stacks.

Wilson and Chui[2] found that the effect of plume rise on roof level contamination could be modelled by an equivalent initial dilution caused by an apparent entrainment rate Q_o which occurs close to the point of exhaust. exhaust. The entrainment rate Q_o is a function of the ratio of exhaust velocity V_e to wind speed U, and produces an apparent initial dilution D_o at the exhaust outlet. This dilution is only "apparent" because, in reality, the dilution factor at the exhaust outlet must be exactly equal to unity. The concept of an "initial" dilution is useful only after the plume has bent over and travelled downwind a distance of 5 to 10 $A^{0.5}$. Wilson and Chui[2] found that the apparent initial dilution could be represented using $M = V_e/U$ as

$$D_o = 1 + 7.0\, M^2 \sin^2\theta \qquad (1)$$

for a non-buoyant momentum jet from a flush exhaust, directed away from the building surface. Equation (1) contains the implicit assumption that it is only the normal component $V_e \sin\theta$ of the exhaust velocity V_e that contributes to plume rise and initial increased entrainment. The velocity ratio $M = V_e/U$ characterizes the exhaust jet intensity for the non buoyant case where the exhaust and ambient densities are equal. For uncapped perpendicular jets the angle $\theta = 90°$ between the velocity V_e and the building surface. For vents with rain caps or louvers, $\theta = 0°$.

ii. Distance Dilution:

As the exhaust plume is carried downwind it is diluted by ambient air. Halitsky[3] carried out wind tunnel simulations of diffusion over building complexes to correlate minimum dilution with exhaust to intake distance. Wilson [4,5] extended this work to a wider range of building shapes, and used upwind roughness to simulate atmospheric turbulence in the approach wind.

Dilution can be modelled theoretically as turbulent diffusion from a point source[4]. Making the assumption that the plume spread increases linearly with distance from the source leads to a distance dilution equation

$$D_d = B_1 \frac{US^2}{Q_e} \qquad (2)$$

in which the minimum dilution increases as the square of S, the "stretched string" exhaust to intake distance. Halitsky[3] defined this distance as the shortest distance between exhaust and intake, measured along the building surface. Wilson[7] extended the concept to deal with exhaust stacks and rooftop obstacles.

More recently Wilson[7] and Wilson and Chui[2] have used an entrainment model, shown in Figure 4, to predict how apparent dilution D_o from plume rise and distance dilution D_d combine to produce the total minimum dilution D_{min},

$$D_{min} = (D_o^{0.5} + D_d^{0.5})^2 \qquad (3)$$

This entrainment model also shows that the constant B_1 in equation 2 is related to an entrainment constant α,

$$B_1 = \frac{\pi\alpha^2}{2} \qquad (4)$$

where α is the ratio of entrainment velocity v_a to wind speed U. Wind tunnel data[2,4,5] for a wide range of exhaust-intake configurations on flat-roofed buildings is correlated by $\alpha = 0.20$ in equation (2) and (4) to yield $B_1 = 0.0625$ so that

$$D_d = 0.0625 \frac{US^2}{Q_e} \qquad (5)$$

A typical correlation of measured exhaust-to-intake dilution is shown in Figure 4. The solid line on Figure 4 shows equations (1) and (5) combined in equation (3) to predict the lower minimum dilution boundary on a dilution-distance plot. The dashed line represents full scale atmospheric data measured by Sagendorf et. al.[8] using tracer gas techniques near two large nuclear reactor complexes. The difference between full scale and wind tunnel measurements is less than a factor of two, and is likely due to the inability of the wind tunnel to simulate the large scale atmospheric turbulence that causes more plume meandering in full scale. The most important points to note about distance dilution are:

1) There is no significant effect of building size or shape on minimum dilution, so the only length that enters equation (3) or (5) is the exhaust to intake spacing, S.
2) Distance dilution decreases in direct proportion to the exhaust volume flow Q_e, which shows the difficulty of obtaining adequate dilution of high volume exhausts.

