Specifying Exhaust Systems That Avoid Fume Reentry and Adverse Health Effects

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ABSTRACT

This paper provides general information regarding the need for good exhaust system design and discusses issues that should be considered when designing exhaust stacks and intakes, such as applicable standards, analytical methods, plume rise, architectural screens, and entrained air exhaust stacks. Whether conventional or entrained air exhaust systems are used, the paper discusses why exhaust specifications (i.e., stack height, volume flow, location, and exhaust velocity) should be based on the appropriate criterion, that is, ensuring acceptable concentrations at air intakes and other appropriate locations. Selecting an exhaust system based on simple geometric methods or an effective stack height specification alone is not sufficient to ensure an adequate exhaust system design. A quantitative approach is discussed to specify exhaust and intake designs that ensure acceptable air quality inside and around buildings. The approach includes wind-tunnel dispersion modeling and the establishment of concentration design goals based on emission rates, health limits, and odor thresholds of emitted chemicals. The approach was utilized for a simple building geometry to illustrate that mathematical methods can give excessively tall stack heights for an unobstructed roof and can give stacks that are not tall enough for a roof with obstructions.

INTRODUCTION

The design of exhaust stacks and air intakes needs careful consideration due to increasing public concern over air pollution in general and because 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. Some of these issues are illustrated by the following excerpts from newspaper articles:

- *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 has forced a circuit board manufacturer to drop, at least temporarily, plans to move next door to a peninsula high school."
- *San Francisco Chronicle* (May 20, 1997): "An outpatient clinic was closed and six of its employees were treated for nausea after they were exposed to fumes from a 16 ounce spill of liquid phenol about noon yesterday."
- *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 utilization, source types, and local meteorology and topography. Figure 1 shows a depiction of the airflow around a simple rectangular building. The figure shows the highly turbulent recirculating region on the building

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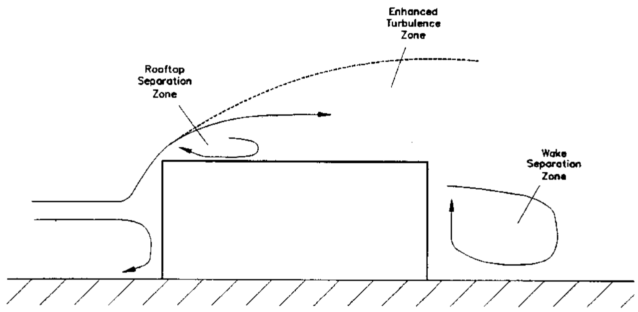


Figure 1 *Airflow around buildings.*

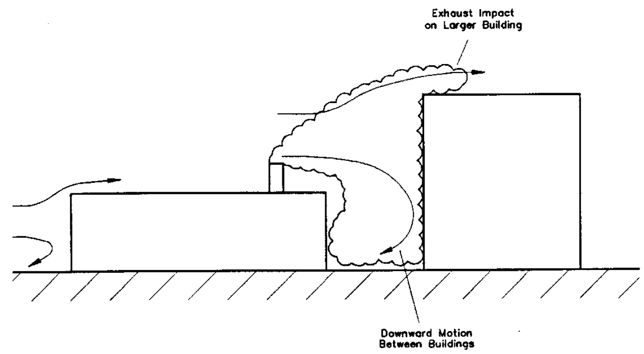


Figure 2 *Plume impact on taller downwind building.*

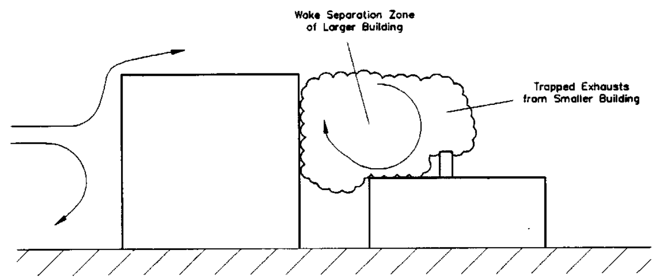


Figure 3 *Plume impact on taller upwind building.*

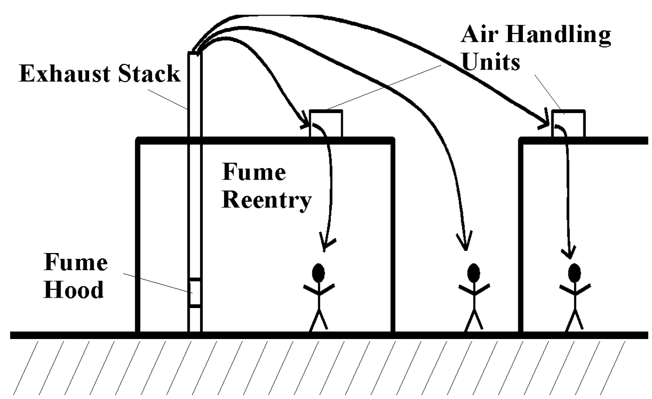


Figure 4 *Ingestion of exhaust at nearby receptors.*

roof, upwind of the building and in the building wake. It has been generally thought that stacks are poorly designed if the exhaust is caught in these highly turbulent regions because the pollutant is not able to escape the building cavity and is thus reentrained back into the building through air intakes, operable windows, and building entrances. However, stack designs may be acceptable even under this situation if the chemicals being emitted from the exhaust are not toxic or odorous and/or if sufficient dilution occurs.

