AIVC 11906

CH-99-7-1

Dilution Calculations for Determining Laboratory Exhaust Stack Heights

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ABSTRACT

Laboratory exhaust stacks should be designed with sufficient height and exit momentum to avoid re-entry of exhaust and possible air quality problems, and the design should be evaluated before construction. One evaluation method is presented in this paper that combines dilution prediction equations from the 1997 ASHRAE Handbook—Fundamentals *(1997) and a dilution criteria of Halitsky (1988). This method is less conservative than a geometric method in the* ASHRAE Handbook *and is less costly than wind-tunnel modeling. The method should only be applied to relatively simple building geometries with no larger buildings adjacent to them.*

A planned change to the ASHRAE equations, which would result in larger stacks being necessary, is discussed. Further investigation of this change is recommended using comparisons to wind tunnel data.

INTRODUCTION

Laboratories routinely emit small amounts of toxic and odorous chemicals from rooftop exhaust stacks. The stack height and/or momentum should be designed (and evaluated) to avoid re-entry of the emissions back into the building through the outside air intakes. This paper recommends an approach to laboratory stack design that combines simple dilution equations with a dilution acceptance criterion based on industry experience. This approach fills a gap between the simple but conservative geometric stack height method described in the *1997 ASHRAE Handbook—Fundamentals*, Chapter 15 (ASHRAE 1997), and more expensive wind tunnel or water flume scale modeling.

The dilution equations are a subset of those that appear in the *1997 ASHRAE Handbook* and can predict worst-case dilution as explicit functions of stack parameters such as stack height, exhaust velocity, and exhaust volume flow rate. However, the *1997 ASHRAE Handbook*, Chapter 15, does not address how to determine a target dilution. In general, an aesthetically acceptable stack height cannot completely exclude the possibility of odors or health effects from potential accidental releases. Therefore, a dilution criterion may be based on a compromise between aesthetics and the probability of air quality impacts. Halitsky (1988) presents one criterion based on much industrial experience. This paper examines how a design stack height can be determined when combining the *1997 ASHRAE Handbook* dilution equations with the Halitsky criterion.

DILUTION PREDICTION EQUATIONS

The suggested dilution equations are from the *1997 ASHRAE Handbook*, Chapter 15, and are based on previous wind tunnel experiments (Wilson and Chui 1985, 1987; Chui and Wilson 1988). Field experiments (Wilson and Lamb 1994) have shown that these equations are conservative predictors of worst-case dilution. Other equations in Chapter 15 are not as readily usable since they do not explicitly include stack height as an input variable.

The suggested dilution equations are most applicable for a rooftop stack with air intakes located on the same roof or the side of the emitting building. It should be warned that these equations are applicable when there are no nearby buildings or terrain larger than the emitting building that can significantly alter the approaching wind pattern. Also, architectural screens

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and major penthouses are not specifically accounted for, so the stack height computed with this procedure should be the stack height above nearby screens and penthouses. The equations are complex in appearance but can be readily programmed in a spreadsheet. The equations are first presented for zero stack height, then a stack height adjustment is given.

Dilution, D, is defined as the ratio of the exit concentration of a chemical at the stack exit, C_{exit}, to the final concentration, C_{final}, at a downwind point of interest such as an air intake:

$$D = C_{exit} / C_{final} \tag{1}$$

Dilution is usually expressed as "x:1". For example, if D=100, then the dilution is expressed as 100:1. The exit concentration of a chemical can be calculated from the total volume flow rate of the stack, Q, and the pure vapor volume emission rate of the chemical, Q_{chem}:

$$C_{exit} = Q_{chem} / Q \tag{2a}$$

or in parts per million,

$$C_{exit}(ppm) = Q_{chem} / Q x 10^6 . \tag{2b}$$

The dilution is calculated for a critical wind speed that produces a worst-case minimum dilution. The critical dilution for zero stack height, $D_{crit,0}$, is

$$D_{crit,0} = \frac{(1 + 26V_e / U_{crit,0})^2}{1 + 13V_e / U_{crit,0}} , \tag{3}$$

where V_e is the exit velocity and $U_{crit,0}$ is the critical wind speed at which the minimum dilution occurs:

$$U_{crit,0} = 3.6 \frac{V_e}{S} \sqrt{\frac{A_e}{B_1}} \tag{4}$$

In Equation 4, S is the "string" distance between the stack top and the air intake, A_e is the exit area of the stack ($\frac{\pi}{4}d^2$ for circular stacks), and B_1 is an empirical constant (= 0.059 for rooftop air intake locations in urban conditions and = 0.13 for air intake locations on the building side).

