Related Commercial Resources

CHAPTER 46. BUILDING AIR INTAKE AND EXHAUST DESIGN

OUTDOOR air enters a building through its air intake to provide ventilation air to building occupants. Likewise, building exhaust systems remove air from a building and expel the contaminants to the atmosphere. If the intake or exhaust system is not well designed, contaminants from nearby outdoor sources (e.g., vehicle exhaust, emergency generators, exhaust stacks on nearby buildings) or from the building itself (e.g., laboratory fume hood exhaust, plumbing vents) can enter the building before sufficient dilution is achieved. Poorly diluted contaminants may cause odors, health impacts, and reduced indoor air quality. This chapter discusses proper design of exhaust stacks and placement of air intakes to avoid adverse air quality impacts. Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals* describes wind and airflow patterns around buildings in greater detail. Related information can also be found in Chapters 9, 18, 33, 34, and 35 of this volume, Chapters 11 and 12 of the 2021 *ASHRAE Handbook—Fundamentals*, and Chapters 29, 30, and 35 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

1. EXHAUST STACK AND AIR INTAKE DESIGN STRATEGIES

Stack Design Strategies

The dilution a stack exhaust can provide is limited by the dispersion capability of the atmosphere. Before discharging out the stack, exhaust contamination can be reduced by filters, collectors, and scrubbers to maintain acceptable air quality. The goal of stack design is to specify the minimum flow of the exhaust system, exhaust velocity, and stack height that ensures acceptable air quality at all locations of concern. This also reduces the exhaust system's energy consumption.

Central exhaust systems that combine airflows from many exhaust sources should always be used where safe and practical. By combining several exhaust streams, central systems can dilute contaminants in the exhaust airstream more efficiently. The combined flow can generate an exhaust plume that rises a greater distance above the emitting building. If necessary for air quality reasons, additional air volume (bypass) can be added to the exhaust near the exit to increase initial dilution and exhaust plume rise. This added air volume does not need heating or cooling, and the additional energy cost is lower than increasing stack exit velocity. A small increase in stack height may also achieve the same benefit without an added energy cost.

In some cases, separate exhaust systems are mandatory. The nature of the contaminants to be combined, recommended industrial hygiene practice, and applicable safety codes need to be considered. Separate exhaust stacks could be grouped in close proximity to one another to take advantage of the larger plume rise of the resulting combined jet. Also, a single stack location for a central exhaust system or a tight cluster of stacks provides more options for locating building air intakes on the building facade or roof. Petersen and Reifschneider (2008) provide guidelines for optimal arrangements of ganged stacks. In general, for a tight cluster to be considered as a single stack (i.e., to add stack momentums together) in dilution calculations, the stacks must be uncapped and nearly be touching the middle stack of the group.

As shown in Figure 1, stack height h_s is measured from the roof level on which the exhaust stack is located to the top of the stack. To take full advantage of their height, stacks should be located on the highest roof of a building. Wilson and Winkel (1982) demonstrated that stacks terminating below the level of adjacent walls and architectural enclosures frequently do not effectively reduce roof-level exhaust contamination. Architectural screens used to mask rooftop equipment adversely affect exhaust dilution, depending on porosity, relative height, and distance from the stack; Petersen et al. (1999) found that exhaust dispersion improves with increased screen porosity.

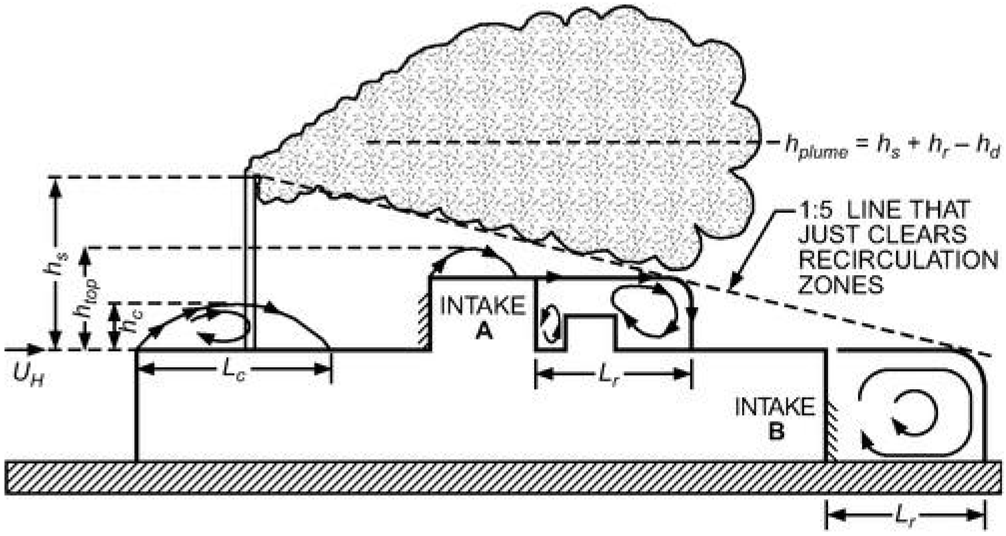

Figure 1. Flow Recirculation Regions and Exhaust Parameters (Wilson 1982)

Large buildings, structures, and terrain close to the emitting building can adversely affect stack exhaust dilution, because the emitting building can be within the flow recirculation zones downwind of these nearby flow obstacles (Wilson et al. 1998a). In addition, ventilation air entering air intakes located on nearby taller buildings can be contaminated by stack exhaust from shorter buildings. Wherever possible, facilities emitting toxic or highly odorous contaminants should not be located near taller buildings or at the base of steep terrain.

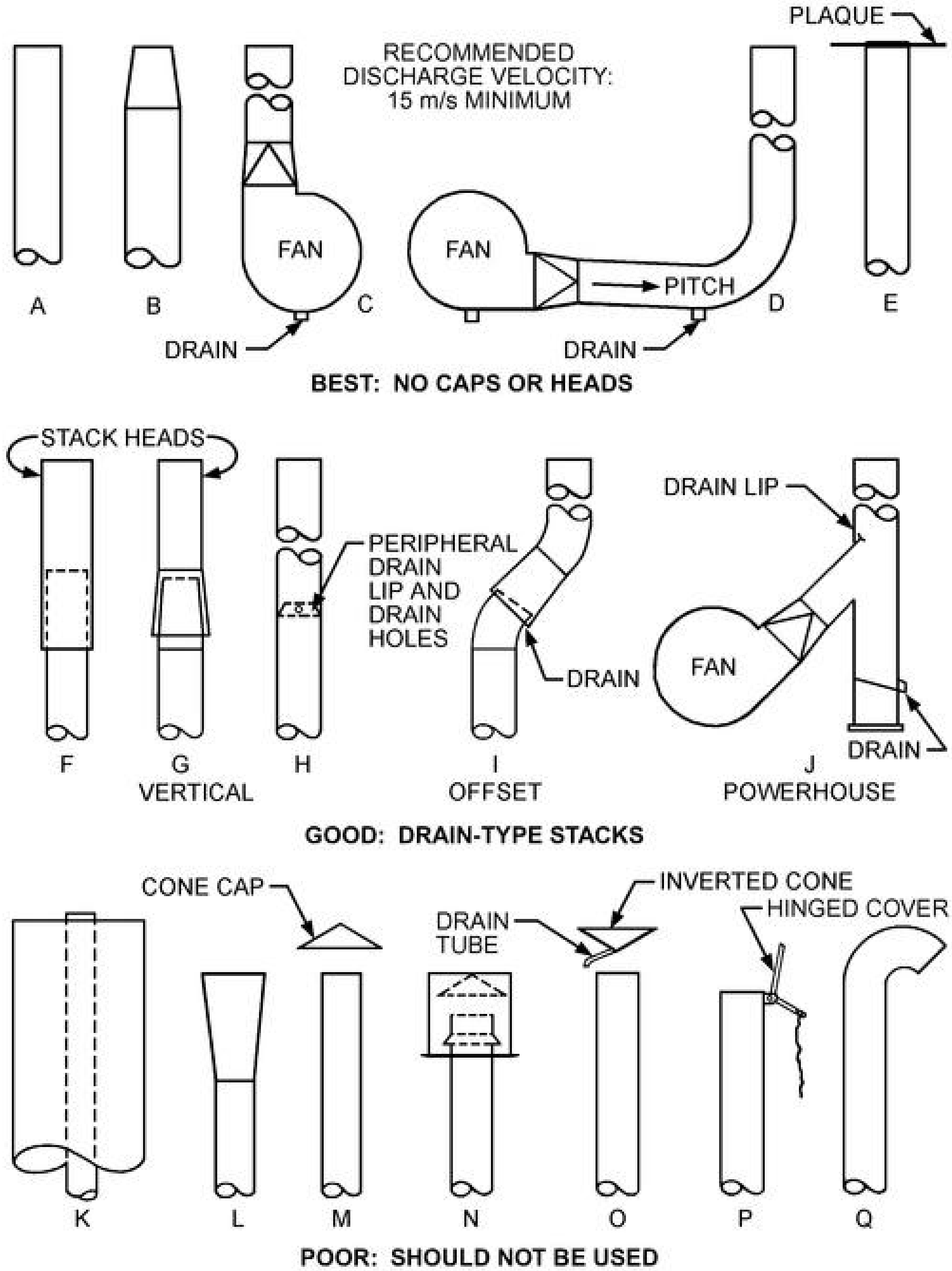

Figure 2. Stack Designs Providing Vertical Discharge and Rain Protection

As shown in Figure 2, stacks should be vertically directed and uncapped. Stack caps that deflect the exhaust jet have a detrimental effect on exhaust plume rise. Small conical stack caps often do not completely exclude rain, because rain does not always fall straight down; periods of heavy rainfall may be accompanied by high winds that deflect raindrops under the cap and into the stack (Changnon 1966). A stack exhaust velocity V_e of about 13 m/s prevents condensed moisture from draining down the stack and keeps rain from entering the stack. For intermittently operated systems, protection from rain and snow should be provided by stack drains, as shown in Figure 2F to 2J, rather than stack caps.