The existing building environment presents a challenge when building heights vary significantly. If a new laboratory building is being designed that is shorter than surrounding buildings, it will be difficult to design a stack such that the exhaust will not impact neighboring buildings. The effect of a taller downwind building is illustrated in Figure 2. The figure shows how the plume hits the face of the downwind building. In addition, when the taller building is upwind, as shown in Figure 3, the wake cavity region of the taller building may trap the exhaust from the shorter building. In this case, the plume once again impacts the face of the taller, upwind building. Hence, the frequency of adverse concentrations on the face of the taller building face is augmented.

Constraints are typically placed on laboratory stack design. The lowest possible stack height is desired for aesthetics and economy. The exit momentum (exit velocity and volume flow rate) is limited by capital and energy costs, noise, and vibration. The laboratory stack design then becomes a balance between these constraints and obtaining adequate air quality at surrounding receptors (air intakes, plazas, operable windows, etc.). Figure 4 illustrates the problem that can be created by a poor stack design. If an exhaust stack is not properly designed, fumes from the exhaust may reenter the building, or adjacent buildings, or impact pedestrians at unacceptable concentration levels. To avoid reentry, taller stacks, higher volume flows, and/or optimum locations on the roof may be necessary.

To determine the optimal exhaust design, predictions of the expected concentrations of pollutants in the exhaust stream at air intakes and other sensitive locations are needed to compare with health limits and odor thresholds. Predictions of concentration levels on and around buildings can be accomplished with varying degrees of accuracy using three different types of studies: (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 very 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. Gaussian-based models fall into the analytical category and are relatively simple models that use generic plume transport algorithms to calculate downwind concentrations. Typical Gaussian-based models include the U.S. Environmental Protection Agency's SCREEN 3 (EPA 1995a), ISC (EPA 1995b), AERMOD (EPA 1998), and PRIME (Schulman et al. 2000) dispersion models and the dilution equations within chapter 43 of *HVAC Applications* (ASHRAE 1999). These models assume a simplified building configuration and provide concentration estimates based on assumed concentration distributions. They do not consider site-specific geometries that may substantially alter the plume behavior.

Computational fluid dynamics (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. The pros and cons of each method are beyond the scope of this paper, and users of either method are advised to review the current literature to determine the expected accuracy of the method selected.

This paper describes a quantitative approach to accurately evaluate exhaust and intake designs to ensure acceptable air quality inside and around buildings. The approach includes wind-tunnel dispersion modeling and the establishment of concentration design goals based on emission rates, health limits, and odor thresholds of emitted chemicals. Also described for background purposes are various exhaust and intake design issues, such as applicable standards, analytical methods, plume rise, architectural screens, and entrained exhaust stacks. Measured quantities are reported in dual units, with the original measured or cited unites listed first.

EXHAUST/INTAKE DESIGN ISSUES

Applicable Standards and Recommendations

Several organizations have published standards or recommendations regarding laboratory exhaust stack design. These are summarized below.

1. Maintain a minimum stack height of 10 ft (3.0 m) to protect rooftop workers (NFPA 1996).
2. Locate intakes away from sources of outdoor contamination, such as mobile traffic, kitchen exhaust, streets, cooling towers, emergency generators, and plumbing vents (ASHRAE 1999).
3. Do not locate air intakes within the same architectural screen enclosure as contaminated exhaust outlets (ASHRAE 1999).
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 (ASHRAE 1999).
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 (ASHRAE 1999).
6. Use high-efficiency particulate air (HEPA) filters or ultraviolet germicidal irradiation (UVGI) systems of similar efficiency in isolation room exhaust streams (CDC 1994).
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 (ASHRAE 1999).
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 (ASHRAE 1999). 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. Alternative design options are provided in chapter 43 of the ASHRAE Handbook—HVAC Applications (ASHRAE 1999).
10. Consider the adverse effect of architectural screens. A solid screen effectively decreases the stack height by 80%, while a 50% porous screen effectively decreases the stack height by approximately 40% (Petersen et al. 1999).

