ASHRAE Research Project Report 1635-RP

SIMPLIFIED PROCEDURE FOR CALCULATING EXHAUST/INTAKE SEPARATION DISTANCES

Approval: January 2016

Contractor: CPP, Inc.
2400 Midpoint Drive, Suite 190
Fort Collins, CO 80525

Principal Investigator: Ronald L. Petersen
Authors: Jared Ritter, Anthony Bova, John Carter

Author Affiliations, Wind Engineering and Air Quality Consultants, CPP, Inc.

Sponsoring Committee: TC - Ventilation Requirements & Infiltration

Co-Sponsoring Committee: N/A

Co-Sponsoring Organizations: N/A

Shaping Tomorrow's
Built Environment Today

FINAL REPORT

SIMPLIFIED PROCEDURE FOR CALCULATING EXHAUST/INTAKE SEPARATION DISTANCES

AMERICAN SOCIETY OF HEATING, REFRIGERATING, AND AIR-CONDITIONING ENGINEERS, INC.

RESEARCH PROJECT 1635-TRP

CPP Project 7499

Prepared for:

The American Society of Heating, Refrigerating,
and Air-Conditioning Engineers, Inc.
1791 Tullie Circle
Atlanta, Georgia 30329

Prepared by:
Ronald L. Petersen, PhD, CCM, FASHRAE
Jared Ritter
Anthony Bova
John C. Carter, MS, MASHRAE

CPP, INC.
WIND ENGINEERING AND AIR QUALITY CONSULTANTS
2400 Midpoint Drive, Suite 190
Fort Collins, Colorado 80525

23 September 2015

EXECUTIVE SUMMARY

This research was sponsored by ASHRAE Technical Committee (TC) 4.3. The purpose of this Research Project is to provide a simple, yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid re-entrainment of exhaust gases. The new procedure addresses the technical deficiencies in the simplified equations and tables that are currently in Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality and model building codes. This new procedure makes use of the knowledge provided in Chapter 45 of the 2015 ASHRAE Handbook—Applications, and was tested against various physical modeling and full-scale studies.

The study demonstrated that the new method is more accurate than the existing Standard 62.1 equation which under-predicts and over-predicts observed dilution more frequently than the new method. In addition, the new method accounts for the following additional important variables: stack height, wind speed and hidden versus visible intakes. The new method also has theoretically justified procedures for addressing heated exhaust, louvered exhaust, capped heated exhaust and horizontal exhaust that is pointed away from the intake.

Included in the report are recommendations and documentation regarding minimum dilution factors for Class 1-4, wood burning kitchen, boiler, vehicle, emergency generator and cooling tower type exhaust.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Currently ASHRAE Standard 62.1-2013 (Standard 62.1) has air intake minimum separations distances, L, specified for various types of exhaust sources in Table 5-1 of the Standard. The minimum separation distance is defined as the shortest "stretched string" distance from the closest point of the outlet opening to the closest point of the outdoor air intake opening or operable window, skylight, or door opening, along a trajectory as if a string were stretched between them. Other codes and standards (e.g., 2012 Uniform Mechanical Code, U.S., Building Codes, Uniform Plumbing Code) also specify minimum separation distances, all of which appear to be "rule of thumb" based with 3 to 10 ft (1 to3 m) being the magic number for most exhaust types. The separation distances can be both far too lenient and far too restrictive, depending on the type of exhaust and exhaust and intake configurations.

Both code and Standard 62.1 requirements are overly simplistic and fail to account for significant variables such as the exhaust airflow rate, the enhanced mixing caused by high exhaust discharge velocity, the orientation of the discharge, or the height of the exhaust relative to intake. Standard 62.1 also includes an informative Appendix F that outlines a procedure to account for exhaust air flow rate and velocity to achieve target dilution levels. The appendix is not mandatory but given as an example of how to use analytical techniques to show that separation distances other than those in Table 5-1 are acceptable.

The purpose of this Research Project is to provide a simple, yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid re-entrainment of exhaust gases. The procedure addresses the technical deficiencies in the simplified equations and tables that are currently in Standard 62.1. This new procedure makes use of the knowledge provided in Chapter 45 of the 2015 ASHRAE Handbook—Applications, and various wind tunnel and full-scale studies discussed herein.

The updated methodology is suitable for standard HVAC engineering practice and has as independent variables: exhaust outlet velocity; exhaust air volumetric flow rate; exhaust outlet configuration (capped/uncapped) and position relative to intake orientation and position; desired dilution ratio; and ambient wind speed. The current Appendix F method includes some of these factors but does not include variable wind speed, stack height, or hidden intake reduction factors. The method discussed herein takes into account all of these variables.

The research started out with an objective to develop two new procedures from existing and new research with the following characteristics:

- Procedure 1.
  - A general procedure suitable for standard HVAC engineering practice that has as independent variables: exhaust outlet velocity; exhaust air volumetric flow rate; exhaust outlet configuration (capped/uncapped/horizontal/louvered) and position (vertical separation distance); exhaust direction; desired dilution ratio; hidden intakes (building sidewall), and ambient wind speed.
  - Other factors, such as location relative to walls and edge of building, geometry of the exhaust discharge and inlets, etc., are reduced to fixed assumptions that are reasonable yet somewhat conservative.
- Procedure 2.
  - A regulatory procedure suitable for Standard 62.1, Standard 62.2, and model building codes that has as independent variables only exhaust outlet velocity, exhaust air volumetric flow rate, desired dilution ratio, and a simple way to account for orientation relative to the inlet.
  - All other variables will be reduced to fixed assumptions that are reasonable yet conservative.
  - This procedure consists of tabulated distances for various classes of exhaust.

In the end, one simple procedure was developed that met the overall objectives of the study and is appropriate for the following exhaust types.

- Toilet exhaust from rain-capped vents or dome exhaust fans
- Grease and other kitchen fan exhausts
- Combustion flues and vents with either forced or natural draft discharge in horizontal or vertical direction, with and without flue caps (this includes diesel generators)
- Diesel vehicle emissions
- Building exhaust at indoor air temperature through louvered or hooded vents
- Plumbing vents
- Cooling towers

The method does not address:

- Laboratory and industrial ventilation process exhausts

- Large, industrial sized combustion flues and stacks
- Packaged units that have integral exhaust and intake locations

A secondary objective of this project is to address dilution targets, a necessary parameter for calculating the separation distance calculation. Accordingly, minimum dilution factors were reviewed and updated for various types of exhausts as appropriate, especially those with known emissions and health impacts such as combustion exhaust.

The following sections provide a review of the Standard 62.1 equation, discussion of data bases that were used to test and compare the Standard 62.1 equation and new equations, development of a new equation, an evaluation of the new and Standard 62.1 equations against observations, development of minimum dilution values, and a section discussing the updated new methodology.

2. REVIEW AND EVALUATION OF STANDARD 62.1 EQUATION

2.1 GENERAL

This section provides background information on the existing Standard 62.1-2013 equation (hereafter referred to as 62.1 equation), a description of dilution databases that will be used to evaluate the 62.1 equation and future equation, and an evaluation of the 62.1 equation against the database.

2.2 BACKGROUND ON STANDARD 62.1-2013 EQUATION

The following discussion illustrates some of the problems with the current Standard 62.1 methodology. Appendix F of Standard 62.1 provides the following tables for Class 3 and Class 4 exhaust. Kitchen Exhaust should be categorized as Class 3 exhaust and Table F-1 would say a minimum separation distance of 15 ft (5 m) is required with a dilution factor of 15. Based on past odor panels studies and anecdotal evidence, as discussed in Section 3, a dilution factor of at least 100 is needed for kitchen exhaust; and for some kitchen types, a dilution factor of 1000 or more may be needed. A 1:300 dilution factor has been found to be adequate for most situations.

TABLE F-1 Minimum Separation Distance

Exhaust Air Class (See Section 5.16)	Separation Distance, *L*, *ft (m)*
Significant contaminant or odor intensity (Class 3)	15 (5)
Noxious or dangerous particles (Class 4)	30 (10)

TABLE F-2 Minimum Dilution Factors

Exhaust Air Class (See Section 5.16)	Dilution Factor, *DF*
Significant contaminant or odor intensity (Class 3)	15
Noxious or dangerous particles (Class 4)	50*

*Does not apply to fume hood exhaust. See Section F2.

Table 2-1. Tables F-1 and F-2 From Standard 62.1-2013.

Table 2.2 below provides example calculations using the Standard 62.1 methodology. If the Class 3 dilution specification is used assuming a capped stack, the minimum separation distance is computed to be 16 ft (5 m) which agrees well with Table F-1. However, if more realistic dilution factors are used, the minimum separation distance varies from 70 to 133 ft (21 to 41m), which are impractically large for most buildings. With a vertically directed exhaust without a cap, the separation distances decrease and vary from 6 to 123 ft (2 to 38 m). These results point out several problems with the current method for kitchen exhaust:

Table 2-2. Example Calculations Using Standard 62.1-2013 Method.

Case	Dilution Factor	Exhaust Flow cfm	Dischange Velocity fpm	Separation Distance ft
Capped Stack				
Appendix F	15	2000	0	16
CPP's recommended value	300	2000	0	70
Grill/Range Hood - Odor Panel Results	570	2000	0	96
Rotisserie Exhaust - Odor Panel Results	1100	2000	0	133
Heated Vertically Directed with no Cap, Unheated				
Appendix F	15	2000	1000	6
CPP's recommended value	300	2000	1000	60
Grill/Range Hood - Odor Panel Results	570	2000	1000	86
Rotisserie Exhaust - Odor Panel Results	1100	2000	1000	123

- the specified minimum separation distance in Table F-1 will not ensure the intake is protected from odors for most kitchen exhaust (e.g., capped or low exit velocity);
- If a vertically directed exhaust is used with a short stack, the Appendix F method will allow the intake to be very close to the exhaust, a poor design from an odor perspective since a higher wind condition may result in no plume rise and direct plume impact on the intake;
- The method does not account for stack height. For a tall stack and vertically directed exhaust, the best intake location will be close to the stack versus farther away directly in conflict with the Table 1 results.
- The method does not account for the added dilution, except in the form of the string distance, if the intake and exhaust are blocked by a screen wall.
- The method does not allow for increased dilution if the intake is on a building sidewall due to the increased turbulence.

2.3 Evaluation of Existing Standard 62.1 Equation

The development of the 62.1 equation can be found in Appendix N of the August 1996 Public Review Draft of the ASHRAE Standard 62, which will be referred to as 62-1989R. The equation development begins with the minimum dilution equation (D_{min}) found in the 1993 ASHRAE Handbook, Fundamentals, Chapter 14 and Wilson and Lamb (1994).

$$D_{min} = [D_o^{0.5} + D_s^{0.5}]^2 \qquad (2.1)$$

where:

$$D_o = 1 + C_1 \beta \left(\frac{V_e}{U_H}\right)^2 \qquad (2.2)$$

$$D_s = \beta_1 \left(\frac{S^2 U_H}{Q_e}\right) \qquad (2.3)$$

D_o represents the initial jet dilution and D_s represents the dilution that occurs versus separation distance. 62-1989R states that the constant C_1 ranges from 1.6 to 7, β_1 (C_2 in 62-1989R) ranges from 0.0625 to 0.25, S is the "stretched string" distance measured along a trajectory, U_H is the wind speed at the roof level, V_e is the discharge velocity, Q_e is the volume flow rate, and β is a factor that relates the nature of discharge outlet. β equals 1 for the vertical discharge and 0 for a capped (or downward) discharge.

To develop the Standard 62.1 equation, equations 2.1, 2.2 and 2.3 were first rearranged to solve for S (L in the Standard 62.1 Equation) which results in.

$$S = \left[\frac{Q_e}{\beta_1 U_H}\right]^{0.5} \left[D^{0.5} - \left(1 + C_1 \beta \left(\frac{V_e}{U_H}\right)^2\right)^{0.5}\right] \qquad (2.4)$$

The equation is then simplified by assuming (62-1989R):

- the 1 term insignificant,
- $V_e = 0$ for capped or non-vertical stacks,
- $U_H = 2.5$ m/s (500 fpm) average wind speed,
- $C_1 = 1.7$ (on the low end of the range, giving less credit for dilution due to discharge velocity which tends to increase the separation distance), and
- $\beta_1 = 0.25$ (on the high end of the range, giving maximum credit for dilution due to separation, and tends to reduce separation distance, and is non-conservative),

The Standard 62.1 equation then results, or

$$S = 0.09\, Q_e^{0.5} \left[D^{0.5} - \frac{V_e}{400}\right] \text{ (in feet)} \qquad (2.5)$$

$$S = 0.04\, Q_e^{0.5} \left[D^{0.5} - \frac{V_e}{2}\right] \text{ (in meters)} \qquad (2.6)$$

where

- Q_e = exhaust air volume, cfm (L/s).
- D = dilution factor for the exhaust type of concern.
- V_e = exhaust air discharge velocity, fpm (m/s).
- V_e is positive when the exhaust is directed away from the outside air intake at a direction that is greater than 45° from the direction of a line drawn from the closest exhaust point the edge of the intake;
- V_e has a negative value when the exhaust is directed toward the intake bounded by lines drawn from the closest exhaust point the edge of the intake; and
- V_e is set to zero for other exhaust air directions regardless of actual velocity. V_e is also set to 0 for vents from gravity (atmospheric) fuel-fired appliances, plumbing vents, and other non-powered exhausts, or if the exhaust discharge is covered by a cap or other device that dissipates the exhaust airstream.
- For hot gas exhausts such as combustion products, an effective additional 500 fpm (2.5 m/s) upward velocity is added to the actual discharge velocity if the exhaust stream is aimed directly upward and unimpeded by devices such as flue caps or louvers.

Equation 2.6 has the following problems in addition to those discussed in Section 2.1:

- The equation in only valid for a flush vents and does not account for stack height or height difference between the stack and air intake.
- Even though an exit velocity term is included, it does not adequately account for high velocity exhaust systems. The velocity term is accounts for the added dilution due to a higher exit velocity but does not account for the added plume rise.
- The assumed value for the constants C_1 or 1.7, while conservative, is not supported by the research. According to Wilson and Chiu (1994) and ASHRAE (1993, 1997), values of 7 and 13 are more appropriate.
- The assumed value for the constant β_1 of 0.25 is non- conservative and is not supported by the research. According to Wilson and Chiu and ASHRAE (1993,1997), values ranging from 0.04 to 0.08 are more appropriate.
- For vertical stacks, a wind speed higher than 2.5 m/s (500 fpm) may be critical because plume rise will decrease as wind speed increases, while at low wind speed the plume rise will be very large.

- For flush vents and capped stacks, a wind speed lower than 2.5 m/s (500 fpm) will most likely be the critical case. Speeds as low as 1 m/s (200 fpm) can occur a significant fraction of the time.
- Setting V_e equal to a negative number when the exhaust is directed away from the intake, while intuitively correct, cannot be derived from the original equation used to develop the Standard 62.1 approach.

To evaluate the Standard 62.1 equation, the equation will be rearranged so dilution can be predicted for comparison with the dilution values recorded in the databases discussed in Section 2.4. The re-arranged equation is provided below.

$$D = \left(\frac{11.1\,S}{{Q_e}^{0.5}} + \frac{V_e}{400}\right)^2 \text{ (IP)}$$

(2.7)

$$D = \left(\frac{25\,S}{{Q_e}^{0.5}} + \frac{V_e}{2}\right)^2 \text{ (SI)}$$

Overall, this section has shown some of the problems with the current Standard 62.1 equation and confirms the need for an improved equation.

2.4 Dilution Databases

During this task, existing wind tunnel and full-scale data were assembled and reviewed. Only those wind tunnel databases that meet the criteria outlined in EPA's Guideline for Fluid Modeling of Atmospheric Diffusion (Snyder, 1981) were be used in this study. Some of the important criteria that were considered are as follows:

- A boundary-layer wind profile representative of the atmosphere was established.
- The approach turbulence profile was representative of the atmosphere.
- Reynolds number independent flow was established

Once the relevant databases were selected, the data were entered into an excel spreadsheet in a form that will expedite comparisons with Appendix F equations and the other numerical methods that are developed in Section 3. The following sub-sections discuss each database.

2.4.1 Database 1 – Wilson and Chui, 1994

The following summarizes the important aspects of this database.

- 1:500 and 1:2000 scale model tests were conducted.
- Building Reynolds numbers exceeded 10^4 to meet Reynolds number independence criterion of Snyder (1981).
- A wind power law exponent of 0.25 was established and wind speeds at building height of 5.9 to 12.1 m/s (1200 to 2400 fpm) were set.
- Eleven model building configurations were tested at six different exhaust momentum velocity ratios as shown in Table 2-3 and Figure 2-1 below.
- Exhaust parameters: flush circular vent with exhaust density ratio varying from 0.14 to 0.38. Momentum ratios varied from 0.8 to 1.5.
- Building height to width ratios varied from 1 to 12.

Wilson and Chiu (1994) showed that Equations 2.1, 2.2 and 2.3 above with β_1 = 0.625 and C_1 = 7 provided a lower bound to the observed dilution values for several building configurations. This database will not be used directly to evaluate the performance of the new equation rather the predicted lower bound using Equations 2.1, 2.2 and 2.3 with recommended constants will be used as a lower bound prediction for comparison purposes.

Table 2-3. Building and exhaust flow configurations from Wilson and Chiu, 1994

Configuration number	Building width-to-height ratio $\frac{W}{H}$	Exhaust density ratio $\frac{\rho_e}{\rho_a}$	Wind speed at roof height U_H $(\mathrm{m\,s^{-1}})$	Exhaust momentum factor $M=\left(\frac{\rho_e}{\rho_a}\right)^{0.5}\frac{W_e}{U_H}$
6	4.0	0.138	5.89	0.768
7	8.0	0.138	5.89	0.768
8	4.0	0.378	5.89	1.76
9	8.0	0.378	5.89	1.76
10	12.0	0.378	5.89	1.76
12	8.0	0.378	5.89	1.76
18	2.0	0.378	6.91	1.50
21	6.0	0.378	6.91	1.50
48	4.0	0.138	8.56	0.103
53	2.0	0.138	10.2	0.087
58	1.0	0.138	12.1	0.073

Figure 2-2 shows a typical comparison of predicted (Equations 2.1, 2.2 and 2.3) and observed dilution versus normalized distance. As can be seen the predicted values using equations 2.1, 2.2 and 2.3) provide a lower bound estimate of the observed dilution.

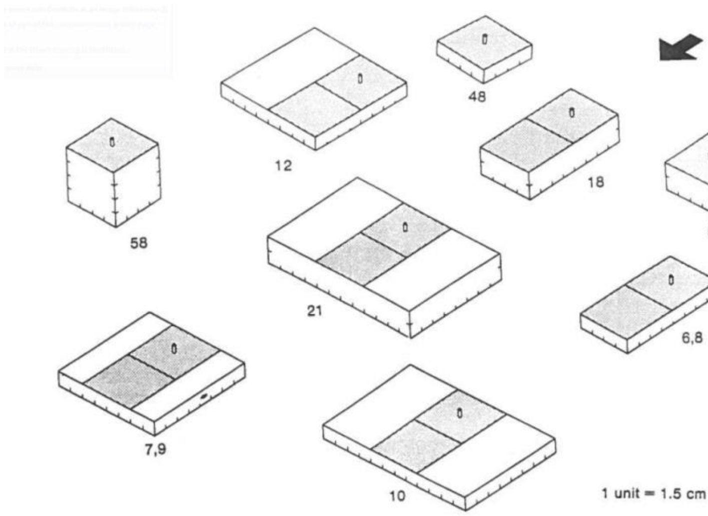


Fig. 3. Building models with intake sampling areas shown shaded.

Figure 2-1. Building models with intake sampling areas shown shaded from Wilson and Chiu (1994).

Rooftop dispersio

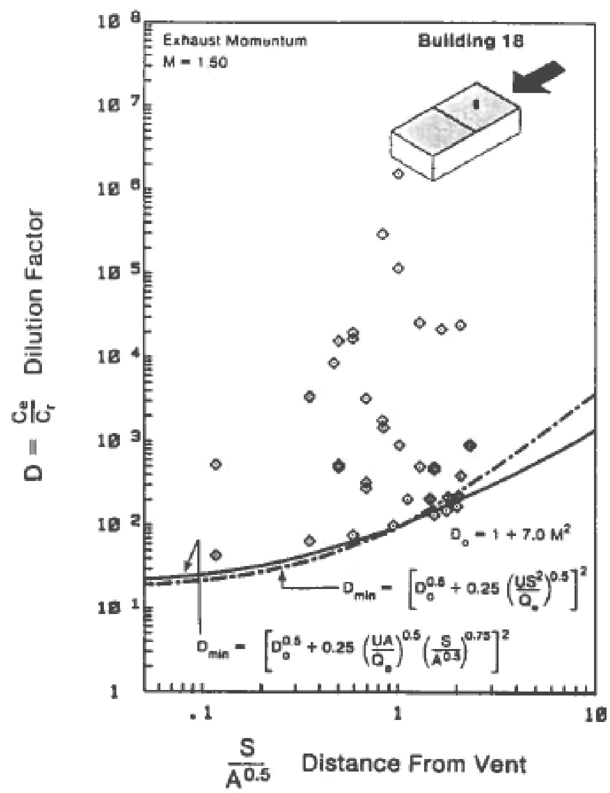


Figure 2-2. Typical predicted versus observed dilution results from Wilson and Chiu (1994).

2.4.2 Database 2 – Wilson and Lamb, 1994

This is a very unique database in that it is based on a full-scale study that was conducted using tracer gas released from stacks and exhaust vents on Washington State University chemistry laboratory buildings "Fulmer" and "Annex", shown in Figure 2-3. While the database is based on laboratory exhaust stacks, the results are valid for any type exhaust.