For nonzero stack heights, the stack height adjustment is based on a parameter, Y, which is a ratio of stack height to plume spread:

$$Y = 28.9 h_s^2 / S^2 (or = 2 \; if > 2) \tag{5}$$

where h_s is the physical stack height above nearby penthouses, architectural screens, or other obstructions. (The so-called "effective stack height," which includes plume rise from the exhaust momentum, should not be used here.) The ratio of critical wind speed with zero stack height, $U_{crit,0}$, to critical wind speed with nonzero stack height is

$$\frac{U_{crit,0}}{U_{crit}} = \sqrt{Y + 1} - \sqrt{Y} , \tag{6}$$

and the critical (minimum) dilution with nonzero stack height is

$$D_{crit} = D_{crit,0} \frac{U_{crit}}{U_{crit,0}} e^{\left(Y + \sqrt{Y}\sqrt{Y+1}\right)} , \tag{7}$$

where e = 2.718, the base of natural logarithms. As stack height increases, the critical wind speed increases (meaning a larger wind speed is needed to bring the plume closer to the building) and the critical dilution increases.

The Y factor of 28.9 in Equation 5 is due to be changed in an upcoming revision of the ASHRAE Handbook (Wilson 1998). To better account for the initial spread of the plume due to vertical exit momentum, Wilson recommends changing the Y factor from 28.9 to 6.7. The implication of this change with regard to dilution predictions is further discussed below.

THE HALITSKY DILUTION CRITERION

Dilution predictions alone cannot determine a stack height but need to be compared to a criterion. For laboratories, odor and health problems with air re-entry are usually caused by an exceptional or accidental release from one fume hood. Therefore, the dilution within the building created by manifolding other fume hood exhaust streams into a common exhaust should also be considered. A simple atmospheric dilution standard is not appropriate for all stacks at a site since some stacks have less internal dilution than other stacks. The recommended method of specifying an acceptance criterion is by specifying an acceptable outside air intake concentration for a given release rate within one fume hood. This criterion can be converted to a direct dilution criterion as a function of the exhaust volume flow rate from the stack.

The Halitsky (1988) criterion for an accidental release is an air intake concentration of 3 ppm or less given a 15 cfm (530 lpm) release of pure vapor for any chemical. This applies to any volume flow rate from the stack.

The Halitsky criteria is also described in the *1995 ASHRAE Handbook—HVAC Applications* (ASHRAE 1995), Chapter 13. It should be noted that Halitsky (1988) applied this criterion for only one specific wind speed: 13.6 mph (6.1 m/s). The method discussed here suggests evaluating a stack at the critical wind speed using Equations 4 and 6. Applying the criterion only at the 13.6 mph (6.1 m/s) wind speed may give an unfair advantage to low momentum stacks with a low critical worst-case wind speed.

The Halitsky criterion can be converted to other forms for convenience. For example, EPA public domain models are sometimes used that report concentrations with units of µg/m³ (micrograms per cubic meter) given mass release rates in units of g/s (gram per second). The Halitsky criterion can be converted to these mass units by converting both the volume emission rate and volume concentrations to mass forms (with subsequent canceling of molecular weight in both terms): an air intake concentration of 423 $\mu g/m^3$ or less given a release rate of 1.0 g/s. This applies to any volume flow rate.

The Halitsky criterion can also be converted to a dilution for a specified volume flow rate. For example, for a 1000 cfm (0.47 m^3/s) exhaust, the Halitsky criterion becomes a stack exit to air intake dilution of 5000:1 or greater for a 1000 cfm (0.47 m^3/s) total volume flow rate exhaust (with subsequent lower dilution needed for higher volume flow rates).

For exhaust rates higher than 1000 cfm (0.47 m^3/s), more dilution of the exhaust takes place within the building exhaust system, so less dilution in the atmosphere is needed. Thus, a 2000 cfm (0.94 m^3/s) exhaust stack would require a 2500:1 dilution, a 10,000 cfm (4.7 m^3/s) exhaust would require a 500:1 dilution, and so on.