Analytical Methods

ASHRAE (1999), chapter 43, discusses exhaust stack design and airflow around buildings in some detail. The chapter contains two primary types of information regarding stack design: (1) a geometric method of determining stack height and (2) mathematical equations for providing conservative prediction (i.e., overprediction) of rooftop concentrations. In the geometric method for determining stack height, the recommended stack height is that for which the bottom edge of the exhaust plume will be above various recirculation and high turbulence zones. Equations are presented for computing the heights and lengths of these zones. The bottom of the plume is assumed to have a 1:5 downward slope from the release point. The initial rise or downwash of the plume is sometimes included. In general, this method is entirely inadequate for exhaust streams that contain toxic or odorous material. The method does not provide an estimated concentration at an air intake or other sensitive location. Hence, no information on the adequacy of the stack to avoid concentrations in excess of health or odor limits is provided.

ASHRAE (1999), chapter 43, also presents analytical equations for estimating exhaust dilution. These 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. For side wall, or hidden intakes, ASHRAE (1999) has some adjustment factors that have not been fully tested. In fact, ASHRAE TC 4.3 is currently moni-

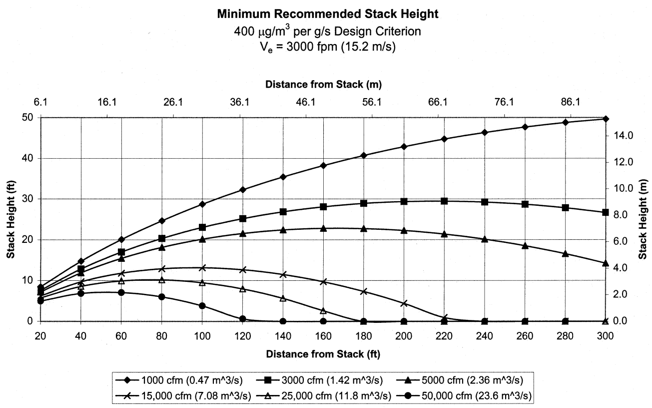


Figure 5 *Minimum stack heights for rooftop air intakes based on the ASHRAE criteria.*

toring a research project (1168-TRP) that will provide information on the concentration reduction factors for hidden air intakes.

Using the ASHRAE (1999) chapter 43 equations and a design criterion recommended by ASHRAE (1999), chapter 13, a graph can be generated giving the minimum recommended stack height to ensure that a dilution or concentration design criterion is met. The ASHRAE (1999) criterion is the concentration that would be less than 3 ppm at an air intake due to an evaporating liquid spill in a fume hood and exhausted at a rate of 7.5 L/s (16 cfm). This is equivalent to a normalized concentration (C/m) value of 400 μg/m^3 per g/s.

Figure 5 shows the graph of minimum recommended stack height versus distance to a rooftop intake using the ASHRAE (1999) equations and the 400 μg/m^3 per g/s ASHRAE criterion for a minimum acceptable normalized concentration. The figure can be used in the following manner. Assume that there is an air intake 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 1000 cfm (0.47 m^3/s), a 15 ft (4.5 m) stack is needed with a 5000 cfm (2.36 m^3/s) volume flow rate, and a 10 ft stack (3 m) is needed with a 25,000 cfm (11.8 m^3/s) volume flow rate. The figure clearly shows the benefit of higher volume flow rates. Lower stack heights can be realized through increasing the volume flow rate while keeping the exit velocity constant at 3000 fpm (15 m/s).

Plume Rise and Dispersion

Exhaust plume rise is important for escaping the high turbulence and recirculation zones on the building roof. Plume rise increases with increased exit momentum and decreases with increased wind speed (Briggs 1969). 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 downward into the wake of the stack structure, creating a 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 (ASHRAE 1999). The wind speed exceeded 1% of the time is commonly used for estimating the minimum exit velocity required to avoid stack-tip downwash. A listing of 1% wind speeds for various metropolitan areas around the world is provided in chapter 27 of *ASHRAE Fundamentals* (ASHRAE 2001).

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 higher plume rise; greater wind speeds provide more dilution due to the greater volume of air passing by an exhaust stack for a given amount of emissions. The critical wind speed increases with exit velocity, exhaust volume flow rate, and stack height.

The decrease of concentration with distance, as the plume expands due to turbulent mixing within the atmosphere, is fairly well modeled in open terrain by numerical models utilized by EPA (1992,1998). However, the nature of the turbulence and airflow patterns immediately around buildings differs from that of open terrain. The ISC regulatory model (EPA 1995) is designed to predict ground level concentrations when structures affect the dispersion. This model does not, however, calculate concentrations within three building heights of the source. The regulatory screening model SCREEN3 (EPA 1995a) does compute concentrations within the wake recirculation zone, but Schulman and Scire (1993) have found some serious deficiencies in the SCREEN3 computation. The dispersion equations in ASHRAE (1999) are designed to provide concentration estimates on the emitting building's rooftop and sidewall. The equations are based on generic wind-tunnel tests and are intended to yield conservative overestimates of concentrations. New improved regulatory models are starting to be used that incorporate boundary-layer similarity theory (EPA 1998) and dispersion in more complex building environments (Schulman et al. 2000).

