Analytical Versus Wind Tunnel Determined Concentrations Due to Laboratory Exhaust

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ABSTRACT

This paper presents a determination of the expected concentrations for an actual building using the analytical and wind-tunnel modeling procedures presented in Chapter 14 of ASHRAE Fundamentals. A comparison of the estimated concentrations using the two methods is presented as well as a description of the calculation methodologies. The results of the comparison showed that for a low exit velocity stack with a small exit diameter and zero stack height, the wind tunnel and analytical estimates compare within a factor of two to six, with the ASHRAE estimates tending to be conservative. For a high exit velocity stack with a large diameter and zero stack height, the wind tunnel intake dilutions were generally an order of magnitude greater than those obtained using the analytical equations. The paper provides further evidence that the equations in Chapter 14 do provide conservative estimates of the expected dilution for laboratory stacks, even for the non-idealized building shape considered. However, the estimates may be overly conservative and may result in added design expense (unnecessarily tall stacks or emission control devices). If a designer wishes to optimize the stack design with respect to cost, aesthetics, and safety, the added accuracy provided by the wind tunnel may be necessary.

INTRODUCTION

The effluent from exhaust stacks may impact nearby fresh air intakes or other locations to which the public may have access. Depending upon the chemicals being released, odors or harmful concentration levels may result at the air intakes or other sensitive locations. Even with a well-designed stack, harmful or annoying concentration levels can result if the mass release rate is high enough. The building designer is faced with the problem of determining an acceptable stack or scrubber design such that harmful or annoying concentration levels will not occur at sensitive locations after the building is constructed.

The first step in the design is to determine the types of chemicals that will be released from the stacks and their quantities. Once the chemicals are known, a list of odor and safety thresholds can be obtained from such agencies as the Occupational Safety and Health Administration (OSHA), the Environmental Protection Agency (EPA), and the American Conference of Governmental Industrial Hygienists (ACGIH). If the concentrations of all chemicals in the gas stream at the stack exit are less than the odor or health thresholds, then any stack height will be acceptable and little further consideration should be given to the stack design. However, if the concentration levels at the stack exit exceed an odor or health threshold, the stack design will require more careful consideration. For this situation, estimates of the concentration levels at air intakes and other sensitive locations are required. If the estimates are below the thresholds, the stack design is acceptable. If not, a taller stack, higher exhaust velocity, or reduced mass release rate (scrubbers) can be considered.

Chapter 14 of ASHRAE Fundamentals contains methods for estimating the concentration levels due to stack discharges. The two main methods discussed are analytical equations and wind tunnel modeling. The analytical equations for minimum dilution (Halitsky 1961, 1963, 1985; Wilson and Chui 1985, 1987) were developed to provide an upper estimate on the expected concentrations, while the wind tunnel (Petersen 1987) will provide more accurate estimates that are site-specific in nature. This paper presents a determination of the expected concentrations for an actual building using the analytical and wind tunnel procedures presented in the ASHRAE Handbook. A comparison of the estimated concentrations using the two methods is presented as well as a description of the calculation methodologies.

ANALYTICAL METHOD FOR DETERMINING CONCENTRATIONS

The primary objective of the present study is to compare measured exhaust gas dilution from a detailed wind tunnel model of a specific site with predictions made using the equations in Chapter 14, "Air Flow around Buildings," of the 1989 ASHRAE Fundamentals. It is important to keep in mind that the equations forming the basis of the analytical method also rely on wind tunnel data to fix the empirical constants in the turbulent diffusion theory on which they are based.

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The semiempirical diffusion equations recommended in Chapter 14 come from two sources. Halitsky (1985) used a combination of wind tunnel data taken in a uniform non-turbulent approach flow and site-specific wind tunnel simulations to determine the constants α and M in the following equations:

$$D_{min} = [\ \alpha + 0.11\ (1 + 0.2\alpha)\ S/A_e^{0.5}\ ]^2 \qquad \text{(H-17)}$$

$$D_{min} = M\,(3.16 + 0.1\ S/A_e^{0.5}\ )^2. \qquad \text{(H-18)}$$

Numbered equations that contain an H prefix refer to equations with the same number in Chapter 14 of the 1989 ASHRAE Fundamentals. The second set of equations was developed by Wilson and Chui (1985) using the concept of an initial dilution D_o caused by exhaust jet turbulence, combined with the distance dilution D_s caused by turbulent air entrainment in the diffusing plume. For zero-stack height,

$$D_{min,o} = [\ D_o^{0.5} + D_s^{0.5}\ ]^2 \qquad \text{(H-19)}$$

with

$$D_o = 1 + 7.0\ \beta\ (V_e/V_H)^2 \qquad \text{(H-20)}$$

and

$$D_s = B_1\ (V_H/V_e)\ (S^2/A_e) \qquad \text{(H-21)}$$

where β = 1.0 for uncapped stacks, and β = 0 for capped stacks.

