ASHRAE Journal

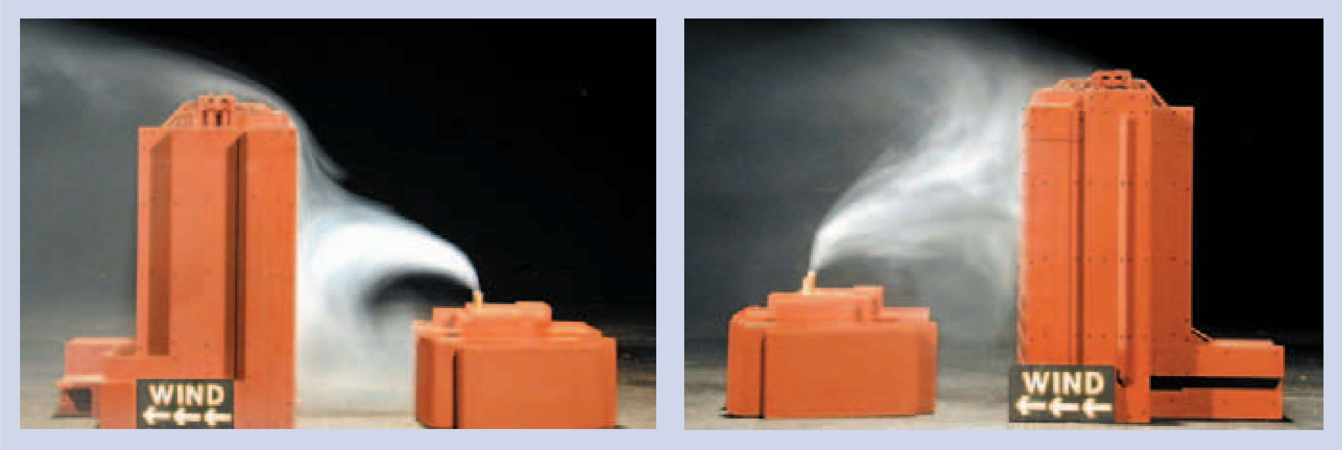


Figure 1a (left): Plume impact on taller downwind building. Figure 1b (right): Plume impact on taller upwind building.

Specifying Exhaust and Intake Systems

By **Ronald L. Petersen, Ph.D.,** Member ASHRAE, **Brad C. Cochran,** Member ASHRAE, and **John J. Carter,** Member ASHRAE

The design of exhaust stacks and air intakes needs careful consideration. Public concern has increased regarding air pollution in general. In addition, adverse exposure to air pollutants in the workplace can affect employee health and productivity. In some cases, releases of toxic pollutants may lead to litigation. The following newspaper article excerpts illustrate some of these issues.

Business Weekly (May 2, 1988): "Local residents were frightened. New pharmacology laboratories at the University of California at San Francisco were investigating everything from AIDS to parasitic diseases. Could disease organisms or toxic chemicals from those labs escape and harm citizens?"

San Francisco Chronicle (September 5, 1996): "A barrage of letters and concerns about toxic chemicals have forced a circuit board manufacturer to drop, at least temporarily, plans to move next door to a peninsula high school."

Chicago Daily Herald (April 17, 1998): "Suspicions confirmed. Public health officials say brain tumors at Amoco center more than coincidence.... A study of Building 503 at the Amoco Research Center in Naperville indicates a rash of malignant brain cancers.... Eighteen Amoco Research Center employees have developed brain tumors in the last 28 years."

Some challenges to specifying a good stack design include the existing building environment, aesthetics, building design issues, chemical use, source types, local meteorology and topography. For example, if a new laboratory building that is being designed is shorter than surrounding buildings, it is difficult to design a stack so the exhaust will not impact neighboring buildings.

The effect of a taller downwind or upwind building is illustrated in *Figure 1*. The figure shows how the plume hits the face of the taller building when it is downwind and how, when it is upwind, the wake cavity region of the taller building traps the exhaust from the shorter building. In either case, the plume impacts the face of the taller building.

