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CALCULATION OF MINIMUM AVAILABLE ATMOSPHERIC DILUTION DOWNWIND OF BUILDING EXHAUSTS

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ABSTRACT

Equations recommended in the ASHRAE Handbook—1989 Fundamentals, *chapter 14 (ASHRAE 1989), for prediction of minimum atmospheric dilution for use in exhaust system design are examined. The equations have no terms representing the larger dilutions in the plume below the centerline; therefore, they yield overly conservative estimates of dilution at receptors at the lower edges of elevated plumes. The equations contain empirical constants that could be adjusted to provide more realistic dilution estimates, but no guidelines are offered in the Handbook for such adjustment. An alternative approach using a jet plume model is described, and model predictions are compared with dilution observations taken in a wind tunnel model test of a laboratory building.*

INTRODUCTION

Atmospheric dilution D, as applied to building ventilation system design, is defined by

$$D = C_0/C \qquad (1)$$

where

C_0 = concentration of waste gas in the exhaust stream, measured at the face of a surface vent or at the top of a stack

C = concentration of waste gas in the atmosphere at the location of a potential receptor, usually a fresh air intake or an inhabited outdoor space

D is dimensionless when C_0 and C are expressed in the same units. The atmosphere provides a range of magnitudes of D, depending on exhaust configuration, receptor location, and the intervening wind properties.

A building exhaust system is designed to achieve a target value of C_0. The size and complexity of the system vary inversely as the assumed value of C_0, i.e., smaller C_0 implies larger gas removal capacity and/or larger exhaust air volume flow. A conservative but economical design employs the largest value of C_0 that will produce a value of C no larger than an assigned allowable concentration for the gas and receptor under consideration. The value of C_0 meeting this condition is obtained from Equation 1 as the product of the allowable C and the smallest expected D during the period of gas release.

ASHRAE (1989) recommends use of chapter 14, Equations 17 through 23, to calculate a conservatively low expected value of D called D_{min}. Petersen and Wilson (1989) applied these equations to a laboratory building in a university complex and compared the predictions of D_{min} with wind tunnel test observations D_{wt}. D_{min} was found to be smaller than D_{wt} by a factor of about 2 or 3 for a cluster of three small-diameter, closely spaced, low-velocity stacks and by a factor of 10 for a large-diameter, high-velocity stack. If the results of the Petersen-Wilson study should be found to be characteristic of most building configurations, use of the ASHRAE (1989) equations would penalize system design, especially in applications that employ large stacks in conjunction with multi-exhaust manifolds.

In this paper, the ASHRAE (1989) equations are examined to determine if they have intrinsic limitations, and an alternative approach suitable for large stacks is explored.

CHAPTER 14, EQUATIONS 17 THROUGH 23

The discussion in this section will be presented in terms of Equation 17. As will be seen, the principal weakness of this equation is the absence of a term that expresses the distribution of D transverse to the plume centerline. Since a similar term is absent in the other equations, the present discussion and conclusions will apply to them as well.

Chapter 14's Equation 17 is

$$D_{min} = \{\alpha + 0.11(1 + 0.2\alpha)s/A_e^{0.5}\}^2 \qquad (2)$$

where

D_{min} = minimum dilution in the plume at distance s

s = stretched-string distance between the center of the exhaust opening and the receptor

A_e = area of the exhaust opening

α = an arbitrary constant.