Recommended Stack Exhaust Velocity

High stack exhaust velocity and temperatures increase plume rise, which tends to reduce intake contamination. Exhaust velocity V_e should be maintained above 10 m/s (even with drains in the stack) to provide adequate plume rise and jet dilution. Velocities above 10 m/s provide greater plume rise and dilution, but above 15 to 20 m/s, noise, vibration, and energy costs can become an important concern. An exit nozzle (Figure 2B) can be used to increase exhaust velocity and plume rise. Many laboratory fume hood systems use variable-volume fans that reduce flow from hoods when they are closed. Stack exhaust velocity calculations must be based on the minimum total flow rate from the system, not the maximum. Additional optimization of the exhaust can be gained through detailed dispersion modeling of the exhaust stack, which can determine the minimum exit velocity needed to maintain acceptable dilution versus stack height, allowing for lower exit velocities. Generally, taller stacks require lower exit velocity and fan energy consumption.

An exception to these exhaust velocity recommendations include when corrosive condensate droplets are discharged. In this case, a velocity of 5 m/s in the stack and a condensate drain are recommended to reduce droplet emission. At this low exhaust velocity, a taller stack may be needed to counteract downwash caused by low exit velocity.

Stack wake downwash occurs where low-velocity exhausts are pulled downward by negative pressures immediately downwind of the stack, as shown in Figure 3. V_e should be at least 1.5 times the design speed U_H at stack height in the approach wind to avoid stack wake downwash. A meteorological station design wind speed U_{met} that is exceeded less than 1% of the time can be used as U_H. This value can be obtained from Chapter 14 of the 2021 *ASHRAE Handbook—Fundamentals*, or estimated by applying Table 2 of Chapter 24 of that volume to annual average wind speed. Because wind speed increases with height, a correction for stack height should be applied for buildings significantly higher than 10 m, using the power law rule described in Equation (4) and Table 1 of Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*.

Other Stack Design Standards

Minimum heights for chimneys and other flues are discussed in the *International Building Code* (ICC 2021). For laboratory fume hood exhausts, ANSI/ASSP (American Society of Safety Professionals) *Standard* Z9.5 recommends a minimum stack height of 3 m above the adjacent roof line to protect maintenance workers from direct exposure from the top of the stack, and an exhaust velocity V_e sufficient to reduce the concentration of hazardous materials in the exhaust to safe levels at all potential receptor locations, and includes a methodology for evaluation. National Fire Protection Association (NFPA) *Standard* 45 specifies a minimum stack height of 3 m to protect rooftop workers. Toxic chemical emissions may also be regulated by federal, state, and local air quality agencies.

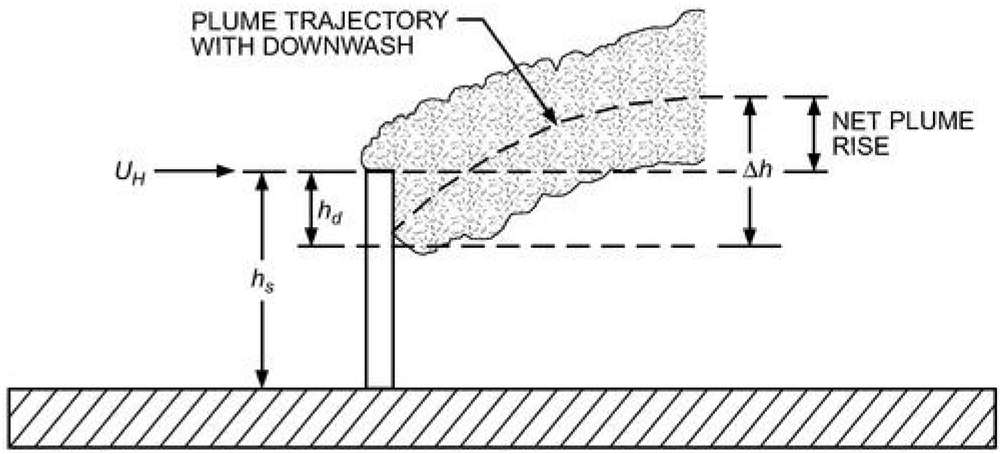

Figure 3. Reduction of Effective Stack Height by Stack Wake Downwash

Contamination Sources

Some contamination sources that need consideration in stack and intake design include the following.

Toxic Stack Exhausts . Boilers, emergency generators, and laboratory fume hoods are some sources that can seriously affect building indoor air quality because of toxic air pollutants. These sources, especially diesel-fueled emergency generators, can also produce strong odors that may require administrative measures, such as generator testing during low building occupancy or temporarily closing the intakes.

Automobile and Truck Traffic. Heavily traveled roads and parking garages emit carbon monoxide, dust, and other pollutants. Diesel trucks and ambulances are common sources of odor complaints (Smeaton et al. 1991). Avoid placing intakes near vehicle loading zones. Overhead canopies on vehicle docks do not prevent hot vehicle exhaust from rising to intakes above the canopy. When the loading zone is in the flow recirculation region downwind from the building, vehicle exhaust may spread upwind over large sections of the building surface (Ratcliff et al. 1994). Garbage containers may also be a source of odors, and garbage trucks may emit diesel exhaust with strong odors.

Kitchen Cooking Hoods. Kitchen exhaust can be a source of odors and cause plugging and corrosion of heat exchangers. Grease hoods have stronger odors than other general kitchen exhausts. Grease and odor removal equipment beyond that for code requirements may be needed if air intakes cannot be placed an appropriate distance away.

Evaporative Cooling Towers. Outbreaks of Legionnaires' disease have been linked to bacteria in cooling tower drift droplets being drawn into the building through air intakes (Puckorius 1999). ASHRAE *Guideline* 12 gives advice on cooling tower maintenance for minimizing the risk of Legionnaires' disease, and suggests keeping cooling towers as far away as possible from intakes, operable windows, and outdoor public areas. No specific minimum separation distance is provided or available. Prevailing wind directions should also be considered to minimize risk. Evaporative cooling towers can have several other effects: water vapor can increase air-conditioning loads, condensing and freezing water vapor can damage equipment, and ice can block intake grilles and filters. Chemicals added to retard scaling and biological contamination may be emitted from the cooling tower, creating odors or health effects, as discussed by Vanderheyden and Schuyler (1994).

Building General Exhaust Air. General indoor air that is exhausted normally contains elevated concentrations of carbon dioxide, dust, copier toner, off-gassing from materials, cleaning agents, and body odors. General exhaust air should not be allowed to reenter the building without sufficient dilution.

Stagnant Water Bodies, Snow, and Leaves. Stagnant water bodies can be sources of objectionable odors and potentially harmful organisms. Avoid poor drainage on the roof or ground near the intake. Restricted airflow from snow drifts, fallen leaves, and other debris can be avoided in the design stage with elevated louvers above ground or roof level.

Rain and Fog. Direct intake of rain and fog can increase growth of microorganisms in the building. AMCA (2009) recommends selecting louvers and grilles with low rain penetration and installing drains just inside the louvers and grilles. In locations with chronic fog, some outdoor air treatment is recommended. One approach is to recirculate part of the indoor air to evaporate entrained water droplets, even during full air-side economizer operation (maximum outdoor air use).

Environmental Tobacco Smoke. Outdoor air intakes should not be placed close to outdoor smoking areas.

Plumbing Vents. Codes frequently require a minimum distance between plumbing vents and intakes to avoid odors.

Smoke from Fires. Smoke from fires is a significant safety hazard because of its direct health effects and from reduced visibility during evacuation. NFPA *Standard* 92A discusses the need for good air intake placement relative to smoke exhaust points.

Construction. Construction dust and equipment exhaust can be a significant nuisance over a long period. Temporary preconditioning of outdoor air is necessary in such situations, but is rarely provided. A simple solution is to provide room and access to the outdoor air duct for adding temporary air treatment filters or other devices, or a sufficient length of duct so that such equipment could be added when needed. Intake louvers and outdoor air ducts also require more frequent inspections and cleaning when construction occurs nearby.

Vandalism and Terrorism. Acts of vandalism and terrorism are of increasing concern. Louvers and grilles are potential points of illegal access to buildings, so their placement and construction are important. Intentional introduction of offensive or potentially harmful gaseous substances is also of concern. Some prudent initial design considerations might be elevating grilles and louvers away from easy pedestrian access and specifying security bars and other devices. Also, unlocked stair tower doors required for roof access during emergency evacuations may limit use of rooftop air intakes in sensitive applications because individuals would have ready access to the louvers. For more information, see ASHRAE's (2003) *Risk Management Guidance for Health, Safety, and Environmental Security under Extraordinary Incidents*.

General Guidance on Intake Placement

Carefully placed outdoor air intakes can reduce stack height requirements and help maintain acceptable indoor air quality. Rock and Moylan (1999) reviewed literature on air intake locations and design, and Petersen and LeCompte (2002) showed the benefit of placing air intakes on building sidewalls. ASHRAE *Standard* 62.1 highlights the need to locate makeup air inlets and exhaust outlets to avoid contamination.

Experience provides some general guidelines on air intake placement. Unless the appropriate dispersion modeling analysis is conducted, intakes should never be located in the same architectural screen enclosure as contaminated exhaust outlets. This is especially the case for low-momentum or capped exhausts (which tend to be trapped in the wind recirculation zone within the screen). For more information, see the section on Influence of Architectural Screens on Exhaust Dilution.

If exhaust is discharged from several locations on a roof, intakes should be sited to minimize contamination. Typically, this means maximizing separation distance. Where all exhausts of concern are emitted from a single, relatively tall stack or tight cluster of stacks, a possible intake location might be close to the base of this tall stack, if this location is not adversely affected by other exhaust locations or is not influenced by tall adjacent structures creating downwash. However, contaminant leakage from the side of the stack has been observed in positively pressurized areas between the exhaust fans and stack exit (Hitchings 1997; Knutson 1997), so air intakes should not be placed very close to highly toxic or odorous exhaust stacks regardless of stack height.