Figure 2 further illustrates problems that can be created by poor stack design. Fumes from the exhaust may reenter the building, enter adjacent buildings, or

About the Authors

Ronald L. Petersen, Ph.D., is vice president of Cermak Peterka Petersen Inc., Fort Collins, Colo. **Brad C. Cochran** is a senior project engineer for Cermak Peterka Petersen Inc. **John J. Carter** is a project engineer for Cermak Peterka Petersen Inc.

Reprinted by Permission

impact pedestrians at unacceptable concentration levels. To avoid adverse air quality, taller stacks, higher volume flows and/or optimum locations on the roof may be necessary.

In most cases, laboratory stack design is a balance between various constraints and obtaining adequate air quality at surrounding sensitive locations (air intakes, plazas, operable windows, etc.). The lowest possible stack height is desired for aesthetics, while exit momentum (exit velocity and volume flow rate) is limited by capital and energy costs, noise, and vibration. To determine the optimal exhaust design, predictions of expected concentrations of exhausted pollutants at sensitive locations are needed to compare against health limits and odor thresholds. These predictions can be accomplished with varying degrees of accuracy using three different methods: 1) a full-scale *field program*; 2) a *mathematical modeling* study; or 3) a reduced-scale study conducted within an atmospheric-boundary-layer *wind tunnel*. A full-scale field program may provide the most accurate prediction of concentration levels but can be expensive and time consuming. In addition, it is impossible to evaluate designs before construction is completed.

Numerical models can be divided into two categories, *analytical* models and *computational fluid dynamics* (CFD) models. Analytical models assume a simplified building configuration and provide concentration estimates based on assumed concentration distributions, i.e., Gaussian. These models do not consider site-specific geometries that may substantially alter plume behavior.

CFD models attempt to resolve the plume transport by solving the Navier-Stokes equations at finite grid locations. *Wind-tunnel modeling*, on the other hand, is much like conducting a field experiment where the concentrations are measured in a simulated flow at the points of interest over a scale model of the buildings under evaluation.

This article describes a quantitative approach to accurately evaluate exhaust and intake designs to ensure acceptable air quality inside and around buildings. Also described for background purposes are various exhaust and intake design issues such as applicable standards and recommendations, analytical methods, plume rise, architectural screens, and entrained air exhaust stacks.

Exhaust/Intake Design Issues

Applicable Standards and Recommendations

Several organizations have published standards or recommendations regarding laboratory exhaust stack design as summarized here.

1. Maintain a minimum stack height of 10 ft (3 m) to protect rooftop workers.[1]

2. Locate intakes away from sources of outdoor contamination such as mobile traffic, kitchen exhaust, streets, cooling towers, emergency generators and plumbing vents.[2]

3. Do not locate air intakes within the same architectural screen enclosure as contaminated exhaust outlets.[2]

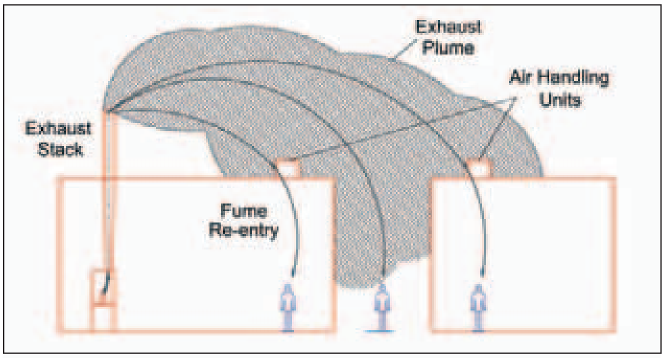


Figure 2: Illustration of potential air quality problems due to laboratory emissions.

4. Locate the air intake at the base of a relatively tall stack or tight cluster of stacks, if this location is not adversely affected by exhaust from nearby buildings. Intakes should not be located near the base of highly toxic stacks due to potential fan leakage.[2]

5. Avoid locating intakes near vehicle loading zones. Canopies over loading docks do not prevent hot vehicle exhaust from rising up to intakes above the canopy.[2]

6. Use High Efficiency Particulate Air (HEPA) filters or Ultra Violet Germicidal Irradiation (UVGI) systems of similar efficiency in isolation room exhaust streams.[3]

7. Combine several exhaust streams internally to dilute intermittent bursts of contamination from a single source, as well as producing an exhaust with greater plume rise. Additional air volume may also be added to the exhaust at the fan to achieve the same end.[2]

8. Group separate stacks together (where separate exhaust systems are mandated) in a tight cluster to take advantage of the increased plume rise from the resulting combined jet.[2] Note that all the exhausts must operate continuously to take full advantage of the combined jet.