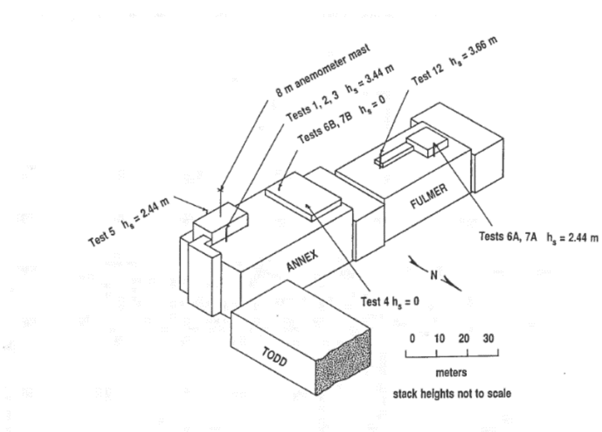


Figure 1 Stack and anemometer locations on source buildings.

Figure 2-3. Full-scale building configuration from Wilson and Lamb (1994).

The following summarizes the important aspects of this database.

- Each test took place on a different day between January 14 and March 11, 1994.
- Hourly meteorological data (wind speed, wind direction, temperature and σ_θ) were collected from an 8 m (26.25 ft) mast erected on the penthouse roof on the Annex Building. This represents the tallest point of the test buildings, which minimizes building wake effects. Wind speeds during the testing period varied from 2.2 to 8.1 m/s (440 to 1600 fpm). Crosswind turbulence indicated by σ_θ ranged from 6.5 to 24.8 degrees.
- Tracer gas dilution measurements were carried out by releasing sulfur hexafluoride (SF_6) from the uncapped fume hood exhaust vents and collecting four sequential hourly average air samples from 44 locations. The distances ranged from S=5 m (16.4 ft) to S= 270 m (886 ft). Sufficient data was collected to ensure that the minimum dilution could be documented.
- Stack heights ranged from 0 to 3.66 m (0 to 12 ft) and average velocity ratios, M, ranged from 0.83 to 8.3.

Figure 2-4 below shows the overall results from the study. The figure shows that equations 2.1, 2.2 and 2.3 with β_1= 0.04 and C_1 = 13 provide a lower bound estimate of dilution when compared to observations. Again, this confirms the validity of these equations for flush vents with low plume rise. As with Wilson and Chui (1994), this database will not be used directly to evaluate the performance of the new equation; rather the predicted lower bound using equations 2.1., 2.2. and 2.3 with the recommended constants from this study will be used as a 2^{nd} lower bound prediction for comparison purposes.

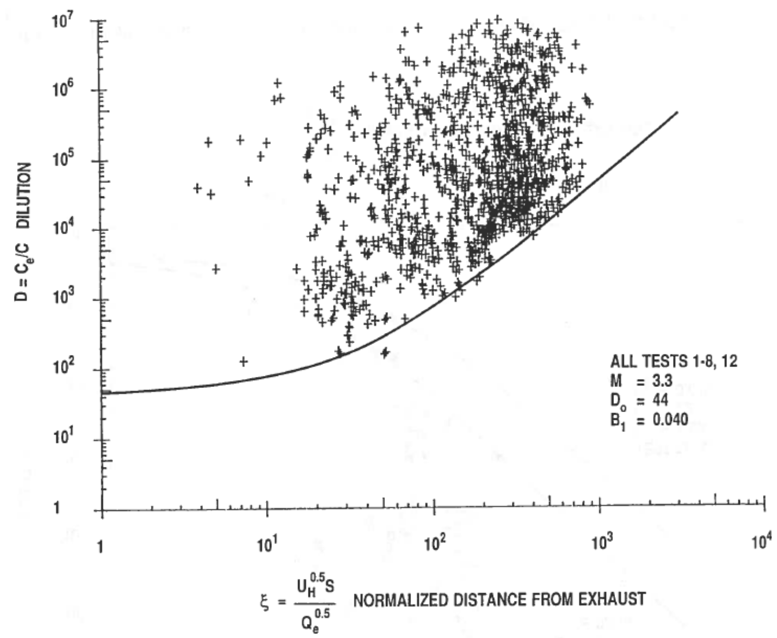


Figure 2-4. Predicted and observed dilution versus normalized distance from Wilson and Lamb (1994).

2.4.3 Database 3 – ASHRAE Research Project 805, Petersen, et.al, 1997

This study was initially commissioned in 1997 as an ASHRAE research project to determine the influence of architectural screens on exhaust dilution. Wind tunnel experiments were performed with generic building geometry in order to generate a database of concentrations to document the effects of several screen wall configurations. Baseline exhaust concentrations obtained without the presence of a screen wall were also included in the wind tunnel assessment.

The following summarizes the important aspects of this database:

- 1:50 scale model tests were conducted in the Cermak Peterka Petersen boundary layer wind tunnel with velocity profile power law exponent of 0.28.
- Building Reynolds Number >11,000 to meet Reynolds Number independence criterion of Snyder (1981).
- Concentration data for various different exhaust configurations:
    - Building measurements 50’ x 100’ x 50’ (15.2m x 30.48m x 15.2m) (H x W x L)
    - Stack heights (h_s): 0, 1, 3, 5, 7, 12 ft (0, 0.3, 0.9, 1.5, 2.1, 3.7 m)
    - Volumetric flow rate of 500 cfm (0.24 m^3/s), 5000 cfm (2.4 m^3/s), 20,000 cfm (9.43 m^3/s)
    - Exhaust momentum ratios ($M=V_e/U_H$): ranging from ~1 to 4
    - Receptors were placed on rooftop and leeward walls.
    - Wind azimuths: 0, 45 and 90 degrees
    - Reference wind speed of U_{ref} = 3.7 m/s (728 fpm) and 11.1 m/s (2185 fpm) in the wind tunnel

For this study, data were only used for results obtained in the wind tunnel for cases with no screen wall on the test building. Only data collected at receptor locations on the test building were used, and no downwind or off-building exhaust concentrations were considered. Data for multiple stack heights, multiple momentum ratios, and wind azimuths of 0 and 45 degrees were considered in this evaluation. The testing configuration is illustrated in Figure 2-5.

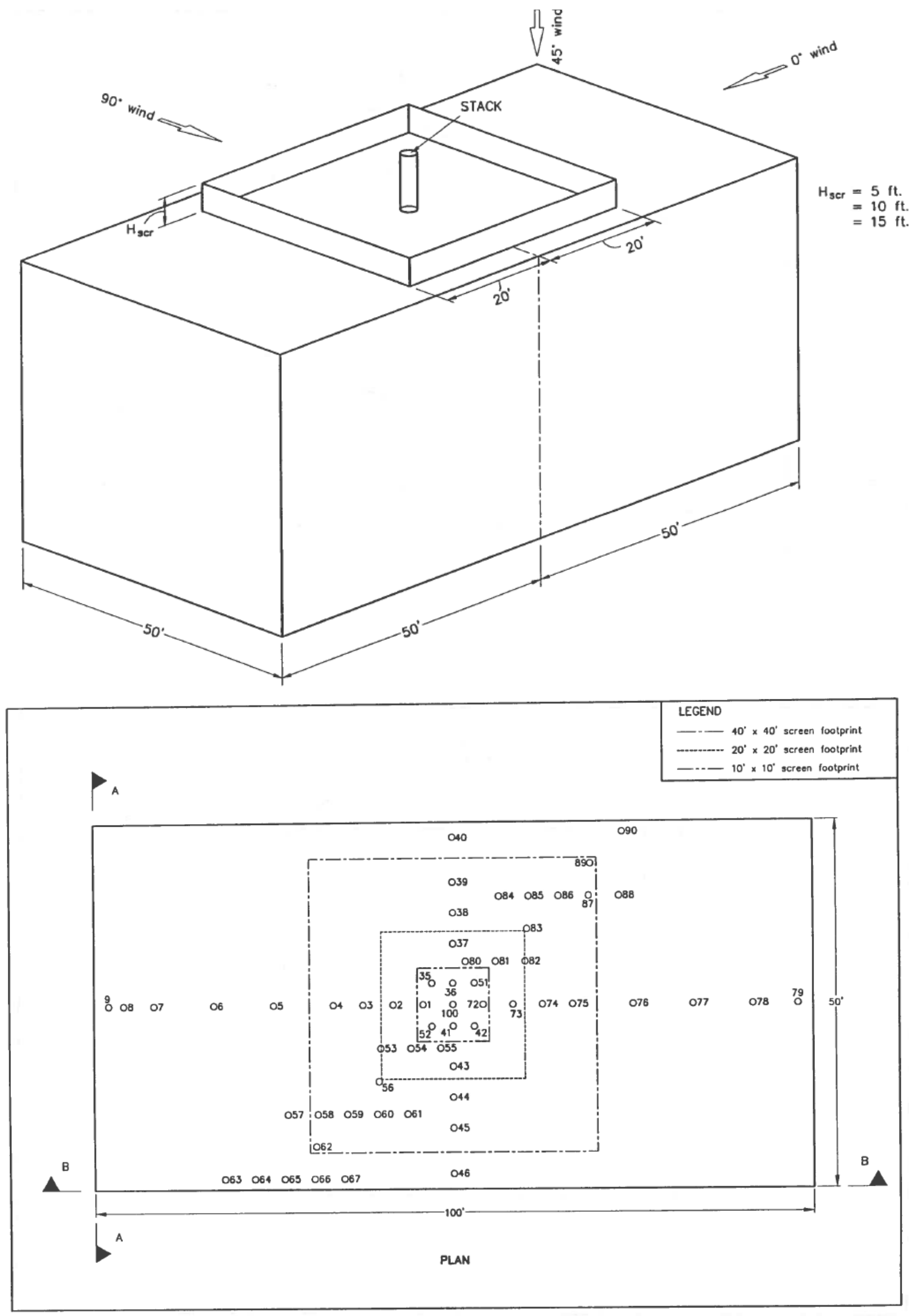


Figure 2-5. Test building and rooftop receptor layout used for the ASHRAE RP 805 Evaluation, Petersen, et.al. (1997).

Concentration measurement data from the original wind tunnel study were entered in tablature format into a spreadsheet. Plots of the measured dilution values versus string distance are provided in Figure 2-6 and Figure 2-7.

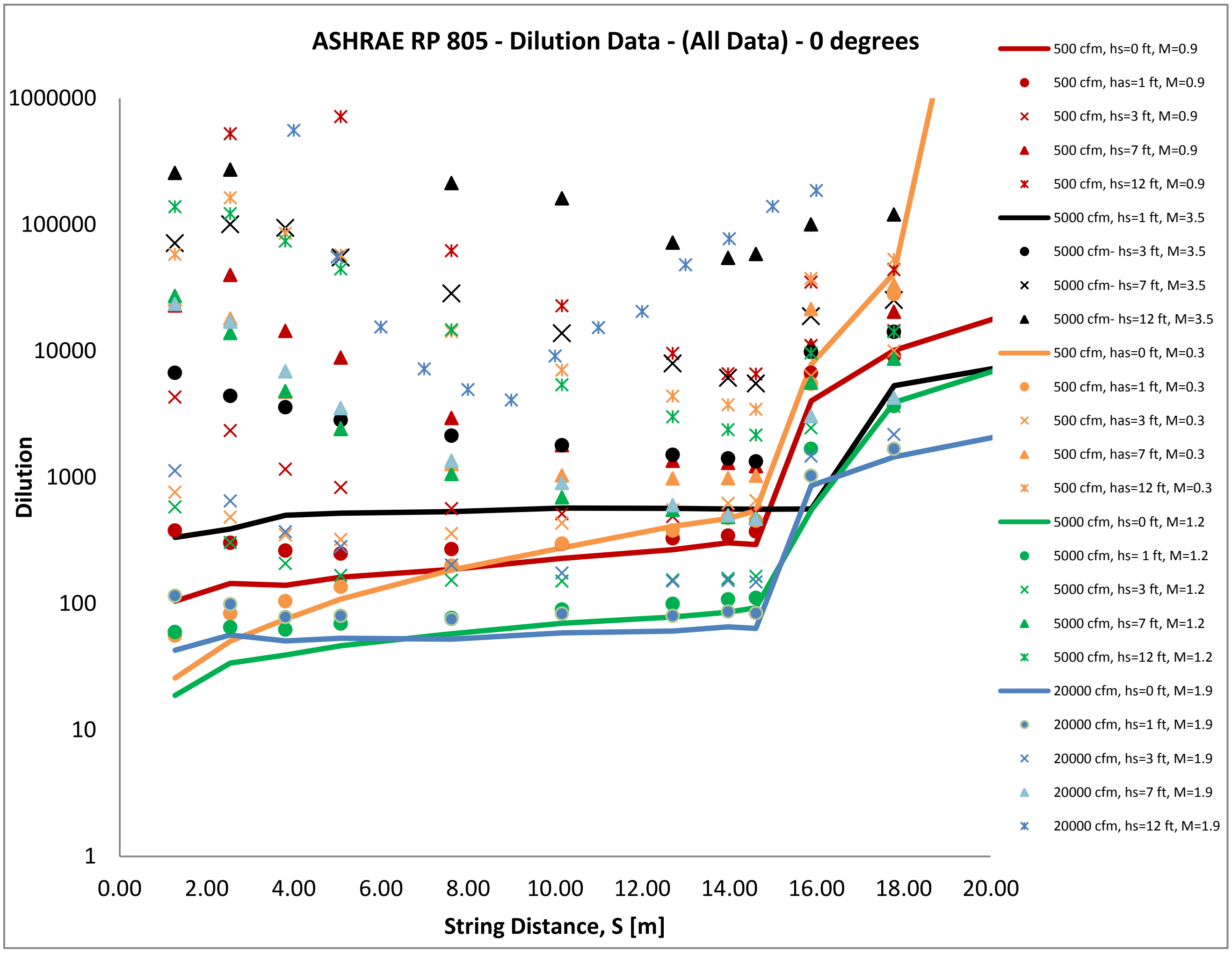


Figure 2-6. Drawing showing observed dilution versus string distance from ASHRAE RP 805 – 0 degree data, Petersen, et.al (1997).

Figure 2-6 above shows that the observed dilution increases as stack height is increased. Similar trends are observed for stacks with similar momentum ratios (e.g. M=1.2 and M=1.9).

For the 0 degree orientation, the furthest rooftop receptor location was located approximately 15 m (49 ft) from the stack. Data taken at distances greater than 15 m (49 ft) indicates concentrations obtained at a receptor in a “sidewall” location. As expected, a noticeable increase in dilution is observed at sidewall receptor locations.

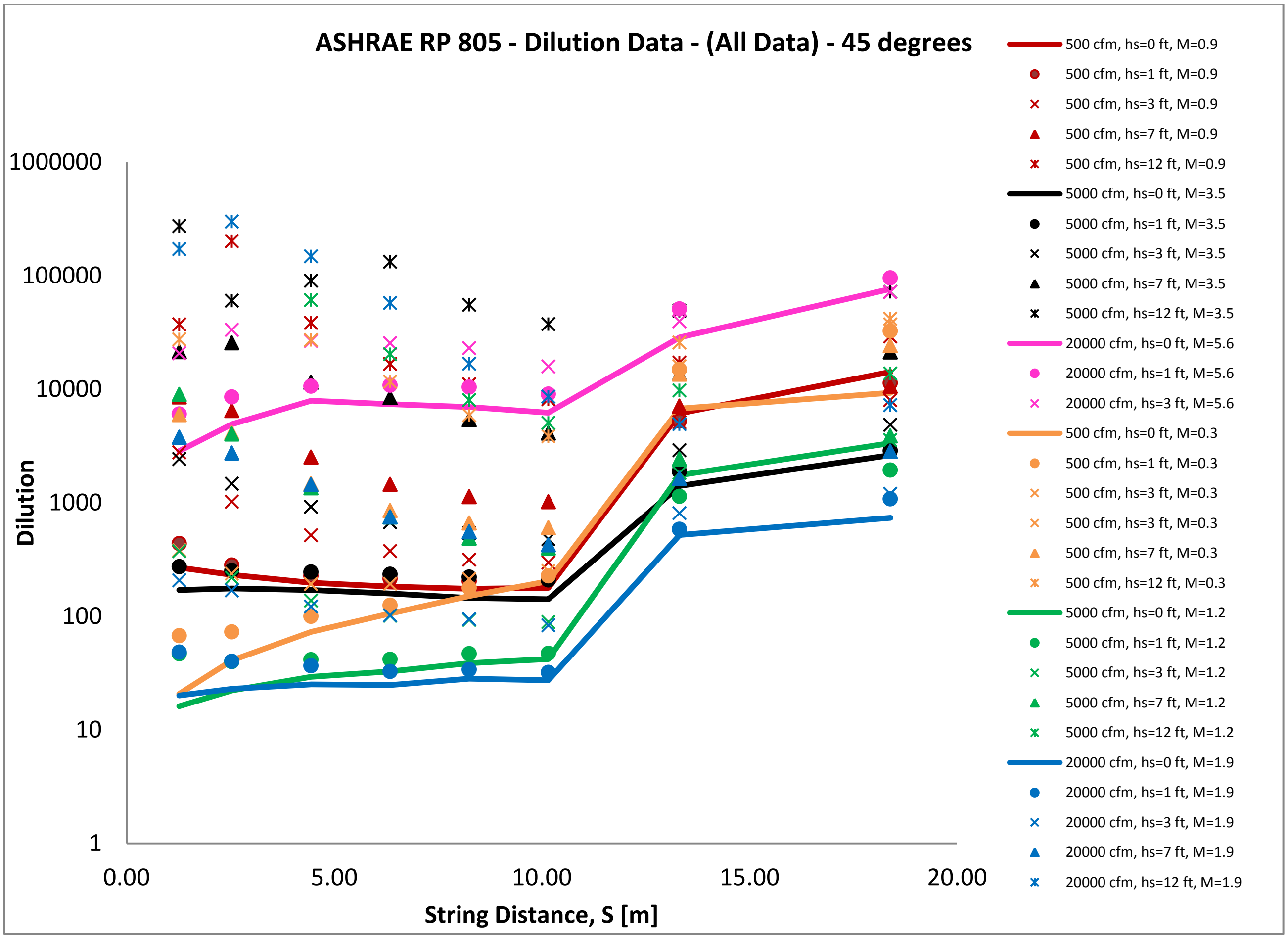


Figure 2-7. Drawing showing observed dilution versus string distance from ASHRAE RP 805 – 45 degree data, Petersen, et.al (1997).

Similar to the 0 degree data, Figure 2-7 shows the most significant increases in dilution occur with increases vertical stack height. Increases in dilution are also observed for cases with higher momentum ratios (i.e., M>3). For the 45 degree data set, the furthest rooftop receptor location is located approximately 13 m (42.7 ft) from the stack. Receptors at a distance greater than 13 m (42.7 ft) were located on the leeward wall of the building (sidewall receptors). As expected, dilution values were observed to increase at the sidewall intake locations.

2.4.4 Database 4 – Hajra and Stathopoulos, 2012

This study was performed to determine the impact of pollutant re-entrainment affecting downstream buildings of different geometries. However, a baseline configuration without downstream buildings was also evaluated. Receptors were placed on rooftop, windward, and leeward walls.

The following summarizes the important aspects of this database:

- 1:200 scale model tests were conducted in the Concordia University boundary layer wind tunnel (12.2 m long (40 ft) with a 3.2 m^2 cross-section (34.4 ft^2)).
- Power law exponent of 0.31 with wind speed at building height U_H of 6.2 m/s (1220 fpm) in the wind tunnel
- Building Reynolds Number >11,000 to meet Reynolds Number independence criterion of Snyder (1981).
- Concentration data for various different exhaust configurations:
    - Stack heights (h_s): 1, 3, 5 m (3.28 ft, 9.84 ft, 16.4 ft)
    - Exhaust momentum ratios ($M=V_e/U_H$): 1, 2, 3
    - Wind azimuths: 0 and 45 degrees

For this evaluation, concentration data for the low-rise building model configuration were used. Data from the configurations with multiple buildings were not used, which included several downwind buildings of various size and distance from the test building. Configuration 1 was considered for this database, as illustrated in Figure 2-8, and has H:W:L characteristics of 15m:50m:50m (49.2 ft:164 ft:164 ft).

For the purposes of this evaluation, data were used for the lowest stack heights (i.e., h_s=1 m (3.28 ft) and h_s=3 m (9.84ft)). Only exhaust momentum ratios of M=1 were considered. These are the cases of most interest since they apply directly to the ASHRAE 62.1 equation.

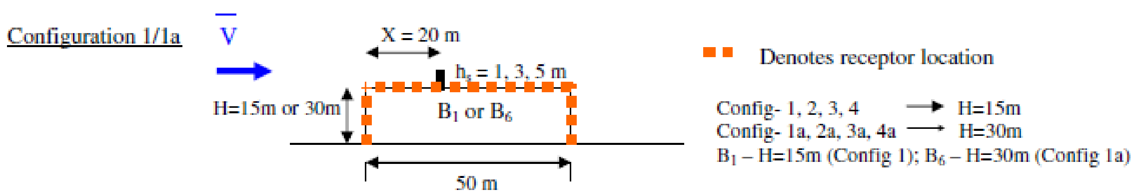


Figure 2-8. Drawing showing building, exhaust and receptor configuration from Hajra and Stathopoulos (2012).

Concentration measurement data was extracted from the database plots using a plot digitizer and entered in tablature format into a spreadsheet. Plots of the measured dilution values versus string distance for each configuration considered for this study are provided in Figure 2-9.

