

# Influence of Architectural Screens on Rooftop Concentrations Due to Effluent from Short Stacks

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## ABSTRACT

*This paper describes the wind tunnel study conducted on behalf of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to evaluate and quantify the effect of architectural screens on rooftop concentration levels due to effluent from short stacks. An equivalent stack height (ESH) concept is introduced, which is used to develop a stack height reduction (SHR) factor that may be used in conjunction with existing stack design procedures found in the 1997 ASHRAE Handbook—Fundamentals to account for the presence of architectural screens.*

## INTRODUCTION

This paper describes the wind tunnel study conducted on behalf of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to evaluate and quantify the effect of architectural screens on rooftop concentration levels due to effluent from short stacks. Architectural screens are often placed around rooftop equipment in order to reduce noise or hide the equipment. Unfortunately, these screens interact with wind flow patterns on the roof and can adversely affect rooftop concentration levels. This, in turn, can lead to high concentrations inside the building due to the effluent entering the building through building air intakes. Presently, there have been no known studies conducted to systematically quantify the effect of screens on rooftop concentrations. There are many studies dealing with the aerodynamics of porous windbreaks and shelter belts. A comprehensive review of these studies was presented in the *World Meteorological Organization Technical Note 59* (van Eimern et al. 1964). There have also been numerous studies of flow

through screens and perforated plates (Castro 1971; Perera 1981; Richardson 1987; Ranga Raju et al. 1988; Richardson 1995); however, only one study relating the effects of a solid parapet to rooftop dilution has been found (Lowery and Jacko 1996).

The primary objective of the study was to evaluate and quantify the effect of architectural screens on rooftop concentration levels. Since there are no simple methods available in the *ASHRAE Handbook—Fundamentals* (1997) for evaluating the effect of screens on exhaust concentration (or dilution), a secondary objective of the study was to develop a method for accounting for screens that can be included in a future *ASHRAE Handbook—Fundamentals* chapter.

To meet the project objectives, a 1:50 scale model of a typical industrial type building was constructed and positioned in an atmospheric boundary layer wind tunnel. Tracer gases were then released from modeled exhausts and the resulting concentrations were measured on the building roof, on the side wall, and immediately downwind. Tests were conducted for various stack heights, screen heights, screen porosities, and screen positions relative to the stacks. The results were analyzed in order to develop a generalized technique for quantifying the effect of screens on exhaust concentration (or dilution).

## EXPERIMENTAL METHODS

All testing was carried out in an atmospheric boundary layer wind tunnel with the following characteristics: 74.5 ft test section length; 12 ft test section width and 7 ft height; wind speed ranges from 1 mph to 15 mph. Flow straighteners and screens at the front end of the tunnel were used to create a

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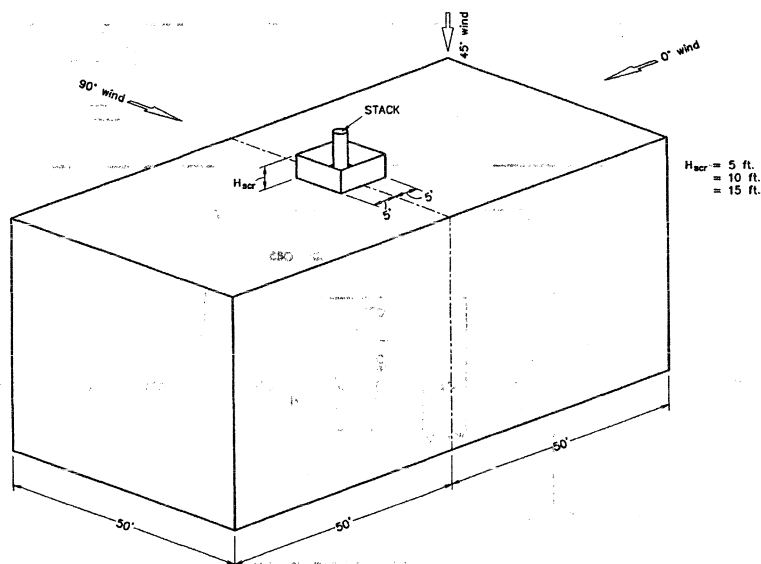


Figure 1 Generic building—10 ft × 10 ft screen.

homogeneous, low-turbulence entry flow. A 16 in. tall trip along with 4 in. and 8 in. tall roughness elements were used to develop and maintain the model atmospheric boundary layer upwind of the model building.