9. Avoid rain caps or other devices that limit plume rise on exhaust stacks. Conical rain caps often do not exclude rain, because rain does not fall straight down. Alternate design options are provided in Chapter 43 of the *ASHRAE Handbook—HVAC Applications.*[2]

10. Consider the adverse effect of architectural screens. A solid screen effectively decreases the stack height by 80%.[4]

Analytical Methods

Chapter 43 of the *ASHRAE Handbook—HVAC Applications* discusses exhaust stack design in some detail.[2] The chapter contains two primary types of information regarding stack design: 1) a geometric method of determining stack height; and 2) mathematical equations for predicting rooftop concentrations. In the geometric method, the recommended stack height is that for which the bottom edge of the exhaust plume will be above various recirculating and high turbulence zones. In general, this method is entirely inadequate for exhaust streams that contain toxic or odorous material, as it does not provide an estimated concentration at an air intake or other sensitive

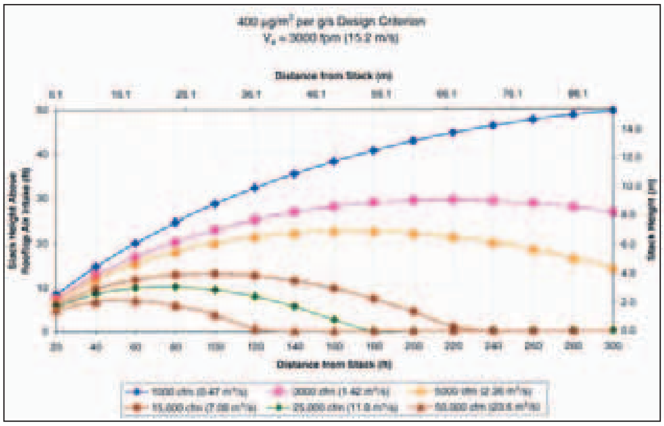


Figure 3: Minimum recommended stack height above rooftop air intake using ASHRAE methods.

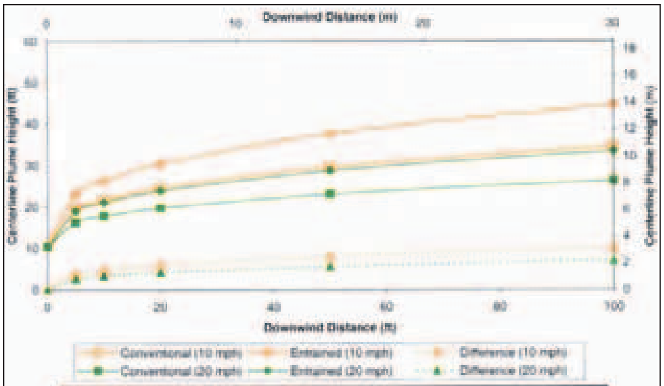
location. Hence, no information on the adequacy of the stack to avoid concentrations in excess of health or odor limits is provided. The analytical equations tend to be conservative for an isolated building or one that is significantly taller than the surrounding buildings and for air intakes on the roof level. Also, they are not appropriate for complex building shapes or when buildings of similar or taller height are nearby.

Using the ASHRAE dispersion equations and a 400 µg/m³ per g/s ASHRAE design criterion, a graph can be generated giving the minimum recommended stack height to ensure that the design criterion is met, as shown in *Figure 3*.[2,5] For example, assume an air intake is located 60 ft (18.3 m) away from an exhaust stack. The figure shows that a 20 ft (6.1 m) stack is needed if the volume flow rate is 1,000 cfm (0.47 m³/s), and a 10 ft stack (3 m) is needed with a 25,000 cfm (11.8 m³/s) volume flow rate. The figure clearly shows the benefit of higher volume flow rates.