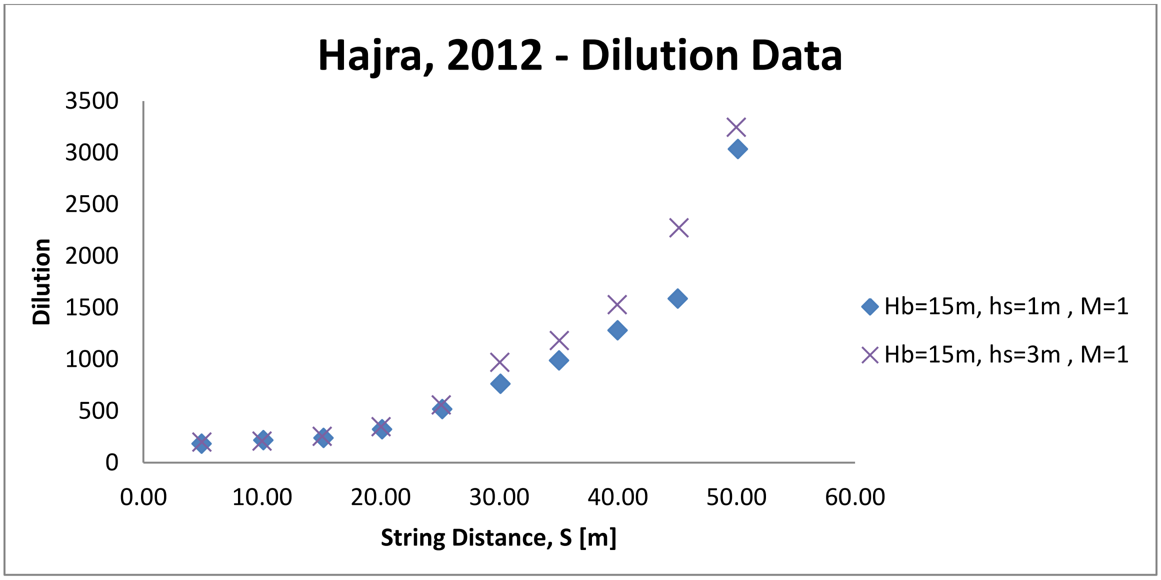


Figure 2-9. Drawing showing observed dilution versus string distance from Hajra and Stathopoulos (2012).

Figure 2-9 shows that the observed dilution versus distance was about the same for the cases with low velocity ratio (M=1), regardless of stack height. In cases with similar plume rise (i.e., equal stack height and M), the dilution values should be the similar. As expected, the taller stack height provides slightly higher dilution at distances greater than 20m from the stack.

2.4.5 Database 5 – Schulman and Scire, 1991

This study was performed to determine the effect of stack height, exhaust plume momentum, and wind direction on downwind exhaust concentrations from a rooftop exhaust source. The results of this database were taken from previous wind tunnel findings from Hoydysh and Schulman (1987). Various stack heights and momentum ratios were evaluated at both 0 and 45 degrees, with receptor locations downwind of the exhaust stack on the test building rooftop and facades.

The following summarizes the important aspects of this database:

- 1:100 scale model in wind tunnel with power-law profile with exponent 0.20
- Building Reynolds Number of 14,000
- Measurements obtained from flame ionization hydrocarbon analyzer, with claimed concentration repeatability of 10%
- Concentration data for various different exhaust configurations:
    - Building measurements 50ft x 250ft x 250ft (15.2m x 76m x 76m) (H x W x L)
    - Stack heights (h_s) of h_s/H= 1.0, 1.1, 1.3 and 1.5

- Exhaust momentum ratios of ($M = V_e/U_H$) of 1.0, 1.1, 3.0 and 5.0
- Receptors on rooftop and leeward walls, in direct line downwind of stack
- Wind azimuths of 0 and 45 deg
- Reference wind speed of 1.37 m/s (270 fpm)

For this study, only stack heights of $h_s/H = 1$ and 1.1 were considered, as they are the stack heights Standard 62.1 is most likely to be applied. Dilution values from this database were used for azimuths of 0 deg and 45 deg at both rooftop and hidden receptors. The testing configuration is illustrated below, in Figure 2-10.

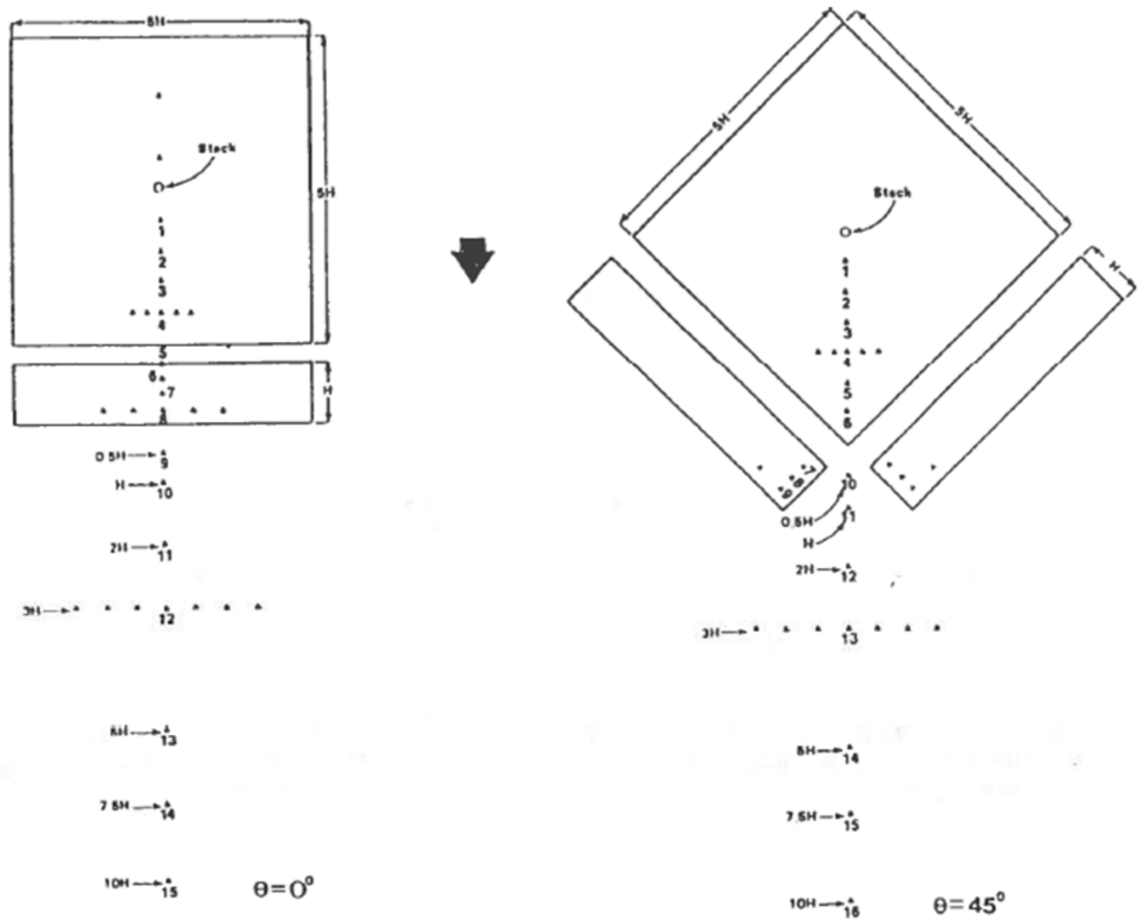


Figure 2-10. Test building and rooftop receptor layout used for the Schulman and Scire Database (1991).

Concentration measurement data was extracted from the database plots using a plot digitizer and entered in tablature format into a spreadsheet. Plots of the measured dilution values versus string distance for each configuration considered for this study are provided in Figure 2-11.

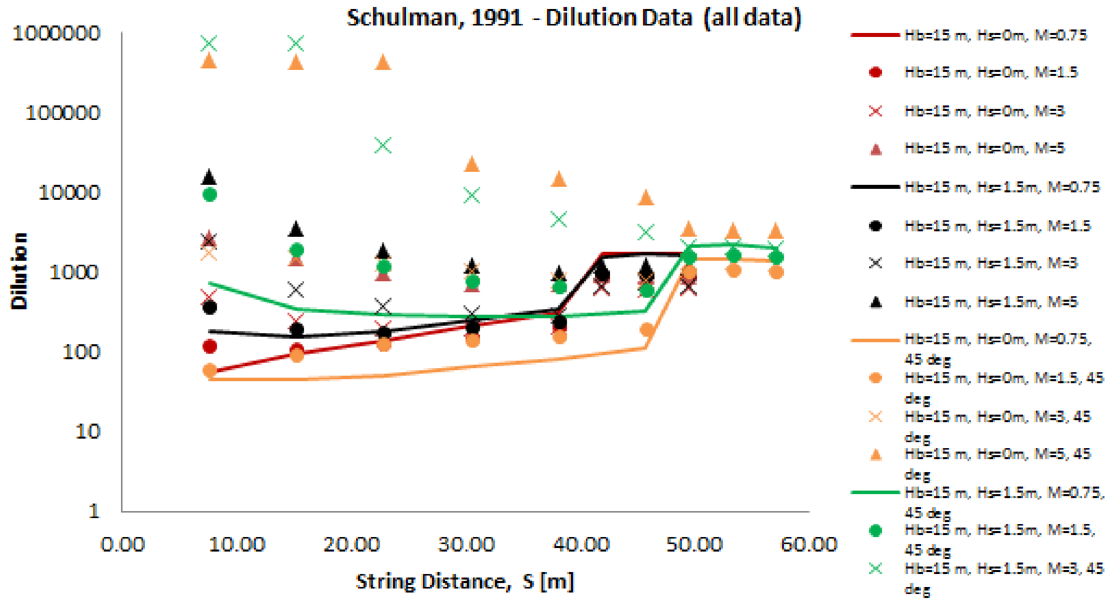


Figure 2-11. Drawing showing observed dilution versus string distance from Schulman and Scire (1991).

The figure above shows a solid line as a "base-line case," with each color representing a stack height and azimuth. The various symbols are increases in exhaust stack momentum ratios. As expected, increased dilution occurs with increased stack height and increases momentum ratio. The abrupt increase in dilution represents a transition from a rooftop to hidden intake, and occurs at approximately 40 m (131ft) for 0 deg azimuth, approximately 50 m (164ft) for 45 deg azimuth.

2.5 DILUTION EQUATION PERFORMANCE METRICS

When evaluating models for measurements and predictions pair in spaced and time, such as for this evaluation, the following model performance measures are often used (Hanna et al., 2004):

$$FB = 2\left[\frac{\overline{D}_o - \overline{D}_p}{\overline{D}_o + \overline{D}_p}\right] \tag{2-1}$$

$$MG = exp\left[\overline{\ln D_0} - \overline{\ln D_p}\right] \tag{2-2}$$

$$NMSE = \left[\frac{\overline{[D_0 - D_p]^2}}{\overline{D}_o \overline{D}_p}\right] \tag{2-3}$$

$$VG = exp\left[\overline{\left(\ln D_0 - \ln D_p\right)^2}\right] \tag{2-4}$$

where

D_p: model prediction of dilution,

D_o: observed dilution, and

overbar: average over the date set.

All four performance measures are calculated and considered together, since each measure has pros and cons. For example, the linear measures FB and NMSE can be overly influenced by infrequently occurring high observed and/or predicted concentrations, whereas the logarithmic measures MH and VG may provide a more balanced treatment of extreme high values.

A perfect model would have FB, NMSE, MG, and VG = 0.0. For this evaluation, the preferred model will have FB and MG ≤ 0 (predictions greater than observations) and the smallest NMSE and VG. These statistics were initially used but were found to provide little useful information since a conservative model is desired, or one that will under-predict dilution most of the time. Hence, more relevant statistics were developed. The ratio, R, of predicted to observed dilution was computed and percent time that the ratio met the following criteria was computed.

- % time R > 1.5 (percent time dilution predictions are a factor of 1.5 or more higher than observed): the best model will have a low percentage.
- 0.5 ≤ % time R ≤ 1.5 (percent time dilution predictions are between a factor of 0.5 low to 1.5 high): the best model will have a high percentage.
- 0.5≤ % time R ≤ 1 (percent time dilution predictions are between a factor of 0.5 low to perfect agreement): the best model will have a high percentage.

Another performance measure is a scatter plot of predicted divided by observed dilution (R) with a one-to-one line. Again, the ideal model will have almost all predicted dilution values equal to the observed dilution with a few values greater than observed and most values less than observed. The goal is that the new equation over and underpredicts less than the current Standard 62.1 equation which would indicate that the new equation is more accurate.

2.6 Evaluation of Standard 62.1 Equation Against Databases 1 and 2

The following sections discuss the evaluation the Standard 62.1 equation against databases 1 and 2 (Wilson and Chiu, 1994 and Wilson and Lamb, 1994). The evaluation of the 62.1 equation against all databases is discussed in Section 3.

Actual data from the Wilson and Chiu (1994) and Wilson and Lamb (1994) databases was not obtained but the equations developed from those databases did bound the measured data and provide a standard from which to evaluate the 62.1 equation discussed in Section 2.3. Figure 2-12 shows the predicted minimum dilution using the 62.1 equation (equation 2.7 in Section 2.3) versus normalized string distance compared with predictions obtained using equations 2.1, 2.2 and 2.3 with V_e/U_H (M) = 3.3 per Wilson and Lamb (1994) and using the following:

- Set $C_1 = 7.0$ and $\beta_1 = 0.0625$ as recommended by Wilson and Chiu (1994);
- Set $C_1 = 13.0$ and $\beta_1 = 0.059$ as recommended in ASHRAE, 1997); and
- Set $C_1 = 13.0$ and $\beta_1 = 0.04$ as recommended by Wilson and Lamb, 1994.

These constants were found to bound all observed dilution values in Wilson and Lamb (1994) and Wilson and Chiu (1991) and should be considered the most conservative. Inspection of Figure 2-12 shows that all three previous minimum dilution equations produced similar results for normalized distances, ξ, greater than about 20, while the Wilson and &Chiu (1994) equation provided the lowed dilution estimates for ξ < 20

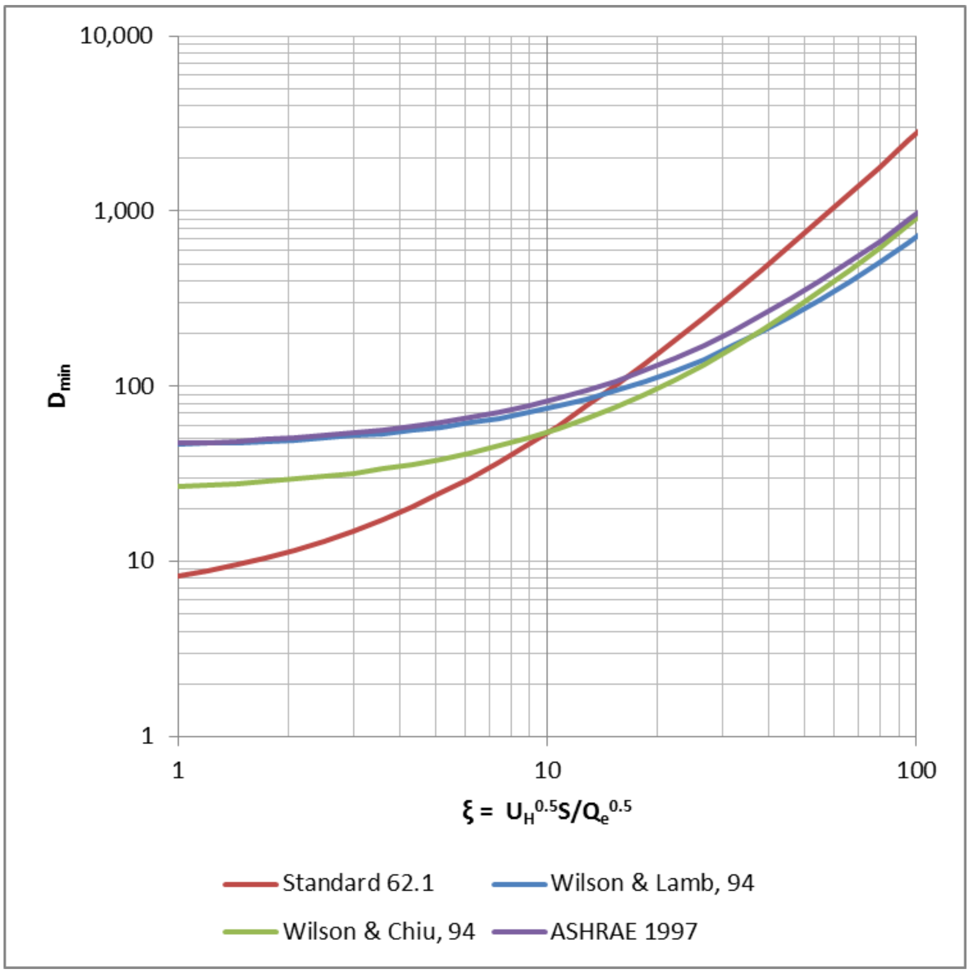


Figure 2-12. Predicted minimum dilution versus dimensionless sting distance using Standard 62.1 equation and other more accurate equations.

Figure 2-12 shows that the 62.1 equation is very conservative (underestimates minimum dilution) for ξ <10 and tends to be non-conservative for ξ >10. This result confirms that the 62.1 equation needs improvement.

3. DEVELOPMENT AND EVALUATION OF NEW STANDARD 62.1 EQUATION

3.1 NEW EQUATION DEVELOPMENT

Four different minimum dilution equations are developed in the sections below followed by and an evaluation of the equations against the Wilson and Chiu and Wilson and Lamb equations discussed above and a comparison with predictions using the 62.1 equation.

3.1.1 New Equation 1 Development (New1)

A new general equation was developed using the method outlined below. First, start with the basic Gaussian dispersion equation from the 2015 ASHRAE Handbook HVAC Applications Chapter 45 (slightly modified) as follows:

$$D\,(s) = \frac{4\,U_H\ \sigma_y\,\sigma_z}{V_e\ d_e^2}\exp\left(\frac{h_p{}^2}{2\sigma_z^2}\right) = Non\ Exponential\ Term(NET)\ \ x\ Exponential\ Term(ET) \qquad (3\text{-}1)$$

Next, the equation can be simplified using the following identities or approximations:

- $\sigma_y = \sigma_z \approx (i^2 s^2 + \sigma_o{}^2)^{0.5}$
- $Q_e = \pi V_e\, d_e{}^2/4$
- i = the average lateral (i_y) and vertical turbulence (i_z) intensity (assume the plume is symmetrical for simplification purposes)
- $\sigma_o{}^2 = d_e{}^2\,(0.125\ \beta M + 0.911\ \beta M^{\,2} + 0.25)$, from ASHRAE 2007

Next, the non-exponential term (NET) can be written as:

$$NET = \frac{\pi U_H}{Q_e}\left[i^2 s^2 + \ d_e^2(0.125\beta M + 0.911\beta M^2 + 0.25)\right] \qquad (3\text{-}2)$$

which can also be written as,

$$NET = \frac{\pi U_H}{Q_e}(i^2 s^2) + \frac{4}{M d_e^2} d_e^2 (0.125\beta M + 0.911\beta M^2 + 0.25\,) \qquad (3\text{-}3a)$$

or simplifying,

$$NET\ = \frac{\pi U_H}{Q_e} i^2 s^2 + \ 0.5\beta + 3.64\beta M + \frac{1}{M} = As^2 + B \qquad (3\text{-}3b)$$

where

$$A = \frac{\pi i^2 U_H}{Q_e}; \;\; B = 0.5\beta + 3.64\beta M + \frac{1}{M} \tag{3-4}$$

For a capped stack the B term above poses a problem since the M term is effectively 0, and B would be become becomes undefined. Hence, for capped stacks B can be computed as follows.

$$B = \frac{0.785\, d_e^2 U_H}{Q_e} \tag{3-5}$$

The first term on left hand side is identical to equation 2.2 with β = 0.071 instead πi^2.

Now consider the plume rise, ET, term:

$$ET = exp\left(\frac{h_p{}^2}{2\sigma_z^2}\right) = 1 + \left(\frac{h_p{}^2}{2\,\sigma_z^2}\right) + \frac{1}{2!}\left(\frac{h_p{}^2}{2\,\sigma_z^2}\right)^2 + \frac{1}{3!}\left(\frac{h_p{}^2}{2\,\sigma_z^2}\right)^3 + Higher\ Order\ Terms \tag{3-6}$$

First, the plume rise needs to be approximated as follows:

$$h_p = h_s + h_f \approx h_s + \lambda\, d_e\, M \tag{3-7}$$

then

$$ET = \leq 1 + \left(\frac{\{h_s + \lambda\, d_e\, M\}^2}{2\, i^2 s^2}\right) \tag{3-8}$$

which is still conservative (will underestimate dilution). An early approximation to final plume (ASHRAE, 2007) had λ = 3.0 which will be the value used in this work.

Expanding,

$$ET \leq 1 + \frac{1}{2\, i^2 s^2}\{h_s^2 + 2\,\lambda\, h_s\, d_e\, M + \lambda^2\, d_e^2 M^2\} = 1 + \frac{C}{s^2} \tag{3-9}$$

where

$$C = \frac{1}{2\, i^2}\{h_s^2 + 2\,\lambda\, \beta h_s\, d_e\, M + \lambda^2\, \beta d_e^2 M^2\} \tag{3-10}$$

Combining the NET and ET terms results in

$$D(s) = (As^2 + B)\left(1 + \frac{C}{s^2}\right) = \left(As^2 + B + AC + \frac{BC}{s^2}\right) \tag{3-11}$$

$$Ds^2 = (As^4 + (B + AC)s^2 + BC\,) \tag{3-12}$$

or

$$0 = (As^4 + (B + AC - D)s^2 + BC\,) = As^4 + (E)s^2 + BC \tag{3-13}$$

which is a form of the Quadratic Equation from which S can be solved for as follows:

$$S^2{}_1 = \frac{-E + \left(E^2 - 4ABC\right)^{0.5}}{2A} \quad S^2{}_2 = \frac{-E - \left(E^2 - 4ABC\right)^{0.5}}{2A} \tag{3-14}$$

where

$$E = B + AC - D \tag{3-15}$$

All dilution values between S1 and S2 will exceed the minimum dilution value and the safe separation distances are outside that zone. New1 will compute minimum separation distances that will account for all important variables (i.e., stack height, wind speed, exit velocity, and dilution criteria).