In an extensive study of exhaust and intake locations on an isolated building, Wilson[4,7] found that with one notable exception there was little effect of where the exhaust-intake pair were located. These wind tunnel experiments, reviewed by Wilson and Britter[9], indicate that "hiding" an intake from an exhaust by locating it around a corner on an adjacent face will have no noticable effect on the minimum dilution compared to an intake on the same face with the same separation distance from the exhaust. Recent data reported by Li and Meroney[10] contradicts this finding and shows that a factor of 2 to 4 times larger dilution will occur at an intake around a corner. At present, we do not know which of these is the correct conclusion, however, it can certainly do no harm to locate intakes and exhausts on different building faces.

One exception to the insensitivity of minimum dilution to the location of intakes and exhausts occurs when the exhaust is located on the lower 1/3 of the upwind wall. Measurements reported by Wilson and Britter[9] show that about a factor of 3 less dilution may occur for this situation as the exhaust is trapped by the upwind separation vortex at ground level and carried around the sides relatively undiluted. This result reinforces our conclusion from flow visualization that intakes and exhausts should not both be placed on the lower 1/3 of building walls.

Exhaust gas buoyancy has not been adequately dealt with in wind tunnel simulations. The main influence of plume buoyancy occurs at low wind speeds on capped or louvered exhausts that have little jet momentum to carry them away from the building surface. In selecting the location of air intakes and exhausts, intakes should always be located below exhausts, so that during light winds or calm periods buoyancy will carry the exhaust away from the intake.

Changing wind direction, which alters the building surface flow patterns (see Figure 2) can change the minimum available dilution. Wind tunnel simulations by Li and Meroney[10] showed that when there is negligible exhaust momentum with $M \sin \theta < 0.1$, exhaust from roof vents on a building in a 45° oblique wind have a distance dilution D_d 3 to 9 times less than for wind normal to the upwind face. However, Wilson and Chui[2] found that this difference decreased with increasing exhaust jet momentum, and that for $M \sin \theta \gtrsim 1.0$, wind direction effects are negligible. This observation strengthens the argument for designing high velocity exhausts with $M \sin \theta > 1.0$, to benefit not only from a factor of 10 increase in apparent initial dilution, but also to avoid a factor of 3 to 9 decrease in distance in dilution.

Exposure Time and Exhaust Plume Meandering

The exposure time over which concentrations are averaged at an air intake is another important factor in determining the available dilution. The question is how to interpret exhaust to intake dilutions from wind ing times of about 3 to 30 minutes, and apply them to situations where exposure times of several hours are being considered.

Because wind tunnel walls constrain the flow, dispersion simulations are incapable of modelling large scale atmospheric turbulence, which produces slow random changes in wind direction that occur over sampling periods of half an hour or longer. For real buildings this produces a slow meandering of the plume, resulting in lower concentration at a fixed intake location, and therefore higher minimum dilution for long sample times. The effect of this meandering may be modelled as an increased crosswind spread which, according to Pasquill[11], should increase as the cube root of the averaging time. The averaging time dependence of the dilution constant B_1 in equations (2) and (5) becomes

$$B_1 = 0.0625 \left(\frac{T_a}{T_w}\right)^{0.33} \tag{6}$$

for averaging time T_a in the range from 1 minute to several hours. The full scale atmospheric dilution data of Sagendorf et. al.,[8] which had $T_a = 60$ minutes was analyzed by Wilson[7] and found to have $B_1 = 0.11$, shown as a dashed line on Figure 4. Comparing this to the wind tunnel data which had $B_1 = 0.0625$, suggests that the two sets of data are in agreement if the wind tunnel has a full scale equivalent averaging time $T_w = 10$ minutes in equation (6), which seems reasonable.

Combining the equations for B_1, D_o and D_d and writing US^2/Q as $S^2/(M\ A_e)$ leads to a final form for the minimum dilution

$$D_{min} = \left[\left(1 + 7.0\ M^2 \sin^2\theta\right)^{0.5} + \left(\frac{0.0625}{M} \left(\frac{T_a}{T_w}\right)^{0.33} \frac{S^2}{A_e}\right)^{0.5} \right]^2 \tag{7}$$

with a reference averaging time of $T_w = 10$ minutes.

Because the velocity ratio M appears in both terms in equation (7), a critical wind speed will exist at which an absolute minimum occurs, for a fixed exhaust to intake spacing. For distances of $S/A_e^{0.5}$ of 5 to 50 the critical exhaust velocity ratio, M, lies in the range from 0.5 to 2.0, with a typical critical value of about 1.0.