The jet entrainment dilution constant of 7.0 in Equation H-20, and the distance dilution constant B_1 in Equation H-21 were determined using tracer gas dilution measurements on isolated rectangular block building models in a turbulent approach wind created by small-scale surface roughness uniformly distributed upwind of the wind tunnel model buildings. To distinguish between this generalized wind tunnel data and the site-specific tests in the present study, the data used to fix constants in the dilution equations will be referred to as "generic."

In these generic studies, the block buildings all have flat, single-level roofs with no penthouses or equipment housings located on the roof. In addition, most of the generic correlation data are for roof-level intakes, so the constants in Equations H-20 and H-21 are biased toward configurations with both intake and exhaust located on the roof.

The dilution of exhaust gas between an exhaust and an intake is caused by entrainment of clean ambient air into the diffusing plume. The three sources of turbulence that produce this mixing are:

- Self-induced turbulence caused by the momentum and buoyancy of the exhaust jet.
- Building-generated turbulence caused by roof edge flow separations, obstacles on the building roof, and the turbulent wake downwind of the building.
- Atmospheric turbulence from upwind terrain roughness and nearby buildings and structures.

The atmospheric turbulence in the generic data sets may not correspond to the actual site turbulence generated by trees, terrain, or densely grouped buildings.

Is it of crucial importance to properly model local conditions to contain correct atmospheric turbulence levels in the approach wind? Wilson and Chui (1987), using the same wind tunnel and building models that were employed to develop Equations H-19 through H-21, found that the constant B_1 decreased from a value of B_1 = 0.0625 to about B_1 = 0.0204 when the upwind approach flow turbulence was reduced to zero and only building-generated turbulence remained. This factor of three decrease in distance dilution D_s clearly demonstrates the need for accurate simulation of local turbulence conditions.

In the present study we will use measurements from a complex site-specific test to determine how well the generic upwind turbulence simulations allow us to estimate dilution.

The minimum dilution, $D_{min,o}$, in Equation H-19 is measured on the plume centerline for a given windspeed, V_H. At very low wind speeds, this dilution will be large because of high levels of exhaust jet entrainment. Dilution is also large at high wind speeds, as the plume is rapidly stretched by the wind. At some intermediate critical wind speed, the lowest possible dilution will occur at a fixed receptor distance, S. The wind speed at which this occurs, $V_{crit,o}$, and the value of the dilution, $D_{crit,o}$, for zero stack height may be determined by taking the derivative of H-19 with respect to wind speed to determine this absolute minimum. These minimum values may be closely approximated by

$$V_{crit,o}/V_e = 2.9\ B_1^{-0.33}\ (S/A_e^{0.5})^{-0.67} \qquad \text{(H-22)}$$

and

$$D_{crit,o} \cong 1 + 7.0\ B_1^{0.67}\ (S/A_e^{0.5})^{1.33}. \qquad \text{(H-23)}$$

The predictions of Equations H-17 through H-23 from the Handbook will be compared to an independent site-specific study in the following sections.

WIND-TUNNEL METHOD FOR CALCULATING DILUTION

When more accurate concentration estimates are required for an exhaust system design, physical modeling in a boundary-layer wind tunnel is an appropriate method. The wind tunnel is, in effect, an analog computer with near infinitesimal resolution and near-infinite memory (Snyder 1981). The wind tunnel simulation "solves" the equations of motion and mass transport for flow around a building (as well as all adjacent buildings) by constructing a scale model of the buildings, positioning the models in a wind tunnel, simulating the flow and dispersion characteristics, and measuring the variables of interest (concentrations, wind speed, temperature, etc.).