New1 was then tested against the W&C and W&L equations and an "i" value of 0.153 was determined that provided a best fit with W&C for $20<\xi,<1{,}000$. Figure 3-1 shows that New1 dilution estimates versus those obtained using W&C and W&L with the graph from Wilson and Lamb, 1994 alongside that includes the measured data. The figures show that New1 does provide a lower bound for the observed dilution values for normalized distance, ξ, > 20 and also shows that dilution starts to increase when you get closer to the stack. This is the effect of the plume rise which was not included in the previous equations. However for $\xi < 10$, the New1 equation might not be conservative since the measured dilution value at $\xi \sim 10$ appears to be lower than the New1 prediction. Overall the results for New1 are encouraging but two alternate equations are discussed below.

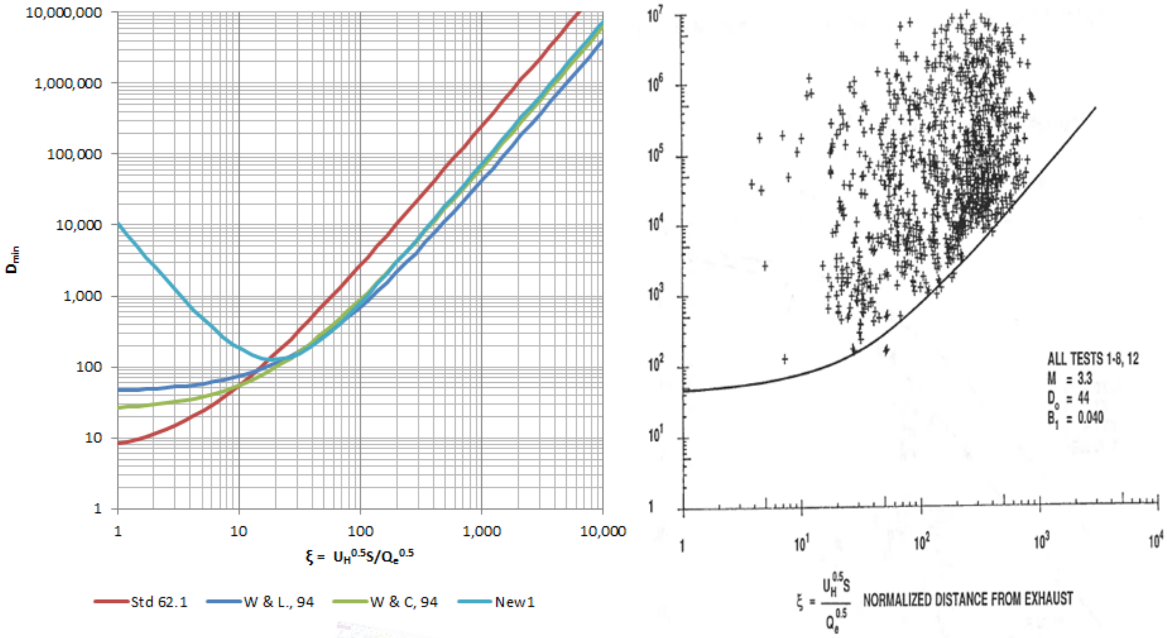


Figure 3-1. Comparison of New Equation 1 predictions versus Wilson and Chui and Wilson and Lamb.

3.1.2 New Equation 2 Development (New2)

A 2nd equation, New2, was developed in very similar manner as discussed in Section 3.1.1. The only difference is that $\sigma_o = 0.35\ d_e$ as specified in ASHRAE (2011). With this definition,

$$NET = \frac{\pi U_H}{Q_e}[i^2 s^2 + 0.123 d_e^2] \tag{3-16}$$

or simplifying,

$$NET = \frac{\pi U_H}{Q_e}(i^2 s^2) + \frac{0.385 U_H d_e^2}{Q_e} = As^2 + B \tag{3-17}$$

where "A" is the same as defined above and,

$$B = \frac{0.385\ d_e^2 U_H}{Q_e} \tag{3-18}$$

The ET term in section 3.1.1 does not change which means all equations are the same except for "B" above.

Figure 3-2 below, again with i = 0.153 and λ = 3.0, shows New2 dilution estimates versus those obtained using Wilson and Chui and Wilson and Lamb with the graph from Wilson and Lamb alongside. The figure shows that New2 provides a better lower bound fit for all normalized

cpp

distances than New1 (see Figure 3.1). Based on this comparison, New2 is the preferred equation for more detailed evaluation.

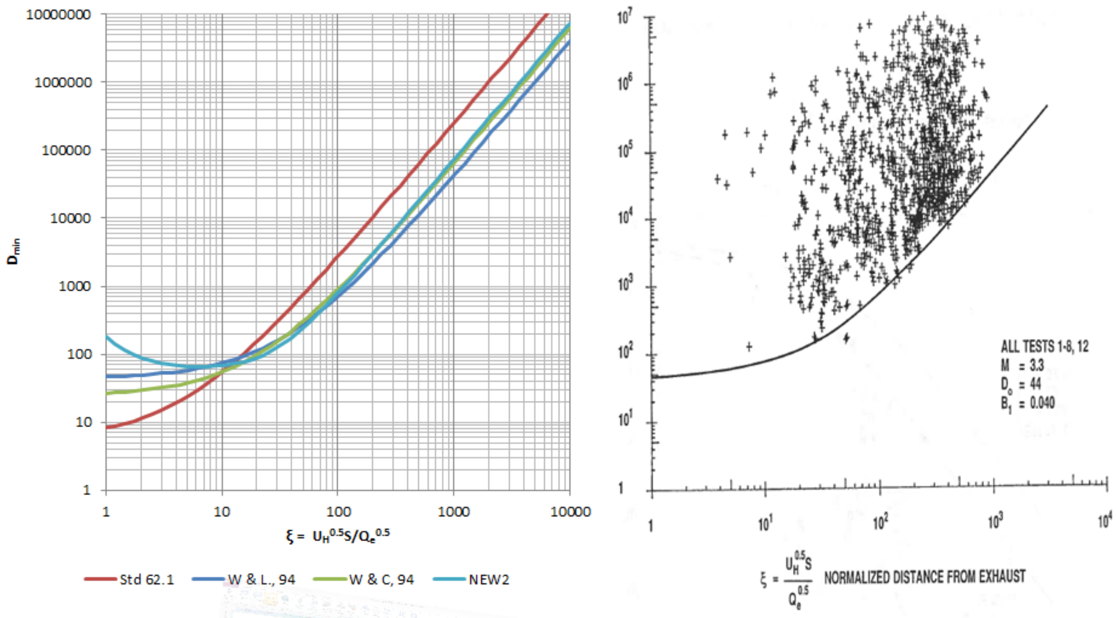


Figure 3-2. Comparison of New Equation 2 predictions versus Wilson and Chui and Wilson and Lamb.

3.1.3 New Equation 3 Development

A 3rd equation, New3, was developed in very similar manner as discussed in Section 3.1.2. The only difference is in the exponential term, ET, where the vertical turbulence intensity, i_z, is used instead of i, as developed below.

$$ET = \leq\ 1 + \left(\frac{{h_s}^2}{2\,{i_z}^2 s^2}\right) \tag{3-19}$$

where i_z is equal to 0.5 times the longitudinal turbulence intensity, i_x, from Snyder (1981) Since i = $(i_y+i_z)/2$ which from Snyder (1981) is equal to $(0.75\ i_x + 0.5\ i_z)/2$, it can be shown that $i_y = 0.8$ i. Substituting into the equation above results in

$$ET = \leq\ 1 + \left(\frac{\{h_s+\lambda\, d_e\, M\}^2}{2\,(0.8\,i)^2 s^2}\right) = \left(\frac{\{h_s+\lambda\, d_e\, M\}^2}{1.28\,i^2 s^2}\right) \tag{3-20}$$

which means that C is now defined as:

$$C = \frac{1}{1.28\, i^2}\{h_s^2 + 2\,\lambda\,\beta h_s\, d_e\, M + \lambda^2\,\beta d_e^2 M^2\} \tag{3-21}$$

The NET term in section 3.1.2 does not change, which means all equations are the same except for "C" above.

Figure 3.3 below, again with i = 0.153 and λ = 3.0, shows New3 dilution estimates versus those obtained using Wilson and Chui and Wilson and Lamb with the graph from Wilson and Lamb alongside. The figure shows that New3 provides a better lower bound fit for all normalized distances than New1 (Figure 3.1) and similar agreement as New2 (Figure 3.2). Based on this comparison and the fact that the vertical turbulence is accounted for more realistically, New3 was initially considered the preferred equation for more detailed evaluation.

Figure 3.4 compares dilution estimates using all three equations and shows that New3 provides dilution estimates that are in between New1 and New2 for small normalized distances. These equations will be evaluated in more detail in the next Section.

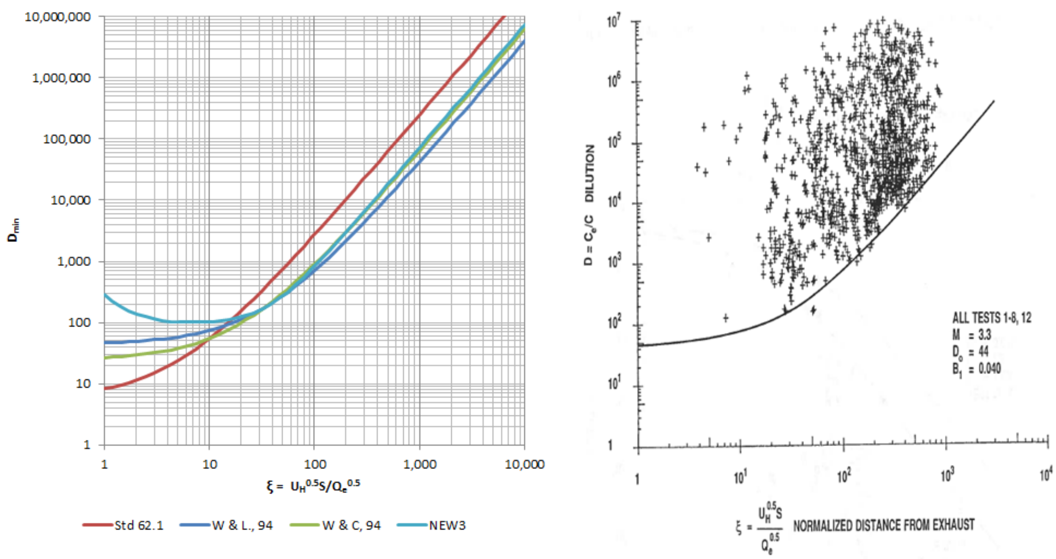


Figure 3-3. Comparison of New3 predictions versus Wilson and Chui and Wilson and Lamb**.**

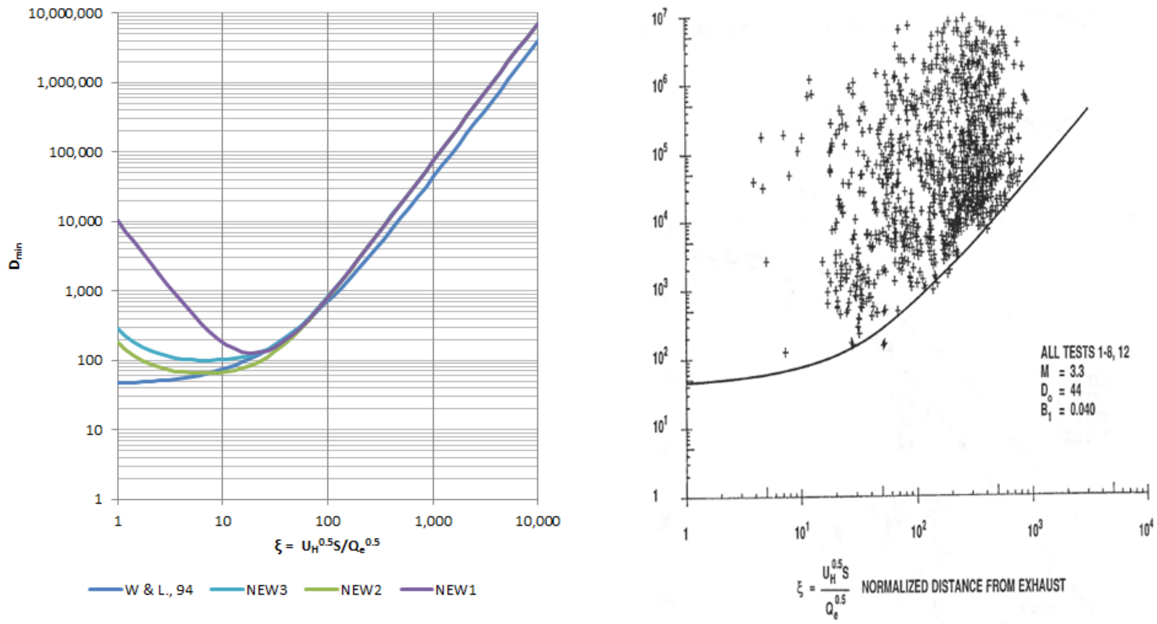


Figure 3-4. Comparison of New1, New2 and New3 predictions versus Wilson and Lamb**.**

3.1.4 New Equation 4 Development

A 4th equation, New4, was developed in very similar manner as discussed in Section 3.1.3. The only difference is that B is set equal to zero to add more simplification. Then

$$L^2{}_1 = 0 \quad \text{and } L^2{}_2 = \frac{-E}{A} = -\frac{(AC-D)}{A} = -C + \frac{D}{A}$$

where

$$A = \frac{0.0735 U_H}{Q_e} \tag{3-22}$$

$$C = \frac{1}{1.28\, i^2}\{h_s^2 + 2\,\lambda\,\beta h_s\, d_e\, M + \lambda^2\,\beta d_e^2 M^2\} = 33.4\{h_s^2 + 6\,\beta h_s\, d_e\, M + 9\,\beta d_e^2 M^2\} \tag{3-23}$$

substituting

$$M = 4Q_e/(\pi d_e^2 U_H) \tag{3-24}$$

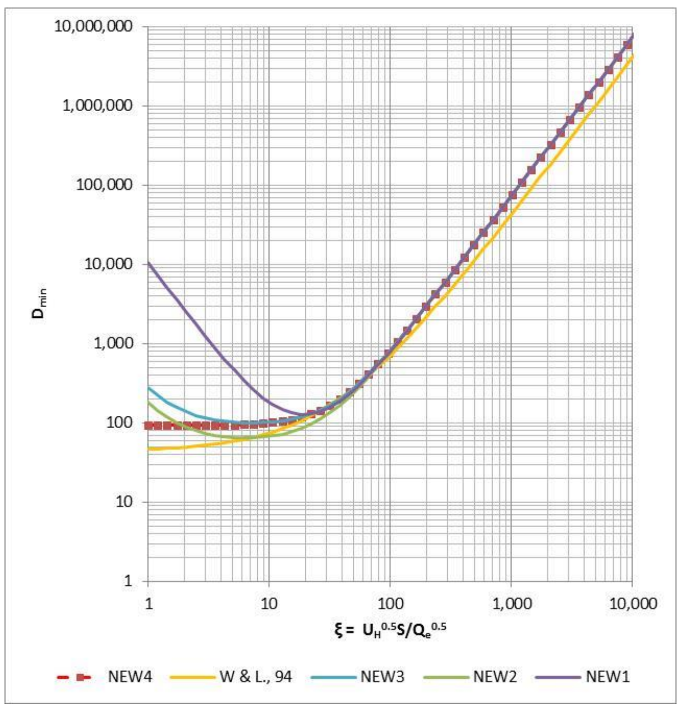
$$C = 33.37\left\{h_s^2 + 6\,\beta h_s \frac{d_e\, 4Q_e}{(\pi d_e^2 U_H)} + 9\,\beta d_e^2 \left[\frac{4Q_e}{(\pi d_e^2 U_H)}\right]^2\right\} \tag{3-25}$$

Then

$$L = -33.37 \left\{h_s^2 + 24\,\beta h_s \frac{Q_e}{(\pi d_e U_H)} + 144\,\beta \left[\frac{Q_e}{(\pi d_e U_H)}\right]^2\right\} + \frac{D\,Q_e}{0.073\,U_H} = -\left\{33.37\,h_s^2 + 254.9\,\beta h_s \frac{Q_e}{(d_e U_H)} + 486.9\,\beta \left[\frac{Q_e}{(d_e U_H)}\right]^2\right\} + 13.6\,DQ_e/U_H \quad (3\text{-}26)$$

Figure 3.5 below, again with i = 0.153 and λ = 3.0, shows New4 dilution estimates versus those obtained using Wilson and Lamb and New1, New2 and New3. The figures shows that New4 provide a better lower bound fit for all normalized distances than New1and similar agreement as New2 and New3. Based on this comparison and the fact that the vertical turbulence is accounted for more realistically and method is simpler, New4 is the preferred equation for Standard 62.1 use.

Figure 3-5. Comparison of New4 with New1, New2 and New3



4. EVALUATION OF 62.1 EQUATION AND NEW EQUATIONS

4.1 ASHRAE Research Project (RP) 805 – 0 Degree Wind Direction (Petersen, et al., 1997)

Figure 4-1 shows scatter plots of predicted versus observed dilution for the existing Standard 62.1 equation and the New1, New2 and New4 equations. Note that a scatter plot for New3 is not included as it was very similar to New2. The figure clearly shows that Standard 62.1 and New1 over predict dilution for certain cases (points shown above the solid black line), while New2 and New4 provide overall better performance. Orange solid lines indicate predicted dilution +/- a factor of 10 and the blue solid lines indicate +/- a factor of 3.

Table 4-1 shows the statistical quantities used to evaluate the model performance. The table shows that New3 and New4 are an improvement over the current Standard 62.1 equation for the following reasons:

- smaller percentage of R values greater than 1.5 (less overprediction);
- greater percentage of R values between 0.5 and 1.0 (less underprediction)
- greater percentage of R values between 0.5 and 1.5 (more frequent predictions that have a reasonable degree of uncertainty)

Table 4-1. Comparison of New Equation predictions versus ASHRAE RP 805 – 0 degree data.

$D_p/D_o = R$	Standard 62.1	New1	New2	New3	New4
% >1.5	3.9%	4.9%	0.5%	1.0%	0.3%
0.5<R<1	9.3%	15.1%	16.2%	16.4%	17.4%
0.5<R<1.5	17.5%	19.8%	17.5%	20.8%	20.8%
	Yellow shading indicates best performance.				

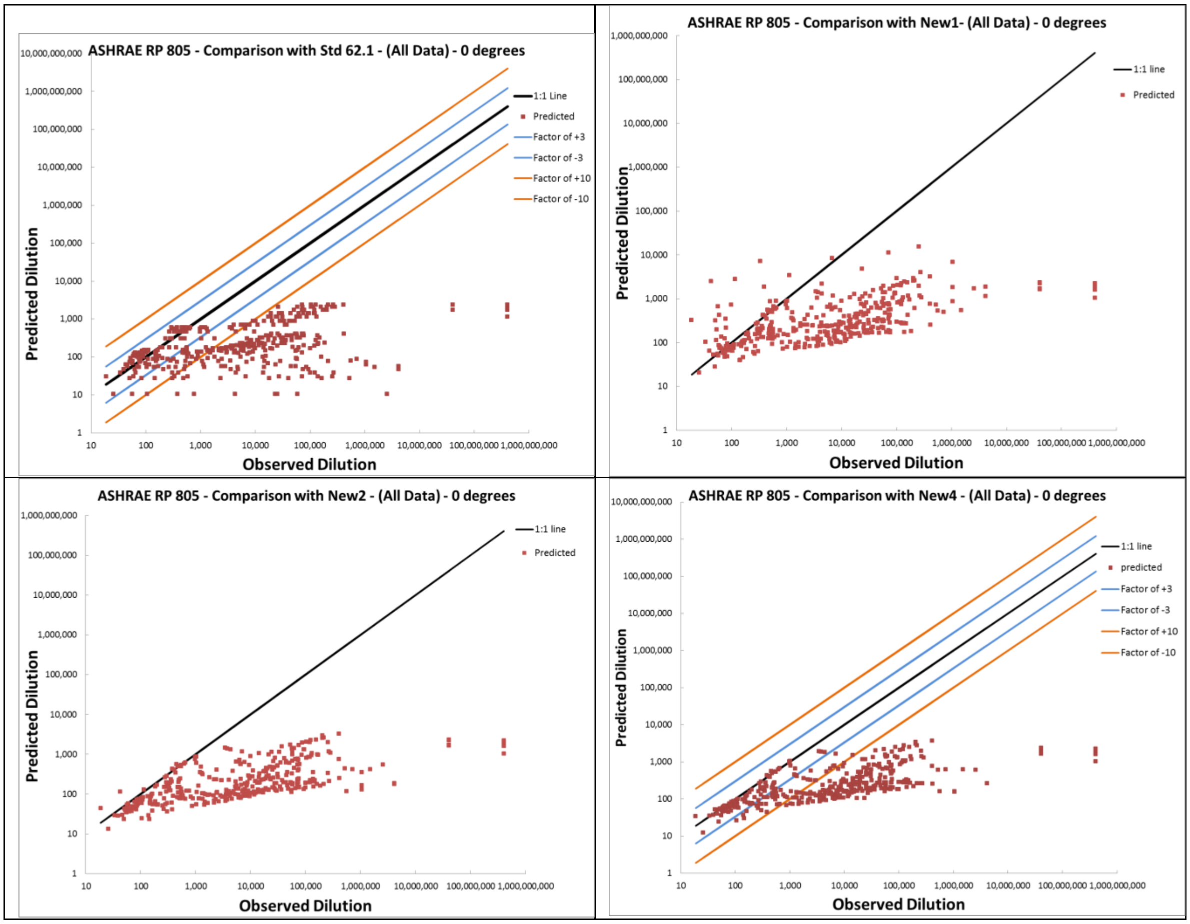


Figure 4-1. Comparison of New1, New2 and New4 predictions versus ASHRAE RP 805 - 0 degree wind direction**.**

4.2 ASHRAE RESEARCH PROJECT 805 , 45 DEGREE WIND DIRECTION (PETERSEN, ET AL., 1997)

Similar to Section 4.1, Table 4-2 and Figure 4-2 (below) compare predicted dilution values for Standard 62.1 and the new equations. The data and metrics shown in this section reflect the 45 degree data taken from the ASHRAE RP 805 data set. It can be seen than the best prediction of dilution come from the New2 and New4 equations for both the 0 degree and 45 degree data set.