Figure 1 illustrates the 1:50 scale model of a 100 ft long by 50 ft wide by 50 ft tall typical laboratory-type building used in all tests. The screen depicted in the figure represents the screen size and location; however, neither the screen porosity nor the 1 ft gap at the bottom of each screen are shown.  $X_{scr}$  is the screen distance from the stack (5 ft in Figure 1),  $H_{scr}$  is the screen height. Table 1 lists all design parameters and their range of variability during the course of the study. These parameters were combined to form 581 tests.

The receptor grid for each wind direction included the receptors along the centerline of the stack parallel to the wind direction. The receptors started at the leading edge of the building, upwind of the stack, and ran the length of the building and the downwind wall, as seen in Figure 2. Six receptors were included on the stack centerline downwind of the building. The grid was expanded to include receptors off the stack centerline in the vicinity of the stack, especially inside the screen. Receptors were also included on the inside of the upwind, downwind, and one side of the screen at two or three elevations, depending on screen height.

Tests were run with no screen present to determine a baseline concentration at each receptor for every combination of wind and exhaust condition evaluated with screens present. These baseline tests were later used to select an equivalent stack height (ESH), as discussed below. Obviously, more than 581 combinations of the parameters in Table 1 are possible; however, some configurations proved to be of little interest. For example, the horizontal stack orientation allowed little effluent to escape the confines of the screen. Tests at 45° and 90° wind directions were used to validate the 0° wind direction results where most of the testing was conducted.

TABLE 1  
Design Parameters and Range of Variability

Parameter	Units	Range
Wind Direction	Degrees	0; 45; 90
Anemometer Wind Speed*	mph	5.5; 16.6
Building Wind Speed	mph	6.6; 19.8
Stack Height, Base Tests	ft	0; 1; 3; 5; 7; 10; 12; 15; 20
Stack Height, Screen Tests	ft	5; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15; 20
Stack Flow Rate†	cfm	519; 5,111; 19,675
Stack Exit Velocity‡	fpm	481; 1,958; 3,052
Stack Orientation	—	Vertical; Horizontal
Screen Height**	ft	5; 10; 15
Screen Distance	ft	5; 10; 20
Screen Porosity	%	0; 35; 50; 66

\* These are actual values; target values were 5 mph and 15 mph.

† These are actual values; target values were 500 cfm, 5,000 cfm, and 20,000 cfm.

‡ These are actual values; target values were 500 fpm, 2,000 fpm, and 3,000 fpm.

\*\* This height includes a 1 ft gap between the bottom of the screen and the roof.

In order to document the wind characteristics approaching the model, a profile of mean velocity and longitudinal turbulence intensity was obtained upwind of the model test area. An analysis of the profile was conducted to determine whether the shape was characteristic of that expected in the atmosphere. Overall, the velocity profile results showed that wind and turbulence profiles approaching the model test area were characteristic of full-scale surfaces with roughness lengths of 28 cm. This is characteristic of a suburban roughness (Snyder 1981).