The methods used for predicting building concentrations from a wind-tunnel experiment will be illustrated by considering an actual application of the procedure for a new laboratory at a California university. The basic elements of a wind-tunnel study (similarity analysis, model construction, data acquisition, and data analysis) are discussed below.

Similarity Analysis

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind-tunnel study of diffusion from a laboratory stack. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. A detailed discussion on these requirements is given in an Environmental Protection Agency (EPA) fluid modeling guideline (Snyder 1981), a Gas Research Institute guideline (Meroney 1986), a recent ASHRAE paper (Petersen 1987), and in Cermak (1971, 1974). The criteria that are used for conducting most laboratory exhaust evaluations are summarized below:

- match (equal in model and full scale) momentum ratio, M_e;

  $$M_e = \lambda \, (V_e / V_H)^2; \qquad (1)$$

- match density ratio;

  $$\lambda = \rho_e / \rho_a; \qquad (2)$$

- match exhaust Froude number to obtain correct momentum to buoyancy force ratio;

  $$Fr^2 = (\rho_e \, V_e^2) / [\, (\rho_e - \rho_a) \, g \, d \,]; \qquad (3)$$

- ensure a fully turbulent stack gas flow—stack Reynolds number ($Re_s = d\,V_e/\nu$) greater than 2000, or place an obstruction inside stack to enhance exhaust turbulence;
- ensure a fully turbulent wake flow—building Reynolds number ($Re_b = V_H H/\nu$) greater than 11,000;
- ensure a fully turbulent wind with surface roughness Reynolds number $Re_z = V^* z_o/\nu$ greater than 2.5;
- build an accurate scale model;
- match atmospheric stability by the bulk Richardson number (see Cermak 1975);
- match velocity and turbulence distributions in the wind approaching the model.

Using the above criteria, model test conditions were computed for two exhaust configurations for the test building. The full-scale conditions for the two configurations are given in Table 1.

TABLE 1

Operating Conditions for Exhaust System

Parameter	Configuration 1	2
Exhaust Velocity, V_e (fpm)	1500	2500
Effective Internal Diameter, d (ft)	1.73	4.5
Number of Stacks, n	3	1
Stack Exit Face Area, A_e (ft^2)	36	15.90
Stack Height, h_s (ft)	0	0
Velocity Ratio, V_e/V_H	1.34	2.25 and 1.5
Building Height Wind Speed (mph)	13	13 and 19
Wind Tunnel Averaging Time (min)	10-15	10-15
Raincap	None	None
Building Height, H (ft)	117	117
Building Width, W (ft)	99	99
Building Length, L (ft)	206	206

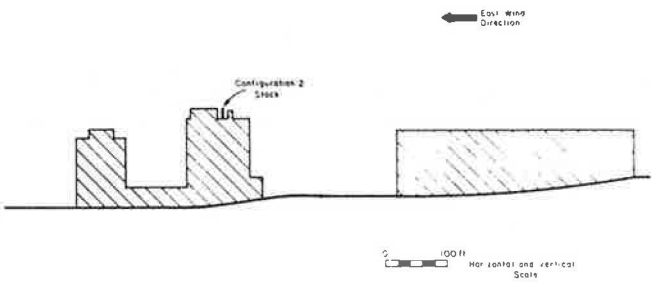

Figure 1a *Cross section of laboratory building and surroundings for east wind direction.*

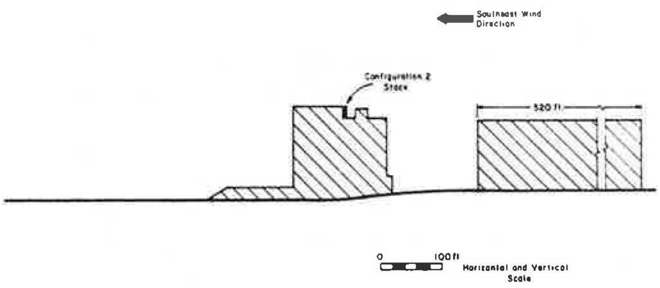

Figure 1b *Cross section of laboratory building and surroundings for southeast wind direction.*

Scale Model

A 1:240 scale model of the laboratory building and surrounding structures and topography within a 1300 ft radius was designed and constructed. The model included all significant buildings, structures, and topography within the 1300 ft radius of the laboratory building. Upwind of the area modeled, two-in-high roughness elements were installed to ensure that an appropriate atmospheric boundary layer was simulated. Figures 1a and 1b show cross sections of the laboratory and surrounding buildings relative to the configuration 2 stack for the east and southeast wind directions (the directions giving the minimum dilution values). The upwind building configuration for the south wind direction (direction giving minimum dilution values for configuration 1 stack) was similar to Figure 1b. Concentration sampling taps were installed at numerous locations on the laboratory roof, at the air intake locations, on adjacent buildings, and at ground level. The sampling points that were considered in this paper are shown in Figures 2a and 2b.