Table 4-2 shows the statistical quantities used to evaluate the model performance. The table shows that New2, New 3 and New4 are an improvement over the current Standard 62.1 equation for the following reasons:

- smaller percentage of R values greater than 1.5 (less overprediction);
- greater percentage of R values between 0.5 and 1.0 (less underprediction)
- greater percentage of R values between 0.5 and 1.5 (more frequent predictions that have a reasonable degree of uncertainty).

Table 4-2. Comparison of New Equation predictions versus ASHRAE RP 805 – 45 degree data**.**

D_p/D_o = R	Standard 62.1	New1	New2	New3	New4
%>1.5	9.4%	17.9%	3.6%	7.6%	6.2%
0.5<R<1	8.0%	10.7%	12.9%	13.4%	12.5%
0.5<R<1.5	15.2%	19.6%	21.4%	22.8%	21.9%
	Yellow shading indicates best performance.				

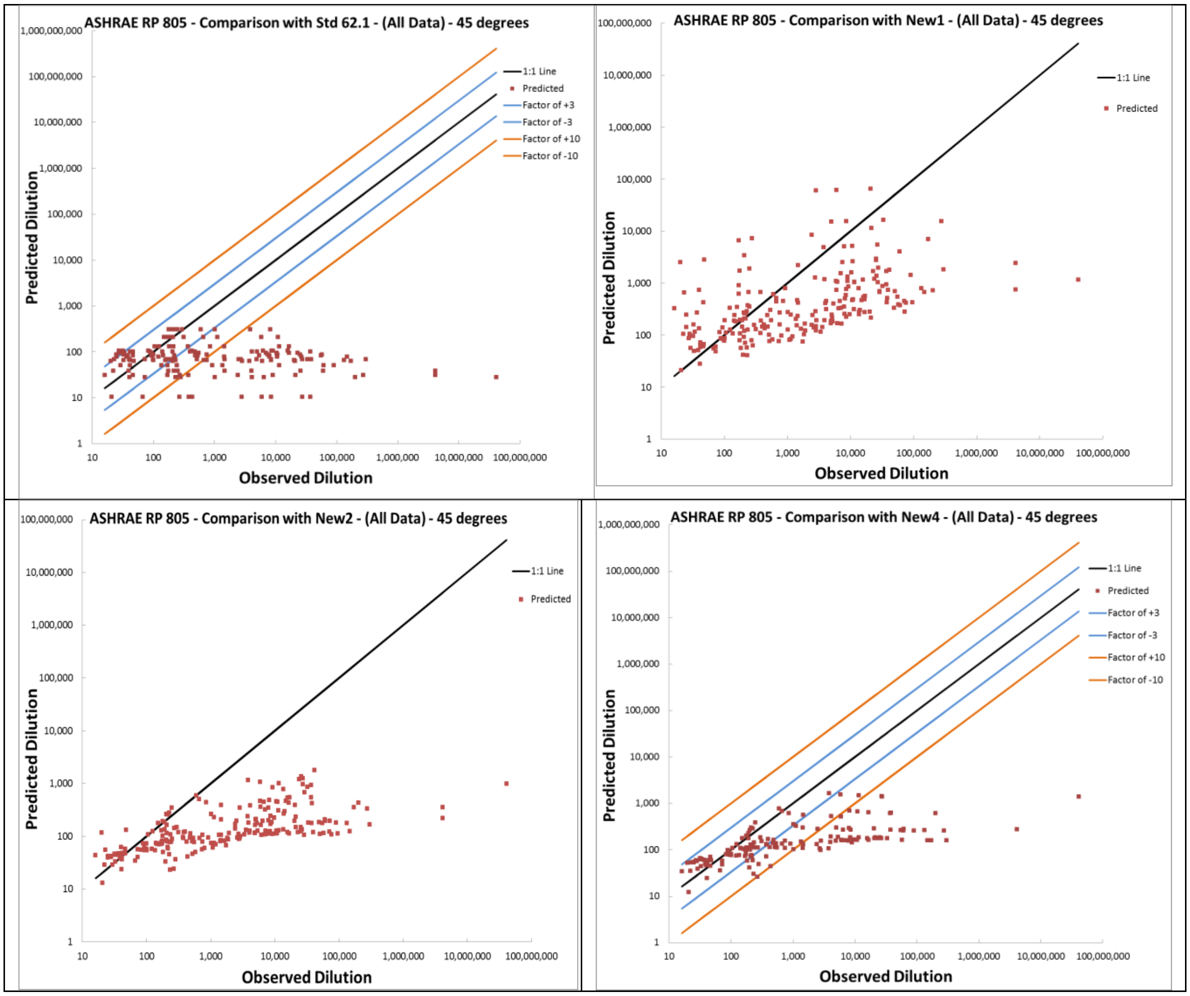


Figure 4-2. Comparison of New1, New2 and New4 predictions versus ASHRAE RP 805 - 45 degree wind direction**.**

The ASHRAE RP 805 database provided by far the most extensive data set, and was used as the primary data set for the evaluation of the new equations. Based on inspection of Figure 4-1 and Figure 4-2, it can be seen that equations New2 and New4 provide the best predicted concentrations, while conservatively bounding the dilution estimates. These equations are very similar; however, equation New4 is theoretically sound and simpler to use, and is therefore preferred for Standard 62.1 use. Equation New4 has been compared against several other data sets, which are discussed in the following sections.

4.3 Hajra and Stathopoulos (2012)

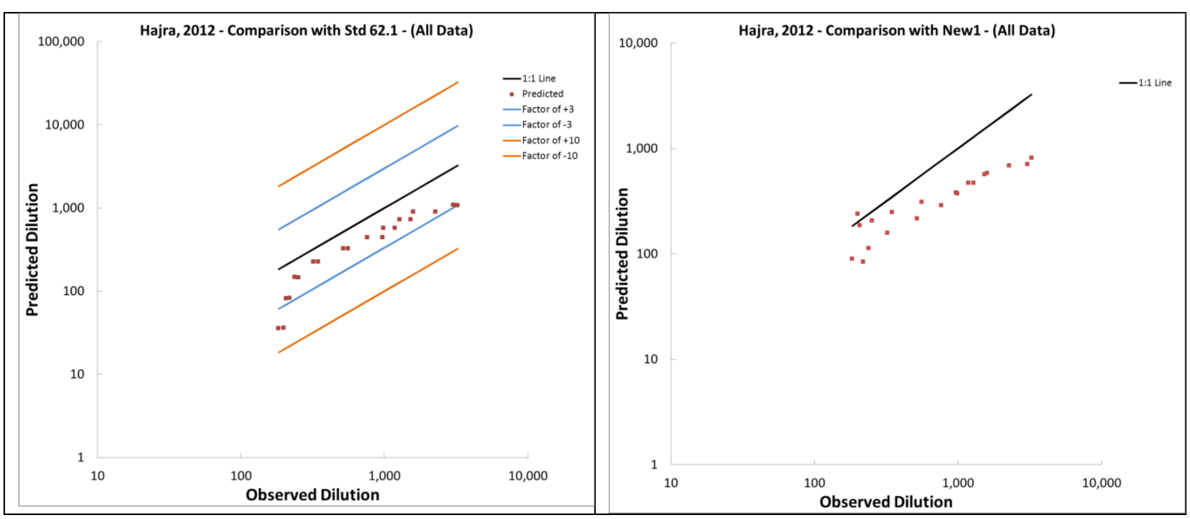
Figure 4-3 shows scatter plots of predicted versus observed dilution for existing Standard 62.1 equation and the New1, New2 and New4 equations (New3 not shown as the result was similar to New2). The orange solid lines indicate predicted dilution +/- a factor of 10 and the blue solid lines indicate +/- a factor of 3.The figure shows that Standard 62.1 has fairly good performance for this database and shows similar performance as the new methods. It should be noted that for this database, a sub-set of the data was used, which included data for a low stack height (1m, 3m) (3.28 ft, 9.84 ft) and low velocity ratio (M=1). Exhaust stacks with these characteristics are of most interest in the implementation of Standard 62.1 and for which the Standard 62.1 equation should perform the best, as it does.

Table 4-3 shows the statistical quantities used to evaluate the model performance. The table shows that New 3 and New4 provide similar results as the current Standard 62.1 equation for the following reasons:

- same percentage of R values greater than 1.5 (minimal overprediction);
- similar percentage of R values between 0.5 and 1.0 (similar underprediction)
- greater percentage of R values between 0.5 and 1.5 (more frequent predictions that have a reasonable degree of uncertainty).

Table 4-3. Comparison of Standard 62.1 and New3 predictions versus Hajra data – **i=0.1527**

D_p/D_o = R	Standard 62.1	New1	New2	New3	New4
>1.5	0.0%	0.0%	0.0%	0.0%	0.0%
0.5<R<1	50%	35%	40%	45%	45%
0.5<R<1.5	50%	40%	40%	60%	60%
	Yellow shading indicates best performance.				



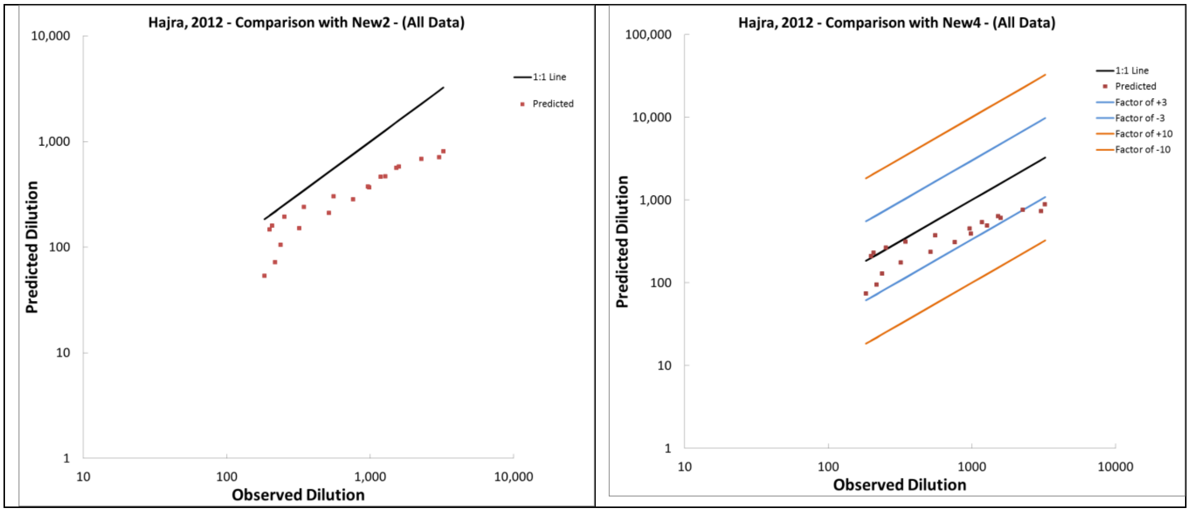


Figure 4-3. Ratio of predicted (ASHRAE 62.1) to observed dilution versus string distance using Hajra and Stathopoulos (2012) database – all data, i=0.1527.

The above case considers a fixed turbulence intensity of i=0.1527. To evaluate turbulence sensitivity, additional analysis was performed on this database. The statistics and plots below are based on the building rooftop turbulence (i), which is an average of the calculated lateral (i_y)and vertical (i_z) turbulence value of 0.175.

Table 4-4 shows the statistical quantities used to evaluate the model performance. The table shows identical results as in Table 4-3. Hence, changing "i" had no effect on model performance.

Table 4-4. Comparison of Standard 62.1 and New3 predictions versus Hajra data – **i=0.175**

D_p/D_o = R	Standard 62.1	New1	New2	New3	New4
>1	0.0%	0.0%	0.0%	0.0%	0.0%
0.5<R<1	50%	35%	40%	45%	45%
0.5<R<1.5	50%	40%	40%	60%	60%
	Yellow shading indicates best performance.				

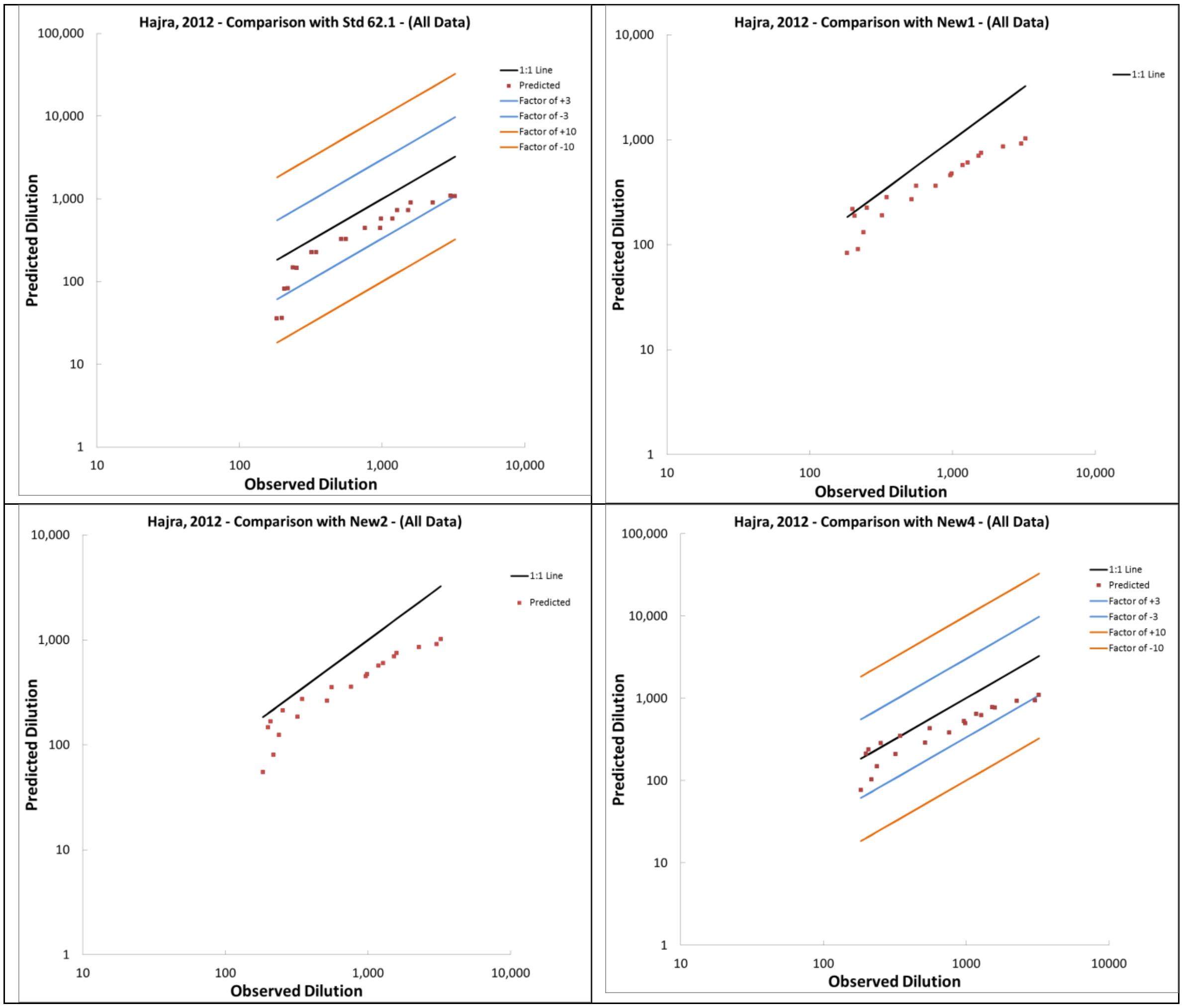


Figure 4-4. Ratio of predicted (ASHRAE 62.1) to observed dilution versus string distance using Hajra and Stathopoulos (2012) database – all data, i=0.175.

Comparing Figure 4-3 and Figure 4-4, it can be seen that there is only a slight difference in the predicted dilution values. Due to the slight variation that is observed, all databases were evaluated with initially specified turbulence intensity of 0.1527.

4.4 Schulman and Scire (1991)

Figure 4-4 shows scatter plots of predicted versus observed dilution for existing Standard 62.1 equation and the New4 equation. The figure shows that New4 performs significantly better than Standard 62.1. New4 predicts dilution more accurately, and provides a much better bound to the data, and covers many more cases without over-predicting dilution. One case where New4 over-predicts dilution is for a case where the wind approaches the building at a 45 degree angle, with the stack operating at a low velocity ratio (M). It should be noted that Standard 62.1 also over-predicts dilution for this case. The over prediction in dilution results in a higher measured exhaust concentration at the location, and may be due to building corner vortices and stack-tip downwash. For such a case, Standard 62.1 over-predicts by nearly a factor of 10, while New4 over-predicts by approximately a factor of 3.

Table 4-5 shows the statistical quantities used to evaluate the model performance. The table shows that New4 is an improvement over the current Standard 62.1 equation for the following reasons:

- much lower percentage of R values greater than 2.0 (significantly less overprediction);
- slightly lower percentage of R values between 0.5 and 1.0 (reasonable underprediction); and
- slightly lower percentage of R values between 0.5 and 1.5 (frequent predictions that have a reasonable degree of uncertainty).

Table 4-5. Comparison of Standard 62.1 and New4 predictions versus Schulman data

D_p/D_o = R	Standard 62.1	New4
>2	33.1%	3.1%
0.5<R<1	25.2%	19.7%
0.5<R<1.5	32.3%	25.9%
	Yellow shading indicates best performance.	

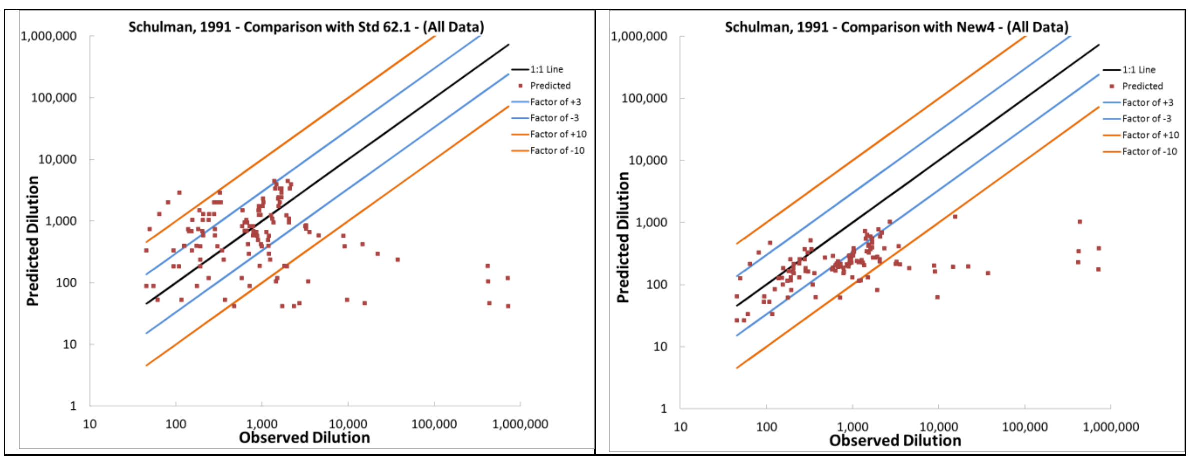


Figure 4-5. Ratio of predicted (Standard 62.1) to observed dilution versus string distance using Schulman and Scire (1991) database.

4.5 SIDEWALL (HIDDEN) INTAKES

Configurations when an intake is not in the line of sight of the exhaust should also be considered. An example of such a configuration is a building with rooftop exhaust sources and intakes located on the building façade. Such sidewall intakes are considered “hidden” from the exhaust source. The 2015ASHRAE HVAC Application Handbook, Chapter 45, specifies that dilution is enhanced by a least a factor two for a hidden intake which is discussed in more detail in Section 6.3.3. Currently, Standard 62.1 does not have specific guidelines for such a case, other than the slight benefit of increased “string distance.”

To account for hidden intakes, New4 dilution estimates are increased by a sidewall concentration reduction factor of 2 (dilution increase factor), to account for the additional dilution provided by the sidewall orientation. Table 4-6 and Figure 4-6 compare predicted values for Standard 62.1 and New4 for cases where the intake is located along the building sidewall. The two databases used for this evaluation are the ASHRAE RP 805 and the Schulman and Scire (1991).

Table 4-6 shows the statistical quantities used to evaluate the model performance. The table shows that New4 is an improvement over the current Standard 62.1 equation for the following reasons:

- equal or lower percentage of R values greater than 1.0 (less overprediction);
- equal or greater percentage of R values between 0.5 and 1.0 (reasonable underprediction); and
- equal or greater percentage of R values between 0.1 and 1.0 (more frequent under predictions that are within a factor of 10).

Table 4-6. Comparison of New Equation predictions versus ASHRAE Research Project 805 – Hidden Intake Data

	ASHRAE Research Project (Petersen, et.al. 1997)		(Schulman and Scire, 1991)	
D_p/D_o = R	Standard 62.1	New4	Standard 62.1	New4
> 1	0%	0%	33.3%	2.2%
0.5< R< 1.0	0%	0%	53.4%	55.6%
0.10 < R < 1.0	6.0%	8.3%	66.7%	97.8%
	Yellow shading indicates best performance.			