Halitsky (1982) may be consulted for the background to Equation 2. Figure 1 presents Equation 2 graphically for several values of α. The physical model represented by Equation 2 is of a plume whose centerline impinges on a receptor. Since dilutions increase

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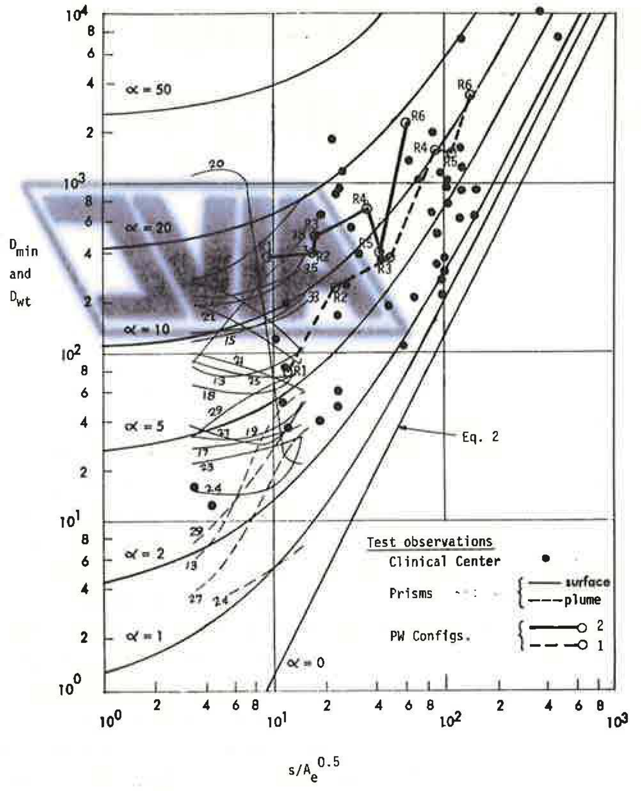

Figure 1 *Graphical presentation of* D_{min} *predicted by Equation 2 and wind tunnel observations of* D_{wt}

radially outward from the centerline, Equation 2 implicitly predicts dilutions at the centerline.

Significance of α

The magnitude of D_{min} depends on building shape, characteristics of the exhaust jet, and wind properties between the exhaust and the receptor, all represented by the single parameter α. Simple equations for calculating α have not been developed. For design purposes, it is sufficiently accurate to employ a value that has been found empirically to represent common configurations.

Chapter 14 recommends use of α = 2. This number evolved from an examination of wind tunnel test observations of dilution at a multi-winged, multi-level building (Halitsky 1962) and several rectangular prisms (Halitsky 1963) presented in the format of Figure 1. Using the hypothesis that the position of the plume in space over a building is different for each tested configuration and impingement of the centerline on a receptor will occur occasionally, it was postulated that observations at the lower bound of dilutions in the data set should represent D_{min}.

In Figure 1, a value of α = 1 provides an absolute lower bound. It represents impingement of the narrowest test plume centerline on a receptor; however, centerline impingement of broader plumes also occurs. A conservative, but not extreme, low value of α should reflect an average D_{wt} for such plumes. It has been approximated (see Appendix) that centerline impingement of plumes in unseparated flow in wind tunnels is characterized by values of α in the range of 1 to 3. Most of the plumes in Figure 1 were of this type.

By inference, most of the data lying above α = 3 should be considered as having been obtained with receptors located off the plume centerline, laterally or vertically. Equation 2 cannot be used to predict D_{wt} for these data because it does not contain a term that relates α to receptor location.

In view of the above, chapter 14's Equation 17 should not be used to estimate D_{min} where there is a strong indication that the plume will pass over a receptor, as is the case with a large-diameter, high-velocity jet from a stack. Chapter 14's Equations 18 through 23 also have no radial term; their use should be limited in the same manner.

APPLICATION OF EQUATION 2 TO THE PETERSEN-WILSON CONFIGURATIONS

Petersen-Wilson Test Specifications

The Petersen-Wilson laboratory building was tested in the two configurations shown in Figures 2, 3, and 4. In Configuration 1, a neutrally buoyant gas-air mixture was released simultaneously through three 1.0-ft-diameter, closely spaced stacks that terminated at the elevation of the top of an enclosure screen. For purposes of analysis, the three stacks were assumed to operate as a single stack having a combined area equal to the sum of the areas of the individual stacks