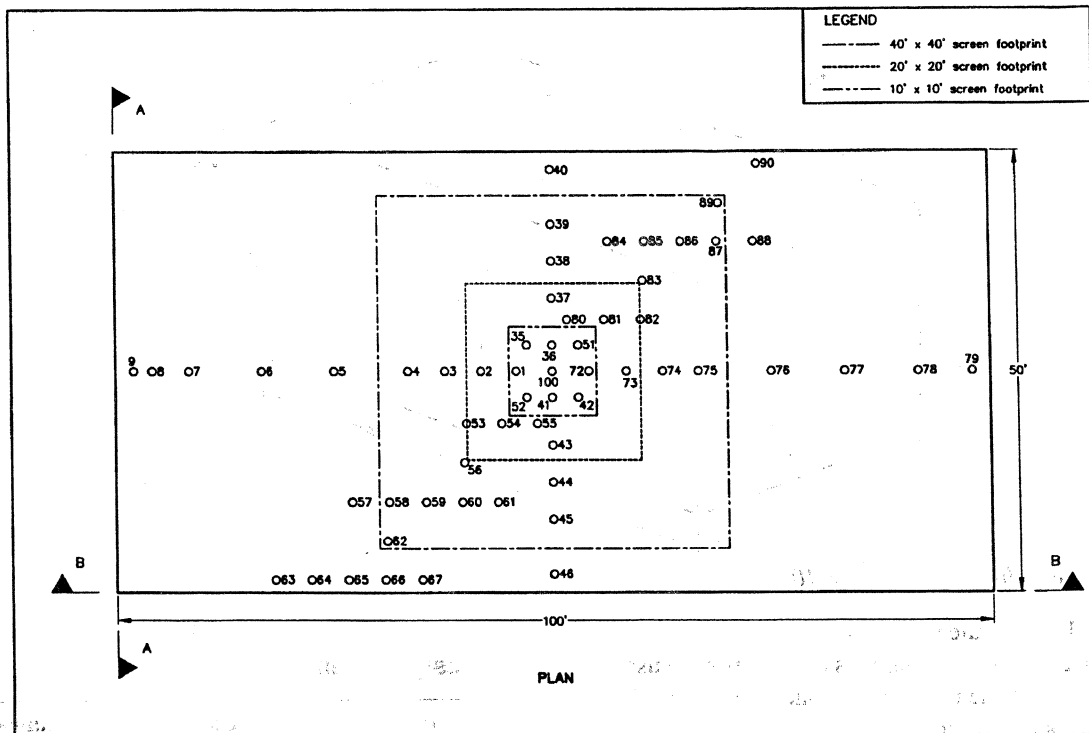


Figure 2 Generic building receptor numbers: plan view.

## THEORETICAL CONSIDERATIONS

### Wind Tunnel Simulation of Airflow and Dispersion

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind-tunnel study of diffusion around buildings. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. A detailed discussion of these requirements is given in the EPA fluid modeling guideline (Snyder 1981). The basis-scaling parameters used during this study are outlined below.

#### Plume Trajectory Simulation Criteria.

- Match velocity ratio:

$$R = \frac{V_e}{U_h} \quad (1)$$

- Match density ratio:

$$\lambda = \frac{\rho_s}{\rho_a} \quad (2)$$

- A trip was used for these simulations to ensure a fully turbulent exhaust flow upon exiting the stack.

**Airflow and Dispersion Simulation Criteria.** Since this study was designed to be generic in nature, a rectangular building was placed in a uniform roughness configuration. The roughness was designed to simulate a suburban environment with a surface roughness length of 0.28 m. Reynolds number independence was ensured: the building Reynolds

number ( $Re_b = U_b H_b / \nu_a$ , the product of the wind speed,  $U_b$ , at the building height,  $H_b$ , times the building height divided by the viscosity of air,  $\nu_a$ ) was greater than 11,000. A neutral atmospheric boundary layer was established.

Using the above criteria and the source characteristics listed in Table 2, the model test conditions were computed for three generic stack configurations designated 500 cfm, 5,000 cfm, and 20,000 cfm, or low to high momentum type exhausts.

### Numerical Dilution Estimates

ASHRAE (1997) presents a series of equations for estimating the minimum dilution (i.e., maximum concentration) vs. distance from an exhaust stack. The equations are detailed in the *ASHRAE Handbook* (1997) and are summarized here.

The worst case dilution from an uncapped, vertical, non-buoyant exhaust jet from a raised stack with plume rise inversely proportional to wind speed ( $D_{crit}$ ) is predicted using:

$$\frac{D_{crit}}{D_{crit,0}} = \left( \frac{U_{crit}}{U_{crit,0}} \right) \exp[Y + (\sqrt{Y})\sqrt{Y+1}] \quad (3)$$

where

$D_{crit,0}$  = absolute lowest dilution (dimensionless) from a stack of negligible height,

$U_{crit,0}$  = wind speed (mph) that produces absolute lowest dilution from a stack of negligible height,

$U_{crit}$  = wind speed (mph) producing the lowest dilution for elevated stacks,