Architectural Screens

Architects or building owners will often want to hide their exhaust stacks using screening material. An ASHRAE-funded research study was conducted (Petersen et al. 1999) to evaluate the effect of architectural screens on rooftop concentration levels. 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. In the study, a relationship was developed between the stack height reduction factor and screen porosity. The resulting graph is shown in Figure 6.

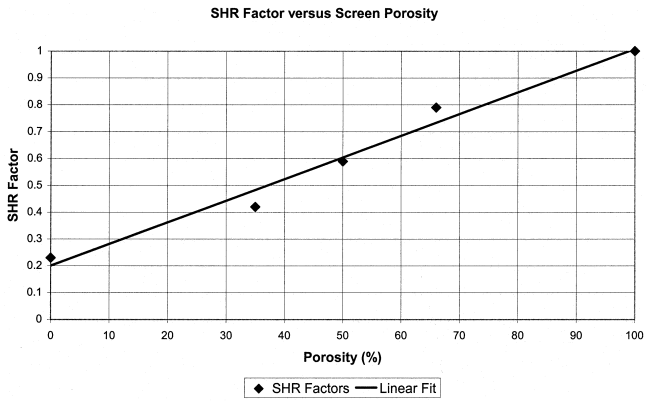


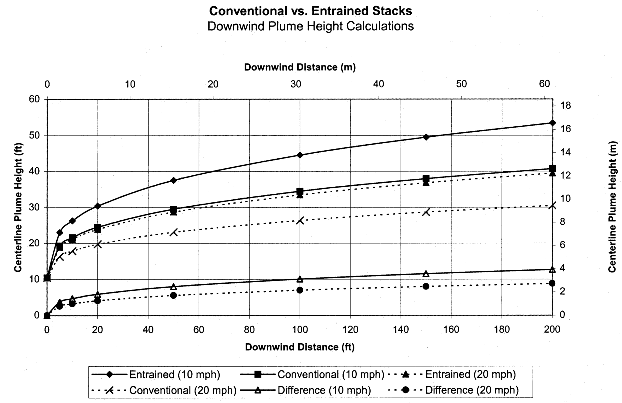
Figure 6 *Stack height reduction factor (SHR) versus screen porosity.*

The use of Figure 6 can be illustrated by the following example. Assume that a 10 ft (3 m) stack is found to be acceptable using the method described above (i.e., Figure 5). It is then decided that a 30% porous screen will be installed surrounding the stack. Figure 6 shows that with a 30% porous screen, a 0.5 stack height reduction factor should be applied. That means the effective stack height is 5 ft (1.5 m), i.e., the 0.5 stack height reduction factor times the 10 ft (3.0 m) physical stack height. Since the initial analysis showed that a 10 ft (3 m) minimum stack height was acceptable, the physical stack height will have to be 20 ft (6.1 m), i.e., 0.5 times 20 ft (6.1 m) gives the desired effective stack height of 10 ft (3.0 m).

Entrained Air Exhausts

Entrained air exhaust manufacturers often quote an effective stack height for their system, which many designers consider when picking the appropriate system. The effective stack height specification is based on a mathematical equation (Briggs 1969) that predicts the height of the centerline of the emitted exhaust stream versus downwind distance. The effective stack height that is presented is in reality the maximum height of the exhaust plume centerline at some large distance (say, 100 to 200 ft) 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 the conventional exhaust system. The stated improvement may not be as great as one might expect, as the following analysis points out.

Figure 7 shows the predicted plume centerline height (called "effective stack height" by some entrained air system suppliers) versus distance from the stack for (1) a conventional exhaust system with a 15,000 cfm (7.1 m^3/s) volume flow rate and a 3000 fpm (15.2 m/s) exhaust velocity and (2) a typical entrained air system with a 25,000 cfm (11.8 m^3/s) volume flow rate and a 4000 fpm (20.3 m/s) exit velocity. Calculations were made for a 10 mph (4.5 m/s) and a 20 mph (8.9 m/s) stack height wind speed. The figure also shows the difference in plume centerline height (effective stack height) for the



Exhaust Parameters	Conventional		Entrained	
Stack Height (ft, m)	10.4	3.18	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 7 *Centerline plume height calculations for conventional and entrained exhaust stack.*

conventional versus entrained air stack. 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 1.0 ft to 2.0 ft (0.30 m to 0.61 m) near the stack and at a distance of 100 ft (30.4 m) downwind increases to 10 ft (3.0 m) for a 10 mph (4.5 m/s) stack height wind speed and 7.0 ft (2.1 m) for a 20 mph (8.9 m/s) wind speed. So what is really gained from the entrained air stack is a 1.0 ft to 2.0 ft (0.30 m to 0.61 m) increase in plume centerline height near the stack and 7.0 ft to10 ft (2.1 m to 3.0 m) farther 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 increase" over a conventional system.