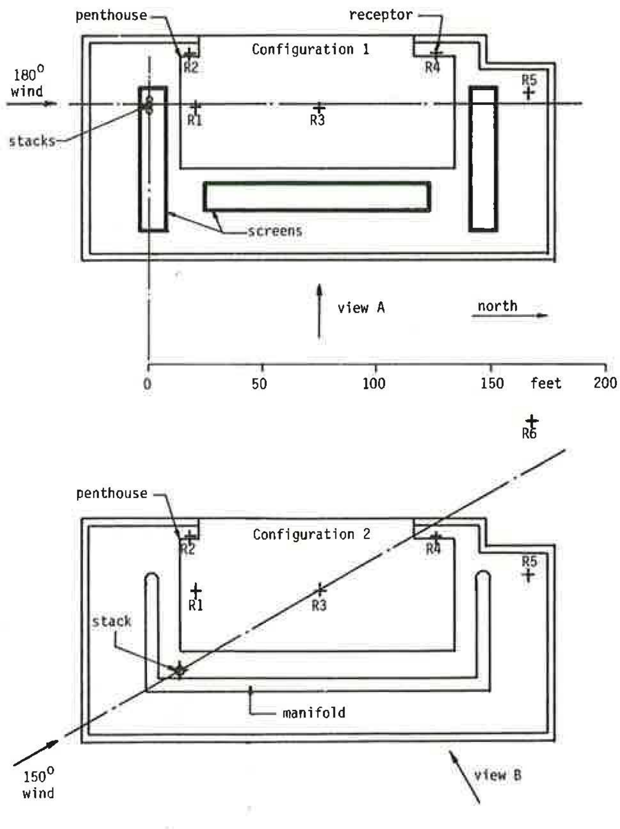

Figure 2 *Plan views of the Petersen-Wilson laboratory building in Configurations 1 and 2*

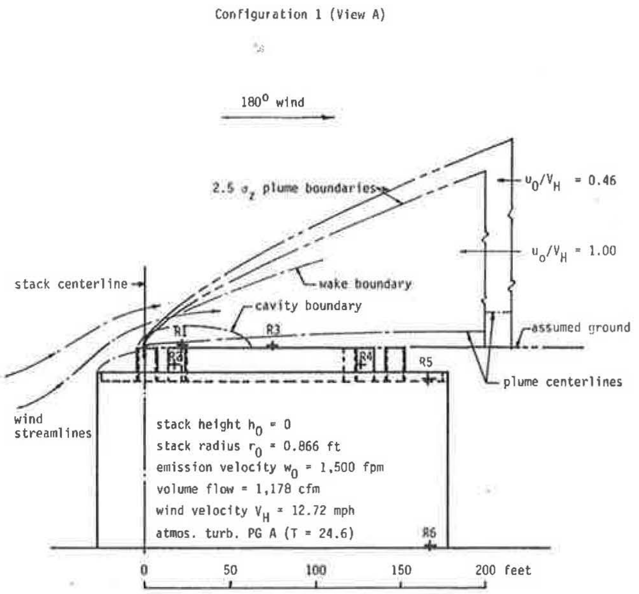

Figure 3 *Elevation view of the Petersen-Wilson laboratory building in Configuration 1, with plumes calculated by the Halitsky (1989) jet plume model in an undisturbed wind stream. Wind streamlines and cavity and wake boundaries are estimated.*