**TABLE 2**  
**Source Parameters for Stack Being Evaluated**

IP Units								
Source Description	Typical Building Height (ft)	Stack Height (ft)	Stack Base (ft, MSL)	Exit Diameter (ft)	Exit Temperature (°F)	Ambient Temperature (°F)	Volume Flow Rate (cfm)	Exit Velocity (fpm)
500 cfm	50	60.0	0.0	1.17	70.0	70.0	519	481.3
5,000 cfm	50	60.0	0.0	1.82	70.0	70.0	5,111	1958.5
20,000 cfm	50	60.0	0.0	2.86	70.0	70.0	19,675	3052.8
SI Units								
Source Description	Typical Building Height (m)	Stack Height (m)	Stack Base (m, MSL)	Exit Diameter (m)	Exit Temperature (K)	Ambient Temperature (K)	Volume Flow Rate (m <sup>3</sup> /s)	Exit Velocity (m/s)
500 cfm	15.24	18.3	0.0	0.36	294.3	294.3	0.24	2.4
5,000 cfm	15.24	18.3	0.0	0.56	294.3	294.3	2.41	9.9
20,000 cfm	15.24	18.3	0.0	0.87	294.3	294.3	9.29	15.5

$Y$  = plume height to spread parameter (dimensionless) for 10-minute averages.

$$Y = 28.9 \left( \frac{h_s}{S} \right)^2 \quad (4)$$

where

$h_s$  = effective stack height (ft),

$S$  = string distance (ft).

$Y$  is limited to values  $Y \leq 2.0$ . It should be noted that in this study, the effective stack height is equal to the physical stack height  $H_s$ .

### Equivalent Stack Height Concept

To quantify the effects of rooftop screens on exhaust concentration (or dilution), an equivalent stack height (ESH) concept was developed. An ESH is the stack height that would give similar concentrations if the screen were not present. To determine ESH values, wind tunnel tests were conducted to obtain a database of concentrations with and without the effect of screens. The data from each test with a screen present were compared to the cases without a screen, and the one giving similar concentrations defined the ESH. The criteria for selecting an ESH are presented in Table 3. An ESH was selected based on the location of the maximum concentration, either inside or outside the screen. The criteria (A, B, and C) were met as required by the location of the maximum concentration.

Figure 3 illustrates the method further. The figure shows the full-scale concentrations from several tests vs. string distance ( $S$ ), where 0 ft string distance is the base of the stack. The wind and exhaust parameters are listed in the subtitle. The screen and stack parameters are listed in the first line in the legend. Stack heights for tests with the same wind and exhaust parameters are also listed in the legend. It is evident that the

location of the maximum concentration is inside the screen at 0 ft string distance. Therefore, Criterion A from Table 3 must be met by any ESH inside the screen ( $-15 \text{ ft} \leq S \leq +15 \text{ ft}$ ). The ESH selected inside the screen is the 1 ft stack. Criterion B must be met at every string distance outside the screen. Since this is a  $0^\circ$  wind direction test, the roof extends to  $S \leq +50 \text{ ft}$ . The 3 ft stack is the ESH outside the screen. On the downwind wall, the 10 ft stack is the tallest stack that meets Criterion B at every string distance; therefore, it is the ESH.

A stack height reduction factor (SHR) was also obtained for each test, where an SHR is defined as

$$SHR = \frac{ESH}{H_s} \quad (5)$$

where  $H_s$  is the physical stack height in feet. The SHR factor is then used to reduce the actual stack height used in the Handbook (ASHRAE 1997) calculations.

### RESULTS

Average concentrations were measured on and downwind of the building for 581 different test conditions. The model concentrations were converted to full-scale normalized concentrations (C/m). Plots of full-scale concentration vs. stretched-string distance ( $S$ ) for each test were then made, as in Figure 3. These plots were used to select an ESH using the criteria in Table 3, as discussed earlier.

An analysis of the data showed the SHR factor could be directly related to the screen porosity such that a conservative estimate (i.e., one that would result in overestimating concentrations) could be developed. Correlations between SHR and other factors were sought (such as screen height, stack height, and screen distance) but no consistent pattern emerged (Carter 1997). The average SHR factor vs. screen porosity is summarized in Table 4. Figure 4 shows a plot of the results in Table 4 along with the following linear best fit equation:

**TABLE 3**  
**Criteria for Equivalent Stack Height (ESH) Selection**

Location of Maximum Concentration	Description
1	If the screen test maximum concentration is located inside the screen, criterion A must be met by any one ESH concentration inside the screen (not necessarily at the same string distance as the screen test maximum concentration).  Criterion B must be met by all ESH concentrations outside the screen.
2	If the screen test maximum concentration is located outside the screen, criterion A must be met by any ESH concentration outside the screen (not necessarily at the same string distance as the screen test maximum concentration).  Criterion B must be met by all ESH concentrations outside the screen.  Criterion C must be met by any ESH concentration inside the screen (not necessarily at the same string distance as the maximum screen test concentration).
<b>Criteria</b>	
A	The maximum concentration of the ESH must meet or exceed the maximum concentration of the screen test.
B	The ESH concentration must be greater than or equal to 80% of the screen test concentration.
C	The ESH concentration inside the screen must be greater than or equal to 80% of the maximum screen test concentration inside the screen.

$$SHR = (0.0081 \times \text{Porosity}) + 0.20 \quad (6)$$

where porosity is in percent. Use of the above equation produces the calculated SHR factors in Table 4.