Intakes near vehicle loading zones should be avoided. Overhead canopies on vehicle docks do not effectively protect air intakes, and vehicle exhaust may spread over large sections of the building surface. Loading zones also may have garbage and solid waste receptacles that create odors; trucks that serve the receptacles also produce odors. Air intakes should also not be placed near traffic or truck waiting areas. General building exhausts should also not be placed near outdoor contamination sources because flow reversal and ingestion of air through exhaust outlets can occur under some conditions (Seem et al. 1998).

Examining airflow around a building can help determine air intake placement. When wind is perpendicular to the upwind wall, air flows up and down the wall, dividing at about two-thirds up the wall (Figures 4 and 5). The downward flow creates ground-level swirl (shown in Figure 4) that stirs up dust and debris. To take advantage of the natural separation of wind over the upper and lower halves of a building, toxic or nuisance exhausts should be located on the roof and intakes located on the lower one-third of the building, but high enough to avoid wind-blown dust, debris, and vehicle exhaust. If ground-level sources (e.g., wind-blown dust, vehicle exhaust) are major sources of contamination, rooftop intake is desirable.

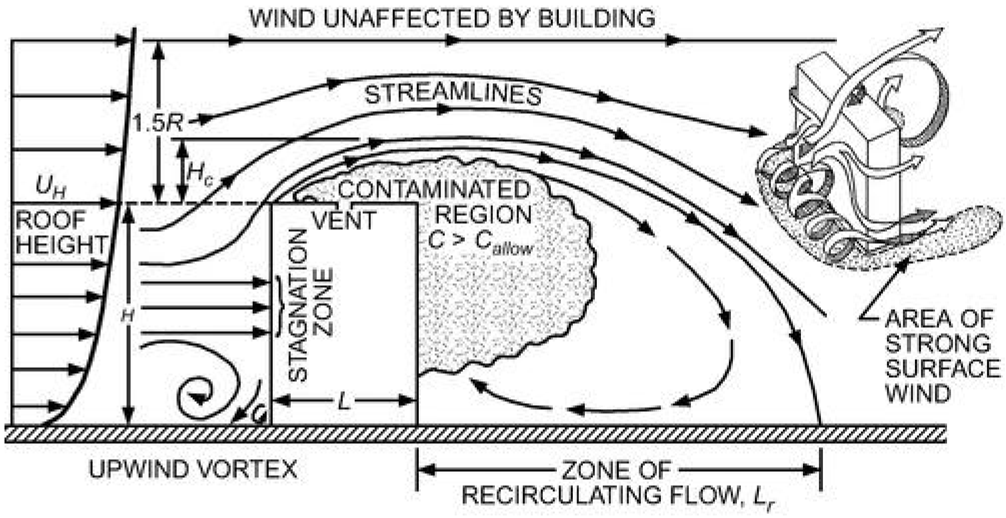

Figure 4. Flow Patterns Around Rectangular Building

Code Requirements for Air Intakes

Many model building codes exist, and local governments adopt and amend codes as needed. Architects and building systems designers need to be familiar with local and national codes applicable to each project. Mechanical and plumbing codes typically give minimum required separation distances for some situations; however, maintaining these separation distances does not necessarily guarantee that intake contamination will not occur.

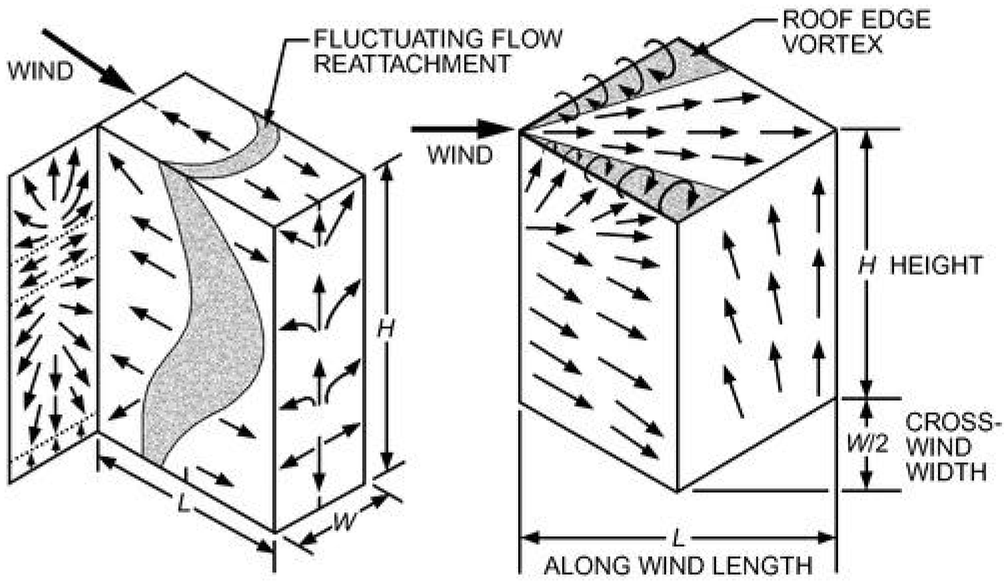

Figure 5. Surface Flow Patterns and Building Dimensions

One example of a model building code is the *Uniform Mechanical Code* (UMC) (IAPMO 1997a), which has been widely adopted in the United States. The UMC requires that exhausts be at least 0.9 m from property lines and 0.9 m from openings into buildings. Makeup air intakes should be placed to avoid recirculation. Grease- and explosives-bearing ducts, combustion vents, and refrigeration equipment have special requirements: intakes should be at least 3 m from combustion or plumbing vents and exhaust air outlets, and be at least 3 m above a road. Cooling towers should be 1.5 m above or 6 m away from intakes.

The *Uniform Plumbing Code* (UPC) (IAPMO 1997b) requires that exhaust vents from domestic water heaters be 0.9 m or more above air inlets. Sanitary vents must be 3 m or more from or 0.9 m above air intakes. When UPC and UMC requirements conflict, the UPC provisions govern. However, local jurisdictions may modify codes, so the adopted versions may have significantly different requirements than the model codes.

Treatment and Control Strategies

When available intake/exhaust separation does not provide the desired dilution factor, or intakes must be placed in undesirable locations, ventilation air requires some degree of treatment, as discussed in Section 6.2.1 of ASHRAE *Standard* 62.1. Fibrous media, inertial collectors, and electrostatic air cleaners, if properly selected, installed, and maintained, can effectively treat airborne particles. Reducing gaseous pollutants requires scrubbing, absorptive, adsorptive, or incinerating techniques. Biological hazards require special methods such as using high-efficiency particulate air (HEPA) filters and ultraviolet light. Chapters 17, 29, and 30 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* describe these treatments in detail. One control approach that should be used with care is selective operation of intakes. If a sensor in the intake airstream detects an unacceptable level of some substance, the outdoor air dampers are closed until the condition passes. This strategy has been used for helicopter landing pads at hospitals and during emergency generator testing. The drawbacks are that pressurization is lost and ventilation air is not provided unless the recirculated air is heavily treated. In areas of chronically poor outdoor air quality, such as large urban areas with stagnant air, extensive and typically costly treatment of recirculated air may be the only effective option when outdoor air dampers are closed for extended periods.

Intake Locations for Heat-Rejection Devices

Cooling towers and similar heat-rejection devices are very sensitive to airflow around buildings. This equipment is frequently roof-mounted and has intakes close to the roof, where air can be considerably hotter and at a higher wet-bulb temperature than air that is not affected by the roof. This can reduce the capacity of cooling towers and air-cooled condensers.

Heat exchangers often take in air on one side and discharge heated, moist air horizontally from the other side. Obstructions immediately adjacent to these horizontal-flow cooling towers can drastically reduce equipment performance by reducing airflow. Furthermore, exhaust-to-intake recirculation can be an even more serious problem for this equipment: recirculation of warm, moist exhaust raises the inlet wet-bulb temperature, which reduces performance. Recirculation can be caused by adverse wind direction or local disturbance of airflow by an upwind obstruction, or by a close downwind obstruction. Vertical exhaust ducts may need to be extended to reduce recirculation and improve equipment effectiveness.

Wind Recirculation Zones on Flat-Roofed Buildings

Stack height design must begin by considering the wind recirculation regions (Figure 6). To avoid exhaust reentry, the stack plume must avoid rooftop air intakes and wind recirculation regions on the roof and in the wake downwind of the building. If stacks or exhaust vents discharge within this region, gases rapidly diffuse to the roof and may enter ventilation intakes or other openings. Figures 4 and 6 show that exhaust gas from an improperly designed stack is entrained into the recirculating flow zone behind the downwind face and is brought back into contact with the building.