Two different stack configurations were considered. The first consisted of a series of single stacks for each fume hood exhaust with a 1500 fpm exit velocity and 1 ft stack inside diameter. Three of these stacks, spaced within one stack diameter edge to

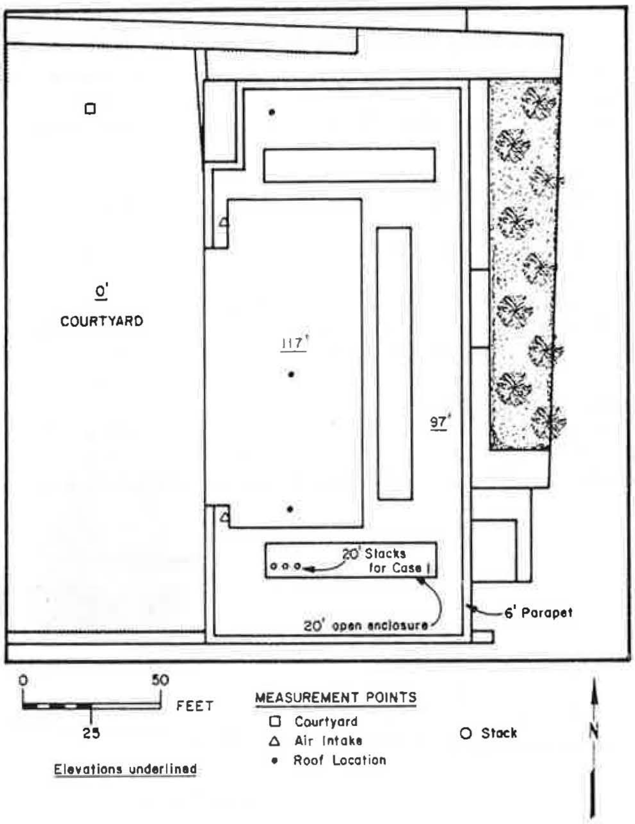

Figure 2a *Plan view of laboratory showing stack location and concentration measurement locations in configuration 1.*

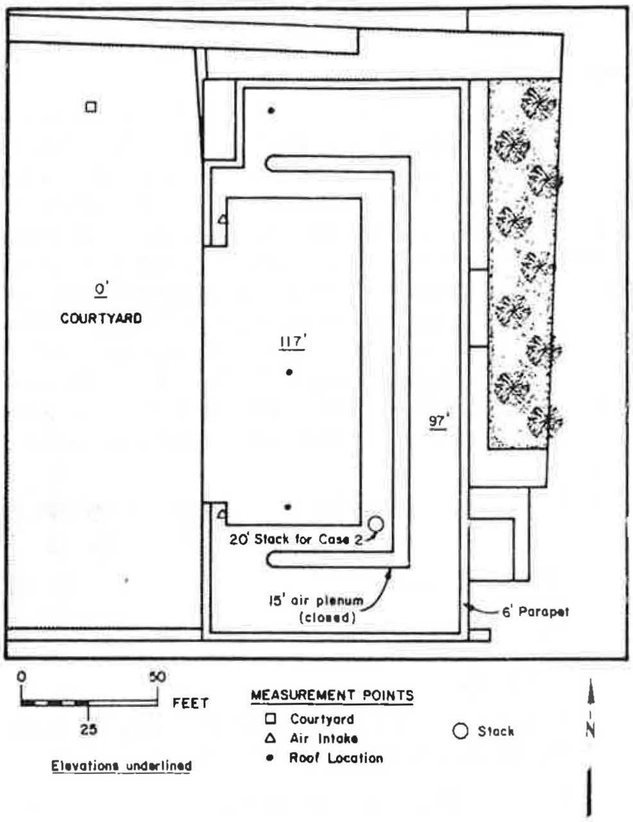

Figure 2b *Plan view of laboratory showing stack location and concentration measurement locations in configuration 2.*