The Halitsky criterion can also be compared to a criterion commonly used for laboratory fume hoods—the *ANSI/ASHRAE Standard 110* (ASHRAE 1995) test method combined with a criterion from the *ANSI/AIHA Standard Z9.5* (AIHA 1992). In the Standard 110 test method, a tracer gas is released at 0.11 cfm (4 Lpm) within the fume hood, and tracer concentration is measured at the breathing zone of a mannequin standing at the hood. The principle of the Standard 110 test is similar to evaluation of an exhaust stack: the concentration a person experiences given a release in the fume hood. The criterion used to judge an installed fume hood is a 0.1 ppm concentration of tracer gas for a 0.11 cfm (4 Lpm) release, described in Standard Z9.5 (AIHA 1992). Scaling the Halitsky criterion from 15 cfm (530 Lpm) to the lower 0.11 cfm (4 Lpm) release, the Halitsky criterion in the fume hood criterion form is a 0.028 ppm concentration or less for a 0.11 cfm (4 Lpm) release of any chemical.

The Halitsky criterion can be thought of as approximately a factor of four stricter than the Standard 110/Standard Z9.5 fume hood criterion, which requires a 0.1 ppm concentration. However, persons exposed at a nearby intake are not necessarily healthy workers as would be assumed for a person at a fume hood, and a stricter criterion than for a fume hood worker might be appropriate. A laboratory near a hospital would be a common example. Therefore, the Halitsky criteria is reasonably consistent with the Standard Z9.5 (AIHA 1992) fume hood criterion.

EXAMPLE DILUTION CALCULATIONS

As an example of the suggested procedure, consider a 10,000 cfm (4.7 m^3/s) exhaust with a 3000 fpm (15.2 m/s) exit velocity and a rooftop air intake 100 ft (30 m) away. What stack height is necessary to meet the Halitsky criteria?

From Equation 4, the critical wind speed for a zero stack height is

$$U_{crit,0} = 3.6\frac{3000}{100}\sqrt{\frac{10000/3000}{0.059}} =$$

$$811\ \text{fpm}(4.1\ \text{m/s})[\text{for 0 stack height}]$$

The critical dilution for zero stack height is found from Equation 3:

$$D_{crit,0} = \frac{(1 + 26x3000\ /\ 811)^2}{1 + 13x3000\ /\ 811} = 192\ :\ 1 \text{ for 0 stack height} .$$

The Halitsky (1988) criterion is a 3 ppm intake concentration for a 15 cfm (530 Lpm) chemical gas or vapor emission. From Equation 2, the stack exit concentration is

$$C_{exit} = (15\ \text{cfm}\ /10{,}000\ \text{cfm})x10^6 = 1500\ \text{ppm} .$$

The required dilution is given by Equation 1:

$$D = C_{exit}/C_{final} = 1500\ /\ 3 = 500 : 1 .$$

The zero stack height dilution of 192:1 is not sufficient in this example to meet the 500:1 dilution required by the Halitsky criterion for this stack. By trial and error, a stack height of 7.75 ft (2.4 m) will just meet the criterion. The stack parameter, *Y*, from Equation 4 is

$$Y = 28.9x7.75^2/100^2 = 0.1736 .$$

The critical wind speed increases from 811 fpm (4.1 m/s) to 1216 fpm (6.2 m/s), according to Equation 5:

$$\frac{811}{U_{crit}} = \sqrt{0.1736 + 1} - \sqrt{0.1736} = 0.667 \Rightarrow$$

$$U_{crit} = \frac{811}{0.667} = 1216\text{fpm}(6.2\ \text{m/s}) .$$

The critical dilution increases from 192:1 to over the desired 500:1 dilution for this stack, according to Equation 7:

$$D_{crit} = 192\frac{1216}{811}\exp(\ 0.1736\ + \sqrt{0.1736}\ \sqrt{1.1736}\ ) = 538 ,$$

so a 7.75 (2.4 m) stack meets the Halitsky criterion.