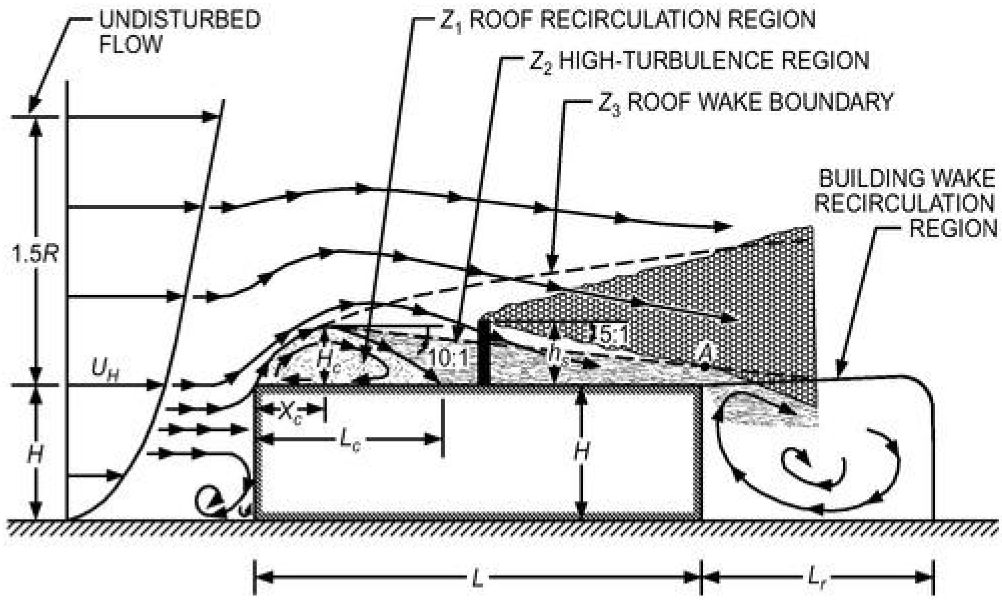

Figure 6. Design Procedure for Required Stack Height to Avoid Contamination (Wilson 1979)

Wilson (1979) found that, for a flat-roofed building, the upwind roof edge recirculation region height H_c at location X_c and its recirculation length L_c (shown in Figures 1 and 6) are proportional to the building size scale R:

$$H_c = 0.22R \quad (1)$$

$$X_c = 0.5R \quad (2)$$

$$L_c = 0.9R \quad (3)$$

and the wind recirculation cavity length L_r on the downwind side of the building is approximately

$$L_r = R \quad (4)$$

where R is the building scaling length:

$$R = B_s^{0.67} B_L^{0.33} \quad (5)$$

where B_s is the smaller of the building upwind face dimensions (height or width) and B_L is the larger. These equations are approximate but are recommended for use. The dimensions of flow recirculating zones depend on the amount of turbulence in the approaching wind. High levels of turbulence from upwind obstacles can decrease the coefficients in Equations (1) to (4) by up to a factor of two. Turbulence in the recirculation region and in the approaching wind also causes considerable fluctuation in the position of flow reattachment locations (Figures 5 and 6).

Rooftop obstacles such as penthouses, equipment housings, and architectural screens are accounted for in stack design by calculating the scale length R for each of these rooftop obstacles from Equation (5) using the upwind face dimensions of the obstacle. The recirculation regions for each obstacle are then calculated from Equations (1) to (4). When a rooftop obstacle is close to the upwind edge of a roof or another obstacle, the flow recirculation zones interact. Wilson (1979) gives methods for dealing with these situations.

Building-generated turbulence is confined to the roof wake region, whose upper boundary Z_3 in Figure 6 is

$$Z_3/R = 0.28(x/R)^{0.33} \quad (6)$$

where x is the distance from the upwind roof edge where the recirculation region forms. Building-generated turbulence decreases with increasing height above roof level. At the edge of rooftop wake boundary Z_3, turbulence intensity is close to the background level in the approach wind. The high levels of turbulence in the air below the boundary Z_2 in Figure 6 rapidly diffuse exhaust gases downward to contaminate roof-level intakes. As shown in Figure 6, the boundary Z_2 of this high-turbulence region downwind of a wind recirculation region is approximated by a straight line sloping at 10:1 downward from the top of the wind recirculation zone to the roof. The stack in Figure 6 may be inadequate because at point A the plume intersects the high turbulence boundary Z_2. The geometric method for stack height is discussed in more detail in the next section.

2. GEOMETRIC METHOD FOR ESTIMATING STACK HEIGHT

This section presents a method of specifying stack height h_s so that the lower edge of the exhaust plume lies above air intakes and wind recirculation zones on the roof and downwind of the emitting building, based on flow visualization studies (Wilson 1979). This method does not calculate exhaust dilution in the plume; instead, it estimates the size of recirculation and high turbulence zones, and the stack height to avoid contamination is calculated from the shape of the exhaust plume. High vertical exhaust velocity is accounted for with a plume rise calculation that shifts the plume upward. Low vertical exhaust velocity that allows stack wake downwash of the plume (see Figure 3) is accounted for by reducing the effective stack height.

This stack height should prevent reentry of exhaust gas into the emitting building most of the time, if no large buildings, structures, or terrain are nearby to disturb the approaching wind. The geometric method considers only intakes on the emitting building. Additional stack height or an exhaust-to-intake roof-level dilution calculation is often required if the exhaust plume can impinge on a nearby building (Wilson et al. 1998b). Dilution calculations should be used if this method produces an unsatisfactorily high stack, or if exhaust gases are highly toxic releases from fume hood exhaust.

Rooftop obstacles can significantly alter dispersion from exhaust stacks immediately downwind of, and of similar height to, the obstacles (Saathoff et al. 2002). The goal of the geometric stack method is to ensure that the exhaust plume is well above the recirculation zones associated with these obstacles.

Step 1. Use Equations (1) to (5) to calculate the height and location of flow recirculation zones 1 and 2 and the recirculation zone downwind of the building (see Figure 6). All zones associated with rooftop obstacles up- and downwind of the stack location should be included. Note that zone 3 is not used in the geometric design method.

Step 2. Draw the recirculation regions on the top and downwind sides of penthouses, equipment housings, architectural screens, and other rooftop obstacles up- and downwind of the stack location. If there are intakes on the downwind wall of the building, include the building recirculation region L_r on this wall. Now, calculate the height h_{sc} of a stack with a rain cap (i.e., no plume rise) and draw a line sloping down at 1:5 (11.3°) in the wind direction above the roof. Slide this line down toward the building as shown in Figure 1 until it contacts any one of the recirculation zones on any obstacle up- or downwind of the stack (or until the line contacts any portion of the building if there are no rooftop zones or sidewall intakes). With the line in this position, its height at the stack location is the smallest allowable plume height h_{sc} for that wind direction. Repeat for other wind directions to find the worst-case (highest) required plume height.

This estimated h_{sc} is based on an assumption that the plume spreads up and down from h_{sc} with a 1:5 slope (11.3°), as shown in Figure 6. (This slope represents a downward spread of approximately two standard deviations of a bell-curve Gaussian plume concentration distribution in the vertical direction.)

Step 3. Reduce the stack height to give credit for plume rise from uncapped stacks. Only jet momentum rise is used; buoyancy rise is neglected as a safety factor. For an uncapped stack of diameter d_e, plume rise h_r from the vertical jet momentum of the exhaust is estimated versus downwind distance from Briggs (1984) as

$$h_r = \min\{\beta h_x, \beta h_f\} \tag{7}$$

where the plume rise versus downwind distance, in m, is

$$h_x = \left\{\left(\frac{3F_m x}{\beta_j^2 U_H^2}\right)^{1/3}\right\}$$

momentum flux, in m^4/s^2, is

$$F_m = V_e^2\left(\frac{d_e^2}{4}\right)$$

the diameter of exhaust is

$$d_e = \sqrt{4A_e/\pi}$$

the jet entrainment coefficient is

$$\beta_j = \frac{1}{3} + \frac{U_H}{V_e}$$

the final plume rise, in m, is

$$h_f = \frac{0.9[F_m U_H/U_*]^{1/2}}{U_H \beta_j}$$

and the logarithmic wind profile equation is

$$U_H/U_* = 2.5\ \ln(H/z_o)$$

where

β	=	stack capping factor: 1.0 without cap, 0 with cap
x	=	distance downwind of stack, m
V_e	=	stack exit velocity, ft/sm/s
A_e	=	area of exhaust
U_H	=	wind speed at stack height, ft/sm/s
H	=	building height above ground level, m
U_*	=	friction velocity, ft/sm/s
z_o	=	surface roughness length, m

Table 1 Atmospheric Boundary Layer Parameters

Terrain Category	**z_o, m**	***a***	**δ, m**
Flat, water, desert	0.01	0.10	213
Flat, airport, grassland	0.05	0.14	274
Suburban	0.65	0.22	365
Urban*	2.0	0.33	457

* See text below for further guidance on the Urban category

Table 1 describes various z_o values for a range of sites. For example if z_o equals 0.65 m and H = 15 m, substituting into the logarithmic wind profile equation gives U_H/U_* = 7.9.

The urban terrain category should only be applied for projects within dense urban centers with many buildings of 30 stories or greater, typical of the New York financial district. For areas outside of dense urban centers, the Suburban terrain category often more accurately characterizes the atmospheric boundary layer.

For an uncapped stack, the capping factor is β = 1.0 in Equation (7). For a capped stack, β = 0, so h_r = 0, and no credit is given for plume rise. U_H is the maximum design wind speed at stack height for which air intake contamination must be avoided. This maximum design speed must be at least as large as the hourly wind speed exceeded 1% of the time. This 1% design speed is listed for many cities in ChapterChapter 14 of the 2021 *ASHRAE Handbook—Fundamentals* (on the CD-ROM and ASHRAE Handbook Online). For cities not on this list, set U_H equal to 2.5 times the annual average hourly wind speed as recommended in Table 2 of Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*.

The plume rise of Equation (7) plus the physical stack height should not be considered equivalent to an effective stack height. A real stack of that height has better performance for two reasons: the effective height is achieved immediately instead of somewhere downstream, and the plume is higher than the effective height because of exhaust momentum. Stack height and plume rise are additive in the geometric method as a simplification, but there are other conservatisms built into the geometric method to offset this approach.

Step 4. Increase stack height, if necessary, to account for stack wake downwash caused by low exhaust velocity, as described in the section on Recommended Stack Exhaust Velocity. For a vertically directed jet from an uncapped stack (β = 1.0), Wilson et al. (1998b) recommend a stack wake downwash adjustment h_d of

$$h_d = d_e(3.0 - 2\beta V_e/U_H) \tag{8}$$

for V_e/U_H < 3.0. For V_e/U_H > 3.0, there is no downwash and h_d = 0. Rain caps and louvers are frequently used on stacks of gas- and oil-fired furnaces and packaged ventilation units, for which β = 0 and h_d = 3.0d_e.