Plume Rise and Dispersion

Adequate plume rise is important to ensure that the exhaust escapes the high turbulence and recirculation zones on the building roof. Plume rise increases with increased exit momentum and decreases with increased wind speed.[6] Reducing the diameter to increase exit velocity will enhance plume rise. However, a high exit velocity in itself does not guarantee adequate plume rise since the volume flow rate, and thus momentum, are factors as well. Plume rise is also degraded by increased atmospheric turbulence since the vertical momentum of the exhaust jet is more quickly diluted.

If the ratio of exit velocity to approach wind speed is too low, the plume can be pulled downwards into the wake of the stack structure creating negative plume rise, a condition referred to as stack-tip-downwash. This downwash defeats some of the effect of a taller stack and can lead to high concentrations at the building surface. A rule of thumb for avoiding stack-tip-downwash is to have the exit velocity be at least 1.5 times the wind speed at the top of the stack.[2] The wind speed exceeded 1% of the time is commonly used for estimating the minimum exit velocity required to avoid stack-tip-downwash.



Exhaust Parameters	Conventional		Entrained	
Stack Height (ft, m)	10.0	3.05	10.4	3.18
Stack Diameter (in., m)	30.3	0.769	33.9	0.860
Volume Flow Rate (cfm, m/s)	15,000	7.08	25,000	11.80
Exit Velocity (fpm, m/s)	3,000	15.24	4,000	20.32
Wind Speed (mph, m/s)	10	4.5	10	4.5

Figure 4: Plume centerline height for conventional and entrained air exhaust systems.

ASHRAE provides a listing of 1% wind speeds for various metropolitan areas around the world.[7]

For a given stack design and receptor location, there is a "critical wind speed" causing the maximum concentration. Wind speeds lower than this critical speed result in greater plume rise; higher wind speeds provide more dilution due to the greater volume of air passing the exhaust stack. The critical wind speed increases with exit velocity, exhaust volume flow rate and stack height.

Architectural Screens

Architects or building owners often want to hide their exhaust stacks using screening material. An ASHRAE funded research study was conducted to evaluate the effect of architectural screens on rooftop concentration levels.[4] The study found that screens can significantly increase concentrations on the roof and, in effect, reduce the effective stack height. The study evaluated various enclosure sizes and heights but found that the main parameter affecting rooftop dispersion was the screen porosity. The results of the study provide a quantitative relationship between screen porosity and stack height.

Entrained Air Exhausts

Entrained air exhaust manufacturers often quote an effective stack height for their system, which many designers consider when choosing the appropriate system. The effective stack height specification is based on a mathematical equation that predicts the height of the centerline of the emitted exhaust stream versus downwind distance.[6] The effective stack height that is often presented is, in reality, the maximum height of the exhaust plume centerline at some large distance (say, 100 to 200 ft [30 to 61 m]) downwind of the stack and *is not* an effective stack height. What the manufacturers should supply as a specification is the "effective stack height improvement" over a conventional exhaust system. The stated improvement may not be as great as might be expected, as shown in the following analysis.

Figure 4 shows the predicted plume centerline height (called effective stack height by some entrained air system suppliers) versus distance from the stack for a conventional exhaust system with a 15,000 cfm (7.1 m^3/s) volume flow rate and a 3,000 fpm (15.2 m/s) exhaust velocity, and a typical entrained air system with a 25,000 cfm (11.8 m^3/s) total volume flow rate and a 4,000 fpm (20.3 m/s) exit velocity. Plume centerline heights were calculated for 10 mph (4.5 m/s) and 20 mph (8.9 m/s) stack height wind speeds. The figure shows that the increase in plume centerline height (effective stack height improvement) for the entrained air system versus the conventional exhaust system is only 1 to 2 ft (0.3 m to 0.61 m) near the stack; and increases to 7 to 10 ft (2.1 to 3 m) at 100 ft (30.4 m) downwind. This analysis shows why the effective stack height specification is misleading. The manufacturers should be encouraged to delete this specification and add the specification of the "effective stack height improvement" over a conventional system.

Recommended Analysis Approach

The Basic Approach

The recommended approach to evaluating the air quality aspects of exhaust stacks is to perform dispersion modeling to demonstrate that expected concentrations do not exceed health limits or odor thresholds. The design recommendations and standards discussed earlier can be helpful in the design process, but they do not guarantee adequate air quality.