The use of Figure 5 is a more appropriate way to specify an entrained air system. For example, assume that initially a 15,000 cfm (7.1 m^3/s) exhaust was specified with a 3000 fpm (15.2 m/s) exit velocity with a rooftop air intake located 60 ft (18.3 m) downwind. The figure shows that a 12 ft (3.7 m) stack height is required to meet the ASHRAE 400 $\mu g/m^3$ per g/s design criterion. If the designer wants a shorter stack, an entrained air stack with 25,000 cfm (11.8 m^3/s) would reduce the required stack height to approximately 10 ft (3 m). Since entrained air stacks typically have higher exit velocities than 3000 fpm (15.2 m/s), the actual stack height specification should be calculated using a modified Figure 5 with the entrained air exit velocity used in the calculation.

The other item of interest regarding entrained exhaust stacks is their performance under high wind conditions. The above analysis assumes that the stacks are able to entrain as much airflow under high wind conditions as they can under low wind speeds. Since the entrained air exhaust stacks gener-

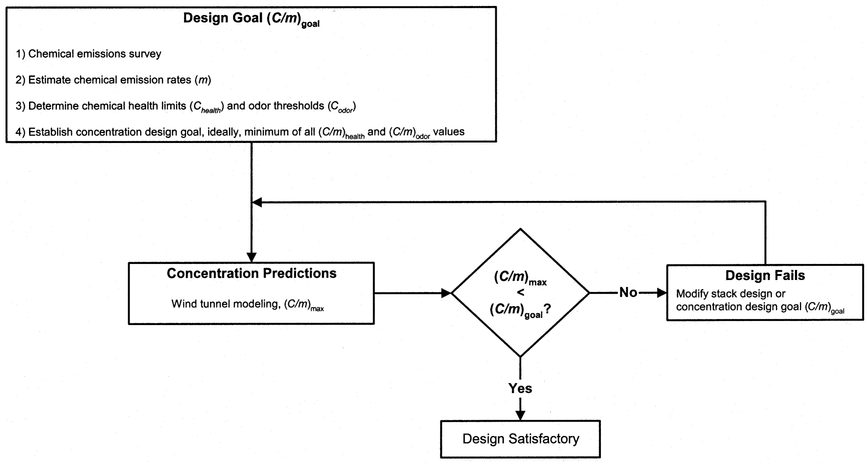


Figure 8 *Recommended design approach.*

ally service high volume flow exhaust systems, high wind speeds are likely to be the most critical (see discussion of critical wind speeds above). To the authors' knowledge, no data are available to indicate whether or not these stacks are able to entrain as much airflow at high wind speeds as they are able to entrain at lower wind speeds. If these stacks do not perform as well under high wind speeds, the advantages of an entrained exhaust stack will be less than stated above.

In summary, no matter what type of exhaust system is used, the important parameters are the physical stack height, exhaust volume flow rate, exhaust velocity, and expected pollutant concentration levels at air intakes and other sensitive locations. Whether conventional or entrained air exhaust air systems are used, the overall performance should be evaluated using the appropriate criterion, i.e., ensuring acceptable concentrations at appropriate locations. Selecting an exhaust system based on an effective stack height specification alone is not sufficient to ensure an adequate exhaust system design.

RECOMMENDED ANALYTICAL APPROACH

The Basic Approach

The recommended approach to evaluating the air quality aspects of laboratory 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 above can be helpful in the design process, but they do not guarantee adequate air quality. Furthermore, the ANSI/AIHA Standard Z9.5 specifies that concentrations at air intakes be below 20% of allowable indoor concentrations (AIHA 1992) and confirming these concentrations requires dispersion modeling.

The air quality acceptability question can be written:

$$C_{max} < C_{health} \ ? \tag{1}$$

and

$$C_{max} < C_{odor} \ ? \tag{2}$$

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

In dispersion modeling, the actual quantity predicted is the ratio of concentration to mass emission rate, C/m, where m is the mass emission rate. The value of C/m is a function of the stack exhaust design, the receptor location, and the wind conditions—not a function of the chemical emitted. 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:

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

and

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

The left side of each equation, $(C/m)_{max}$, is only dependent on external factors, such as stack design, receptor location, and wind conditions. The right side of each equation is related to the chemical emissions. For a given chemical, the relationship 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.

This process of analysis is simplified by establishing a C/m design goal for the dispersion modeling that is the lowest value of normalized health limits or odor thresholds, $(C/m)_{health}$ and $(C/m)_{odor}$, for any emitted chemical. The process is illustrated in Figure 8. A chemical inventory for each exhaust type is examined to determine the appropriate values of $(C/m)_{health}$ and $(C/m)_{odor}$ for any released chemicals. The lowest value is of the most concern, and that value is ideally the design goal, $(C/m)_{goal}$. Dispersion modeling is performed to determine $(C/m)_{max}$ for all stack designs studied. Those designs that yield concentrations lower than the design goal, i.e., $(C/m)_{max}$ less than $(C/m)_{goal}$, are the recommended exhaust stack designs.