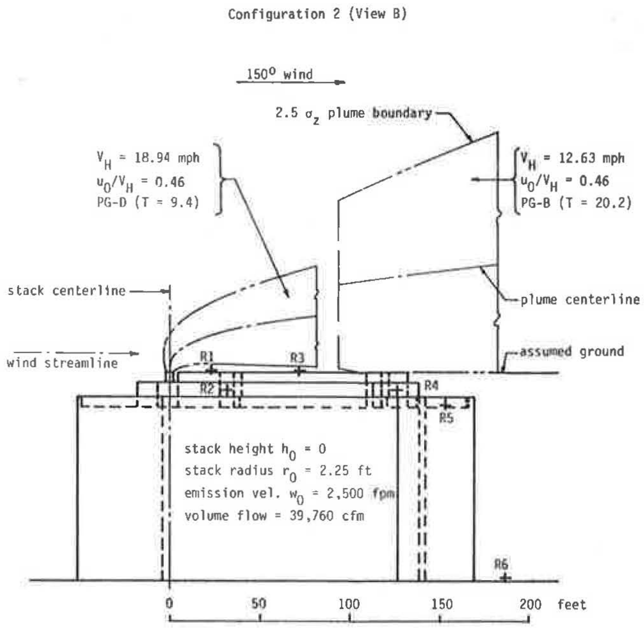

Figure 4 *Same as Figure 3 but for Configuration 2*

for which the effective diameter was 1.73 ft. In Configuration 2, the mixture was released through one 4.5-ft-diameter stack located between a large penthouse and a large exhaust manifold, terminating at the same elevation as the three stacks in Configuration I. Test results were reported for six receptors: R1 and R3 on the penthouse roof, R2 and R4 in the penthouse walls, R5 on the main roof, and R6 on the ground.

The model was tested in an unspecified number of wind directions from east through south. Only the lowest measured dilution was reported as D_{wt} in Petersen-Wilson Tables 2 and 3; the associated wind direction was not indicated. The reported wind speed, V_H, was measured at stack-top elevation in the fully developed boundary layer approach flow to the building complex. Modification of V_H by large buildings between the wind sensor and the laboratory building was not explored in the tests.

Calculation of D_{min}

The Petersen-Wilson observations of D_{wt} are shown in Figure 1 as open circles connected by heavy solid or dashed lines. The values of α needed to predict $D_{min} = D_{wt}$ by Equation 2 are in the range of 7 to 17. Since these greatly exceed the cutoff value of $\alpha = 3$ for centerline impingement, use of the chapter 14 equations to estimate D_{wt} is not justified.

APPLICATION OF A JET PLUME MODEL TO THE PETERSEN-WILSON CONFIGURATIONS

Halitsky (1989) Jet Plume Model

The Gaussian dispersion model for a continuous elevated source above a fully reflecting ground plane (Turner 1970) contains the off-centerline term that Equation 2 lacks, but its application to dispersion near buildings is hampered by three factors: (1) it has no provision for initial plume enlargement by the exhaust jet; (2) no data are presented to describe the growth of dispersion parameters σ_y and σ_z at distances less than 328 ft (100 m); and (3) the applicability of published dispersion parameter growth rates, which were developed for stability-dependent turbulence, to the essentially mechanically generated turbulence over a building roof has not been demonstrated.

The Halitsky (1989) jet plume model employs an initial jet plume region (Halitsky 1966) followed by a Gaussian plume whose sigma growth is described by equations designed to extrapolate the PG curves to short distances. The model provides no guidance as to the PG class that is appropriate for a given configuration, but it is expected that application of the model to tested configurations as the results become available will provide a data base from which a recommendation for an effective PG class for ventilation system design may evolve.

Figure 5 shows the plume described by, and the nomenclature used in, the jet plume model. A full description of the model is given in Halitsky (1989). The following are the equations needed for its implementation in the region downwind of the end of the jet region at Station 2.

$$C_0 = Q_g/\pi r_0^2 w_0 \tag{3}$$

$$D = \frac{2\sigma_y\sigma_z}{r_0^2 m} \exp \frac{+y^2}{2\sigma_y^2} \left[\exp - \frac{(z-h)^2}{2\sigma_z^2} + \exp - \frac{(z+h)^2}{2\sigma_z^2} \right]^{-1} \tag{4}$$