edge, were selected as the configuration 1 example shown in Figure 2a. These stacks were spaced sufficiently close to be considered a single exhaust with an effective diameter (d) of 1.7 ft and a face area (A_e) of 2.36 ft^2. It was thought that this configuration would result in high concentrations at the nearby air intakes, so a second configuration was considered that consisted of merging several of the fume hood exhausts into a single stack with an exit velocity of 2500 fpm and a 4.5 ft inside diameter. The location of the configuration 2 merged-flow stack is shown in Figure 2b. Both of the tested configurations were for a roof-level vertical exhaust with zero effective stack height. In order to document the wind characteristics approaching the model, profiles of mean velocity and longitudinal turbulence intensity were obtained upwind of the model test area. An analysis of the profiles was conducted that demonstrated that the shape was characteristic of that expected in the atmosphere. The wind power law exponent was determined to be 0.21 and the surface roughness length, Z_o = 0.66 ft. These values are characteristic of a site with many trees, hedges, and a few buildings (Engineering Science Data Unit 1972). This description approximately fits the surroundings for the laboratory site.

The simulated wind speeds were 12 and 18 mph at the Los Angeles International Airport and the wind directions simulated were east, east-southeast, southeast, south-southeast, and south. The airport speeds were converted to wind speeds at the building height by scaling the airport speed to a freestream height of 960 ft at the airport using a power law wind profile with a value for the wind power law exponent of a = 0.16:

$$V_{free} = V_{met}\,(960/30)^a \qquad (4)$$

The top of the boundary layer over the site was assumed to be at 1200 ft and the wind power law exponent was taken to be 0.21, typical of a suburban site (Snyder 1981). The wind speed at the building height was then estimated using

$$V_H = V_{free}\,(H/1200)^{0.21} \qquad (5)$$

The resulting building height wind speeds were 12.7 and 18.9 mph. The ratio of exhaust velocity to building height wind speed for the cases simulated is given in Table 1.

How well does this site-specific value compare with estimates using Chapter 14 of the 1989 Fundamentals? Using Figure 4 of Chapter 14 with a rural airport meteorological station and a suburban building site, the values of A_o = 0.60 and a = 0.28 are recommended for use in the following equations:

$$V_{ref} = A_o\, V_{met} \qquad \text{(H-9)}$$

and

$$V_H = V_{ref}\,(H/H_{ref})^a. \qquad \text{(H-10)}$$

Using the building wall height H = 117 ft gives a Handbook prediction of V_H = 0.878 V_{met}. Using this same height, the site-specific test on the UCLA model yields V_H = 1.07 Vmet in Equation 5. The difference in these values is due almost entirely to the exponent of a = 0.28 recommended by the Handbook, rather than the site-specific value of a 0.21.

Averaging Time

The fundamental difference between plume dispersion in a wind tunnel and in the atmosphere is that as the averaging (sampling) time at a receptor increases, the time-averaged atmospheric concentration decreases continuously, while the wind tunnel data settle down to a constant value. The reason for this is that the large scales of atmospheric turbulence that cause plume meandering and shifts in wind direction are absent in the wind tunnel. The sidewalls of a wind tunnel constrain the flow to a single wind direction and prevent the slow plume meandering that causes the constant decrease of atmospheric concentrations that are observed with increasing averaging time. By comparing wind tunnel and full-scale dispersion data, Wilson (1983, 1985) estimated that the wind tunnel data represented full-scale averaging times of about 10 minutes and suggested the correction equation

$$D_{min,1}/D_{min,2} = (t_{a1}/t_{a2})^{0.33} \qquad \text{(H-16)}$$

to adjust the predicted values from generic wind tunnel correlations to other averaging times.

The important point to realize is that the present study compares semi-empirical equations developed from generic wind tunnel data to a single site-specific wind tunnel model. Because both the analytical equations and the test configurations are based on wind tunnel data, it is not possible to validate the averaging time correction of Equation H-16. This can only be done by gathering more full-scale building dilution measurements for comparison.