Now, with a general equation for estimating the SHR factor, the effect of an architectural screen on rooftop dilution can be estimated. First, the stack and screen design parameters

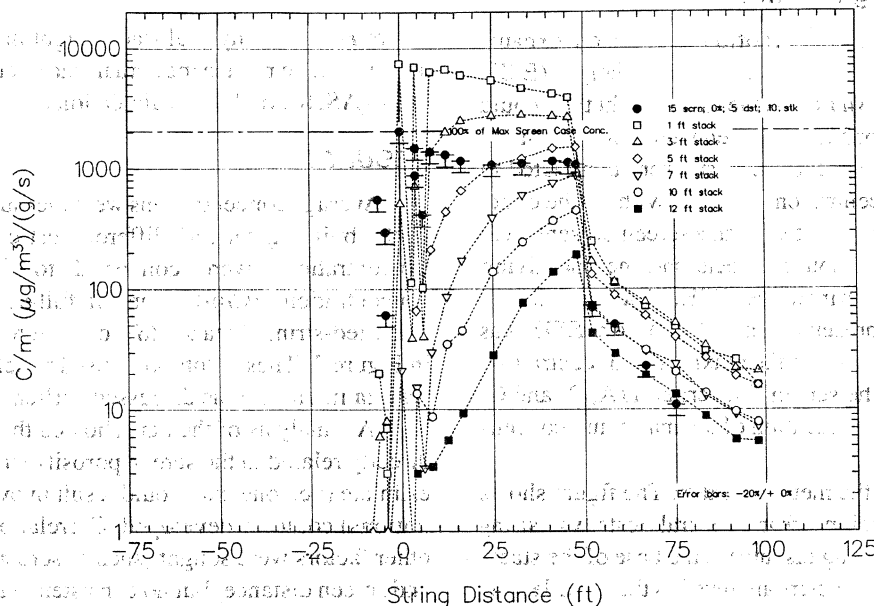
are specified. Second, the SHR is calculated using Equation 6. Next, the height to spread parameter is modified as follows,

$$Y = 28.9 \left( \frac{SHR h_s}{S} \right)^2, \quad (7)$$

and is used in the Handbook (ASHRAE 1997) calculations.

**CONCENTRATION vs STRING DISTANCE**

246; 5, 111 cfm; Vert; 16.6 mph; 0 Deg



**Figure 3** Full-scale concentration vs. string distance ( $\mu\text{g}/\text{m}^3$  per g/s); run 246; 15 ft screen height; 0% screen porosity; 5 ft screen distance; 10 ft stack height; 5, 111 cfm; vertical stack orientation; 16.6 mph wind speed; 0° wind direction.

**TABLE 4**  
**Recommended\* Stack Height Reduction (SHR) Factor as a Function of Screen Porosity**

Wind Direction (°)	Porosity	Concentration Measurement Region	Mean SHR Factor	Calculated SHR <sup>†</sup> Factor
ALL	0%	Rooftop <sup>‡</sup>	0.23	0.20
		Downwind Wall	0.23	
ALL	35%	Rooftop <sup>‡</sup>	0.42	0.48
		Downwind Wall	0.25	
ALL	50%	Rooftop <sup>‡</sup>	0.59	0.60
		Downwind Wall	0.42	
ALL	66%	Rooftop <sup>‡</sup>	0.79	0.73
		Downwind Wall	0.44	
ALL	100%	Rooftop <sup>‡</sup>	1.00	1.00
		Downwind Wall	1.00	

\* Recommendations based on 0° wind direction.

† SHR calculated using linear fit to rooftop SHR mean.  $SHR = (0.0081 \cdot Porosity) + 0.20$ .