The air quality acceptability question can be written:

$$C_{\text{max}} < C_{\text{health}}\ ? \qquad (1)$$

and

$$C_{\text{max}} < C_{\text{odor}}\ ? \qquad (2)$$

where C_{max} is the maximum concentration expected at a sensitive location (air intakes, operable windows, pedestrian areas), C_{health} is the health limit concentration and C_{odor} is the odor threshold concentration of any emitted chemical.

When a large number of potential chemicals are emitted from a building, a variety of mass emission rates, health limits and odor thresholds are examined. It then becomes operationally simpler to recast the acceptability question by normalizing (dividing) Equations 1 and 2 by the mass emission rate, m:

$$\left(\frac{C}{m}\right)_{\text{max}} < \left(\frac{C}{m}\right)_{\text{health}}\ ? \qquad (3)$$

and

$$\left(\frac{C}{m}\right)_{\text{max}} < \left(\frac{C}{m}\right)_{\text{odor}}\ ? \qquad (4)$$

The left side of each equation, $(C/m)_{\text{max}}$, is only dependent on external factors such as stack design, receptor location, and atmospheric conditions. The right side of each equation is related to the emissions and is defined as the ratio of the health limit or odor threshold to the emission rate. Therefore, a highly toxic chemical with a low emission rate may be of less concern than a less toxic chemical emitted at a very high rate.

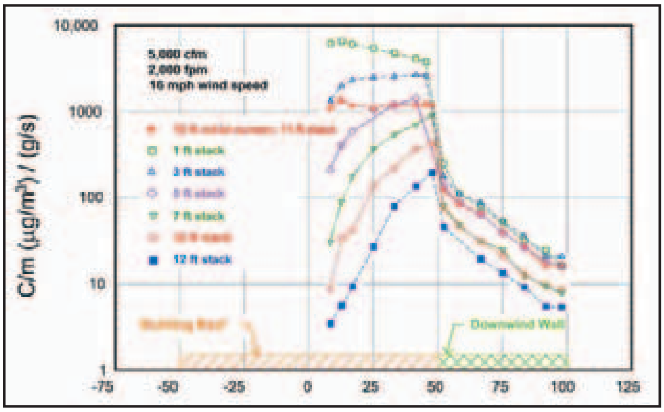


Figure 5: Concentration distribution along building roof and sidewall.

In practice, a chemical inventory for each exhaust type is examined to determine the appropriate values of $(C/m)_{\text{health}}$ and $(C/m)_{\text{odor}}$ for any released chemicals. Dispersion modeling is performed to determine $(C/m)_{\text{max}}$ for all stack designs studied. Those designs that yield concentrations lower than the design goal, i.e., $(C/m)_{\text{max}} < (C/m)_{\text{goal}}$, are the recommended exhaust stack designs.

Formulating a Concentration Design Goal

Three types of information are needed to develop normalized health limits and odor thresholds: 1) a listing of the toxic or odorous substances that may be emitted, 2) health limits and odor thresholds for each emitted substance, and 3) the maximum potential emission rate for each substance.

Substances Emitted. A list of toxic and odorous chemicals is usually obtained from the building owners. The list may be a chemical inventory or a list prepared to meet environmental regulations. Storage amounts are useful for obtaining an upper-bound estimate of the largest amount released.

Health Limits. Recommended health limits, C_{health}, are based on the ANSI/AIHA Standard Z9.5 for Laboratory Ventilation, which specifies air intake concentrations no higher than 20% of acceptable indoor concentrations.[8] Acceptable indoor concentrations are taken to be the minimum short-term exposure limits (STEL) from the American Conference of Governmental Industrial Hygienists (ACGIH), the Occupational Safety and Health Administration (OSHA), and the National Institute of Occupational Safety and Health (NIOSH), as listed in ACGIH.[9,10]

Odor Thresholds. ACGIH provides a good source for odor thresholds, C_{odor}.[11] ACGIH critically reviews previous experimental data and lists geometric means of accepted data. For chemicals not listed in ACGIH, geometric means of high and low values provided in Ruth, 1986 are recommended.[11,12]