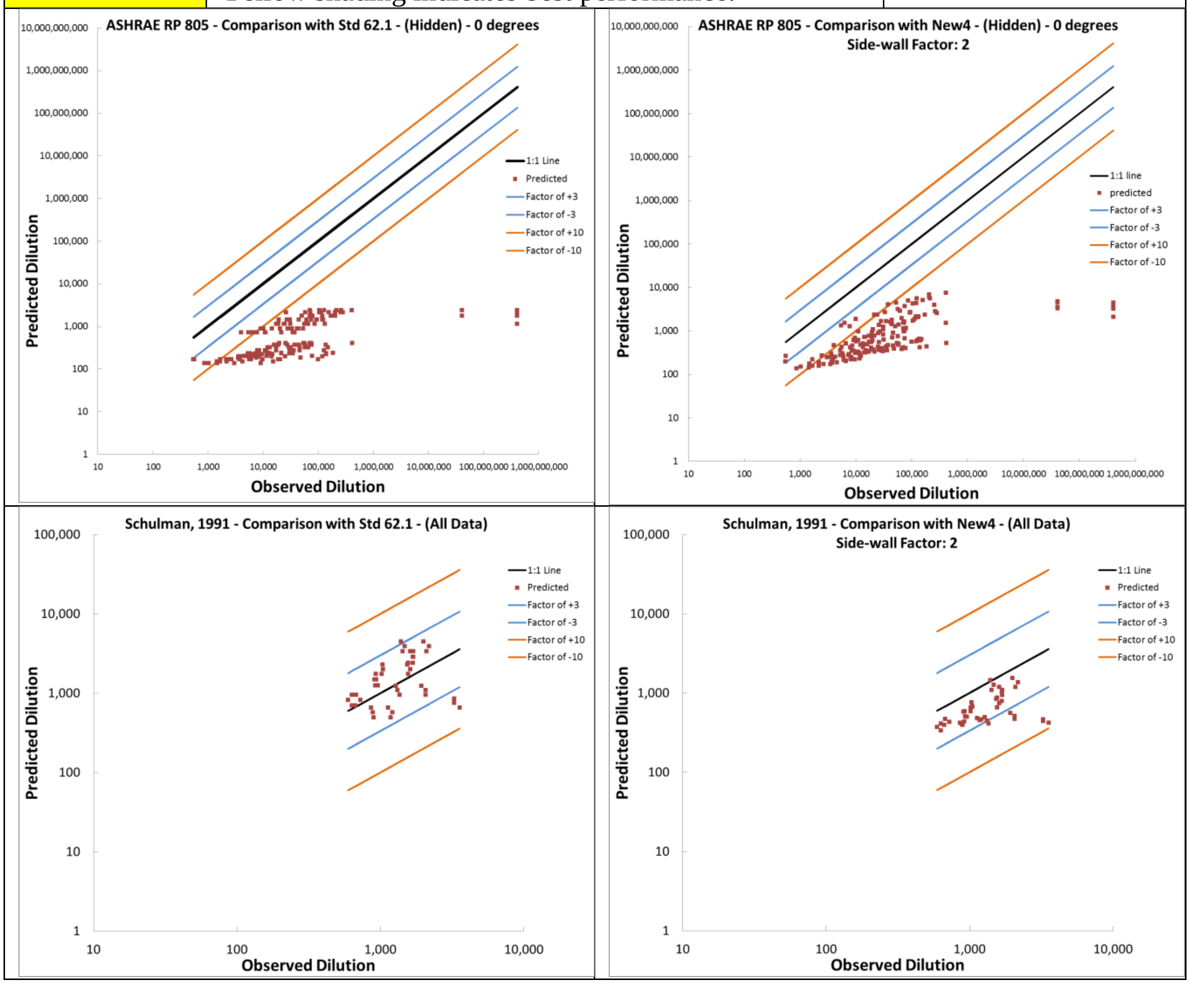


Figure 4-6. Comparison of New1, New2 and New4 predictions versus ASHRAE RP 805 and Schulman - hidden intake data.

Figure 4-6 also shows that New4 with the factor of two sidewall dilution increase factor generally provides better dilution predictions for sidewall receptors, with fewer predictions varying greater than a factor of 10 from the measured dilution. In addition, based on the Schulman database, Standard 62.1 has the potential to significantly over-predict dilution, which can result in a potentially unsatisfactory design.

5. DEVELOPMENT OF REFINED DILUTION FACTORS

5.1 Background and Objective

Table 5.1 provides a list of the minimum dilution factors provided in Standard 62.1 along with the specified minimum separation distances. The table shows that dilution factors are only provided for Class 3 and 4 exhaust, but the standard provides no basis for the criteria. Table 5.2 provides a summary of the minimum dilution factors from 62-1989R together with the minimum separation distances. 62-1989R provides minimum dilution factors for Class 1 through 5 exhaust but again no documentation was provided to support these factors. It should be noted that 62-1989R provided no minimum separation distances for exhaust Classes 1-5 but the distances were to be computed using the formula. This seems like a good approach since the distances will vary with flow rate and exhaust velocity, and since the Standard 62.1 equation is rather simple. Standard 62.1 just specifies one minimum distance for each exhaust class which is a problem as discussed in Section 2.1 and demonstrated in Section 6.

Standard 62.1 provides the following definitions for the various air classifications.

- Class 1: Air with low contaminant concentration, low sensory-irritation intensity, and inoffensive odor.
- Class 2: Air with moderate contaminant concentration, mild sensory-irritation intensity, or mildly offensive odors. Class 2 air also includes air that is not necessarily harmful or objectionable but that is inappropriate for transfer or recirculation to spaces used for different purposes.
- Class 3: Air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.
- Class 4: Air with highly objectionable fumes or gases or with potentially dangerous particles, bioaerosols, or gases, at concentrations high enough to be considered harmful.

62-1989R provided similar definitions except for Class 4 and an added Class 5.

- Class 4: Air drawn or vented from locations with noxious or toxic fumes or gases, such as paint spray booths, garages, tunnels, kitchens (grease hood exhaust), laboratories (filtered fume hood exhaust), chemical storage rooms, refrigerating machinery rooms, natural gas and propane burning appliance vents, and soiled laundry storage.

- Class 5: Effluent of exhaust air having a high concentration of dangerous particles, bioaerosols, or gases such as that from fuel burning appliance vents other than those burning natural gas and propane, uncleaned fume hood exhaust, evaporative condenser and cooling tower outlets (due to possible microbial contamination such as Legionella the causative agent of Legionnaire's Disease and Pontiac Fever).

Below is a typical listing of airstreams by class found in Standard 62.1-2013:

- Class 1: arena, classroom, lecture hall, media center, computer lab, break room and office space;
- Class 2: auto repair room, locker room, kitchenettes, parking garage, toilet (private and public), art class room, restaurant dining room, *science laboratory*, and *university/college laboratory*;
- Class 3: commercial kitchen hood other than grease, residential kitchen vented hood, trash room, refrigerating machinery room, and daycare sickroom;
- Class 4: commercial kitchen grease hood, paint spray booth, diazo printing equipment discharge, *chemical storage room*, and *laboratory hoods*

Table 5.1 shows that plumbing vents have the same, or shorter, separation distance specified as Class 2 air and hence will be treated as Class 2 air in this report.

Based on the above, the objective of this phase is to provide minimum dilution factors which are based on sound scientific evidence, for many of the source types indicated in Table 5.1. The following sections discuss the methodology and scientific evidence from which minimum dilution factors are recommended.

Table 5-1 Minimum Separation Distances and Dilution Factors From Standard 62.1

Object	Separation Distance, L ft	m	Minimum Dilution Factor, DF
Class 2 air exhaust/relief outlet	10	3	
Class 3 air exhaust/relief outlet	15	5	15
Class 4 air exhaust/relief outlet	30	10	50
Plumbing vents teminaing less than 3ft (1 m) above the level of the outdoor intake	10	3	
Plumbing vents teminating at least 3ft (1 m) above the level of the outdoor intake	3	1	
Vent, chimneys, and flues from combustion applicances and equipment (Note 3)	15	5	
Garage entry, automobile loading area, or drive-in queue	15	5	
Truck loading area or dock, bus parking/idling area	25	7.5	
Driveway, street, or parking place	5	1.5	
Thououghfare with high traffic volume	25	7.5	
Roof, Landscaped grade, or other surface directl below intake	1	0.3	
Garbage storage/pick-up area, dumpsters	15	5	
Cooling tower intake or basin	15	5	
Cooling tower exhaust	25	7.5	

Table 5-2. Summary of Minimum Separation Distances and Dilution Criteria From Standard 62-1989R. As indicated, an equation was used to calculate the minimum separation distance based on the Minimum Dilution Factor. Distances were not specified.

Object	Minimum Separation Distance, ft	m	Minimum Dilution Factor,
Class 1 air exhaust/relief outlet	Equation		5
Class 2 air exhaust/relief outlet	Equation		10
Class 3 air exhaust/relief outlet	Equation		15
Class 4 air exhaust/relief outlet	Equation		25
Class 5 air exhaust/relief outlet	Equation		50

5.2 General Factors to Consider

Developing minimum dilution factors (DF) is an important input for calculating minimum separation distance, L. Dilution predictions by themselves are not useful for examining minimum separation distances unless some minimum acceptable dilution, or design criterion, is specified. This criterion will vary with source type and each source type may have a criterion that varies depending upon such things as chemical utilization, chemical inventory, boiler or engine size, or vehicle type or size. Standard 62.1-2013 currently defines only two minimum dilution factors: 15 for Class 3 exhaust and 50 for Class 4 exhaust. The method for obtaining the factors is not described and, as shown below, are not reasonable for many sources with this classification.

An air quality "acceptability question" can be written:

$$C_{max,predicted} < C_{health,odor} \qquad (5\text{-}1)$$

where $C_{max,predicted}$ is the maximum predicted concentration at an air intake, C_{health} is the health limit concentration and C_{odor} is the odor threshold concentration of any emitted chemical. When a large number of potential chemicals are emitted from a pollutant source, it becomes operationally simpler to recast the acceptability question by converting to dilution and then determining the minimum dilution factor (DF) as follows:

$$C_o/C_{max,predicted} > C_o/C_{health/odor} = D_{min}(predicted) > D_{min,health/odor} \quad (5\text{-}2)$$

where

$$D_{min,health/odor} = Minimum\ Dilution\ Factor = DF \qquad (5\text{-}3)$$

The left side of Equation 5-2 is dependent on only external factors such as stack design, receptor location, and atmospheric conditions. The right side of the equation is related to the concentration of pollutant in exhaust stream and the health and/or odor threshold. Therefore, highly toxic chemicals (small C_{health}) with a low initial concentration may be of less concern than a less toxic chemical with high initial concentration. The same holds true for odor thresholds. Three pieces of information are needed to develop minimum dilution factors:

1) a list of the toxic or odorous substances that may be emitted, and
2) the health limits and odor thresholds for each emitted substance, and
3) the initial concentration of each substance in the exhaust stream.

It should be noted that the minimum dilution factors discussed below are derived from occupational exposure limits, odor thresholds and estimated initial concentrations. The occupational exposure limits are based on a mixture of guidelines, recommendations, and regulatory limits from the ACGIH, OSHA or NIOSH. The limits provided by ACGIH and NIOSH were developed as guidelines to assist in the control of health hazards, and are not intended for use as legal standards. The limits provided by OSHA are regulatory limits on the amount or concentration of an airborne substance that may be present in the workplace, and are enforceable.

Defining minimum dilution factors for odors is often not simple. By itself, the concentration of an odorous substance in air is not necessarily an indicator of the corresponding human response. Other factors include the detection threshold, intensity (perceived strength), character (sweet, grassy, etc.) and hedonic tone (offensiveness) of an odorant (ANSI/ASHRAE 2013). Reviews of odor measurement techniques, and the factors that influence odor annoyance thresholds, are available in Pullen (2007) and ANSI/ASHRAE (2013). In this report, we are concerned with odor concentration only, and leave aside factors such as the frequency and duration of an offending odor.

Below, we discuss dilution factors for odors that are typically unpleasant in hedonic tone (i.e., sense pleasure or displeasure), such as diesel or toilet odors, and odors that may be unpleasant when out of context, such as kitchen odors that infiltrate an office space. Amoore (1985) provides a "provisional rule" that an unpleasant odor will be at its annoyance threshold for 50% of people when the concentration of the odorant is at 5 times its detectable level (i.e., 5 odor units (OU)). This is also cited by Mahin (2001) who provides a table of off-site odor standards and guidelines from around the world. We adopt this rule in our analysis when no other values were available. Standards for U.S. locations are shown in Table 5.3 below.

The detection threshold of an odorant is typically defined as the concentration at which 50% of people (often trained odor judges) are able to detect, though not necessarily identify, an odor. Concentrations of odorants in air are sometimes given in units typically used in air quality, such as ppmv, ppbv or μg/m3. However, these units are not easily applied to odorants comprising chemical mixtures; therefore odorant concentration is often expressed in odor units (OU) (Nicell 2003). An odor unit signifies the number of dilutions, by non-odorous air, of a pure odorant until it is at the detection threshold (ANSI/ASHRAE 2013, Pullen 2007, Nicell 2003). In other words, an odorant concentration of 50 OU (or, equivalently, 50 OU/m3 in Europe) is at 50 times its detection threshold. Equivalently, 50 dilutions-to-threshold (D/T) are needed to render the odorant undetectable by 50% of people. These units are used interchangeably here.

The following paragraphs discuss the specific minimum dilution factors for different source types.

5.3 Recommended Dilution Factors

5.3.1 Combustion Type Sources

5.3.1.1 General

Health limits for combustion type sources are primarily related to the release of CO, NO_x, SO_2 and particulate matter (PM). These chemicals may also be limiting for defining an odor threshold for combustion equipment using natural gas; however, for diesel exhaust, the limiting odor is a caused by a complex mixture of various chemicals and particulates.

Objection levels to various dilutions were obtained from Vanderheyden (1994) and Cernansky (1983). Dilutions that produced a 20 percent objection level were used to quantify the odor occurrences. At the 20 percent objection level, Vanderheyden (1994) indicates a dilution of 1:2000 is necessary to avoid odors. In an unpublished study by CPP of exhaust from a 2.5 MW diesel generator, odor panel results gave a mean odor detection threshold of 2,830, which agrees fairly well with the 1:2000 dilution value of Vanderheyden (1994).

After-market filters are available for some diesel combustion sources. These filters typically reduce unburned hydrocarbons (the odorous exhaust components), by about 80%. If these filters are installed, the 1:2000 dilution requirement stated above is reduced to a 1:400 dilution requirement.

Table 5-3 provides a summary of the health and odor limits used to determine minimum dilution factors for combustion type sources. National Ambient Air Quality Standards (NAAQS) are also provided in the table for reference purposes but are only applicable at the property line and beyond and will not be used to set minimum dilution factors. It should be noted that Table 5-3 is not all inclusive as other countries and states have different standards or thresholds (e.g., for CO, Health Canada has a 25 ppm threshold and California has a 20 ppm threshold; for NO_2 the California limit is 30 ppb).

To determine the minimum dilution factors, the initial concentrations of the pollutants in the exhaust streams are needed and can be computed from emission rates often provided by the manufacturer. For this evaluation, emission rates were obtained from EPA's AP-42 Compilation of Air Pollutant Emission Factors, Volume I, Stationary Sources Point and Area Sources (1995) or from the Code of Federal Regulations (CFR, 2002).

Emission factors are provided for NO_X but a conversion factor is needed to estimate the

Table 5-3. Health and Odor Thresholds for Combustion Equipment

Pollutant	*NAAQS (1-hr)* [2] *(µg/m³)*	Health (µg/m³) TWA	Health (µg/m³) STEL	*Odor (µg/m³)*	*NAAQS Reference*	*Odor Reference*
Combined Exhaust (dilution):				2,000		Vanderheyden, M.D., D.S. Chadder, and A.E. Davies, "A Novel Methodology for Predicting the Impact of Model Sources on Air Quality," presented at the 87th Annual Meeting of the Air & Waste Management Association, June 1994.
CO - ACGIH(1)	43,200	NA	229,000		76 FR 54294, Aug 31,2011, 35 ppm 1-hour, once per year	
NO - NIOSH(1)		30,000	90,000	657		Ruth, 1986, geometric mean of range 0.36 and 1.2 mg/m3
NO_2 - NIOSH (1)	188		1,800	332	75 FR 6474, Feb 9, 2010, 100 ppb, 98th percentile of 1-hr daily maximum concentrations, average over 3 years	AIHA, Odor Thresholds, 2013, geometric mean of range 0.058 - 0.5 ppm (0.11-1.0 mg/m^3)
SO_2 - ACGIH(1)	196.5		13,000.0	3,755	75 FR 35520, June 22, 2010, 75 ppb 99th percentile of 1-hour daily maximum concentrations, average over 3 years	AIHA, Odor Thresholds, 2013,, gemometric mean of range range of 0.33 - 8 ppm (0.87 - 21 mg/m3)
PM_{10} OSHA(1)	375.0	15,000.0	45,000.0		40 CFR part 50, 24 average of 150 scaled to 1-hr using 0.4 scaling factor	
$PM_{2.5}$ OSHA(1)	88	5,000	15,000		40 CFR part 50, 24 average of 35 scaled to 1-hr using 0.4 scaling factor	

1) Only applies to Health Limits.
2) National Ambient Air Quality Standards (NAAQS) only apply off-site (at the property line and beyond)

emission rates for nitric oxide (NO) and nitrogen dioxide (NO_2). For this study, a 75% conversion factor was used to convert NO_x to NO_2 and a 25% conversion factor was used to convert NO_x to NO.

5.3.1.2 Diesel generators and diesel vehicles

For diesel generators and diesel vehicles, health and odor criteria based on chemical emission rates are not limiting with regard to a minimum dilution factor, rather the odor due to the exhaust mixture is limiting as discussed above. The recommended dilution factor is 2000 for unfiltered diesel exhaust. If an 80% efficient odor filter is used, either on the exhaust or on the intake, the minimum dilution factor would be 400. If a 90% efficient odor filter is used, either on the exhaust or intake, the dilution factor would be 200.

5.3.1.3 Light duty gas vehicles

Table 5.4 shows the calculation of the minimum dilution factor for a single idling light duty gas vehicle and for multiple idling gas vehicles. For both cases, the dilution factor is 47 (the recommended value is 50). The single idling vehicle dilution factor is appropriate for garage entry, automobile loading area or drive-in queue intake separation distance calculations. The multiple idling vehicle case is provided so that criteria can be developed for parking garage exhaust vents. If the exhaust vent flow is increased, the dilution criterion is computed as follows: $DF_{new} = DF * n$ where n is equal to the maximum number of vehicles idling times the exhaust flow per vehicle divided by the fan exhaust flow. According to the California Mechanical Code, the exhaust flow per active vehicle is 14,000 cfm (6.6 m^3/s). Table 5.4 provides an example calculation based on this exhaust flow per active vehicle. The table shows that very little additional dilution is needed (i.e., a dilution target value of 0.3).

Table 5-4. Minimum dilution factor calculation for light duty gasoline vehicles

Description		Automobile		
		Idle	Exhaust Vent	Exhaust Vent
Emissions Data		(1)		(1)
Vehicle information	Number of vehicles	1	1	5
	Auto Volume Flow (m^3/s):	0.047	0.047	0.236
	Auto Volume Flow (cfm):	100	100	500
	Exhaust Fan Volume Flow (m^3/s):	NA	**6.612**	**33.06**
	Exhaust Fan Volume Flow (cfm):	NA	14,000	70,000
Emission Factors:				
	CO (g/hr/vehicle):	71.23	71.23	71.23
	NO_x (g/hr/vehicle):	3.52	3.52	3.52
Emission Rates:				
	CO (g/s):	0.0198	0.0198	0.0989
	NO_x (g/s):	0.0010	0.0010	0.0049
	NO (g/s):	0.000	0.0002	0.0012
	NO_2 (g/s):	0.001	0.0007	0.0037
Normalized Health Limits and Odor Thresholds				
Health Limits				
	CO (µg/m³)/(g/s):	11,574,587.57	11,574,587.57	2,314,917.51
	NO (µg/m³)/(g/s):	368,705,547.65	368,705,547.65	73,741,109.53
	NIOSH - NO_2 (µg/m³)/(g/s):	2,458,036.98	2,458,036.98	491,607.40
	OSHA - NO_2 (µg/m³)/(g/s):	2,458,036.98	2,458,036.98	491,607.40
	Health Design Criteria (µg/m³)/(g/s):	**2,458,037**	**2,458,037**	**491,607**
Odor Thresholds				
	Combined Exhaust (µg/m³)/(g/s):	#N/A	#N/A	#N/A
	CO (µg/m³)/(g/s):	#N/A	#N/A	#N/A
	NIOSH - NO_2 (µg/m³)/(g/s):	2,691,550.50	2,691,550.50	538,310.10
	OSHA - NO_2 (µg/m³)/(g/s):	453,371.27	453,371.27	90,674.25
	Odor Design Criteria (µg/m³)/(g/s):	**453,371**	**453,371**	**90,674**
	Minimum Design Criteria (µg/m³)/(g/s):	**453,371**	**453,371**	**90,674**
	Dilution Target Value:	**47**	**0.3**	**0.3**
Notes:				
1) Emissions based on EPA420-F-08-025, October, 2008, Light Duty Gas Vehicles				

5.3.1.4 Boilers

Table 5.5 below shows the calculation of minimum dilution factor for boiler exhaust based on the discussion in Section 5.3.1. Based on Table 5.5 the following equation can be used for calculating the minimum dilution factor: DF = 2.8 x ppm NOx. For example, a boiler exhaust with 10 ppm NOx would have a minimum dilution factor of 28.

Table 5-5. Calculation of Dilution Targets for Boiler Exhaust.