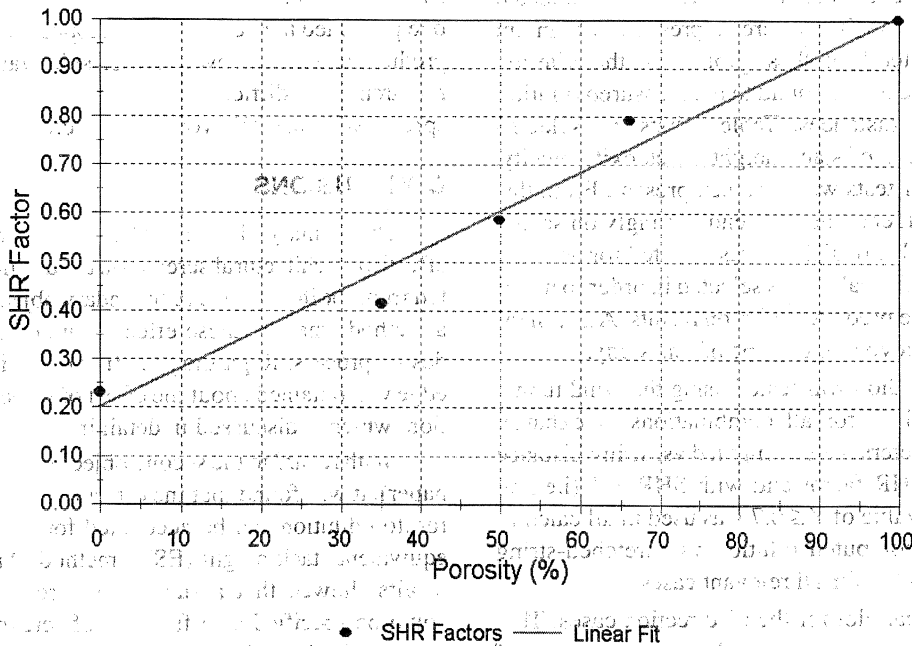
‡ Rooftop SHR = (inside screen + outside screen)/2.

SHR factors were developed on the side of the building and are also presented in Table 4. A general equation or technique for estimating concentrations on the downwind wall was not developed and tested as part of this study but is an area of suggested additional research. It is expected that a similar method could be developed.

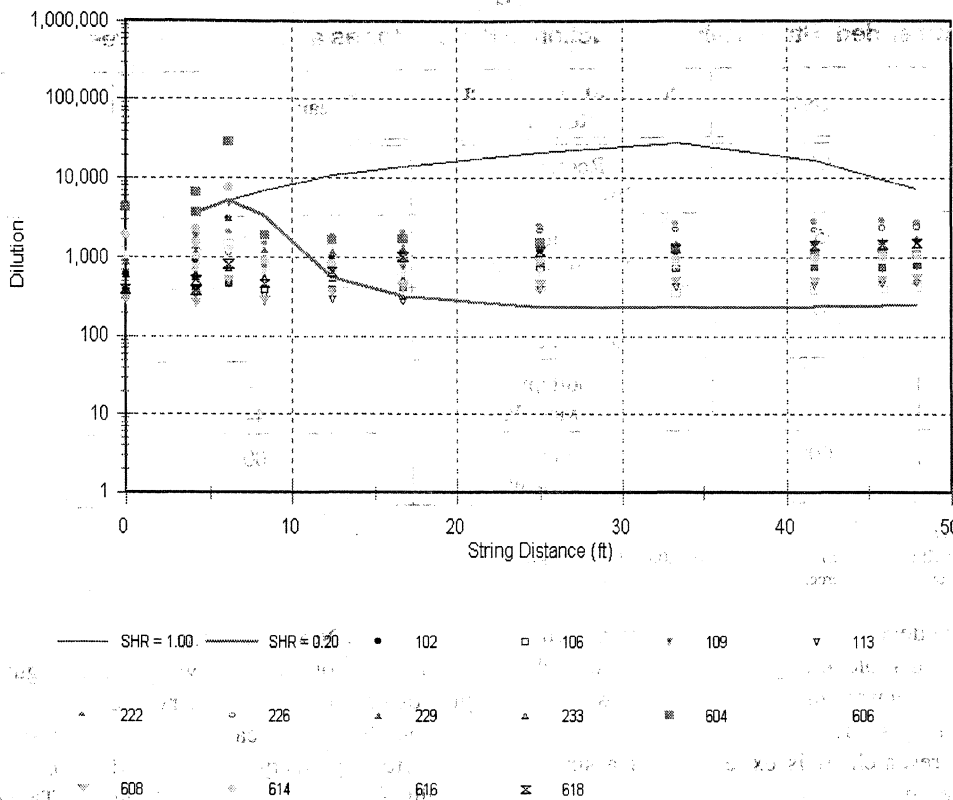
#### EVALUATION OF METHOD

The method discussed in Section 4 was tested using the concentration database developed in the wind tunnel. First, the minimum dilutions were calculated using an SHR = 1.00 (no stack height reduction) as well as the SHR calculated using