Emission Rates. For laboratories, the emission rates are typically based on small-scale accidental releases, either liquid spills or emptying of a lecture bottle of compressed gas. The actual emission rates from experimental procedures are difficult to quantify, especially at large laboratories with diverse research. Small accidental releases have two advantages: 1) they can be considered to be the upper limit of the largely unknown release rates occurring in laboratories; and 2) they can be quantified. Evaporation from liquid spills is computed from EPA equations based on a worst-case spill within a fume hood.[13] Typically, the worst-case spill is defined as the complete evacuation of a 1 L (0.26 gal) beaker over a 1 m^2 (11 ft^2) area. Appropriate adjustments to the worst-case spill volume can be made to account for maximum storage quantities less than 1 L (0.26 gal) and for fume hood counter surface areas that are less than or greater than 1 m^2 (11 ft^2).

Compressed gas leaks typically assume the emptying of a fractured lecture bottle in one minute. For other sources, such as emergency generators, boilers, and vehicles, chemical emissions rates are often available from the manufacturer.

Concentration Design Goal Selection. Once the information on chemical usage, health limits, odor thresholds, and emission rates is gathered, the normalized health and odor limits, $(C/m)_{health}$ and $(C/m)_{odor}$, are computed. The concentration design goal, $(C/m)_{goal}$, for the stack/receptor design will ideally be the minimum value of these limits for all of the chemicals. As new processes and chemicals are used in the laboratory, the quantities $(C/m)_{health}$ and $(C/m)_{odor}$ can be evaluated for each chemical added to the inventory. If these values are less than $(C/m)_{goal}$, air quality problems may arise, and usage or emission controls may be warranted.

Often for a facility with intensive chemical usage, the minimum normalized concentration value is below the minimum normalized concentration achievable with a reasonable stack design. Usage controls can reduce the worst-case emission rates, m, and raise the concentration design goal to achievable levels. Such usage controls can include diluted mixtures, smaller liquid storage quantities or smaller gas bottles.

Wind-Tunnel Modeling

In the recommended approach, wind-tunnel modeling is used to predict maximum concentrations, normalized by emission rate, (C/m), for the stack designs and locations of interest. ASHRAE provides more information on scale model simulation and testing methods.[14] Wind tunnel modeling is recommended because it provides the most accurate estimates of concentration levels in complex building environments.[15]

As part of ASHRAE research project RP-805, a simple rectangular building 50 ft high, 50 ft wide and 100 ft long (15.2 by 15.2 by 30.5 m) was modeled and positioned in a boundary layer wind tunnel with a simulated suburban approach wind condition.[4] A tracer gas mixture was released from a stack installed on the roof of the model building at the building center. The simulated parameters were: 5,000 cfm (2.41 m^3/s) volume flow rate, 2,000 fpm (10.2 m/s) exit velocity, stack height varying from 1 ft to 12 ft (0.3 m to 3.7 m), with a 16 mph (7.2 m/s) wind speed at 33 ft (10 m). Concentration levels were measured on the building roof and sidewall for each condition. One test was run with a 10 ft (3 m) solid screen positioned around an 11 ft (3.4 m) stack. All other tests had an unobstructed roof.

Figure 5 shows the normalized concentrations (C/m) on the building roof and sidewall for the various configurations. It should be noted that string distances between 0 ft and 50 ft (15.2 m) are on the building roof, and string distances between 50 and 100 ft (15.2 and 30.4 m) are on the sidewall. The figure shows the expected trend that as stack height increases, the concentrations on the roof decrease with the point of maximum C/m moving farther away from the stack location. Concentrations on the building sidewall are much lower than those on the roof for each configuration evaluated, which shows the advantage of locating air intakes on building sidewalls versus the roof.