The final adjusted stack height h_s recommended is

$$h_s = h_{sc} - h_r + h_d \tag{9}$$

The advantage of using an uncapped stack instead of a capped stack is considerable. If the minimum recommended exhaust velocity V_e of 1.5U_H is maintained for an uncapped stack (β = 1.0), plume downwash h_d = 1.5d_e and h_r = 4.5d_e. For a capped stack (β = 0), h_d = 3.0d_e and h_r = 0. Using these values in Equation (10), an uncapped stack can be made 6.0d_e shorter than a capped stack.

Example 1. The stack height h_s of the uncapped vertical exhaust on the building in Figure 1 must be specified to avoid excessive contamination of intakes A and B by stack gases. The stack has a diameter d_e of 0.5 m and an exhaust velocity V_e of 9.0 m/s. It is located 16 m from the upwind edge of the roof. The penthouse's upwind wall (with intake A) is located 30 m from the upwind edge of the roof, 4 m high, and 7 m long in the wind direction. The top of intake A is 2 m below the penthouse roof. The building has a height H of 15 m and a length of 62 m. The top of intake B is 6 m below roof level. The width (measured into the page) of the building is 50 m, and the penthouse is 9 m wide. The annual average hourly wind speed is 12.8 km/h at a nearby airport with an anemometer height H_{met} of 10 m. The building is in suburban terrain (see Table 1). Calculate the required stack height h_s by the geometrical method using the lowest allowable design wind speed.

Solution: The first step is to set the height h_{sc} of a capped stack by projecting lines with 1:5 slopes so that recirculation zones are covered, as shown in Figure 1. The only influence of intake location is that the downwind recirculation zone must be considered if there is an intake on the downwind wall, which is true for intake B in this example.

First, check the rooftop recirculation zone associated with the penthouse. To find the height of this recirculation zone, use Equation (5):

$$R = (4)^{0.67}(9.0)^{0.33} = 5.23 \text{ m}$$

Then use Equations (1) and (2):

$$H_c = (0.22)(5.23) = 1.15 \text{ m}$$

$$X_c = (0.5)(5.23) = 2.62 \text{ m}$$

With the 1:5 slope of the lower plume boundary shown in Figure 6, the capped stack height in Figure 1 (measured from the main roof) must be

$$h_{sc} = 0.2(30 - 16 + 2.62) + 1.15 + 4.0 = 8.5 \text{ m}$$

to avoid the recirculation zone above the penthouse.

Next, check the building wake recirculation zone downwind of the building. The plume must also avoid this region because intake B is located there. The length of this recirculation region is found using Equation (4):

$$L_r = (15)^{0.67}(50)^{0.33} = 22.3 \text{ m}$$

Projecting the downwind corner of this recirculation region upwind with a 1:5 slope to the stack location gives the required height of a no-downwash capped stack above the main roof level as

$$h_{sc} = 0.2(62 + 22.3 - 16) = 13.7 \text{ m}$$

for the plume to avoid the recirculation zone on the downwind side of the building.

The design stack height is set by the condition of avoiding contamination of the building wake, because avoiding the penthouse roof recirculation requires only a 8.5 m capped stack. Credit for plume rise h_r from the uncapped stack requires calculation of the building wind speed U_H at H = 15 m. The minimum allowable design wind speed is the speed that is exceeded 1% of the time at the meteorological station. In this case, for H_{met} = 10 m at the airport meteorological station, this 1% wind speed is U_{met} = 2.5(12.8) = 32 km/h = 9 m/s, using the relationship described in Table 2 of Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*. With the airport in open terrain (see Table 1), and the building in suburban terrain, the wind speed adjustment parameters are a_{met} = 0.14 and δ_{met} = 274 m at the airport, and a = 0.22 and δ = 365 m at the building. Using Equation (4) in Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*, with building height H = 15 m,

$$U_H = 9\left(\frac{274}{10}\right)^{0.14}\left(\frac{15}{365}\right)^{0.22} = 7.1 \text{ m/s}$$

Because V_e / U_H = 9.0/7.1 = 1.27 is less than 3.0, there is some plume downwash as shown in Figure 3. From Equation (9),

$$h_d = 0.5[3 - 1.0(1.27)] = 0.86 \text{ m}$$

Then, using Equation (7), the plume rise at the design wind speed and the distance to the closest intake A is calculated to be

x	=	14.1 m
H	=	15 m
d	=	0.5 m
V_e	=	9 m/s
U_H	=	7 m/s
z_o	=	0.65 m
F_m	=	5.1 m^4/s^2
B_j	=	1.11
h_x	=	1.52 m
U_H/U_*	=	7.9
h_f	=	0.73 m
h_r	=	0.73 m

Using these values in Equation (10), the uncapped height h_{sc} is, with the height reduction credit for the 1.92 m rise and the height addition to account for the 0.86 m downwash,

$$h_s = 13.7 - 0.74 + 0.86 = 13.82 \text{ m}$$

As shown in Figure 1, this stack height is measured above the main roof. If stack height is higher than desirable, an alternative is to use dilution calculations. The geometric method does not directly account for dilution within the plume.

3. EXHAUST-TO-INTAKE DILUTION OR CONCENTRATION CALCULATIONS

Worst-Case Critical Dilution or Maximum Concentration

The geometric stack design procedure does not give a quantitative estimate of the worst-case critical dilution factor D_{crit} at an air intake. If a required dilution can be specified with known stack emissions and required health limits, odor thresholds, or air quality regulations, computing critical dilutions is the preferred method for specifying stack heights. Petersen et al. (2002, 2004) and Smeaton et al. (1991) discuss use of emission information and formulation of dilution requirements in more detail. Exhaust from a single-source dedicated stack may require more atmospheric dilution than a single stack with the same exhausts combined, because emissions are diluted in the exhaust manifold.

This section describes the methods for computing outdoor dilution of exhausts emitted from a rooftop stack because of atmospheric dispersion processes. The resulting dilution can be converted to contaminant concentration for comparison to odor thresholds or health limits. Dispersion of pollutants from building exhausts depends on the combined effect of atmospheric turbulence in the wind approaching the building and turbulence generated by the building itself. This building-generated turbulence is most intense in and near the flow recirculation zones that occur on the upwind edges of the building (Figures 1 and 5). Dilution of exhaust gas is estimated using design procedures developed for tall isolated stacks (EPA 1995, 2004), with modifications to include the high turbulence levels experienced by a plume diffusing over a building roof in an urban area (Schulman et al. 2000). Halitsky (1982), Hosker (1984), Meroney (1982), and Wilson and Britter (1982) are good references regarding gas diffusion near buildings.

Dispersion models (including physical models) ranging from the simple to very complex are intended to help the designer investigate how pollutants will be distributed in the atmosphere, around the building, and around adjacent buildings and areas. These models identify potential problems that could result in too-high pollution concentrations by air intakes, entrances, or other sensitive areas that can fairly easily be corrected during design by changing design parameters such as exhaust exit velocity, stack location or height, etc. Identifying these problems during the design phase allows for a less expensive, more efficient solution than trying to correct a real problem after the building is completed, when, for example, changing the location and/or height of the stack can be very costly.

Dilution and Concentration Definitions

A building exhaust system releases a mixture of building air and pollutant gas at concentration C_e (mass of pollutant per volume of air) into the atmosphere through a stack or vent on the building. The exhaust mixes with atmospheric air to produce a pollutant concentration C, which may contaminate an air intake or receptor if the concentration is larger than some specified allowable value C_{allow} (see Figure 4). The dilution factor D between source and receptor mass concentrations is defined as

$$D = C_e/C \tag{10}$$

where

C_e	=	contaminant mass concentration in exhaust, kg/m^3
C	=	contaminant mass concentration at receptor, kg/m^3

The dilution increases with distance from the source, starting from its initial value of unity. If C is replaced by C_{allow} in Equation (11), the atmospheric dilution D_{req} required to meet the allowable concentration at the intake (receptor) is

$$D_{req} = C_e/C_{allow} \tag{11}$$

The exhaust (source) concentration is given by

$$C_e = \dot{m}/Q_e = \dot{m}/(A_e V_e) \tag{12}$$

where

$\dot{m}$	=	contaminant mass release rate, kg/s
Q_e	=	$A_e V_e$ = total exhaust volumetric flow rate, m^3/s
A_e	=	exhaust face area, m^2
V_e	=	exhaust face velocity, m/s

The concentration units of mass per mixture volume are appropriate for gaseous pollutants, aerosols, dusts, and vapors. The concentration of gaseous pollutants is usually stated as a volume fraction f (contaminant volume/mixture volume), or as ppm (parts per million) if the volume fraction is multiplied by 10^6. The pollutant volume fraction f_e in the exhaust is

$$f_e = Q/Q_e \tag{13}$$

where Q is the volumetric release rate of the contaminant gas. Both Q and Q_e are calculated at exhaust temperature T_e.

The volume concentration dilution factor D_v is

$$D_v = f_e / f \tag{14}$$

where f is the contaminant volume fraction at the receptor. If the exhaust gas mixture has a relative molecular mass close to that of air, D_v may be calculated from the mass concentration dilution D by

$$D_v = (T_e / T_a) D \tag{15}$$

where

T_e	=	exhaust air absolute temperature, K
T_a	=	outdoor ambient air absolute temperature, K

Many building exhausts are close enough to ambient temperature that volume fraction and mass concentration dilutions D_v and D are equal.

Roof-Level Dilution Estimation Method

This section presents equations for predicting worst-case roof-level dilution of exhaust from a vertical stack on a roof. The equations assume a bell-shaped Gaussian concentration profile in both the vertical and cross-wind horizontal directions. Gaussian profiles have been used in many atmospheric dispersion models, such as those used by the U.S. Environmental Protection Agency. Considering their simplicity, bell-shaped Gaussian concentration profiles in the cross-wind y and vertical z directions at a given horizontal distance x represent atmospheric dispersion remarkably well (Brown et al. 1993).