Equation 6. Next, the computed values were compared with the observations from the wind tunnel. Figure 5 is an example plot of computed and observed dilution vs. stretched-string distance for all test cases with the following parameters: (1) 0% screen porosity, (2) 0° wind direction, (3) 10 ft stack height, and (4) 519 cfm stack flow rate. This figure shows that the computed values with SHR = 1.00 (no stack reduction) do not agree well with observations. In fact, dilutions are over-estimated by an order of magnitude when a screen is present! The computed values with SHR = 0.20 (the SHR computed for 0% porosity screens using Equation 6) give a reasonable prediction of measured dilution except at small distances, as indicated by the hump in the curve for  $0 \text{ ft} \leq S \leq \sim 12 \text{ ft}$ . This



**Figure 4** SHR as a function of screen porosity with linear curve fit.



**Figure 5** Dilution vs. string distance with  $Y \leq 2.0$ ; all tests with the following parameters: 0% screen porosity,  $0^\circ$  wind direction, 10 ft stack height, 519 cfm volume flow.

hump is due to the plume height to spread parameter limiting value ( $Y \leq 2.0$ ), as previously discussed.

In order to determine a better limiting value for  $Y$ , additional analysis was undertaken. Tests from the concentration database were grouped by the same parameters indicated above, including tests with no screen present. Maximum values of  $Y$  were selected from these plots using the criterion that the curve must be a lower bound to the measured dilution at all stretched-string distances. Table 5 lists the selected values of  $Y$  as a function of stack height, stack exit velocity, and screen porosity for tests with a screen present. From this analysis, it became evident that  $Y$  depends strongly on screen porosity. A limiting value of  $Y \leq 0.7$  was selected for use with all screen porosities. This value was selected in order to maintain conservatism in the predicted dilution results. Also, an in-depth study of  $Y$  was beyond the scope of this study.

This modified method was tested using the wind tunnel database. Dilution values for all combinations of exhaust, stack, and wind parameters were computed vs. string distance using the computed SHR factor and with  $SHR = 1$  (i.e., no screen). The limiting value of  $Y \leq 0.7$  was used in all calculations. Observed and computed dilution vs. stretched-string distance were then plotted for all relevant cases.

Figure 6 is a typical plot for the  $0^\circ$  direction cases. This figure shows that the new method provides a good estimate of the lower bound for dilution when the SHR factor is utilized.

With  $SHR = 1$  (the original equation in the ASHRAE Handbook), the dilution estimates are not lower bounds and would not provide conservative estimates.

This method does not extend to predicting dilution on the side walls of the building. However, a method similar to the one presented here could be developed and tested for dilution predictions on the downwind or side walls. Without further research, it is difficult to predict how the plume height to spread parameter ( $Y$ ) would be affected in these locations.

## CONCLUSIONS

The primary objective of this study was to quantify the effects of architectural screens on the dilution of effluent emitted from rooftop stacks. A secondary objective was to suggest a method whereby these effects can be accounted for in the design process. Regarding the first objective, general knowledge was obtained about the effect of screens on exhaust dilution, which is discussed in detail in Carter (1997).