Data Acquisition

The model was placed in an open-circuit boundary-layer wind tunnel and several wind directions and wind speeds were simulated. For each simulation, concentrations due to the stack exhaust were measured at the locations shown in Figures 2a and 2b and several other locations not reported in this paper. The concentration measurements were obtained using a flame ionization gas chromatograph and a syringe sampling system, as described in Petersen (1988). Volume flow and wind speed measurements were also obtained for documentation and to set wind tunnel operating conditions.

Concentrations measured in the wind tunnel were converted to dilution values, D_{wt}, for comparison with the estimates obtained using the analytical expressions discussed previously. Tables 2 and 3 provide tabulations of the smallest dilution values measured at each sampling point and the associated meteorological conditions for each exhaust configuration.

APPLICATION AND COMPARISON OF METHODS FOR ACTUAL EXHAUST DESIGN

Tables 2 and 3 show the minimum dilution values, Dwt, measured in the wind tunnel at each measurement point indicated in Figures 2a and 2b compared with predictions made using Equations H-17 through H-23. Values of α = 2 and M = 1.5 (M = 4 for courtyard locations) were used in Equations H-17 and H-18, reflecting conservative practice recommended in ASHRAE Chapter 14. A value of B_1 = 0.0625 was used in Equation H-21. Dilution estimates were made for the critical wind speed using Equations H-22 and H-23. For configuration 1, the critical wind speeds were generally less than those simulated in the wind tunnel, except at the closest measurement point. For configuration 2, the critical wind speed was nearly the same or higher. The most conservative (lowest) dilution estimates were obtained using Equations H-17 and H-18.

Before estimates could be made, the exhaust-to-receptor stretched- string distance at each measurement point had to be specified. This distance was determined using the laboratory model and actually stretching a string between the appropriate stack and the measurement points. It should also be noted that for stack configuration 1 calculations, the three stacks were sufficiently close to be treated as a single exhaust with an effective face area of 2.36 ft^2. An alternate method for evaluating configuration 1 would have been to calculate dilution values for one stack and adjust the wind tunnel results by multiplying the measured dilution values by three. Use of this method would have given even worse agreement between prediction and observation, further justifying the assumption that the three stacks could be treated as a single stack.

Figures 3 and 4 show graphs of the observed and computed dilution values vs. stretched-string distance. Figure 3 shows that the ASHRAE equations always gave conservative estimates (less dilution) and that the estimates obtained using Equation H-19 agree best with the observations. The average ratio of observed to predicted concentration using Equation H-19 is 2.4, while for Equations H- 17, H-18, and H-23, the average ratios are 5.6, 4.4, and 3.0, respectively. The tendency for H-17 and H-18 to underpredict the actual dilution is to be expected, because the most conservative values of α = 2 and M = 1.5 were used. Hence, for stack configuration 1, the ASHRAE equations will provide conservative estimates that are, at best, a factor of two lower than the wind tunnel observations and, at worst, a factor of six lower than wind tunnel observations.

The results for stack configuration 2, shown in Figure 4, show a slightly different pattern. The ASHRAE equations still predict lower dilution but by a more significant factor. Considering all equations, the predicted dilutions are more than a factor of five less than the wind tunnel observations within 150 ft of the release, decreasing to, at best, a factor of two using Equation 19 beyond that distance. Hence, use of the

TABLE 2

Dilution Factors for Configuration 1

h_s = 0; V_e = 1500 fpm; d = 1.73 ft

		Critical Conditions		Modeled Conditions				
Location Type	String Distance (ft)	$V_{H,crit}$ (mph) Eq H-22	D_{crit} Eq H-23	V_H (mph)	D_{min} Eq H-17 α=2	D_{min} Eq H-18 M=1.5	D_{min} Eq H-19	D_{wt} measured
roof	21	21	36	13	17	31	44	79
air intake	35	15	71	13	31	44	74	242
roof	75	9	190	13	91	97	200	369
air intake	140	6	440	13	260	230	550	1570
roof	172	5	580	13	370	310	780	1551
courtyard	216	4	790	13	560	1200*	1200	3366

TABLE 3

Dilution Factors for Configuration 2

h_s = 0 V_e = 2500 fpm; d = 4.5 ft

		Critical Conditions		Modeled Conditions				
Location Type	String Distance (ft)	$V_{H,crit}$ (mph) Eq H-22	D_{crit} Eq H-23	V_H (mph)	D_{min} Eq H-17 α=2	D_{min} Eq H-18 M=1.5	D_{min} Eq H-19	D_{wt} measured
roof	36	47	9	19	11	25	35	366
air intake	70	30	50	19	22	36	59	384
roof	72	30	62	19	23	37	60	493
air intake	139	19	120	13	54	66	140	709
roof	166	17	160	13	71	80	170	385
courtyard	241	13	257	13	130	340*	260	2277