The dispersion modeling results can also be expressed as a dilution rate between the stack exit and receptor location. At first glance, a dilution design goal may be easier to comprehend because one can visualize the relationship between the emitted exhaust plume and the percentage of the plume that is present at a nearby receptor location. Unfortunately, the dilution design goal to achieve safe or odorless concentrations is also a function of the exhaust volume flow rate, Q. The higher the volume flow rate, the greater the interior dilution of the emitted substance that is present at the stack exit. Looking at only the exterior dilution between the exhaust stack and the receptor ignores the interior dilution component. For a single stack design where volume flow rate does not vary or where no internal dilution occurs, diesel generators, for example, a dilution-based approach is satisfactory. However, dilution goals or standards are not transferable to other designs with differing volume flow rates when the emission rate of a particular substance is not proportional with the total volume flow rate through the exhaust stack. This emission scenario is characteristic of exhaust sources such as a laboratory fume hood, biological safety cabinet, or isolation room exhaust. Thus, a dilution design goal for an entire university campus or industrial facility would not be practical where volume flow rates through individual exhaust stacks may vary widely.

Formulating a Concentration Design Goal

Three types of information are needed to develop normalized health limits and odor thresholds, $(C/m)_{health}$ and $(C/m)_{odor}$, for comparison to the dispersion modeling results: (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.

Chemicals 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. The recommended health limits (C_{health}) are based on ANSI/AIHA Standard Z9.5 on laboratory ventilation discussed above, which specifies air intake concentrations no higher than 20% of acceptable indoor concentrations. 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 (2001a). STELs are usually assumed appropriate for a 15-minute averaging time. For chemicals with only an eight-hour time weighted average (TWA) limit, the TWA can be adjusted to a short-term exposure limit (STEL) by multiplying the TWA by three (ACGIH 2001b). Conversation factors from one concentration averaging time to another (i.e., 3 hour, 24 hour, and annual averages) can be found in EPA (1992).

Odor Thresholds. ACGIH (1989) provides a good source for odor thresholds (C_{odor}). ACGIH critically reviews previous experimental data and lists geometric means of accepted data. For chemicals not listed in ACGIH (1989), geometric means of high and low values provided in Ruth (1986), another review article, are recommended. Geometric means are used since there are large variations in the sense of smell among individuals. Concentrations at the geometric mean of the reported odor thresholds are detectable by approximately 50% of the population. Higher concentrations are required to recognize the character or the odor ("fishy," "sweet," etc.). In most cases, a person will smell a chemical well before the health limit is reached.

Emission Rates. For laboratories, emission rates are typically based on small-scale accidental releases, either liquid spills or emptying of a small 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. However, there are several assumptions concerning spill amounts and gas bottle release rates that affect the concentration design goal. Evaporation from liquid spills is computed from equations in EPA (1992) based on a worst-case spill within a fume hood. Typically, the worst-case spill is defined as the complete evacuation of a 1.0 L (0.26 gal) beaker. A 1.0 L (0.26 gal) beaker is used as a worst-case scenario for two reasons. First, a 1.0 L (0.26 gal) beaker is often the largest container size typically found within a fume hood. Second, the typical countertop within a fume hood is on the order of 0.9 m (3.0 ft) deep by 1.1 m (3.6 ft) wide or 1.0 m^2 (11 ft^2). EPA (1992) suggests that the area of a liquid spill should be calculated assuming a 1 mm (0.004 in.) depth over the area of the spill. Thus, an area of 1.0 m^2 (11 ft^2) covered at a depth of 1 mm (0.004 in.) requires a volume of 1.0 L (0.26 gal). Since the evaporation of a liquid spill is proportional to the area of the spill, and not the depth, a spill volume of greater than 1.0 L (0.26 gal) over an area of 1.0 m^2 (11 ft^2) will not result in an increased emission rate. However, if the spill volume is decreased, the evaporation rate will decrease proportionally. Appropriate adjustments to the worst-case spill volume can be made to account for maximum storage quantities less than 1.0 L (0.26 gal) and for fume hood counter surface areas that are less than or greater than 1.0 m^2 (11 ft^2).

Compressed gas leaks assume the emptying of a lecture bottle in five minutes. Five minutes is the minimum time listed

Figure 9 *Photograph of a model installed in an atmospheric boundary-layer wind tunnel.*

in the Uniform Fire Code (UFC 1991) for control of accidental releases, although a deliberate opening of a lecture bottle can result in emptying times of less than one minute. Compressed gas bottle contents can be obtained from the provided inventories or from commercial catalogs. If a bottle much larger than a lecture bottle is specified, the emission time is either five minutes for a chemical in the gas phase in the bottle or 30 minutes if the gas is in a liquid phase inside the bottle (UFC 1991).