$$m = w_0/u_0 \tag{5}$$

$$h = h_0 + 3\{r_0 m^2/(m+3)\}^{2/3} x^{1/3} \tag{6}$$

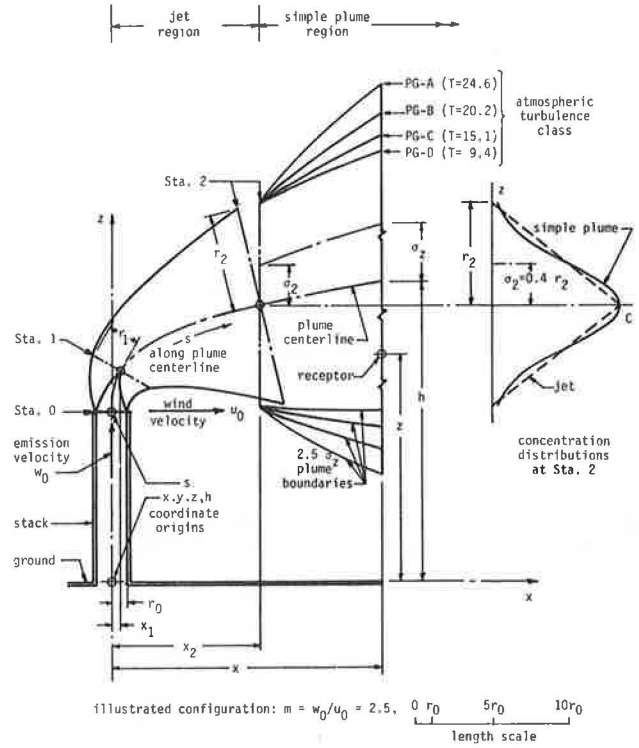

***Figure 5** Characteristics of the Halitsky (1989) jet plume model*

$$\sigma_y = \sigma_2 + 0.66e^{0.08(T-30)}(x - x_2)^{0.92} \tag{7}$$

$$\sigma_z = \sigma_2 + 0.82e^{0.08(T-30)}(x - x_2)^{0.80} \tag{8}$$

$$\sigma_2 = (-0.81 + 1.78m^{0.727})r_0 \tag{9}$$

$$x_2 = (-10.66 + 11.07m^{0.673})r_0 \tag{10}$$

where

C_0 = emission concentration
D = dilution
h = plume centerline height above an assumed ground plane at distance x
h_0 = emission opening height above the assumed ground plane
Q_g = pure gas flow rate in the exhaust jet
r_0 = radius of the emission opening
T = wind turbulence index
u_0 = wind velocity near the emission opening
w_0 = emission velocity (assumed vertically upward)
x,y,z = receptor coordinates (downwind, lateral, vertical) referred to an origin in the assumed ground plane directly below the center of the emission opening

Numerical values of the coefficients in Equations 7 through 10 are for use with lengths in feet. Any consistent units may be used for the other quantities, but the coefficients must be adjusted to conform. The nondimensional turbulence index T in Equations 7 and 8 provides a one-parameter continuous approximation to the *PG* sigma curves at short distances. The values of T for *PG-A* through *PG-D* are given in Figure 5. *PG-E* and *PG-F* are not used in the present application.

The parameters that must be specified for the calculation of D are the elevation of the assumed ground plane, the emission characteristics h_0, r_0, and w_0, the wind properties u_0 and T, and the receptor coordinates x, y, and z. A neutrally buoyant emission is assumed. Equation 6 is the Briggs momentum centerline for an origin at the center of the emission opening, adjusted for stack height.

Calibration of the Model with Petersen-Wilson Observations of D_{wt}

The stack parameters and the ground plane assumed at the penthouse roof are shown in Figures 3 and 4. The wind field was assumed to have straight, horizontal streamlines parallel to a line from the stack to each receptor in turn. All the receptors were assumed to lie in the ground plane and to have the coordinates *x,0,0*. Provision was made in the model for a possible reduction of wind speed by the obstruction created by the upwind buildings by introducing a velocity reduction factor, u_0/V_H, from which the local wind velocity may be calculated by

$$u_0 = (u_0/V_H)V_H \tag{11}$$

As prepared, the model contains two free parameters, T and u_0/V_H. A trial-and-error procedure using combinations of T and u_0/V_H was used to generate model predictions of D that best fit the D_{wt} values in Petersen-Wilson Tables 2 and 3. The predictions will be referred to as D_{mod}.