The dilution equations predict the roof-level dilution D_r, which is the ratio of contaminant concentration C_e at the exit point of the exhaust to the maximum concentration C_r on the plume centerline at roof level, giving $D_r = C_e/C_r$. The centerline of the plume is defined in the x direction, with y the lateral (cross-wind) distance off the plume centerline (axis), and z the vertical. Dilution is affected by three processes:

- Wind carries the plume downwind. The higher the wind speed, the greater the dilution on the plume axis. Wind speed U_H carrying the plume is the wind speed in the undisturbed flow approaching the top of the building.
- Wind turbulence spreads the plume vertically and laterally (cross-wind). Plume spreads in the cross-wind y direction and the vertical z direction are σ_y and σ_z. These plume spreads increase with downwind distance.
- The plume is carried vertically by the initial buoyancy and vertical momentum of the exhaust at the stack exit. The higher the plume, the greater the dilution at the roof surface. The stronger the wind, the less the plume rises, which may produce less dilution.

Thus, wind speed can have two effects: (1) at very low wind speed, the exhaust jet from an uncapped stack rises high above roof level, producing a large exhaust dilution D_r at a given intake location; and (2) at high wind speed, the plume rise is low but the dilution is large because of longitudinal stretching of the plume by the wind. Between these extremes is the critical wind speed $U_{H,crit}$, at which the smallest amount of dilution occurs for a given exhaust and intake location.

Before performing Gaussian dilution calculations on a rooftop, the effect of rooftop obstacles, wind recirculation zones, and intake location(s) must be considered. Dilution depends on the vertical separation ζ between the plume centerline h_{plume} and h_{top}. Zakeri and Clark (2019) suggest defining h_{top} as the highest of the intake, all active obstacles (discussed later), and 60% of the recirculation zone height, defined in Equation (1). Vertical separation ζ is defined as

$$\begin{aligned}\zeta &= h_{plume} - h_{top} \\ &= 0 \text{ if } h_{p\ lume} < h_{top}\end{aligned} \tag{16}$$

Plume centerline h_{plume} versus downwind distance defined as

$$h_{plume} = h_s + h_r - h_d \tag{17}$$

where h_s is the physical stack height above the roof, h_r is the plume rise versus downwind distance defined in Equation (7), and h_d is the stack wake downwash defined in Equation (8) (see Figure 1).

To determine which rooftop obstacles are considered active in defining h_{top}, start by drawing a line in plan view through the stack location and the intake of interest. All obstacles along this line or one obstacle width laterally (y-direction) from the line are considered active. Obstacles and recirculation zones upstream of the stack and downstream of the intake should also be considered. The value of h_{top} is the higher of the active obstacles, recirculation zones (including zones on top of active obstacles) defined in Equation (1), and the height of the intakes. All of these heights should be referenced to the same roof level used to determine h_s. Once h_{top} is defined and ζ is calculated, dilution at the intake is calculated from

$$D_r(x) = \frac{4U_H\sigma_y\sigma_z}{V_e d_e^2} x \exp\left(max\left\{ 7, \frac{\zeta^2}{2\sigma_z^2} \right\}\right) \quad \textbf{(18)}$$

When plume height is less than the height of intakes, active obstacles, and recirculation zones (i.e., $h_{plume} < h_{top}$), then ζ = 0 and dilution should be calculated using Equation (23).

If exhaust gases are hot, buoyancy increases the rise of the exhaust gas mixture and produces lower concentrations (higher dilutions) at roof level. For all exhausts except very hot flue gases from combustion appliances, it is recommended that plume rise from buoyancy be neglected in dilution calculations and stack design on buildings. By neglecting buoyant plume rise, the predicted dilution has an inherent safety factor, particularly at low wind speed, where buoyancy rise is significant.

Cross-Wind and Vertical Plume Spreads for Dilution Calculations

Close to the stack, dispersion is governed by mechanical mixing, and the following equations for lateral and vertical plume spread can be used (Cimorelli et al. 2005):

$$\sigma_y = (i_y^2 x^2 + \sigma_o^2)^{1/2} \quad \textbf{(19)}$$

$$\sigma_z = (i_z^2 x^2 + \sigma_o^2)^{1/2} \quad \textbf{(20)}$$

where i_y is lateral turbulence intensity, i_z is vertical turbulence intensity, x is distance downwind from the stack, and σ_o is initial source size. Zakeri and Clark, (2019) found that measured data is best predicted using a value of σ_o equal to the exhaust diameter, d_e. The lateral and vertical turbulence intensity can be calculated using the following equations. Scrase (1930) measured directional turbulence intensity at heights of 5 1.5 and 62 ft 19 m and found lateral and vertical turbulence intensities 1.16 and 0.75 times the horizontal turbulence intensity, respectively, at a height of 5 ft 1.5 m. At 62 ft 19 m these ratios were 0.73 and 0.56, and at heights greater than 200 ft 60 m the velocity components can be assumed to be equal. Teunissen (1970) measured turbulence intensity variation with height over a flat terrain and found that although the turbulence intensities decrease with height, the ratio of lateral and vertical to horizontal turbulence intensities are invariant with height. Counihan (1975), after a review of published values, suggest the following model:

$$i_y = 0.75 i_x; \quad i_z = 0.5 i_x \quad \textbf{(21)}$$

where

$$i_x = n \ln\left(\frac{30}{z_o}\right) / \ln\left(\frac{z}{z_o}\right)$$

$$n = 0.24 + 0.096 \log_{10} z_o + 0.016 (\log_{10} z_o)^2$$

where inputs z and z_o are in metres.

The averaging time over which exhaust gas concentration exposures are predicted is important in determining roof-level dilution. The preceding equations provide dilution estimates for a 10 to 15 min averaging time, which corresponds to the averaging time for ACGIH short-term exposure limits. If odors are a concern, peak minimum dilution may be needed; dilution for shorter averaging times can be estimated as

$$(D_r)_s = (D_r)_{15} \times \left(\frac{t_s}{15}\right)^{0.2} \quad \textbf{(22)}$$

where $(D_r)_s$ is the estimate for a shorter averaging time t_s and $(D_r)_{15}$ is the estimate for the 15 min averaging time. For example, assume a predicted dilution of $(D_r)_{15}$ = 100. The dilution for a 1 min averaging time would be 100 × $(1/15)^{0.2}$ = 58. If estimates for longer averaging times are needed, the preceding estimates should be assumed to be hourly averages and the following conservative multiplication factors (EPA 1992) should be used to obtain the estimated maximum concentrations for 3 h, 8 h, 24 h, or annual averaging times:

Averaging Time	Scaling or Multiplying Factors
3 h	1.1
8 h	1.4
24 h	2.5
Annual	12.5

Equations (17), (18), (19), and (20) imply that dilution does not depend on the location of either the exhaust or intake, only on the horizontal distance *x* between them and the vertical separation ζ. This is reasonable when both exhaust and intake locations are on the same building wall or on the roof. Dilution can increase if the intake is below roof level on the sidewall of a building and the exhaust stack is located on the roof. Petersen et al. (2004) provide methods for estimating the increased dilution on sidewalls, as summarized below.

Stack Design Using Dilution Calculations

Example 2. In general, a spreadsheet should be designed using the preceding equations to calculate dilution from an exhaust at any specified location on the roof. This example shows the results for a calculation at intake A using the information provided in Example 1. The distance from stack to intake is 14.1 m, and highest point on intake A is 2 m above the roof. Assume a 6.1 m stack height above the roof. Figure 7 provides the calculated dilution versus wind speed. The recommended method involves the following steps: (1) specify the site conditions using Table 1; (2) carry out the calculations outlined in Figure 7 using surface roughness in Table 1 for range of wind speeds; (3) repeat the calculations using a surface roughness half this value and 1.5 times this value; (4) find the lowest dilution for the range of wind speeds of interest for each surface roughness; and (5) determine the overall minimum dilution and use this value to determine the acceptability of the exhaust design.

Zo =	0.65	m		n =	0.22										
U_H	σ_0	i_x	$i_y x$	$i_z x$	σ_y	σ_z	h_d	β_j	U_H/U_*	h_x	h_f	h	h_{plume}	ζ	D_r
(m/s)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(-)	(-)	(m)	(m)	(m)	(m)	(m)	
5.00	0.18	0.27	2.87	1.92	2.88	1.92	0.60	0.89	7.85	2.21	1.28	1.28	6.77	4.78	1100
7.00	0.18	0.27	2.87	1.92	2.88	1.92	0.86	1.11	7.85	1.52	0.73	0.73	5.97	3.98	591
9.00	0.18	0.27	2.87	1.92	2.88	1.92	1.00	1.33	7.85	1.14	0.47	0.47	5.57	3.58	504
														Min	504
Zo =	0.325	m		n =	0.20										
U_H	σ_0	i_x	$i_y x$	$i_z x$	σ_y	σ_z	h_d	β_j	U_H/U_*	h_x	h_f	h	h_{plume}	ζ	D_r
(m/s)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(-)	(-)	(m)	(m)	(m)	(m)	(m)	
5.00	0.18	0.23	2.46	1.64	2.47	1.64	0.60	0.89	9.58	2.21	1.41	1.41	6.91	4.91	3194
7.00	0.18	0.23	2.46	1.64	2.47	1.64	0.86	1.11	9.58	1.52	0.81	0.81	6.05	4.05	1065
9.00	0.18	0.23	2.46	1.64	2.47	1.64	1.00	1.33	9.58	1.14	0.52	0.52	5.62	3.63	745
														Min	745
Zo =	0.975	m		n =	0.24										
U_H	σ_0	i_x	$i_y x$	$i_z x$	σ_y	σ_z	h_d	β_j	U_H/U_*	h_x	h_f	h	h_{plume}	ζ	D_r
(m/s)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(-)	(-)	(m)	(m)	(m)	(m)	(m)	
5.00	0.18	0.30	3.17	2.11	3.17	2.11	0.60	0.89	6.83	2.21	1.19	1.19	6.69	4.69	704
7.00	0.18	0.30	3.17	2.11	3.17	2.11	0.86	1.11	6.83	1.52	0.68	0.68	5.92	3.93	470
9.00	0.18	0.30	3.17	2.11	3.17	2.11	1.00	1.33	6.83	1.14	0.44	0.44	5.54	3.54	438
														Min	438
													Overall Minimum		438

Figure 7. Spreadsheet for Example 2

Dilution from Flush Exhaust Vents with No Stack

For exhaust grilles and louvers on the roof or walls of a building or penthouse, vertical separation ζ = 0 in Equation (19). Combining Equations (19), (20), and (21) gives

$$D_s(x) = \frac{4U_H\sigma_y\sigma_z}{V_e d_e^2} \tag{23}$$

The subscript *s* in the dilution D_s from a surface exhaust distinguishes it from the roof-level dilution D_r from a stack [Equation (19)].