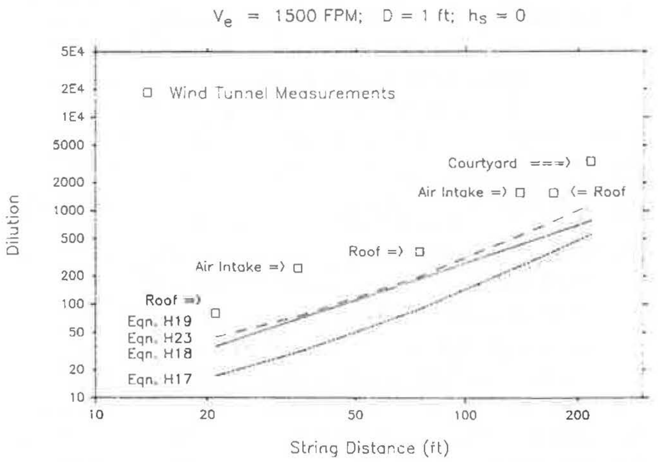

Figure 3 *Dilution versus stretched string distance based on ASHRAE equations and wind tunnel measurements for stack configuration 1.*

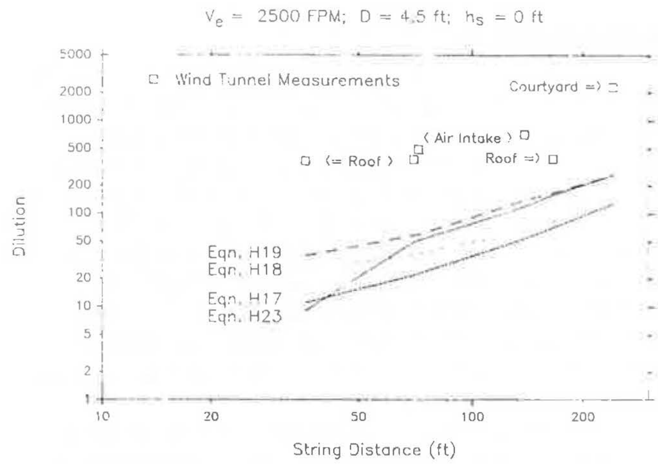

Figure 4 *Dilution versus stretched string distance based on ASHRAE equations and wind tunnel measurements for stack configuration 2.*

ASHRAE equations for this configuration would greatly overstate the expected concentrations and give a conservative design.

The tendency for the site-specific dilutions to be higher than those predicted by the ASHRAE equations suggests that the plume centerline is above the height of the various measurement points. Concentrations are greatest at the plume centerline and rapidly decrease with distance from the centerline. The ASHRAE equations used in this evaluation generally assume that the plume centerline intersects the receptor. Other factors contributing to the difference are that the atmospheric turbulence levels may be higher at the laboratory site than for the isolated buildings used to generate the generic data on which the equations are based. Considering the large number of densely packed high buildings on the site, the higher level of atmospheric turbulence would be expected. Another possibility is that the wakes from nearby buildings caused the wind speed, V_H, at building height to be less than the value predicted by the velocity profile extrapolations used in Equations 4 and 5.

For configuration 2 the most plausible explanation for the larger dilutions observed on the laboratory building is that the exhaust jet from the large-diameter exhaust would be able to penetrate the low-velocity zone and experience a much larger plume rise than the smaller-diameter exhaust in the different location in configuration 1. This higher plume rise in configuration 2 would produce the larger measured dilution values that cannot be accounted for by the analytical equations, which predict dilution on the plume centerline. The lower concentration (i.e., higher dilution) that occurs near the edges of a plume could easily account for a factor of 10 difference.