Implications for Indoor Air Quality

What levels of minimum dilution should we expect in practical situations? Because efficient duct design often places the intake and exhaust in close proximity, many practical situations will involve intake to exhaust spacings that range from 10 to 50 times the exhaust size $A_e^{0.5}$.

A wind tunnel test was carried out to study this type of practical dilution situation. The roof of a wide low-rise building was simulated using a two dimensional step that spanned the width of the small tracer gas wind tunnel described by Wilson[4]. Roof concentrations were measured downwind from a flush vertically directed exhaust vent at two different exhaust velocity to wind speed ratios of $M = 0.98$ and 2.06. The results are shown in Figure 5 and compared with the theoretical predictions from equation (7).

Both the experiments and the theory show a relative small change in dilution as distance from exhaust to intake increases from 5 to 50 $A_e^{0.5}$. It is clear from this that the exhaust velocity ratio M, is the most important factor in determining minimum dilution close to the vent. The importance of using uncapped exhausts with a high exit velocity is illustrated in Figure 6 which shows the effect of adding a rain cap or louvers, which destroy vertical momentum. Figures 5 and 6 show that for an exhaust located at $S/A_e^{0.5} = 10$, an uncapped vent with an exhaust velocity twice the local wind speed will produce about 5 times more dilution than a louvered or raincapped vent with no vertical exhaust momentum. The entry of water and snow into uncapped vents can be prevented by having the exhaust operate continuously. For vents which must be operated intermittently, the use of elbows with rain traps and drains is a proven design alternative to raincaps.

The fan power required to exhaust a given flow rate Q_e increases as the square of the exit velocity V_e, so high exhaust velocities are incompatible with energy conservation, which dictates low fan power loads. Do low values of exhaust velocity V_e necessarily mean a lower minimum dilution? The answer is no, because critical dilution occurs at a fixed value of M for a given exhaust intake distance, and a lower exhaust velocity simply means a lower value of critical wind speed at which absolute minimum dilution will be observed. However, because lower windspeeds occur more frequently, this critical condition, which produces the <u>same</u> value of dilution factor for all exhaust velocities, will occur more often when exhaust velocities are low.

Finally, it should be kept in mind that practical situations often involve high volume exhaust rates of relatively low contaminant concentrations rather than the typical industrial release of a highly toxic gas at a very low exhaust volume rate. Because distance dilution D_d due to separation distance is inversely proportional to exhaust volume flow rate (see equation 2), these high volume exhausts must rely on plume rise and initial dilution to prevent contamination of air intakes.

Summary: Basic Design Principles to Avoid Exhaust Gas Re-entry

A review of previous studies on exhaust gas dilution around buildings has led to equation (7) which predicts minimum exhaust to intake dilution factors. This equation is capable of accounting for the intake dilution due to exhaust jet momentum, turbulent entrainment of ambient air with downwind distance, and the effect of the averaging time over which the intake is exposed. As illustrated in Figures 4 and 5, wind tunnel simulation of dilution close to an exhaust demonstrate that equation (7) is accurate, within a factor of 2, over a wide range of exhaust to intake spacing distances.

To minimize intake air contamination, exhausts should be designed to:

1) maintain a minimum distance of at least 10 $A_e^{0.5}$ from intakes in order to take advantage of distance dilution, D_d
2) have uncapped exhausts that produce a strong exhaust jet perpendicular to the building surface. Louvers and rain caps should be avoided and the exhaust velocity should be kept at least as high as the local average airport windspeed. These measures will maintain an adequate initial dilution D_o
3) be located on the upper two thirds of the building, and always above the level of intakes to take advantage of exhaust buoyancy, and to avoid being trapped in flow recirculation regions near the ground.

With these factors in mind it should be possible to avoid having more than 1% of exhaust gas contamination of intake air, when averaged over an exposure time of several hours.