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 $(C/m)_{odor}$ for all emitted chemicals are computed. The computation can be limited to those known to have high toxicity, odor strength, and/or emission rates since these chemicals will have the most influence on the concentration design goal. The concentration design goal for the stack/receptor design will ideally be the minimum value of these limits for all of the chemicals.

Often for a facility with intensive chemical usage, this minimum normalized concentration value is below the minimum normalized concentration achievable with a reasonable stack design. There are limits to the effectiveness that a stack can provide in dispersing its exhaust. For example, if 1.0 L (0.26 gal) of undiluted ethyl mercaptan (a toxic chemical with a strong odor) were spilled, strong odors would be detectable throughout the site regardless of 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. The concentration design goal then becomes a compromise between these administrative measures and the aggressiveness of the stack design.

Use of the Concentration Design Goal for the Analysis. Once a concentration design goal has been selected and a stack design is installed that meets the goal, the concentration design goal is a useful quantity for the safety officer in charge of the laboratory to retain. 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 below the concentration design goal, air quality problems may arise, and usage or emission controls are warranted.

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 receptors of interest (ASHRAE 2001, chapter 16). The following section provides a description of typical wind-tunnel modeling methods.

Wind-Tunnel Similarity Criteria. An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind-tunnel study of diffusion for a laboratory facility. Wind-tunnel modeling uses similarity requirements obtained from dimensional arguments and the equations governing fluid motion. The similarity requirements are described in Cermak (1975) and the Environmental Protection Agency fluid modeling guidelines (EPA 1981). The more important similarity requirements for wind-tunnel modeling are:

1. Use of a physical model with similar geometric features to the real-world configuration that has no distortion of the vertical scale compared to the horizontal scale.
2. The matching of ratios of stack exit momentum to approach flow momentum and exhaust density to ambient density.
3. Sufficient airflow velocities within the wind tunnel to provide fully turbulent flow over the buildings.
4. Sufficient stack volume flow rate in the wind tunnel to provide fully turbulent exit flows for sources with significant upward momentum, or the use of “trips” within the stack to mechanically create a fully turbulent exit flow.
5. A representative approach “atmospheric boundary layer” flow that duplicates the increase of wind speed and decrease of turbulence with height above the ground seen in the full-scale atmosphere.

Scale Model and Wind Tunnel Setup. A scale model of the facility under evaluation and nearby surroundings, within a 1000 ft (300 m) to 3000 ft (900 m) radius, is constructed and placed on a turntable. A typical model turntable is shown in Figure 9. Model stacks are installed at the appropriate locations. Most stacks are supplied with a tracer gas mixture (e.g., an ethane and nitrogen mixture) with a density similar to room temperature air. Sources with a temperature hotter than ambient air, such as diesel generators and boilers, are supplied with a gas mixture with a density lighter than ambient air (e.g.,

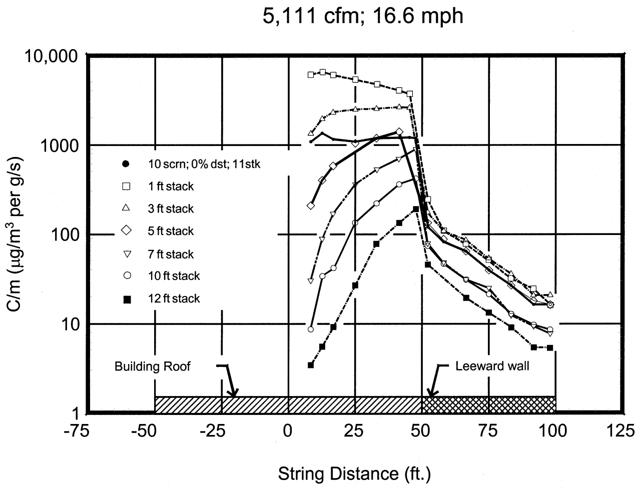


Figure 10 *Concentration distribution along roof and downwind side of rectangular building.*

ethane and helium). Precision mass flow controllers are used to monitor and regulate the discharge velocities. Concentration sampling points (receptors) are installed at the locations of interest for the particular facility under evaluation, i.e., air intakes, entrances, operable windows, courtyards, etc.

Testing is carried out in an atmospheric boundary-layer wind tunnel. Flow straighteners and screens at the tunnel inlet are used to create a homogenous, low-turbulence entrance flow. Spires and a trip downwind of the flow straighteners begin the development of the atmospheric boundary layer. The long boundary layer development region between the spires and the site model is filled with roughness blocks placed in the repeating roughness pattern. The roughness pattern is experimentally set to develop the appropriate approach boundary-layer wind profiles and approach surface roughness lengths. The approach profile is normally characterized by a surface roughness length, z_o, which is determined by fitting the measured velocity profile to the following equation:

$$\frac{U}{U_*} = \frac{1}{k}\ln\left(\frac{z}{z_o}\right) \tag{5}$$

where

U = velocity at height z,

z = elevation above ground level,

z_o = surface roughness length,

U^* = the friction velocity,

k = von Karmans constant (which is equal to 0.4).