With regard to the second objective (the main topic of this paper), it was found that the effect of architectural screens on rooftop dilution can be accounted for through the use of an equivalent stack height (ESH) method. An evaluation of the results showed that a stack height reduction factor (SHR) could be specified as a function of screen porosity. Using a computed SHR and existing equations in the ASHRAE Handbook (1997) to assess the effect of the screen on rooftop dilu-

**TABLE 5**  
**Height to Spread Parameter (y) as a Function of Stack Height and Exit Velocity: Tests with Screens**

0° Wind Direction - 0% Porosity												
Exit Velocity	Stack Height (ft)											
	5	6*	7*	8*	9*	10	11*	12*	13*	14*	15	20
481 fpm	0.8	1.0	0.9	0.9	0.9	0.7	1.0	1.0	1.1	1.2	0.5	0.5
1,958 fpm	0.7	0.8	0.9	0.9	1.0	0.7	0.9	1.2	1.4	1.8	0.5	0.5
3,052 fpm	1.0					0.9					0.7	0.7
0° Wind Direction - 35% Porosity												
Exit Velocity	Stack Height (ft)											
	5	6*	7*	8*	9*	10	11*	12*	13*	14*	15	20
481 fpm						0.7						
1,958 fpm						0.7						
3,052 fpm						1.6						
0° Wind Direction - 50% Porosity												
Exit Velocity	Stack Height (ft)											
	5	6*	7*	8*	9*	10	11*	12*	13*	14*	15	20
481 fpm	1.5					1.5					2.0	2.0
1,958 fpm	2.0					2.0					2.0	2.0
3,052 fpm	2.0					2.0					2.0	2.0
0° Wind Direction - 66% Porosity												
Exit Velocity	Stack Height (ft)											
	5	6*	7*	8*	9*	10	11*	12*	13*	14*	15	20
481 fpm						2.0						
1,958 fpm						2.0						
3,052 fpm						2.0						

\* Two data sets only.  
 Shaded area indicates no data.

tion, the resulting concentration at roof-mounted air intakes can be calculated. With this information, a laboratory designer can estimate whether acceptable concentrations will occur at the intake.

During the course of the work, several areas of additional research have also been identified. The study has shown that one of the parameters used in an existing method (ASHRAE 1997) for estimating rooftop dilution (i.e.,  $Y$ ) needs to be re-evaluated. This study found that a limiting value of 0.7 works better than the 2.0 value presently in use for cases when a screen is present. Another area of research is estimating the dilution on building sidewalls when screens are present. While these concentrations are not generally the highest, a method similar to that developed for the building roof could also be developed for the building side wall.

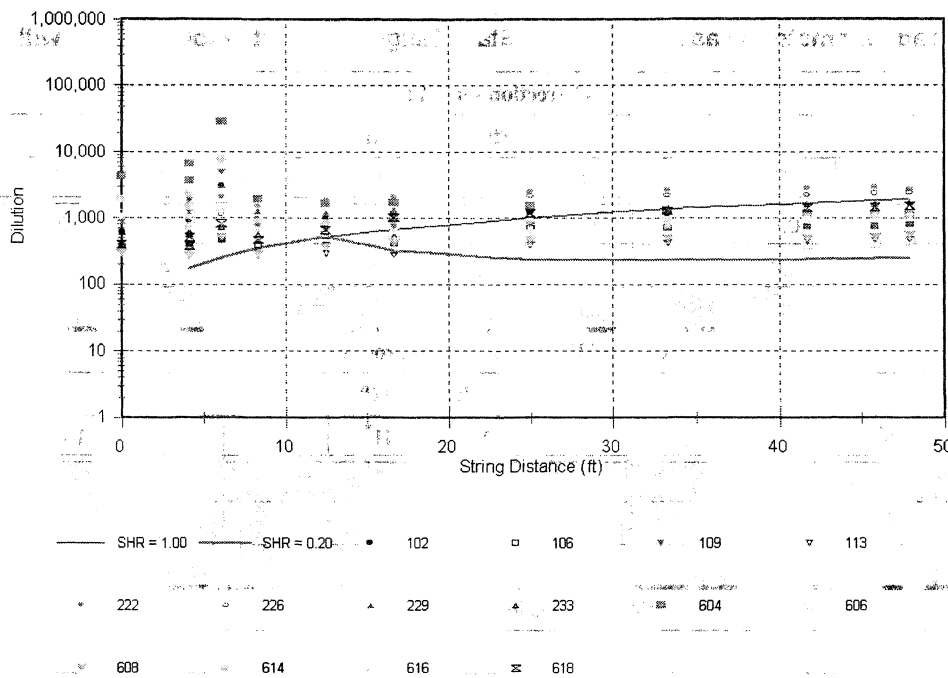
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**Figure 6** Dilution vs. string distance with  $Y \leq 0.7$ ; all tests with the following parameters: 0% screen porosity, 0° wind direction, 10 ft stack height, 519 cfm volume flow.

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