Acknowledgements

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Nomenclature

A = projected area of upwind building face, m^2
A_e = face area of exhaust outlet, m^2
B_1 = dilution constant
C_e = contaminant concentration in exhaust gases, µg/m^3
C_r = contaminant concentration at building surface, µg/m^2
D = dilution factor, C_e/C_r
D_d = minimum distance dilution factor, C_e/C_r
D_o = initial effective dilution factor due to plume rise effects
D_{min} = total minimum exhaust to intake dilution factor, equation (3)
M = ratio of V_e/U, exhaust velocity to windspeed
Q_e = V_eA_e, total exhaust volume flow rate, m^3/s
Q_o = initial ambient air entrainment rate, m^3/s
R = plume radius after travel distance x, m
R_o = initial plume spread, m
S = "stretched string" exhaust to intake distace measured along building surface, m
T_a = exposure time over which contaminant concentration at an inlet is averaged, minutes
T_w = full scale equivalent averaging time obtained in wind tunnel simulations, minutes
U = wind speed at exhaust height in the undisturbed flow approaching the building, m/s

turbulent diffusion, m/s

V_e = exhaust gas face velocity at outlet, m/s

α = v_a/U, entrainment constant

θ = angle between building surface and exhaust velocity V

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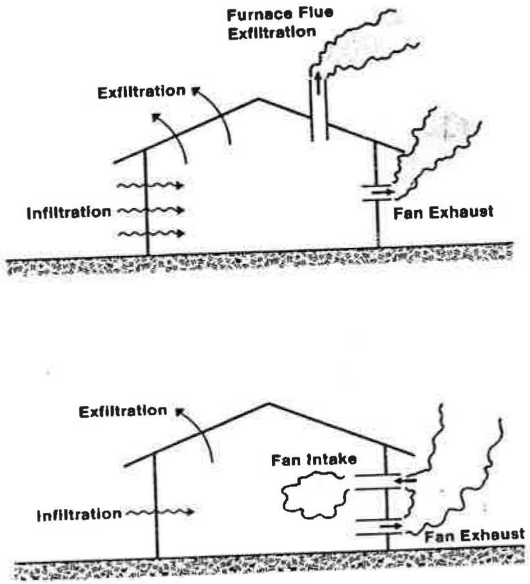

Figure 1. Buildings with ventilation intake fans are more susceptible to exhaust re-entry than buildings with only natural infiltration.

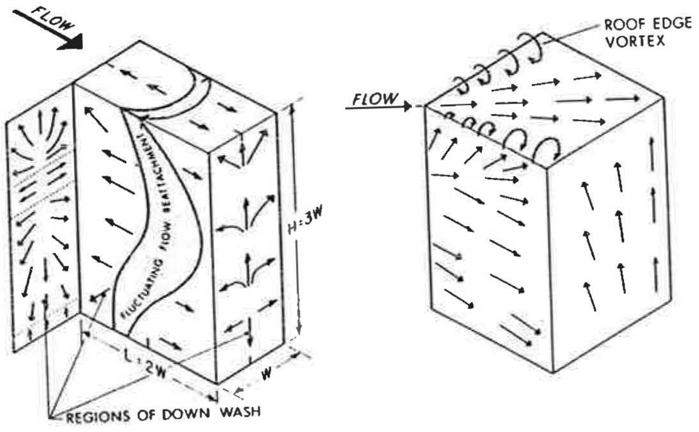

Figure 2. Flow patterns over flat roofed buildings: from Wilson[1]