Data Acquisition. The primary data of interest collected during the course of a study is concentration due to the tracer gas release from each source being simulated. Volume flow and wind speed measurements are also obtained for documentation and to set the wind-tunnel operating conditions. The following is a summary of the general concentration data collection procedures: (1) the airflow velocity within the wind tunnel is set to the specified value; (2) a tracer gas mixture with the appropriate density is released from the specified stack at the specified volume flow rate; (3) concentrations are measured at the receptor of interest and mean and root-mean-square normalized concentrations are displayed for the operator and saved to a computer file; (4) step three is repeated for a range of wind directions and wind speeds such that the maximum normalized concentration is found and such that sufficient dataare obtained to develop an equation to describe normalized concentration as a function of wind speed and direction; (5) the above process is repeated for every source/receptor combination identified in the concentration measurement test plan; and (6) the saved data files are then used to generate summary tables and for additional analysis, e.g., percent time a certain concentration is exceeded, total concentrations, annual averages, etc.

RESULTS FOR SIMPLE RECTANGULAR BUILDING

A simple rectangular building (Petersen et al. 1999) that is 50.0 ft (15.2 m) high, 50.0 ft (15.2 m) wide, and 100 ft (30.5 m) long was constructed and positioned in a boundary layer wind tunnel with a simulated suburban approach wind condition, i.e., surface roughness length of 0.50 m (19.7 in.). A tracer gas mixture with the same density as ambient air was released from a stack installed on the roof of the model building. The simulated volume flow rate from the stack was 5111 cfm (2.41 m^3/s), the exhaust velocity was 2000 fpm (10.2 m/s), and the stack height was varied from 1 ft to 12 ft (0.3 m to 3.7 m) while maintaining a 16 mph (7.2 m/s) wind speed at 33 ft (10 m). Concentration levels were measured on the building roof and building side for each condition. One test was run with an 11 ft (3.4 m) stack and 10 ft (3.0 m) solid screen positioned around the stack. All other tests had an unobstructed roof.

Figure 10 shows the normalized concentrations (*C*/*m*) on the building roof and the building side for various stack heights and screen configurations. It should be noted that string distances between 0 ft and 50.0 ft (15.2 m) are on the building roof, and string distances between 50.0 ft (15.2 m) and 100 ft (30.4 m) are on the side wall of the building. 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. This result points out the advantage of locating air intakes on building sidewalls versus the roof.

The results in Figure 10 can be used to assess the adequacy of the simple ASHRAE method for specifying stack heights illustrated in Figure 5. Using Figure 5, the minimum acceptable stack height for a 5000 cfm (2.4 m^3/s) and 3000 fpm (15.2 m/s) exhaust with an air intake 50.0 ft (15.2 m) from the exhaust point is approximately 13 ft (4.0 m). Figure 10 shows that a 10 ft (3.0 m) stack would be adequate to meet the 400 $\mu g/m^3$ per g/s ASHRAE design criterion. If the air intake is on the building side wall, there is presently no reliable method for accounting for the concentration decrease and a conservative approach would have to be taken, i.e., use Figure

5, which would give a 13 ft (4.0 m) stack height. Figure 10 shows that if the air intake were on the building side wall, a 5 ft stack would meet the ASHRAE criterion.

Figure 10 also shows that with a 10 ft (3.0 m) solid screen positioned around a 12 ft (3.7 m) stack, the concentrations on the roof are high and are similar to those for a 5.0 ft (1.5 m) stack. Hence, the solid screen has in effect reduced the effective stack height by a factor of 0.4. This result illustrates the adverse effect of rooftop features. The effect of these elements are often not accounted for using the simplified methods discussed previously and, hence, stack heights can be specified that are not tall enough to ensure acceptable air quality. It should be noted that the effect of screens on rooftop concentrations is discussed in detail in Petersen et al. (1999).

DISCUSSION AND CONCLUSIONS

This paper 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, the exhaust volume flow rate, exhaust velocity, and expected pollutant concentration levels at air intakes and other sensitive locations. Whether conventional or entrained exhaust air systems are used, the exhaust specification should be based on the appropriate criterion, that is, ensuring acceptable concentrations at appropriate locations. Selecting an exhaust system based on an effective stack height specification alone is not sufficient to ensure an adequate exhaust system design.

The paper 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 likely receptors, such as air intakes, operable windows, and pedestrian areas. Concentration goals for design acceptability are based on emission rates of chemicals likely to be used at the facility. Health limits, odor thresholds, and emission rates for the emitted chemicals are incorporated into the concentration design goal. Utilizing the approach for a simple building geometry demonstrated that the mathematical methods tended to give unnecessarily tall stack heights for an unobstructed roof and gave stacks that are not tall enough for a roof with obstructions.

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