DISCUSSION AND CONCLUSIONS

This paper has described the wind tunnel and analytical methods for estimating dilution from a laboratory stack. The two methods were applied to an actual laboratory building rather than an idealized rectangular building for which the ASHRAE equations were designed to predict best. The results of this comparison showed that for a low exit velocity stack with a small exit diameter, the wind tunnel and analytical estimates for zero stack height compare within a factor of two to six, with the ASHRAE estimates tending to be conservative. For a high exit velocity stack with a large diameter, the wind tunnel intake dilutions were generally an order of magnitude greater than those obtained using the analytical equations.

When considering odors due to noxious chemicals, the instantaneous peak concentration may be of more importance than the average values estimated using the ASHRAE equations. These peak concentrations can be two to three times higher than the mean, which suggests that the ASHRAE equations may not provide conservative estimates. If designers wish to ensure nuisance odors are avoided, wind tunnel tests using a detector that measures peak concentrations would be required or an adjustment made to the existing ASHRAE equations. The averaging time for the health and safety concentration limits is usually on the order of 15 minutes or longer, an appropriate averaging time for the ASHRAE equations.

This analysis has provided further evidence that the equations in ASHRAE Chapter 14 do provide conservative estimates of the expected dilution (10-minute averaging time) for laboratory stacks, even for the nonidealized building shape considered in this paper. However, the estimates may be overly conservative (especially for merged stacks with high-volume flow rates) and may result in added design expense (unnecessarily tall stacks or emission control devices). If a designer wishes to optimize a stack design with respect to cost, aesthetics, and safety, the added accuracy provided by the wind tunnel may be necessary. When odors are of concern, the ASHRAE equation may not be conservative. For this case, wind tunnel testing or modified ASHRAE equations may be required.

Future studies should focus on the effects of averaging time and exhaust stack height, in order to test the validity of Handbook equations H-16, H-23, H-24, and H-25.

NOMENCLATURE

a	=	exponent in power law wind speed profile
A_e	=	stack exit face area, ft^2
A_o	=	terrain roughness correction factor for 33 ft wind speeds
C_e	=	contaminant mass concentration in exhaust at exhaust temperature T_e, lb/ft^3
C	=	contaminant mass concentration at a receptor at ambient air temperature, T_a, lb/ft^3
d	=	$(4 A_e/\pi)^{0.5}$, effective exhaust stack diameter, ft
D	=	C_e/C dilution factor between source and receptor mass concentrations
D_{min}	=	minimum dilution factor, D, at a given wind speed for all exhaust locations at the same fixed distance, S, from an intake
$D_{min,o}$	=	minimum dilution factor, D_{min}, at roof level for a flush vent with zero stack height, $h_s = 0$
D_{crit}	=	critical dilution factor at roof level for an uncapped vertical exhaust at the critical wind speed, V_{crit}, that produces the smallest value of Dmin for a given exhaust to intake distance, S, and stack height, h_s
D_{wt}	=	measured dilution in the site-specific wind tunnel study
g	=	acceleration of gravity, ft/s^2
H	=	wall height above ground on the upwind building face, ft
H_{ref}	=	height of wind anemometer at meteorological station, ft
h_s	=	effective exhaust stack height above rooftop obstacles and enclosures, ft
L	=	length of building in the wind direction, ft
M	=	dilution constant in Equation H-18
M_e	=	momentum ratio between exhaust and wind
Q_e	=	A_eV_e, total exhaust gas mixture flow rate, cfm

S = stretched-string distance; the shortest distance from exhaust to intake over and along the building surface, ft

V^* = ground surface friction velocity, ft/s

V_{ref} = windspeed at the height of the meteorological station anemometer in an undisturbed wind in the same terrain roughness in which the building is located, ft/s

V_{crit} = critical wind speed that produces the smallest minimum dilution factor, D_{crit}, for an uncapped vertical exhaust at a given S and h_s, ft/s

V_{free} = wind speed in free stream air

V_H = mean wind speed for 10-minute averaging at the height of the upwind wall in the undisturbed flow approaching a building, ft/s

V_{met} = meteorological station wind speed, measured (or corrected to) a height of Z = 33 ft (10 m) above ground in smooth terrain, ft/s

V_e = exhaust face velocity, Q_e/A_e, ft/s

W = width of the upwind building face, ft

Z = height above local ground level, ft

ρ_a = density of outdoor air, lb/ft^3

ρ_e = density of exhaust gas mixture, lb/ft^3

ν = kinematic viscosity of outdoor air, ft^2/s

α = dilution constant in Equation H-17

β = stack capping factor

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