		4.5 MMBTU Boiler		
		Oil Fired (1)	**Gas Fired (1)**	**Gas Fired - Low NO_x (1)**
		4.5 MMBTU Boiler		
Input Data:	Energy Input (MMBTU / hr):	4.50	4.50	4.50
Output Data:				
	Mass Emission Rate (g/s):	512.50	512.50	512.50
	Mass Emission Rate (lb/hr):	4,067.55	4,067.55	4,067.55
	Volume Flow (m^3/s):	0.60	0.60	0.60
	MMBtu/hr per m3/s	7.5		
Emission Factors:				
	CO (ppm-Boiler):	42.00	113.50	113.50
	NO_x (ppm-Boiler):	280.00	81.00	40.50
	SO_2 (ppm-Boiler):	140.75	0.32	0.32
	PM (ppm-Boiler):	#N/A	#N/A	#N/A
	CO (g/kWhr-DG; lb/MMBTU - Boiler):	0.033	0.0834	0.0834
	lb/10^6 scf or lb/10^3 gal	5.0	85.1	85.1
	NO_x (g/kWhr-DG; lb/MMBTU - Boiler):	0.367	0.0977	0.0489
	lb/10^6 scf or lb/10^3 gal	55.0	100	50
	SO_2 (g/kWhr-DG; lb/MMBTU - Boiler):	0.262	0.0006	0.0006
	lb/10^6 scf or lb/10^3 gal	39.2	0.604	0.604
	PM (g/kWhr-DG; lb/MMBTU - Boiler):	0.067	0.007	0.007
	lb/10^6 scf or lb/10^3 gal	10.0	7.600	7.600
Emission Rates:				
	CO (g/s):	0.019	0.047	0.047
	NO_x (g/s):	0.208	0.055	0.028
	NO (g/s):	0.052	0.014	0.007
	NO_2 (g/s):	0.156	0.042	0.021
	SO_2 (g/s):	0.148	0.000	0.000
	PM_{10} (g/s):	0.038	0.004	0.004
Normalized Health Limits and Odor Thresholds				
Health Limits				
	CO (µg/m³)/(g/s):	12,212,833	4,843,109	4,843,109
	NO (µg/m³)/(g/s):	1,730,197	6,498,282	12,996,563
	NO2 (µg/m³)/(g/s):	11,535	43,322	86,644
	SO2 (µg/m³)/(g/s):	87,640	38,691,329	38,691,329
	PM_{10} (µg/m³)/(g/s):	9,921	88,766	88,766
	Health Design Criteria (µg/m³)/(g/s):	**9,921**	**43,322**	**86,644**
Odor Thresholds				
	Combined Exhaust (µg/m³)/(g/s):	#N/A	#N/A	#N/A
	CO (µg/m³)/(g/s):	#N/A	#N/A	#N/A
	NO (µg/m³)/(g/s):	12,636	47,457	94,913
	NO_2 (µg/m³)/(g/s):	2,125	7,982	15,965
	SO_2 (µg/m³)/(g/s):	25,315	11,175,832	11,175,832
	PM_{10} (µg/m³)/(g/s):	#N/A	#N/A	#N/A
	Odor Design Criteria (µg/m³)/(g/s):	**2,125**	**7,982**	**15,965**
	Minimum Design Criteria (µg/m³)/(g/s):	**2,125**	**7,982**	**15,965**
	Minimum Dilution Factor (DF):	**781**	**208**	**104**
	n = DF/NOx:	2.8	2.6	2.6

Notes:
1: Emission faction factors based EPA AP-42
2: to convert to lb/MMBtu, divide by a heating value of 150 lb/10^3 gal for NOx 4,5,6 fuel oil
3: to convert to lb/MMBtu, divide by a heating value of 1020 lb/10^6 scf for Natural Gas
4: 0.5 % max Sulfur for fuel oil assumed

5.3.2 Kitchen

Commercial kitchen grease exhaust is regarded as Class 4 air (non-grease exhaust is regarded as Class 3 air) in ANSI/ASHRAE Standard 62.1 (ANSI/ASHRAE, 2013). Section 5 of the standard requires a minimum separation distance of 30 ft (10 m) between exhaust and any air intakes, or 50 dilutions (see Table 5-1), for Class 4 air. Generally, health effects are not considered for Kitchen exhaust as there are no published chemical emissions rates.

Abundant research exists on the composition and nature of odors and aromas resulting from food production (e.g., Belitz 2009, Nicolay 2006, Grosch 2001), but much of it is not immediately applicable to the definition of kitchen odor thresholds or dilution requirements. This is due in part to the chemical nature of food aromas and odors, which comprise multiple chemicals that have synergistic effects on human olfactory systems (Nicolay 2006). In other words, odors produced by chemical mixtures may produce odor characteristics that are not indicative of any single component. For example, methanethiol is a key odorant of flatus (see section 5.3.4), but is also a key odorant in the aroma of french fries (Wagner 1998) and boiled beef (Grosch 2001). An additional complication is that, like all odors, food odors have different hedonic tones (levels of pleasantness or offensiveness) that influence the threshold at which an odor becomes annoying. Fresh baked bread, for example, is given a hedonic score of 3.53 on Dravnieks' scale (the most pleasant odor being 4), while the odor of eggs is near neutral at 0.45, and sauerkraut is slightly unpleasant with a score of -0.60 (Dravnieks, et al. 1984).

Unfortunately, there is a paucity of published data defining odor thresholds for typical commercial restaurants. However, odor analysis of the exhaust from two restaurants, each belonging to a different well-known fast-food chain, was performed by the IVL Swedish Environmental Research Institute in the context of analyzing an air purification system (Peterson 2011, 2008). Bagged exhaust samples were taken from the rooftop ductwork of the restaurants and analyzed by odor panels comprising trained members. Depending on sampling location (within the duct work) and time of day, odor concentrations based on detection (not recognition) in untreated exhaust ranged from about 1,500 to almost 3,400 OU/m3 between the two restaurants.

Although the exhausts from only two different restaurants were sampled, we assume that these are representative of the type of kitchen grease exhaust that is likely to initiate odor complaints. In addition, the odor concentrations reported in above are of the same order and range as unpublished data, obtained by CPP, indicating odor detection thresholds of 850 OU for a grill exhaust, and 3,200 OU for a rotisserie exhaust, of a wood burning restaurant kitchen.

Assuming an annoyance threshold of 5 OU (Amoore 1985), and ignoring issues of hedonic tone, the range of odor thresholds derived from Peterson (2011, 2008) results in a corresponding range of about 300 to 700 dilutions to decrease the odor concentration of commercial kitchen exhaust below the level of annoyance. Although much greater than the ANSI/ASHRAE standard of 50 dilutions (62.1, 2013, Appendix F), these values accord with CPP's experience regarding effective dilutions for kitchen grease exhaust.

Based on these results, a 300 dilution factor will be recommended for commercial kitchen exhaust and a dilution factor of 700 for wood burning kitchen exhaust.

5.3.3 Cooling Tower

The minimum dilution factor for cooling tower exhaust is based estimated emission rates for various chemicals that are used to reduce and/or eliminate algae, bacterial and fungal growth as well as reduced corrosion of equipment. These chemicals are also used to help avoid Legionella (EPA, 1999). Vanderheyden and Schulyer, 1994 evaluated various chemicals in the cooling towers exhaust and found that the worst case chemical was glutaraldehydes with an initial exhaust concentration range of 140 to 4320 ug/m3 was observed. The NIOSH recommended exposure limit (REL) is 800 ug/m3 and the ACHIH TLV is 200 ug/m3 which gives a dilution range of about 5 to 20 using the highest observed initial exhaust concentration. Based on the range dilution range of 5 to 20, a reasonable recommended value is 10.

5.3.4 Toilet

Exhaust from public and private toilets is regarded as class 2 air in ASHRAE standard 62.1-2013. Such emissions are generally not harmful, but may be a source of odor annoyance or nuisance if the exhaust is re-entrained into fresh air intakes that service areas used or other purposes. The minimum separation distance between a single toilet exhaust and any outdoor air intake is 10 ft (3 m) for class 2 air (ASHRAE 62.1).

There are several sources of odor that may be emitted from toilets and bathrooms, including those of cleaning products, but human flatus is most often the cause of objectionable odors. Three volatile sulfur compounds (VSCs)—hydrogen sulfide, methanethiol (methyl mercaptan) and dimethyl sulfide—are largely responsible for odor arising from human feces and flatus (Tangerman 2009, Suarez et al. 1998). Suarez et al. (1998) identified hydrogen sulfide as the primary correlate for the odor of human flatus, but Tangerman (2009) notes that pinto beans were added to the diets of the subjects in the Suarez et al. study, which may have influenced the hydrogen sulfide content of the flatus. Measured concentrations of hydrogen sulfide differed greatly between the Suarez and Tangerman studies, with mean values of 25.4 (±4.8) ppmv and 3.6 (±1.3) ppmv, respectively. In addition to this difference, Tangerman (2009) notes that methanethiol has a stronger foul odor than hydrogen sulfide even when the concentration of hydrogen sulfide is five times higher than that of methanethiol. Based on this and other evidence, he concludes that methanethiol is mainly responsible for the objectionable odor of human flatus. We assume that this conclusion is correct in the following analysis.

Odor thresholds of methanethiol reported in the literature range over several orders of magnitude, from 0.01 ppbv to 42 ppbv. This range may reflect differences in the training, age and natural sensitivities of odor panel members, as well as vagueness in the definition of an odor threshold. There may also be confusion between reported perception thresholds, in which a smell is merely perceived, and recognition thresholds, in which more than half of odor panel members can identify the odor. Tangerman (2009) reports that the odor of methanethiol is perceivable at a concentration of only 0.01 ppbv, and objectionable at 12 ppbv, though it is not clear how "objectionable" is defined. The NRC (2013) predicts a "level of awareness" (i.e., a level at which more than half of people will perceive "a distinct odor intensity") of 1.9 ppbv for methanethiol. Reported thresholds are given in Table 5-6. Note that the median of these threshold values (0.111 ppbv) is less influenced by the outlying values and is close to the value given by Van Doorn (2002, as cited in NRC 2013). In the analysis below, we assume an annoyance threshold of five times the detection threshold (Mahin 2001, Amoore 1985).

Table 5-6. Odor detection thresholds reported for methanethiol.

Threshold (ppbv)	Reference	*Cited in*
41	Katz and Talbert 1930	NRC 2013
0.990	Wilby 1969	
0.015	Williams 1977	
0.120	Van Doorn 2002	
19	Nishida et al. 1979	
0.102	Van Harreveld 2003	Pullen 2007
0.070	Nagata 2003	
0.500	WEF 1995	
0.010	Tangerman 2009	Tangerman 2009
0.020	Ruth 1986 (low value)	Ruth 1986

The volume of gas passed by healthy humans varies from 400 to 2400 ml per day and emissions occur about 14 (±4) times per day (Levitt and Bond 1980). Suarez et al. (1998) report an average flatus emission volume of 107 (±8.1) ml, while Tangerman (2009) reports a somewhat lower value of 84 (±16) ml. Average concentrations of methanethiol in flatus were statistically identical in both studies, with values of 5.04 (±0.960) ppmv and 5.18 (±1.06) ppmv in Suarez et al. (1998) and Tangerman (2009), respectively. Here, we assume an average emission volume of 100 ml with a methanethiol concentration of 5 ppmv per emission.

To estimate external dilutions required for restroom exhaust, we multiply the assumed emission volume by a typical "safety factor" of five to give an emission volume of 500 ml per stall. Though toilet stalls are obviously not airtight, the dimensions of a typical, non-ADA toilet stall (3 ft x 5 ft x 6 ft) provide a reasonable volume scale (90 ft^3 or 2.6 m^3) with which to estimate dilution within the restroom space, and by which to normalize dilutions on a 'per stall' basis. Table 5-7 provides estimates of interior dilutions, and the corresponding exhaust dilutions required to obtain the annoyance threshold, based on the high and low annoyance threshold values found in the studies referenced above. This calculation assumes the ASHRAE standard (2013) ventilation rate of 70 CFM (0.033 m3/s) per urinal or water closet.

The minimum threshold value, combined with our assumptions of emission volume, concentration and interior dilution volume, provides an upper limit of 20 exterior dilutions to decrease the methanethiol concentration to an acceptable level (Table 5-7). However, the geometric mean threshold value results in only 5.8 exterior dilutions, and, based on CPP's experience with restroom exhausts, is likely to be the most realistic value. Based on these results, the 62-1989R Class 2 recommended dilution factor of 10 seems appropriate for toilet exhaust which is classified as Class 2 exhaust in Standard 62.1 (2013).

Table 5-7. Summary of Toilet Exhaust Odor Study Results

Threshold Statistic Based on Recent Research	Reference	Odor Annoyance Threshold (ppbv)	Necessary Dilution	Dilution due to Room Volume	Exhaust Dilution Requirement
High	Van Dorn (NRC,2013)	0.600	8333	5100	1.6
Low	Tangerman (2009)	0.048	104167	5100	20.4
Geometric Mean of High and Low		0.221	22670	5100	5.8
Emission Volume =		500 ml			
Room Volume =		2.55 m3			
Emission Concentration =		5000 ppmv			

5.4 Summary of Recommended Values and Discussion

Table 5-8 below provides a summary of the recommended minimum dilution factors for the source types investigated as part of this research. The following discussion provides the basis for the recommendations.

- Class 1. This exhaust type is normally room air with minimal odors and no hazardous air pollutants and therefore very little dilution of the exhaust stream is needed. Standard 672-1989R specified minimum dilution factor of 5 which still seems adequate, if not somewhat conservative.
- Class 2. Of all the exhaust steams with this classification, toilet exhaust seems to be the most potentially offensive one from an odor perspective. The recommended DF value for this exhaust per the discussion in Section 5.3.4 is 10 which is the recommended value and is the same value specified in Standard 61.1 (2013).
- Class 3. No additional documentation was found regarding the appropriate dilution factor for Class 3 exhaust. A reasonable assumption is to use the geometric mean between the Class 2 and Class 4 dilution factors which are fairly well documented. The geometric mean is approximately 50 and is the recommended value.
- Class 4. The documentation for a minimum dilution factor of 300 for commercial kitchen exhaust is fairly well documented as discussed in Section 0.

Table 5-8. Summary of Recommended Minimum Dilution Factors, DF

Exhaust Type	Minimum Dilution Factor, DF
Class 1 air exhaust/relief outlet	5
Class 2 air exhaust/relief outlet	10
Class 3 air exhaust/relief outlet	50
Class 4 air exhaust/relief - based on kitchen grease hoods	300
Wood burning kitchen exhaust	700
General Boilers, Natural Gas and Fuel Oil, Based on NOx ppm factor - See Note 1	2.8*p
Garage entry, automobile loading area, or drive-in queue (light duty gasoline vehicles)	50
Diesel generators, diesel truck loading area or dock, diesel bus parking/idling area - See Note 2	2000 * e
Cooling tower exhaust (based chemicals used for treatment)	10
Notes:	
1) If the NOx ppm is 10 ppm, p = 10 and DF = 28	
2) e = 1- the efficienty of the odor filter. For example if the filter is 80% efficient, e = 0.2 and DF = 400.	

cpp

6. UPDATED SEPARATION DISTANCE METHODOLOGY

6.1 CALCULATED SEPARATION DISTANCES (GENERAL AND REGULATORY PROCEDURE)

The stated purpose of this research project is to provide a simple, yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid re-entrainment of exhaust gases. Two new procedures were originally thought to be needed. One a general procedure suitable for standard HVAC engineering practice that has as independent variables: exhaust outlet velocity; exhaust air volumetric flow rate; exhaust outlet configuration (capped/uncapped) and position (vertical separation distance); desired dilution ratio; ambient wind speed; and exhaust direction. The second method was to be a regulatory procedure suitable for Standard 62.1, Standard 62.2, and model building codes that has as independent variables only exhaust outlet velocity, exhaust air volumetric flow rate, desired dilution ratio, and a simple way to account for orientation relative to the inlet. The recommended equation (New4), with the addition of "special cases" discussed in the next section, meets both requirements. New4 accounts for all the important variables, yet is simple enough to be used as a regulatory method.

The methodology for computing minimum separation distances using New4 along with example calculations and additional documentation is found in the following sections.

6.2 GENERAL EQUATION AND METHOD

To compute the minimum separation distance, L, the following methodology should be utilized, where L replaces S from Section 3. First, setup a spreadsheet as shown in Table 6-1. Next, the values in yellow are input, and all other values are computed using the equations below. The details on the special cases (i.e., horizontal exhaust pointed away from intake, upblast exhaust, heated exhaust, hidden intake, and heated capped or louvered exhaust) are discussed in Section 6.3.

The equations and method are provided below.

$$F1 = 13.6\frac{DQ_e}{U_H}; \qquad (6\text{-}1)$$

$$F2 = 33.37\, h_s^2 + 254.9\,\beta\frac{B_{fac}h_sQ_e}{d_eU_H} + 486.9\,\beta\left[\frac{B_{fac}Q_e}{d_eU_H}\right]^2 \qquad (6\text{-}2)$$

$$Bfac = \left[1 + \left(\frac{1180800\,(T_S - T_a)T_S}{{T_a}^2 U_H V_e}\right)\right]^{0.5} \quad (SI) \tag{6-3}$$

$$Bfac = \left[1 + \left(\frac{30.5\,(T_S - T_a)T_S}{{T_a}^2 U_H V_e}\right)\right]^{0.5} \quad \text{(I-P)} \tag{6-4}$$

$$Find\ maximum\ of\ [F1 - F2]\ by\ varying\ U_H\ between\ 1.5\,m/s\ and\ 10\,m/s$$

$$if\ max[F1 - F2] > 0; L = [F1 - F2]^{0.5} \tag{6-5}$$

$$if\ max[F1 - F2] \leq 0; L = 0$$

where:

- L = minimum separation (stretched string as shown in Figure 6-1) distance (m, ft);
- U_H = wind speed at stack top (m/s; fpm);
- D = dilution factor (taken from Table 5-8);
- T_s = exhaust temperature (K; R);
- T_a = ambient temperature (K; R);
- h_s = stack height above the top the air intake (m; ft);
- Q_e = exhaust air volume flow rate (m^3/s; cfm); for gravity vents, such as plumbing vents, use an exhaust rate of 150 cfm (75 L/s); for flue vents from fuel-burning appliances, assume a value of 250 cfm per million Btu/h (0.43 L/s per kW) of combustion input (or obtain actual rates from the combustion appliance manufacturer;
- d_e = exhaust diameter (m; ft); for rectangular exhaust (capped, horizontal or vertical), an equivalent round stack diameter should be calculated using the following equation:

  $$d_{e,,eff} = [\text{Exhaust Area x } 4/\pi]^{0.5}$$

  for louvered round or rectangular exhaust (capped, horizontal or vertical), an equivalent round stack diameter should be calculated as follows:

  $$d_{e,eff} = [\text{Exhaust Area x Open Fraction x } 4/\pi]^{0.5};$$

  for heated capped or horizontal (including louvered) exhaust, the exhaust diameter is the actual or effective diameter multiplied by 10 as discussed in Section 6.3.5;
- β = 1 for uncapped stacks and 0 for capped or horizontal (includes louvered) exhaust; Section 6.3.1 discusses the method to treat horizontal exhaust pointed away from the intake; for heated capped or horizontal exhaust, β = 1 and d_e and Q_e are computed as discussed in Section 6.3.5.

The following describes the calculations and information that is input into Table 6.1.

Row 1: The exhaust type first needs to be specified from Table 5-8 and then the appropriate dilution factor from the table is input. For Class 1 exhaust, the dilution factor is 5 which is the value in the table.

Row 2: If the intake is on a building sidewall or on the opposite side of a roof top obstacle (hidden), the dilution factor can be decreased by a factor of 2 which is then input into the table. If the intake is not hidden, the value should be set to 1. More details are found in Section 6.3.3.

Row 3: If the exhaust is horizontal and pointed away from the intake as described in Section 6.3.1, the dilution factor can decreased by an additional factor of 1.7 and that value is input into the table. For all other cases, a value of 1 is input.

Row 4: The final dilution factor is computed by dividing the dilution factor in Row 1 by the factors in Rows 2 and 3.

Row 5: The height of the stack above the top of the intake is input. For intakes on a building sidewall or behind a roof-top obstacle, the height of the stack above the roof or obstacle top where the intake is located should be used. If the intake, is above the stack height, the height difference is negative and the stack height input is also negative.

Row 6: For capped or horizontal exhaust (including louvered), a value of zero is entered; For all other exhaust types including heated capped or horizontal exhaust pointed away from the input, the value should be 1.0.

Row 7: The exhaust diameter is entered using the methods described above.

Row 8: The exhaust volume flow rate is entered.

Row 9: The exhaust temperature is entered. Unless the exhaust is heated, this temperature should be the same as the ambient temperature.

Row 10: Enter the ambient temperature. A default value of 21.1 C (70 F) should typically be used.

Row 11: The heated exhaust factor is computed using Equation 6-4 as discussed in detail in Section 6.3.4.

Row 12: The exhaust velocity is computed using the equation in the table.

Row 13: F1 is computed using Equation 6-1.

Row 14: F2 is computed using Equation 6-2.

Row 15: For non-capped or heated horizontal exhaust and heated capped exhaust, the wind speed is varied between 1.5 and 10 m/s (300 and 2000 fpm) and the difference between F1 and F2 is maximized. If the maximum value is negative, the minimum separation distance is zero. If the difference is positive, then the initial separation distance is computed using Equation 6-5. For capped stacks or horizontal exhaust not pointed away from the intake, a wind speed of 1.5 m/s should be used. For horizontal exhaust pointed away from the intake the wind speed should be set equal to the exit velocity (see Section 6.3.1).

Row 16: F1-F2 is computed.

Row 17: $L_{initial}$ is computed using Equation 6.5

Row 18: L_{final} is the same as $L_{initial}$ for all exhaust except horizontal exhaust that is pointed away. For the latter case, L_{final} is computed using the equation in the table as discussed in Section 6.3.1.