Figure 6 shows the comparison of D_{mod} and D_{wt} in Configuration 1 for *PG-A* and *PG-B* and u_0/V_H = 1.00 and 0.46. The combination of *PG-A* and u_0/V_H =

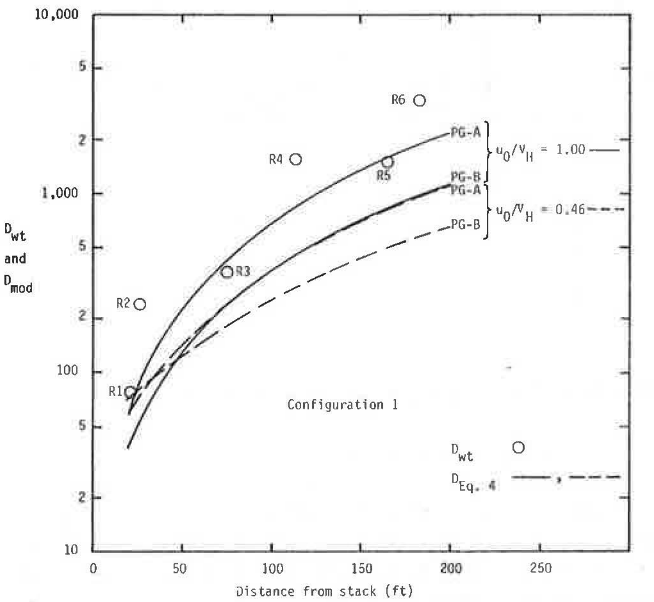

***Figure 6** Comparison of Petersen-Wilson observations, D_{wt}, and Halitsky model predictions, D_{mod}, using assumed values of PG stability class and wind velocity reduction factor, u_0/V_H, for Configuration 1*

1.00 provides an excellent fit to R1, R3, and R5. The underprediction at R2, R4, and R6 is to be expected, since these receptors are located in the building lee cavity in these wind directions.

The centerline and 2.5 σ_z upper boundary of the *PG-A*, $u_0/V_H = 1.00$ plume is shown in true-length scale in Figure 3 (the building and receptors are shown in View A projection). The top of the stack is seen to lie near the very turbulent cavity boundary created by both the upwind parapet of the building and the upwind wall of the screen in southerly winds. The small value of m (= 1.34) provides insufficient vertical momentum to carry the bulk of the plume through the cavity boundary into the free stream; therefore, the plume disperses first in the building roof cavity and then in the wake above and downwind of the cavity to create a broad plume resembling what would have been created in the assumed idealized flow with *PG-A* stability. The *PG-A*, $u_0/V_H = 0.46$ plume is also shown in Figure 3. The lower wind velocity produces a somewhat higher centerline and an approximately twofold increase of concentration; the latter effect dominates at the receptors, resulting in the smaller values of D_{mod} in Figure 6. The model prediction is satisfactory for either value of u_0/V_H, within the limits of predictive error in this type of calculation.

The better fit achieved with $u_0/V_H = 1.00$ rather than 0.46 in Configuration 1 contrasts with the opposite performance in Configuration 2 (see later). In both cases, it is physically reasonable that the wind velocity was reduced initially in the wake of large upwind buildings separated from the laboratory building by about one building length. In Configuration 1, the laboratory building was in normal orientation to the wind, and velocity recovery could have occurred during streamline convergence over the upwind edge of the building and its roof cavity (see Figure 3). In Configuration 2, however, the building was in corner orientation, which does not produce a cavity at the upwind portion of the roof, and velocity recovery may not have occurred.