Minimum critical dilutions for flush exhausts can be calculated using the approximate value $U_{H,crit}$ = 2 m/s based on the observation that, for wind speeds less than 2 m/s) at roof height, the atmosphere tends to develop high levels of turbulence that increase exhaust-to-intake dilution. For flush roof exhausts with no stack, and for sidewall intakes, the experiments of Petersen et al. (2004) suggest that D_s at the intake is at least a factor of 2 larger than the dilution at a roof-level intake at the same stretched-string distance *S* from the stack.

Example 3. The exhaust flow of Q_e = 1.76 m^3/s in Example 1 comes from a louvered grille at location A. The exhaust grille is 0.7 m high and 0.7 m wide. What is the critical exhaust-to-intake dilution factor at intake B on the downwind wall of the building for an averaging time of 15 min?

Solution: Exhaust grille A has a face area of A_e = 0.49 m^2 and an exhaust velocity V_e of 707 fpm (3.59 m/s). From Equation (8), the effective exhaust diameter is d_e = [(4)(0.49)/π]$^{0.5}$ = 0.79 m. The stretched-string distance S from exhaust A to intake B is the sum of the 2 m from the top of A to the top of the penthouse, plus the 7 m length of the penthouse, plus the sloped line of horizontal length 24.9 m from the downwind edge of the penthouse roof, and a vertical drop of 4 m to the roof, plus the 6 m to intake B:

$$S = 2 + 7 + \sqrt{24.9^2 + (4+6)^2} = 35.8 \text{ m}$$

The critical wind speed is assumed to be $U_{H,crit}$ = 2 m/s for capped stacks and flush vents. The critical dilution of exhaust from A at intake B is calculated from Equation (23). Using a similar method as outlined in Example 2, Figure 8 shows the calculation table results where S and x are assumed equal.

These are conservative estimates because they represent the dilution at a low critical wind speed of 400 fpm, which is 4.5 mph.

Zo =	0.65	m		n =	0.22				
U_H	σ_0	i_x	$i_y x$	$i_z x$	σ_y	σ_z	h_d	ζ	D_r
(m/s)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(m)	
2.00	0.28	0.27	7.30	4.86	7.30	4.87	0.96	-	126
Zo =	0.325	m		n =	0.20				
U_H	σ_0	i_x	$i_y x$	$i_z x$	σ_y	σ_z	h_d	ζ	D_r
(m/s)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(m)	
2.00	0.28	0.23	6.24	4.16	6.25	4.16	0.96	-	93
Zo =	0.975	m		n =	0.24				
U_H	σ_0	i_x	$i_y x$	$i_z x$	σ_y	σ_z	h_d	ζ	D_r
(m/s)	(m)	(-)	(m)	(m)	(m)	(m)	(m)	(m)	
2.00	0.28	0.30	8.04	5.36	8.05	5.36	0.96	-	153
							Overall Minimum		93

Figure 8. Spreadsheet for Example 3

Dilution at a Building Sidewall (Hidden) Intakes

Petersen et al. (2004) provided results of an ASHRAE research study that outlined methods for estimating dilution or concentration for visible versus hidden intakes. A hidden intake is typically on a building side wall or on the side wall of a roof obstruction opposite the exhaust source. A visible intake is at roof level or on top of an obstruction, directly above the exhaust source. The basic approach starts following the method for estimating dilution at a rooftop intake. Dilution is calculated at the rooftop location above the side-wall receptor; dilution at this distance is then increased by the factors given in Petersen et al. (2004). A conservative dilution increase factor for most building configurations is 2.0.

EPA Models

In late 2005, the EPA recommended that the AERMOD modeling system (Cimorelli et al. 2005) be used instead of the previously preferred industrial source complex (ISC3) model (EPA 1995). The new model includes state-of-the-art boundary layer parameterization techniques, convective dispersion, plume rise formulations, and complex terrain/plume interactions, as well as a building downwash algorithm. AERMOD can be used to calculate short-term (hourly) exposure and long-term (monthly and annual) exposure. Both the short- and long-term models are divided into three source classifications: (1) point source, (2) line source, and (3) area source. For exhaust stack design, the point source is the model of interest. The EPA (2006) guideline also describes a short- and a long-term dry deposition model. AERMOD uses the Gaussian equation to calculate the concentration of the contaminant concentration downwind of the source. The models consider the wind speed profile, use plume rise formulas, calculate dispersions factors (which take into consideration different landscapes, building wakes and downwash, and buoyancy), calculate the vertical distribution, and consider decay of the contaminant. More information on AERMOD and other EPA models can be found at www.epa.gov/scram. Remember that the EPA models are primarily designed to predict concentration (or dilution) values downwind of the building on which the exhausts are located. For predicting effects at building intakes, operable windows, and entrances, alternative modeling methods are required.

Wind Tunnel Modeling

Wind tunnel modeling is often the preferred method for predicting maximum concentrations for stack designs and locations of interest when energy and equipment optimization is desired. It is the recommended approach because it gives the most accurate estimates of concentration levels in complex building environments. A wind tunnel modeling study is like a full-scale field study, except it is conducted before a project is built. Typically, a scale model of the building under evaluation, along with the surrounding buildings and terrain within a 300 m radius, is placed in an atmospheric boundary layer wind tunnel. A tracer gas is released from the exhaust sources of interest, and concentration levels of this gas are then measured at receptor locations of interest (e.g., air intakes, operable windows) and converted to full-scale concentration values. Next, these values are compared against the appropriate health or odor design criteria to evaluate the acceptability of the exhaust design. Petersen and Cochran (2008) and Snyder (1981) provide more information on scale-model simulation and testing methods. Scale modeling is also discussed in Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*.

Wind-tunnel studies are highly technical, so care should be taken when selecting a dispersion modeling consultant. Factors such as past experience and staff technical qualifications are extremely important.

Computer Simulations Using Computational Fluid Dynamics (CFD)

CFD models are used successfully to model internal flow paths in areas such as vivariums and atriums, as well as in external aerodynamics for the aerospace industry. Aerospace CFD turbulence models, however, are ill suited for modeling atmospheric turbulence in complex full-scale building environments because of the differing geometric scales. More information on CFD modeling is in Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*.

Based on the current state of the art, CFD models should be used with extreme caution when modeling exhaust plumes from laboratory or other building pollutant sources. Currently, CFD models can both over- and underpredict concentration levels by orders of magnitude, leading to potentially unsafe designs. If a CFD study is conducted for such an application, supporting full-scale or wind tunnel validation studies should be carried out. Various commercial software packages are available for CFD-driven airflow analysis; most have advanced user interfaces and resulting visualization capabilities, as well as sophisticated physical models and solver options. Usually, commercial software includes advanced technical user support provided by vendor specialists. Several open-source research codes are available, as well, but require a much greater user insight into the underlying solution methods and hardware platforms. Normally, no user support or problem-specific validation data are available. Regardless of the software package choice, obtaining an accurate numerical solution requires expertise, training, and understanding of the fundamental aspects of CFD algorithm construction and implementation.

4. OTHER CONSIDERATIONS

Annual Hours of Occurrence of Highest Intake Contamination

To assess the severity of the hazard caused by intake contamination, it is useful to know the number of hours per year that exhaust-to-intake dilution is likely to be lower than some allowable minimum dilution. The first step in making a frequency-of-occurrence estimate is to use the method outlined in Examples 2 and 3 to estimate the minimum dilution versus wind speed at the intake or receptor location of interest. Next, specify the wind speed range at which the dilution is unacceptable. Weather data are then used to calculate the number of hours per year that wind speeds fall in this range for the 22.5° wind direction sector centered on a line joining the exhaust and intake.

Combined Exhausts

When exhaust from several collecting stations is combined in a single vent (as recommended in the section on Exhaust Stack and Air Intake Design Strategies), the plume rise increases because of the higher mass flow in the combined jet and results in significantly lower roof-level intake concentration C_r compared to that from separate exhausts. Where possible, exhausts should be combined before release to take advantage of this increase in overall dilution. For example, consider a single fume hood exhaust stack at 0.5 m^3/s with a 15.24 m/s exit velocity (A_e = 0.1 m) versus 10 such fume hoods combined into a single stack at 5 m^3/s and 15.24 m/s (A_e = 1 m). The F_m term in Equation (7) is proportional to the exhaust velocity times the exhaust area. For this example, F_m would increase by a factor of 10. Based on Equation (7), the plume rise would increase by a factor of $(10)^{0.33}$, or 2.1.

Ganged Exhausts

Greater plume rise and dilution can be achieved by grouping individual stacks close together. Petersen and Reifschneider (2008) summarized ASHRAE research project RP-1167 on this topic and provided a method for calculating the plume rise and subsequent dilution for ganged stacks, to optimize stack arrangements. They found that, when stacks are nearly touching, the momentum terms for the individual stacks can add together and Equation (7) can be used to compute plume rise for ganged arrangements. If stacks are situated up- and downwind of each other, the F_m terms can also be added for quite large separation distances. If the stacks are not up- or downwind of each other, the paper presents an equation that can used to estimate the fraction of the momentum that can be added. This is a particularly advantageous strategy when a dedicated low-flow exhaust is needed that has toxic chemicals. This stack can be placed next to any high-flow stack and achieve the same plume rise and resulting high dilution.