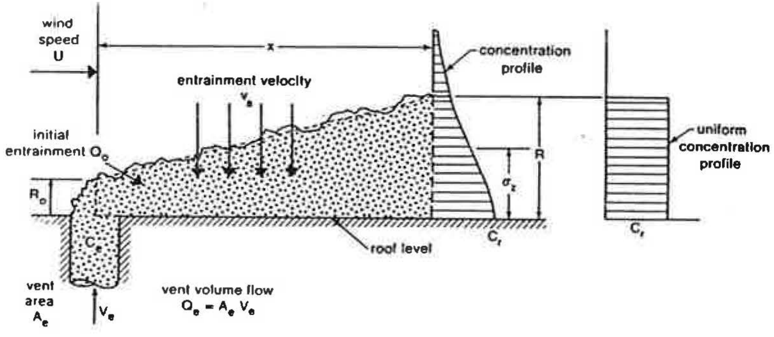

Figure 3. Idealized model of dilution from a flush exhaust vent

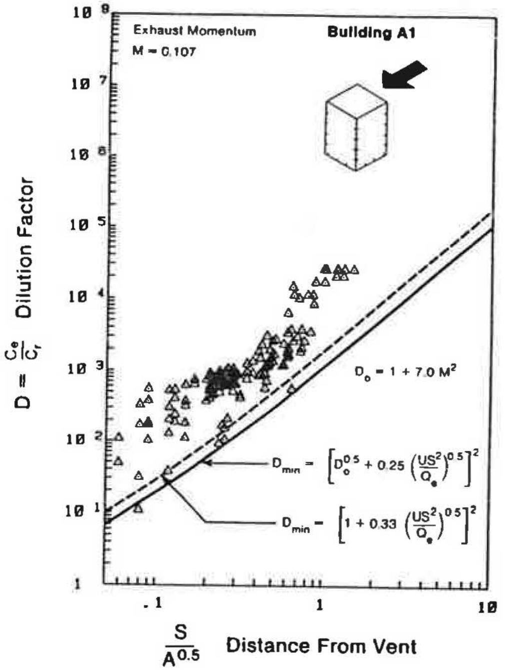

Figure 4. Wind tunnel tracer gas measurements of minimum dilution, for low exhaust velocity, M = 0.107, from uncapped flush vents: solid line, theory of Wilson and Chui[2], dashed line, full scale data Sagendorf et. al.[8] for M = 0 tracer release near large buildings.

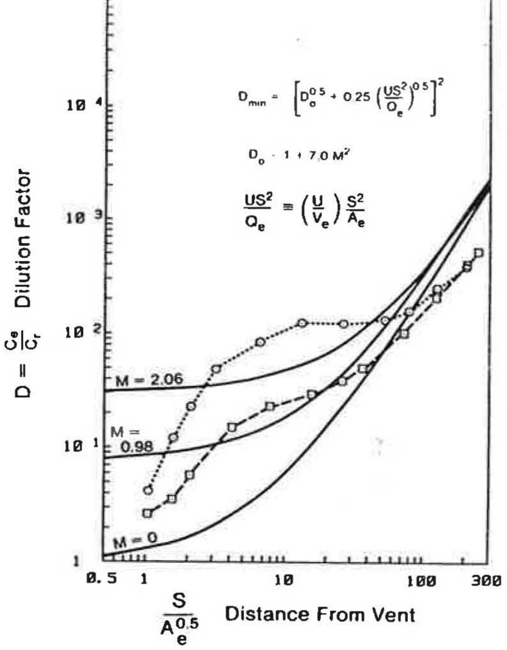

Figure 5. Dilution close to a flush, vertically directed roof vent on a wind tunnel model of a wide building for two exhaust velocity ratios M = 0.98 and 2.06, compared to theory of Wilson and Chui[2], equation (7): solid line for equivalent full scale exposure time T_a = 10 minutes.

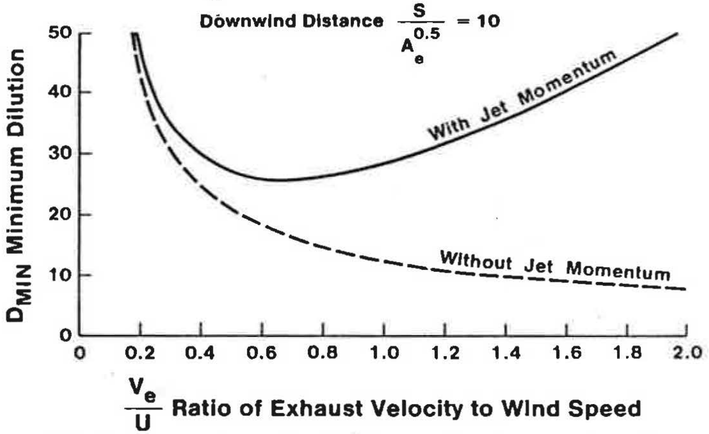

Figure 6. Effect of removing exhaust jet momentum by capped or louvered outlets, for exposure time T_a = 10 minutes: equation (7), θ = 90° solid line, and θ = 0° dashed line