Figure 7 shows the comparison of D_{mod} and D_{wt} in Configuration 2 for $u_0/V_H = 1.00$ and the four stability classes. The figure is drawn in two parts because R1, R2, and R3 were tested at a higher wind velocity. D_{wt} is seen to be much larger than the largest prediction of D_{mod}. As discussed previously, this could be attributed, in principle, to a plume diameter that is larger than would be produced by *PG-A* turbulence, or by a centerline passing over the receptors. The former is not plausible because higher turbulence than occurs with *PG-A* stability exists only in localized regions of a cavity, and such regions do not exist over the center of the roof of a building in corner orientation. The alternative is to assume a plume centerline at higher elevation, which can be generated in the model by using a lower wind velocity. Figure 8 shows D_{mod} for $u_0/V_H = 0.46$. Good agreement with D_{wt} is obtained with *PG-D* at R1, R2, and R3 and with *PG-B* at R5. The higher effective stability class for R5 may have resulted from the flow disturbances created by the manifold lee cavity and the roof-edge vortices. R4 and R6 are in the building lee cavity; model predictions are not accurate in such locations because cavity mixing is not addressed.

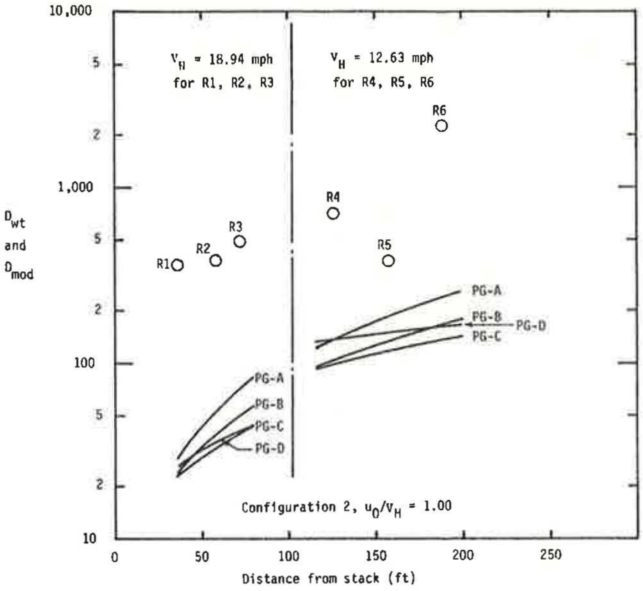

Figure 7 *Same as Figure 6 but for Configuration 2 and $u_0/V_H = 1.00$*

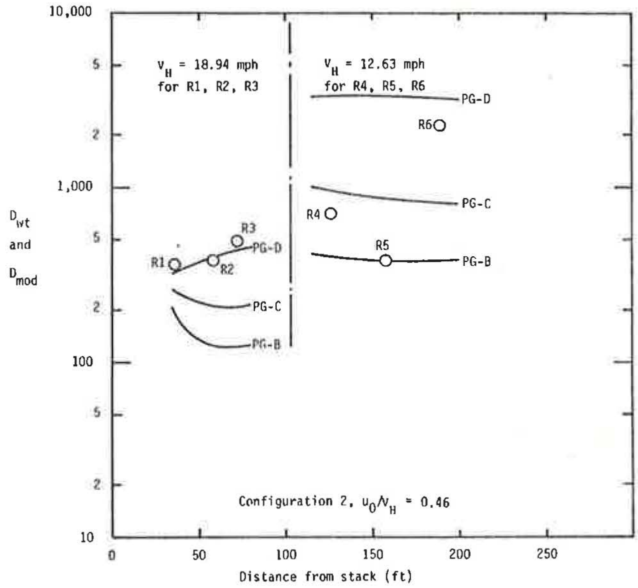

Figure 8 *Same as Figure 6 but for Configuration 2 and $u_0/V_H = 0.46$*

The best-fit plumes are shown in Figure 4. The centerlines are markedly elevated and the roof receptors are located at the bottom edges of the plumes, in contrast with their locations near the centerlines in Figure 3. This low receptor location accounts for the high values of D_{wt} in Configuration 2 and the reversed progression of D_{mod} with PG class in Figures 7 and 8, compared to the progression in Figure 6.