The results in *Figure 5* can be used to assess the adequacy of the ASHRAE mathematical method illustrated in *Figure 3*. Using *Figure 3*, a 13 ft (4 m) stack is recommended when the air intake is 50 ft (15.2 m) from a 5,000 cfm (2.4 m^3/s) exhaust with 3,000 fpm (15.2 m/s) exit velocity. *Figure 5* shows that a 10 ft (3 m) stack would be adequate to meet the 400 $\mu g/m^3$ per g/s ASHRAE design criterion with a 2,000 fpm (10 m/s) exit velocity. If the air intake is on the sidewall, there is presently no reliable mathematical method to account for the concentration decrease. Thus, a conservative approach would have to be taken, i.e., use *Figure 3*, which would result in a 13 ft (4 m) stack. *Figure 5* shows that a 1 ft (0.3 m) stack would meet the ASHRAE criterion if the air intake were on the building sidewall.

Figure 5 also shows that with a 10 ft (3 m) solid screen positioned around an 11 ft (3.4 m) stack, the concentrations on the roof are similar to those for a 5 ft (1.5 m) stack without a screen present. Hence, the solid screen has reduced the effective stack height by a factor of 0.4. This result illustrates the adverse effect of rooftop features, which are often not accounted for using the simplified methods discussed previously. Hence, stack heights can be specified that are not tall enough to ensure acceptable air quality. The effect of screens on rooftop concentrations is discussed in detail in Petersen, et al.[4]

Discussion and Conclusions

This article has provided general information regarding the need for good stack design and discusses issues that should be considered when specifying exhausts and intakes. No matter what type of exhaust system is used, the important parameters are the physical stack height, volume flow rate, exit velocity, expected pollutant emission rates and concentration levels at sensitive locations. Whether conventional or entrained air exhaust systems are used, the overall performance should be evaluated using the appropriate criterion, i.e., ensuring acceptable concentrations at sensitive locations. Selecting an exhaust system based on an effective stack height alone is not sufficient to ensure an adequate exhaust system design.

The article also presented a quantitative approach to evaluate the air quality aspects of exhaust stack design. The approach includes dispersion modeling, specifically wind-tunnel modeling, to predict maximum concentrations at sensitive locations such as air intakes, operable windows, and pedestrian areas. Concentration goals for design acceptability are based health limits, odor thresholds, and emission rates of chemicals likely to be used at the facility. Using the approach for a simple building geometry demonstrated that the mathematical methods tend to give unnecessarily tall stack heights for an unobstructed roof and give stacks that are not tall enough for a roof with obstructions.

References

1. NFPA. 1996. *Fire Protection for Laboratories Using Chemicals*. ANSI/NFPA Standard 45-96. National Fire Protection Association, Quincy, Mass.

2. *1999 ASHRAE Handbook—HVAC Applications,* Chapter 43.

3. CDC. 1994. “Guidelines for preventing the transmission of Mycobacterium tuberculosis in health-care facilities.” U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention.

4. Petersen, R.L., et al. 1999. “Influence of architectural screens on rooftop concentrations due to effluent from short stacks.” *ASHRAE Transactions* 105(1).

5. *1999 ASHRAE Handbook—HVAC Applications,* Chapter 13.

6. Briggs, G.A. 1969. *Plume Rise*. Critical Review Series, U.S. Atomic Energy Commission, NTIS #TID-25075.

7. *2001 ASHRAE Handbook—Fundamentals,* Chapter 27.

8. AIHA. *1992 ANSI/AIHA Standard Z9.5 Laboratory Ventilation.* American Industrial Hygiene Association.

9. ACGIH 2001. *Guide to Occupational Exposure Values – 2001.* American Conference on Governmental Industrial Hygienists.

10. ACGIH. *2001 Threshold Limit Values for Chemical Substances and Physical Agents*.

11. ACGIH. 1989. *Odor Thresholds for Chemicals with Established Occupational Health Standards*.

12. Ruth, J.H. 1986. “Odor threshold and irritation levels of several chemical substances: a review.” *Journal of American Industrial Hygiene Association* 47:A-142.

13. EPA. 1992. *Workbook of Screening Techniques for Assessing Impacts of Toxic Air Pollutants (Revised)*, U.S. Environmental Protection Agency, Office of Air Quality, Planning and Standards, Research Triangle Park, N.C., EPA-454/R-92-024.

14. *2001 ASHRAE, Handbook—Fundamentals,* Chapter 16.

15. EPA. 1981. *Guideline for Use of Fluid Modeling of Atmospheric Dispersion*. U.S. Environmental Protection Agency, EPA-600/8-81-009.⬢