In contrast, the geometric stack height method of the *1997 ASHRAE Handbook*, Chapter 15, would result in a stack height of at least 20 ft (6.1 m) minus a credit for vertical momentum. (This height is based on the 5:1 slope of the bottom plume edge and assumes that the intake is near the building edge.) The vertical plume rise or credit for vertical momentum is

$$h_{rise} = 3dV_e/U_{design} \qquad (8)$$

where d is stack diameter and U_{design} is the maximum design wind speed. It is suggested to use the wind speeds exceeded 1% of the time, available from ASHRAE (1997), Chapter 26, Tables 1A, 2A, and 3A. This wind speed should not be confused with the critical wind speed of Equations 4 and 6. The maximum design wind speed is only to be used for computing the worst-case plume rise, which is not necessarily the wind speed for the worst-case dilution. Continuing the example case, the stack diameter, *d*, is 2.06 ft (0.63 m) for the

10,000 cfm (4.7 m^3/s) flow rate and the 3000 fpm (15.2 m/s) exit velocity. A moderate design wind speed is 2000 fpm (10.2 m/s) from ASHRAE (1997), Chapter 26. The vertical momentum credit from Equation 8 in this case is

$$h_{rise} = 3x2.06x3000 / 2000 = 9.3\text{ft (2.8 m)}.$$

The recommended stack height using the geometric method is then 20 ft to 9.3 ft = 10.7 ft (3.3 m), not much higher than the 7.75 ft (2.4 m) from the dilution equations and the Halitsky criteria. However, the geometric stack height method becomes much more conservative as the intake or building edge is moved farther away since the 5:1 height/distance ratio does not account for the dilution within the plume.

STACK HEIGHT REQUIREMENTS

As seen from the above example calculation, required stack heights (above nearby obstructions) can be computed as a function of the stack operating parameters, distance to the intake, and whether the intake is on the roof or at the side of the building. Figure 1 shows required stack heights as functions of volume flow rate and distance to the air intake for an exit velocity of 3000 fpm (15.2 m/s) and a roof air intake location. The *Y* factor of Equation 5 is the 1997 value of 28.9. Figure 1 shows several interesting trends. First, a lower flow rate requires a taller stack to meet the Halitsky criteria since the lower flow rate has a lower plume rise. Also, for an intake located very close to the stack, only short stacks are needed. For short travel distances, the plume is relatively narrow and will overshoot air intakes located close to the base of the stack. In practice, this advantage of close air intakes is hard to realize because there are usually several stacks on the roof to consider. Leakage at the base of positively pressured exhaust stacks has been noticed within penthouses (Hitchings 1997), so air intakes immediately adjacent to the base of a stack are not recommended.

As discussed above, a new revision of the ASHRAE Handbook, Chapter 15, will adopt a new coefficient of 6.7 in Equation 5 rather than 28.9. The change will theoretically better account for initial plume spread due to the exit vertical momentum that widens the plume. Figure 2 shows the effect of using the 6.7 factor for the same case as Figure 1. Compared to Figure 1, the required stacks with the new factor will be approximately double the previous height.

A side air intake can substantially improve the stack height. Figure 3 shows the required stack heights for the same conditions as Figure 2 (with the new *Y* factor of 6.7) except that the air intake is located on the side of the building (B_1 = 0.13). In general, shorter stacks are needed, so an air intake on the side of the building is beneficial provided that ground level pollutant sources are avoided, such as idling diesel trucks at loading docks. Figure 3 also shows that a high exit velocity (3000 fpm; 15.2 m/s), a high volume flow rate (>10,000 cfm; > 4.7 m^3/s), and side air intakes will permit moderate, aesthetically acceptable stack heights.

CONCLUSION

This paper discusses how the Halitsky (1988) criterion can be combined with the ASHRAE Handbook (ASHRAE 1997) dilution equations to provide a method of specifying stack heights. This method is not as conservative as the highly conservative "geometric method" of the ASHRAE Handbook. A future revision of the Handbook's dilution equations (the *Y* factor of 6.7 in Equation 5) will require significantly taller stacks, and comparisons of wind tunnel data to the revised equations should be conducted.