Influence of Architectural Screens on Exhaust Dilution

Architectural screens are often placed around rooftop equipment to reduce noise or hide equipment. Unfortunately, these screens interact with windflow patterns on the roof and can adversely affect exhaust dilution and thermal efficiency of equipment inside the screen. This section describes a method to account for these screens by modifying the physical stack height h. Architectural screens generate flow recirculation regions similar to those shown downwind of the building and penthouse in Figure 1. These screens are often made of porous materials with mesh or louvers, which influence the height of the recirculation cavity above the screens.

To incorporate the effect of architectural screens into existing dilution prediction equations, use the stack height reduction factor F_h. Stack height h_s above the roof must be multiplied by F_h when the stack is enclosed within a screen (Petersen et al. 1999). Effective stack height $h_{s,eff}$ measured above roof level is

$$h_{s,eff} = F_h h_s \tag{24}$$

The stack height reduction factor F_h is directly related to screen porosity P_s. For stack heights above the top of the screen that are less than 2.5 times the height of the screen,

$$F_h = 0.81 P_s + 0.20 \tag{25}$$

where porosity is

$$P_s = \frac{\text{Open area}}{\text{Total area}} \tag{26}$$

F_h is applied directly to h_s after the required stack height has been calculated, and should be included where the physical stack height is less than 2.5 times the height of the architectural screen.

Example 4. Calculate the required stack height for an uncapped stack with a height of 4.7 m above roof level, surrounded by a 3 m high, 50% porous architectural screen.

Solution: To determine the effect of the 50% porous screen, use Equation (25) with P_s = 0.5

$$F_h = 0.81(0.5) + 0.2 = 0.605$$

The screen has reduced the effective stack height from its actual height of 4.7 m to

$$h_{s,eff} = 0.605(4.7) = 2.84 \text{ m}$$

When the effect of the 50% porous screen is added, the 4.7 m stack height is found to behave like a 2.86 m stack. The actual stack height h_s must be increased to account for the screen's effect. This is most easily done by dividing h_s by the stack height reduction factor:

$$h_{s,\,corrected} = \frac{h_s}{F_h} = \frac{4.7}{0.605} = 7.8 \text{ m}$$

The corrected 7.8 m high stack effectively behaves like a 4.7 m tall stack, and should produce the same dilution at downwind air intakes. The correct height should be used for input when estimating dilution.

Emissions Characterization

Typical exhaust sources of concern are fume hoods, emergency generators, kitchens, vivariums, loading docks, traffic, cooling towers, and boilers. Chemical emissions from each source should be characterized to determine a design criterion, or critical concentration. Three types of information are needed to characterize the emissions: (1) a list of the toxic or odorous substances that may be emitted, (2) the health limits and odor thresholds for each emitted substance, and (3) the maximum potential emission rate for each substance.

Recommended health limits C_{health} are based on AIHA *Standard* Z9.5, which specifies air intake concentrations no higher than 20% of acceptable indoor concentrations for routine emission and 100% of acceptable indoor concentrations for accidental releases. Acceptable indoor concentrations are frequently 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. ACGIH also provides odor thresholds.

For laboratories, emission rates are typically based on small-scale accidental releases in fume hoods or in room, either liquid spills or emptying of a lecture bottle of compressed gas. Evaporation from liquid spills is computed from equations in EPA (1992) based on a worst-case spill in a fume hood or a room. Compressed gas leaks typically assume a fractured lecture bottle empties in one minute. For other sources, such as emergency generators, boilers, and vehicles, chemical emissions rates are often available from the manufacturer.

For general laboratory design purposes, Chapter 17 provides an example emission characterization (i.e., design criterion). A 7.5 L/s chemical emission rate (e.g., from a liquid spill or lecture bottle fracture) is assumed, along with a limiting concentration of 3 mg/kg or less at an intake. For dispersion modeling purposes, the emission characterization can be expressed in SI units as 400 μg/m^3 per g/s, or in dilution units of 1:5000 per 500 L/s of exhaust flow. Chapter 17 includes the following disclaimers regarding this design criterion: (1) laboratories using extremely hazardous substances should conduct a chemical-specific analysis based on published health limits, (2) a more lenient limit may be justified for laboratories with low levels of chemical usage, and (3) project-specific requirements must be developed in consultation with the safety officer.

Chapter 17's criterion may be put into perspective by considering the as-manufactured and as-installed chemical hood containment requirements outlined in ANSI/AIHA *Standard* Z9.5-2003 (i.e., a concentration at a manikin outside the chemical hood of 0.05 ppm or less for as-manufactured, and 0.10 ppm or less for as-installed, with a 0.07 L/s accidental release in the hood as measured using the ASHRAE *Standard* 110-2016 test method). The as-manufactured requirement is equivalent to a design criterion of 750 μg/m^3 per g/s, and the as-installed requirement is equivalent to a design criterion of 1500 μg/m^3 per g/s. Hence, the ASHRAE criterion for a manikin representing a worker outside the chemical hood is 1.9 to 3.8 times less restrictive than that for the air intake or other outdoor locations. It seems reasonable that the air intake has more strict criteria, because the worker at the chemical hood can shut the hood or walk away to avoid adverse exposure. Also, the ASHRAE *Standard* 110-2016 test is not necessarily a worst-case exposure scenario for the worker.

SYMBOLS

A_e	=	stack or exhaust exit face area, m^2
B_L	=	larger of two upwind building face dimensions H and W, m
B_s	=	smaller of two upwind building face dimensions H and W, m
C	=	contaminant mass concentration at receptor at ambient air temperature T_e, Equation (11), kg/m^3
C_{allow}	=	allowable concentration of contaminant at receptor, Equation (12)
C_e	=	contaminant mass concentration in exhaust at exhaust temperature T_e, Equation (11), kg/m^3
C_r	=	maximum mass concentration, kg/m^3
D	=	dilution factor between source and receptor mass concentrations, Equation (11)
D_{crit}	=	critical dilution factor at roof level for uncapped vertical exhaust at critical wind speed $U_{H,crit}$ that produces smallest value of D_r for given exhaust-to-intake distance S and stack height h_s
D_r	=	roof-level dilution factor D at given wind speed for all exhaust locations at same fixed distance S from intake, Equation (19)
D_{req}	=	atmospheric dilution required to meet allowable concentration of contaminant C_{allow}, Equation (12)
D_s	=	dilution at a wall or roof intake from a flush exhaust grille or louvered exhaust, Equation (23)
D_v	=	dilution factor between source and receptor using volume fraction concentrations, Equation (15)
d_e	=	effective exhaust stack diameter, Equation (8), m
F_h	=	stack height adjustment factor to adjust existing stack height above screen for influence of screen of exhaust gas dilution, Equation (25)
F_m	=	momentum flux, m^4/s^2
f	=	contaminant volume concentration fraction at receptor; ratio of contaminant gas volume to total mixture volume, Equation (15), ppm × 10^{-6}
f_e	=	contaminant volume concentration fraction in exhaust gas; ratio of contaminant gas volume to total mixture volume, Equation (14), ppm × 10^{-6}

H = building height above ground level, m
H_c = maximum height above roof level of upwind roof edge flow recirculation zone, Equation (1), m
H_{met} = anemometer height, m
h_d = downwash correction to be subtracted from stack height, Equation (9), m
h_f = final plume rise, m
h_{plume} = final plume height, Equation (18), m
h_r = plume rise of uncapped vertical exhaust jet, Equation (7), m
h_s = physical exhaust stack height (typically above roof unless otherwise specified), m
h_{sc} = required height of capped exhaust stack to avoid excessive intake contamination, Equation (10), m
$h_{s,eff}$ = effective exhaust stack height above roof on which it is located, corrected for an architectural screen surrounding the stack, Equation (24), m
h_{top} = height of highest of intake, active obstacle, or recirculation zone on a rooftop between the stack and intake, Equation (17), m
h_x = plume rise at downwind distance x, m
i_y = lateral turbulence intensity
i_z = vertical turbulence intensity
L = length of building in wind direction, Figure 5, m
L_c = length of upwind roof edge recirculation zone, Equation (3), m
L_r = length of flow recirculation zone behind rooftop obstacle or building, Equation (4), m
$\dot{m}$ = contaminant mass release rate, Equation (13), kg/s
P_s = porosity of an architectural screen near a stack, Equation (26)
Q = contaminant volumetric release rate, Equation (14), m^3/s
Q_e = total exhaust volumetric flow rate, Equation (13), m^3/s
R = scaling length for roof flow patterns, Equation (5), m
S = stretched string distance from exhaust to intake, m
T_a = outdoor ambient air absolute temperature, Equation (16), K
T_e = exhaust air mixture absolute temperature, Equation (16), K
U_* = friction velocity, ft/sm/s
U_H = mean wind speed at height H of exhaust stack in undisturbed flow approaching building, Equation (7), m/s
$U_{H,crit}$ = critical wind speed that produces smallest roof-level dilution factor D_{crit} for uncapped vertical exhaust at given X and h_s, m/s
V_e = exhaust gas velocity, Equation (13), m/s
W = width of upwind building face, m
X_c = distance from upwind roof edge to H_c, Equation (2), m
x = horizontal distance from upwind roof edge where recirculation region forms in direction of wind, m
x = downwind horizontal distance from center of stack, Equations (20) and (21), m
y = cross-wind distance off the plume centerline, m
z = vertical distance above grade, m
z_o = surface roughness length, m
Z_1 = height of flow recirculation zone boundary above roof, Figure 6, m
Z_2 = height of high-turbulence zone boundary above roof, Figure 6, m
Z_3 = height of roof edge wake boundary above the roof, Equation (6) and Figure 6, m

Greek

β = capping factor; 1.0 for vertical uncapped roof exhaust; 0 for capped, louvered, or downward-facing exhaust
β_j = jet entrainment coefficient
ζ = vertical separation above h_{top}, Equation (17), m
σ_o = standard deviation of initial plume spread at the exhaust used to account for initial dilution, Equation (20), m
σ_y = standard deviation of cross-wind plume spread, Equation (20), m
σ_z = standard deviation of vertical plume spread, Equation (21), m

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