SUMMARY

An examination of chapter 14's Equation 17 clarifies what may be a misperception of the meaning of

D_{min} and the conditions under which it should be used. Equation 17, together with the chapter 14 recommendation of $\alpha = 2$, applies only to plumes whose centerlines impinge on receptors. It should perform well with small-diameter, low-velocity, near-roof-level exhausts in smooth flow over the building roof. Its use for configurations in which the centerline passes over the receptor will result in an underestimate of available dilution and consequent overdesign of the exhaust system. Chapter 14's Equations 18 through 23 have the same limitation.

Modern design practice increasingly employs large-diameter, high-velocity exhaust jets whose centerlines may be expected to pass over roof receptors. New models for prediction of available dilution in such cases are needed. Use of Equations 17 through 23 with constants adjusted to generate higher dilutions requires guidelines for determination of the constants. Such guidelines do not exist. The alternative is a new, physically realistic model that has the capability of predicting off-centerline dilutions. The Halitsky (1989) jet plume model has this capability and is simple to implement, although judgment is needed in the selection of a wind parameter, placement of the ground plane, and estimation of the possibility of building-generated flow separation and vortices.

The jet plume model was applied to the Petersen-Wilson test configurations in order to extract a value of the atmospheric turbulence parameter that would provide the best match between predicted and observed dilutions. The extracted parameters corresponded to *PG-A* stability in Configuration 1, where there is reason to believe that the emission was captured in the building roof cavity, and *PG-D* in Configuration 2, where there is reason to believe the plume was in smooth flow. Some ambiguity was present because of the absence of a wind velocity measurement in the vicinity of the stack; the reported values were measured in the approach flow.

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APPENDIX

Determination of α for Centerline Impingement in Figure 1

Assumptions

1) Centerline dilution D_{cent} provided by Equation 4 with stability class *PG-D* is equal to centerline dilution D_{min} provided by Equation 2 with $\alpha = 1$.

2) Centerline dilution increase ratio $R = D_{cent}/D_{cent,PG\text{-}D}$ is equally applicable to $D_{min}/D_{min,\ \alpha = 1}$.

Analysis

D_{cent} for any stability class is proportional to $\sigma_y\sigma_z$ at short distances, as may be seen by setting $y = 0$, $z = h$, and $\sigma_z << 2h$ in Equation 4; therefore, R also equals $(\sigma_y\sigma_z)/(\sigma_y\sigma_z)_{PG\text{-}D}$. Employing Equations 7 and 8 with $x_2 = \sigma_2 \simeq 0$, we find $R = \{\exp 0.16(T - 30)\}/\{\exp 0.16(T_D - 30)\}$, where T is the turbulence index for any class and T_D is the turbulence index for *PG-D*. Using the values of T in Figure 5, R is found to have the values 11.4(A), 5.6(B), 2.3(C), and 1.0(D).

$D_{min,\alpha=1}$ is found by Equation 2 to equal 39.4 at a representative distance $s/A_e^{0.5} = 40$. Therefore, D_{min} for any class is equal to 39.4R. Using the above values of R, D_{min} is found to have the values 449(A), 221(B), 91(C), and 39(D). The values of α that yield these values of D_{min} by Equation 2 are 8.9(A), 5.6(B), 2.9(C), and 1.0(D).

Neutrally stable wind tunnel airstreams, which were used for the observations in Figure 1, typically exhibit *PG-C* to *PG-D* stability; therefore, in the absence of plume enlargement in a building cavity, centerline impingement of the plumes in Figure 1 could have occurred only with plumes characterized by α in the range of 1 to 3. The chapter 14 recommendation of $\alpha = 2$ falls in this range.