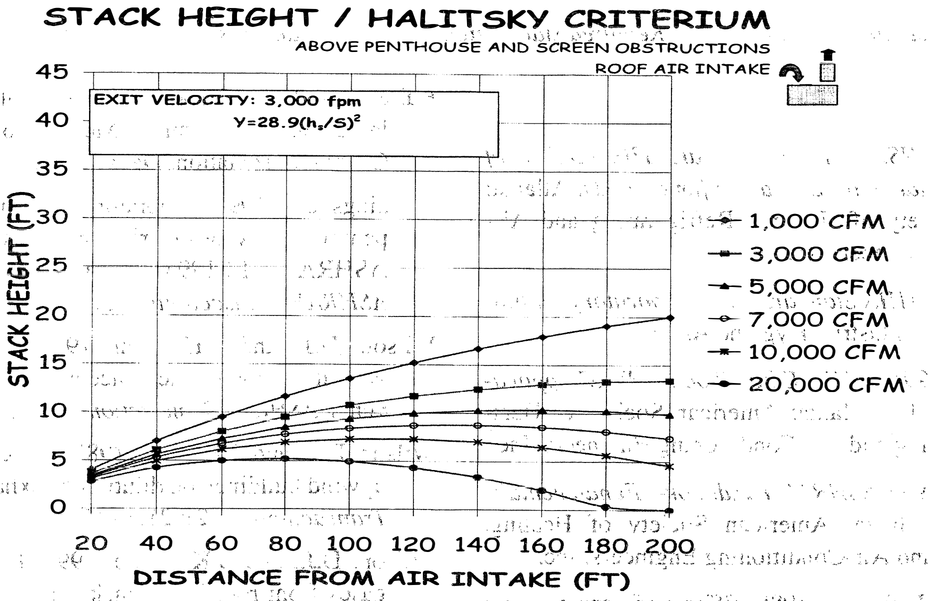

Figure 1 *Stack height/Halitsky criterion. Required stack heights as functions of volume flow rate and distance to the air intake for an exit velocity of 3000 fpm.*

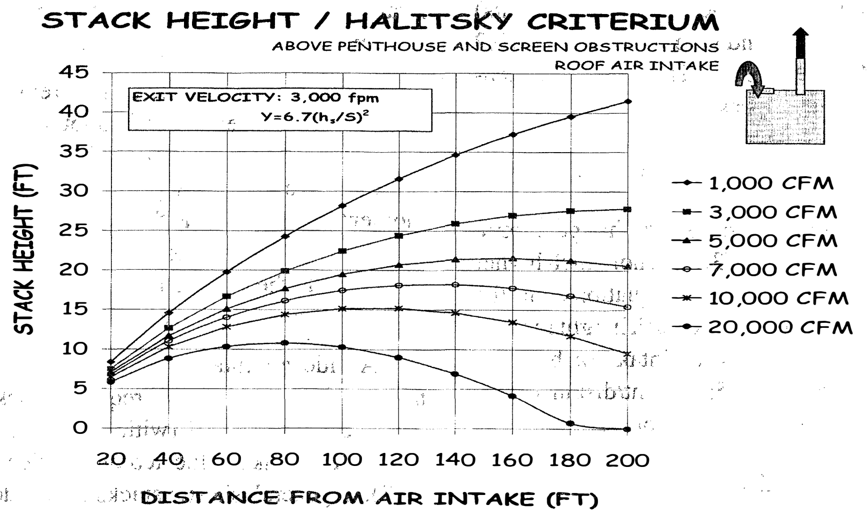

Figure 2 Stack height/Halitsky criterion. Effect of using the 6.7 factor for the same case as Figure 1.

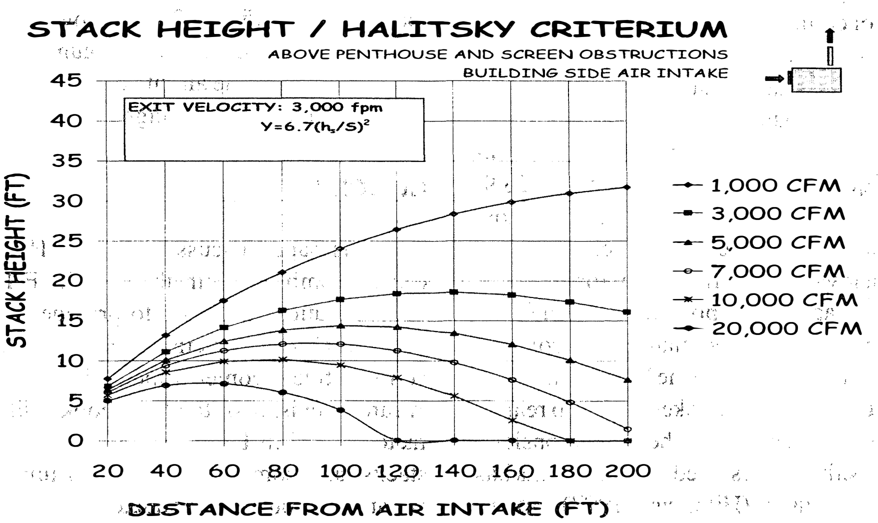

Figure 3 Stack height/Halitsky criterion. Required stack heights with air intake at side of building.

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