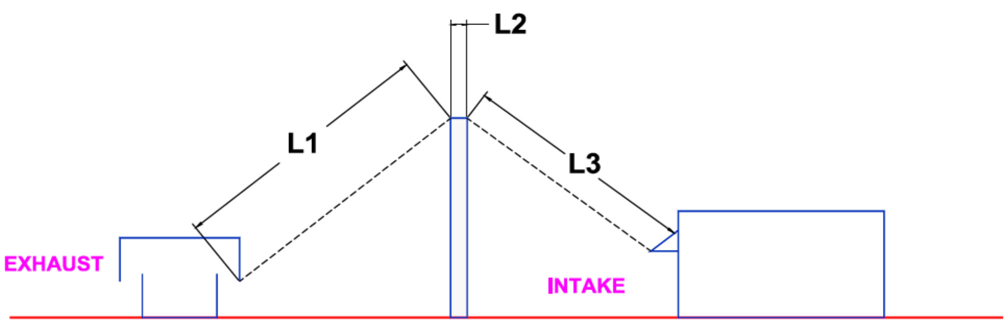


Figure 6-1. Diagram showing how to calculate string distance, L. In the figure L = L1+L2+L3

Table 6-1 Example Spreadsheet for Use in Calculating Separation Distances

Exhaust Type: Class 1			SI Units
1	Input Dilution Factor From Table 5-8	5	
2	Hidden Intake (Yes/No)	2	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.7	If yes, set equal to 1.7. If no, set equal to 1. See Section 6.3.1.
4	Final Dilution Factor	1.5	Divide line 1 by line 2 and line 3
5	hs (m) =	0.31	Height above the top of intake
6	β =	0	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (m) =	1.2	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (m3/s) =	2.0	
9	Exhaust Temperature (Kelvin, K)	294.3	Default is set to ambient, K = C + 273.14
10	Ambient Temperature (Kelvin, K)	294.3	Default is 21.1 C , K = C + 273.14
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (m/s) =	1.8	**Ve = Qe/(πde^2/4)**
13	F1	22.6	**Equation 6.1**
14	F2	3.2	**Equation 6.2**
15	UH (m/s) =	1.8	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 1.5 m/s
16	F1-F2	19.5	Maximize by changing UH between 1.5 and 10 m/s, unless pointed away or capped
17	$L_{Initial}$ (m)	4.4	Equals zero if max F1-F2 is negative
18	L_{Final} (m)	2.3	L_{Final}=$L_{Initial}$ unles pointed away. Then L_{Final}=$L_{Initial}$ - 1.75d_e

Exhaust Type: Class 1			I-P Units
1	Input Dilution Factor From Table 5-8	5	
2	Hidden Intake (Yes/No)	1.0	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.7	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
4	Final Dilution Factor	1.5	Divide line 1 by line 2 and line 3
5	hs (ft) =	1.0	Height above the top of intake
6	β =	0	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (ft) =	3.94	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (cfm) =	4235	
9	Exhaust Temperature (Rankine,R)	529.7	Default is set to ambient, R = F+ 459.67
10	Ambient Temperature (Rankine,R)	529.7	Default is 70 F, R = F+ 459.67
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (fpm) =	348.0	**Ve = Qe/(πde2/4)**
13	F1	243.3	**Equation 6.1**
14	F2	34.1	**Equation 6.2**
15	UH (fpm) =	348	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 295 fpm
16	F1-F2	209.3	Maximize by changing UH between 300 and 2000 fpm
17	$L_{Initial}$ (ft)	14.5	Equals zero if max F1-F2 is negative
18	L_{Final} (ft)	7.6	L_{Final}=$L_{Initial}$ unles pointed away. Then L_{Final}=$L_{Initial}$ - 1.75d_e

Legend
Input
Calculation
Vary
Final Result

6.3 SPECIAL CASES

6.3.1 Horizontal Exhaust

When an exhaust is pointed away from an intake and the wind is blowing toward the intake, the exhaust travels some direction upwind and then turns around. The upwind distance traveled depends upon the ratio of exhaust velocity to wind speed (velocity ratio). The plume is also diluted as it travels upwind. For small velocity ratios, the exhaust turns around quickly (within $0.5d_e$ for a velocity ratio of 0.5) and for high velocity ratios, the plume travels upwind for a larger distance ($6d_e$ for a velocity ratio of 5). An integral plume model (Petersen, 1987) was used to estimate the dilution and travel distance versus velocity ratio. From this analysis, the following rules were developed when an exhaust is pointed away from an intake.

- "Pointed away" includes cases where the direction of the exhaust is oriented 180 degrees away from the intake ± 45 degrees;
- Set $U_H = V_e$;
- Decrease the minimum dilution factor by a 1.7;
- Decrease the separation distance by 1.75 d_e.

6.3.2 Upblast and Downblast Exhaust

For upblast exhaust (typically used for Kitchen exhaust), the effective exhaust velocity is computed using the dimension "A" for d_e in the figure below and the exhaust volume flow rate along with the following equation:

$$V_e = {Q_e}/{(\pi d_e^2/4)} \qquad (6\text{-}6)$$

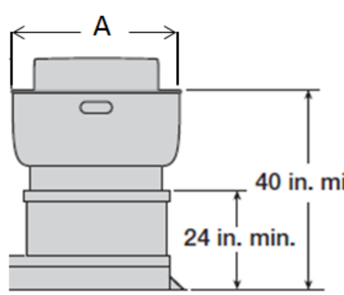


Figure 6-2 Typical Upblast Exhaust

Downblast exhaust (e.g. “mushroom” exhausters) are treated the same as a capped exhaust stack and input exhaust diameter is “A” in the figure above. If the downblast stack is heated, the method in Section 6.3.5 can be used.

6.3.3 Hidden Intakes

A hidden intake is defined as one that cannot be seen if standing at the exhaust location. Typically, hidden intakes are on building sidewalls or on the side of a large mechanical penthouse or unit. The 2015ASHRAE HVAC Application Handbook, Chapter 45, specifies that dilution is enhanced by a least a factor two for a hidden intake. Hence, for hidden intakes the minimum Dilution Factors in Table 5-8 are divided 2.0. It should be noted that a hidden intake should meet one of the following criteria: 1) be off the same roof as the exhaust and on a building sidewall; 2) be on the same roof as the exhaust but on the other side of a significant obstruction.

A significant obstruction is defined as one that would increase the size the plume by at least a factor of two which would result in a dilution increase of at least a factor of two. The minimum obstruction height and width can estimated using initial plume spread estimates (σ_{yo} and σ_{zo}) defined as follows:

$$\sigma_{yo} = \frac{W}{4.3};\ \sigma_{zo} = \frac{H}{2.15} \tag{6-7}$$

The dilution increase can be used using the following equation:

$$Dilution\ Increase\ factor = \frac{(\sigma_{yo} + \sigma_y)(\sigma_{zo} + \sigma_z)}{(\sigma_z\ \sigma_y)} \tag{6-8}$$

where

$$\sigma_y = 0.75\ i_x\ x;\ \sigma_z = 0.5\ i_x\ x \tag{6-9}$$

and i_x is longitudinal turbulence intensity and x is the distance from stack to the windward side of the barrier. A reasonable value for i_x on a building roof is 0.35 and a reasonable maximum downwind distance, x, for a barrier wall from a stack is 10 m (33 ft). This gives values of 2.4 and 1.6 m for σ_y and σ_z and an estimated dilution increase of about a factor of two for a wall that is 10 m (33ft) wide and 4.6 m high (15 ft) high. Therefore, a significant obstacle is defined as follows:

- is located no farther than 10 m (33 ft) from the stack, and
- has a vertical plane square footage of at least 46.5 m^2 (500 ft^2), and
- a height that is greater than one $\sigma_{z,}$ or 1.6 m (5.2 ft), and

- a width that is greater than two σ_y, or 4.8 m (16 ft).

Alternate larger dilution enhancement factors may be justified in some cases if additional analysis is carried out using the method outline above for barriers and as outlined in Petersen et al. (2002, 2004) for building sidewall intakes. Larger downwind distances for the barrier may also be justified using the method outlined above.

6.3.4 Heated Exhaust

The general equation assumes plume buoyancy effects are not significant for plume rise. Therefore some method needs to be developed to provide some plume rise enhancement for hot exhaust. To develop the method, we need to start with the following plume rise equation due to momentum and buoyancy (EPA, 1995, 2004):

$$\Delta h = [Mo + Bo]^{\frac{1}{3}} = \left[\left(\frac{3\, T_a\, r^2\, V_e^2 x}{T_s \beta U_H^2}\right) + \left(\frac{3\, g(T_s - T_a)\, r^2\, V_e x^2}{2T_a \beta U_H^3}\right)\right]^{\frac{1}{3}} \quad (6\text{-}9)$$

where

$$Mo = \text{ Momentum Rise } = \left(\frac{3\, T_a\, r^2\, V_e^2 x}{T_s \beta U_H^2}\right)^{1/3} \quad (6\text{-}10)$$

$$Bo = \text{Buoyant Rise} = \left(\frac{3\, (T_s - T_a)\, r^2\, V_e x^2}{2T_a \beta U_H^3}\right)^{1/3} \quad (6\text{-}11)$$

and T_s = the exhaust temperature, T_a = ambient temperature, x = downwind distance; and r = stack radius.

Since the new equation was developed assuming all plume rise is due to momentum, an equivalent momentum, *Mo,equivalent*, needs to be computed that gives the same plume rise as that due to momentum and buoyancy effect combined, or

$$Mo, equivalent = [Mo + Bo] \quad (6\text{-}12)$$

expanding,

$$\left(\frac{3\, T_a\, r^2\, V_{e,b}^2 x}{T_s \beta U_H^2}\right) = \left(\frac{3\, T_a\, r^2\, V_e^2 x}{T_s \beta U_H^2}\right) + \left(\frac{3\, g(T_s - T_a)\, r^2\, V_e x^2}{2T_a \beta U_H^3}\right) \quad (6\text{-}13)$$

where $Q_{e,b}$ is the volume flow that gives the same momentum plume rise as that due to momentum and buoyancy effects combined. First, solving for $V_{e,b}$, simplifying and setting x = 3.05 m (10 ft) and g = 9.8 m/s^2(118080 ft/min^2), the following equations results:

$$\left(V_{e,b}^2\right) = \left(V_e^2\right) + \left(\frac{g(T_s-T_a)T_s\,V_e x}{2{T_a}^2 U_H}\right) \quad (6\text{-}14)$$

Next, both sides of the equation are multiplied by stack area to obtain volume flow rate and the following equation results:

$$\left(Q_{e,b}\right) = Q_e\left[1+\left(\frac{30.5\,(T_s-T_a)T_s}{{T_a}^2 U_H V_e}\right)\right]^{0.5} = Q_e * Bfac \qquad \text{(SI)} \qquad (6\text{-}15)$$

$$\left(Q_{e,b}\right) = Q_e\left[1+\left(\frac{1180800\,(T_s-T_a)T_s}{{T_a}^2 U_H V_e}\right)\right]^{0.5} = Q_e * Bfac \qquad \text{(I-P)} \qquad 6\text{-}16)$$

where *Bfac* is the correction factor for heated exhaust. The above equation shows *Bfac* is highest for low winds and low exit velocities. It tends toward a value of 1 for high wind speeds and high exit velocities.

B_{fac} only affects the final plume rise, h_f in Equation 3.7 and hence the factor is only applied to volume flow terms in Equation 6.2. For a simplified regulatory procedure, this term can be set equal to 1.0.

6.3.5 Capped Heated Exhaust

Capped stacks that are heated will have still have plume rise due to buoyancy effects. To account for this additional plume rise, a method similar to that recommended by U.S. Environmental Protection Agency will be utilized (Brode, 2015). Brode (2015) suggested two alternate methods:

- Method 1: set the exit velocity (V_e) to 0.001 m/s and then adjust the stack diameter using Equation 6-17 to maintain the actual flow rate and buoyancy of the plume.

$$d_e = \left({}^{4\,Q_e}\!/_{\pi V_e}\right)^{0.5} \quad (6\text{-}17)$$

- Method 2: divide the exit velocity by 4 and multiply the diameter by 2 which also maintains the actual volume flow rate.

Method 1 results in very large and unrealistic stack diameters and Method 2 results in unreasonable high exit velocities for a capped stack. Hence, Method 3 will be utilized that provides more reasonable exhaust diameters and exit velocities.

- Method 3 (Recommended): multiply diameter by 10 and maintain the actual volume flow rate which decreases the exit velocity by a factor of 100. This method results in more reasonable exit velocities (much greater than 0.001 m/s) and exhaust diameters.

For this calculation β is set equal to 1. An example calculation is provided in Section 6.4.5.

6.4 EXAMPLE CALCULATIONS

6.4.1 Class 1 Exhaust

For this example, consider an 1000 ft^2 (93 m^2) class room with 30 students. Standard 62.1 requires a minimum outdoor air flow of 30x10cfm + 1000x0.12 cfm/ft^2 = 420 cfm (0.2 m^3/s). A 500 cfm (0.24 m^3/s) capped exhaust is selected that is 3 ft (0.31 m) high with a 6 inches (0.15 m) exhaust diameter. Table 6-2 below shows that the minimum separation distance is computed to be 9 ft (2.7 m). If the cap is removed, the minimum separation distance is 0 ft (0 m).

Table 6-2. Class 1 Exhaust Example Calculation

Exhaust Type: Class 1			SI Units
1	Input Dilution Factor From Table 5-8	5	
2	Hidden Intake (Yes/No)	1	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.0	If yes, set equal to 1.7. If no, set equal to 1. See Section 6.3.1.
4	Final Dilution Factor	5.0	Divide line 1 by line 2 and line 3
5	hs (m) =	0.31	Height above the top of intake
6	β =	0	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (m) =	0.15	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (m3/s) =	0.236	
9	Exhaust Temperature (Kelvin, K)	294.3	Default is set to ambient, K = C + 273.14
10	Ambient Temperature (Kelvin, K)	294.3	Default is 21.1 C , K = C + 273.14
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (m/s) =	12.94	**$Ve = Qe/(\pi de^2/4)$**
13	F1	10.7	**Equation 6.1**
14	F2	3.2	**Equation 6.2**
15	UH (m/s) =	1.5	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 1.5 m/s
16	F1-F2	7.5	Maximize by changing UH between 1.5 and 10 m/s. Unless Pointed Away
17	$L_{initial}$ (m)	2.7	Equals zero if max F1-F2 is negative
18	L_{Final} (m)	2.7	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

Exhaust Type: Class 1			I-P Units
1	Input Dilution Factor From Table 5-8	5	
2	Hidden Intake (Yes/No)	1.0	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.7	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
4	Final Dilution Factor	5.0	Divide line 1 by line 2 and line 3
5	hs (ft) =	1.0	Height above the top of intake
6	β =	0	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (ft) =	0.50	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (cfm) =	500	
9	Exhaust Temperature (Rankine,R)	529.7	Default is set to ambient, R = F+ 459.67
10	Ambient Temperature (Rankine,R)	529.7	Default is 70 F, R = F+ 459.67
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (fpm) =	2546.1	**Ve = Qe/(πde2/4)**
13	F1	115.1	**Equation 6.1**
14	F2	34.1	**Equation 6.2**
15	UH (fpm) =	295	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 295 fpm
16	F1-F2	81.0	Maximize by changing UH between 300 and 2000 fpm
17	$L_{initial}$ (ft)	9.0	Equals zero if max F1-F2 is negative
18	L_{Final} (ft)	9.0	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

6.4.2 Class 2 Exhaust

Assume this a toilet with four units which, according to Standard 62.1, require 50/70 cfm (24/35 L/s) per unit. A 300 cfm (142 L/s) fan is selected with a 6 inch (0.15 m) exhaust diameter. The exhaust height is 1 ft (0.31m) and is a capped stack (or a downblast mushroom exhauster). The computed minimum separation distance shown in Table 6-3 is 10.2 ft (3.1 m). Without a cap (or with an upblast exhaust fan), the separation distance is compute to be 0 ft (0 m).

Table 6-3. Class 2 Exhaust Example Calculation

Exhaust Type: Class 2. Toilet Exhaust			SI Units
1	Input Dilution Factor From Table 5-8	10	
2	Hidden Intake (Yes/No)	1	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.0	If yes, set equal to 1.7. If no, set equal to 1. See Section 6.3.1.
4	Final Dilution Factor	10.0	Divide line 1 by line 2 and line 3
5	hs (m) =	0.31	Height above the top of intake
6	β =	0	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (m) =	0.15	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (m3/s) =	0.142	
9	Exhaust Temperature (Kelvin, K)	294.3	Default is set to ambient, K = C + 273.14
10	Ambient Temperature (Kelvin, K)	294.3	Default is 21.1 C , K = C + 273.14
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (m/s) =	7.8	**Ve = Qe/(πde^2/4)**
13	F1	12.8	**Equation 6.1**
14	F2	3.2	**Equation 6.2**
15	UH (m/s) =	1.5	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 1.5 m/s
16	F1-F2	9.7	Maximize by changing UH between 1.5 and 10 m/s. Unless Pointed Away
17	$L_{initial}$ (m)	3.1	Equals zero if max F1-F2 is negative
18	L_{Final} (m)	3.1	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

Exhaust Type: Class 2. Toilet Exhaust			I-P Units
1	Input Dilution Factor From Table 5-8	10	
2	Hidden Intake (Yes/No)	1.0	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.7	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
4	Final Dilution Factor	10.0	Divide line 1 by line 2 and line 3
5	hs (ft) =	1.0	Height above the top of intake
6	β =	0	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (ft) =	0.50	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (cfm) =	300	
9	Exhaust Temperature (Rankine,R)	529.7	Default is set to ambient, R = F+ 459.67
10	Ambient Temperature (Rankine,R)	529.7	Default is 70 F, R = F+ 459.67
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (fpm) =	1527.7	**Ve = Qe/(πde2/4)**
13	F1	138.1	**Equation 6.1**
14	F2	34.1	**Equation 6.2**
15	UH (fpm) =	295	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 295 fpm
16	F1-F2	104.1	Maximize by changing UH between 300 and 2000 fpm
17	$L_{initial}$ (ft)	10.2	Equals zero if max F1-F2 is negative
18	L_{Final} (ft)	10.2	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

6.4.3 Class 3 Exhaust

For this example, consider a 10,000 ft^2 (93 m^2) general manufacturing room with 100 people. Standard 62.1 requires a minimum outdoor air flow of 100x10cfm + 10,000*0.18 cfm/ft^2 = 2800 cfm (0.85 m^3/s) which is the fan size selected. A 1 ft (0.31 m) vertical exhaust is selected with a 16 inches (0.41 m) exhaust diameter. Table 6-4 below shows that the minimum separation distance is computed to be 10.4 ft (3.2 m). If the cap is added, the minimum separation distance becomes unrealistically large at 80 ft (24.4 m).

Table 6-4. Class 3 Exhaust Example Calculation

Exhaust Type: Class 3. General Manufacturing Exhaust Fan			SI Units
1	Input Dilution Factor From Table 5-8	50	
2	Hidden Intake (Yes/No)	1	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.0	If yes, set equal to 1.7. If no, set equal to 1. See Section 6.3.1.
4	Final Dilution Factor	50.0	Divide line 1 by line 2 and line 3
5	hs (m) =	0.30	Height above the top of intake
6	β =	1	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (m) =	0.41	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (m3/s) =	1.322	
9	Exhaust Temperature (Kelvin, K)	294.3	Default is set to ambient, K = C + 273.14
10	Ambient Temperature (Kelvin, K)	294.3	Default is 21.1 C , K = C + 273.14
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (m/s) =	10.2	**Ve = Qe/(πde^2/4)**
13	F1	89.9	**Equation 6.1**
14	F2	79.9	**Equation 6.2**
15	UH (m/s) =	10.0	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 1.5 m/s
16	F1-F2	10.0	Maximize by changing UH between 1.5 and 10 m/s. Unless Pointed Away
17	$L_{Initial}$ (m)	3.2	Equals zero if max F1-F2 is negative
18	L_{Final} (m)	3.2	L_{Final}=$L_{Initial}$ unles pointed away. Then L_{Final}=$L_{Initial}$ - 1.75d_e

Exhaust Type: Class 3. General Manufacturing Exhaust Fan			I-P Units
1	Input Dilution Factor From Table 5-8	50	
2	Hidden Intake (Yes/No)	1.0	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.7	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
4	Final Dilution Factor	50.0	Divide line 1 by line 2 and line 3
5	hs (ft) =	1.0	Height above the top of intake
6	β =	1	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (ft) =	1.33	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (cfm) =	2800	
9	Exhaust Temperature (Rankine,R)	529.7	Default is set to ambient, R = F+ 459.67
10	Ambient Temperature (Rankine,R)	529.7	Default is 70 F, R = F+ 459.67
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (fpm) =	2006.1	**Ve = Qe/(πde2/4)**
13	F1	967.4	**Equation 6.1**
14	F2	860.0	**Equation 6.2**
15	UH (fpm) =	1968	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 295 fpm
16	F1-F2	107.4	Maximize by changing UH between 300 and 2000 fpm
17	$L_{Initial}$ (ft)	10.4	Equals zero if max F1-F2 is negative
18	L_{Final} (ft)	10.4	L_{Final}=$L_{Initial}$ unles pointed away. Then L_{Final}=$L_{Initial}$ - 1.75d_e

6.4.4 Class 4 Exhaust

This example will consider a commercial kitchen grease hood with an initial design as follows: Upblast, "A" dimension in Figure 6-1 = 28 inches (0.71 m); flow = 2000 cfm (0.95 m^3/s), stack height above intake = 27 inches (0.7 m). The first calculation shows that the minimum separation distance is 147 ft (45 m) and an intake will need to be located closer than that. An acceptable separation distance of 6.6 ft (2 m) was found by changing the design to: utility fan, stack height = 9.5 ft (2.9 m), exhaust diameter = 14 inches (0.4 m), exhaust flow = 2000 cfm (0.95 m^3/s). The calculations are provided below.

Table 6-5. Class 4 Exhaust Example Calculation

Exhaust Type: Class 4. Commercial Kitchen Exhaust			SI Units
1	Input Dilution Factor From Table 5-8	300	
2	Hidden Intake (Yes/No)	1	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.0	If yes, set equal to 1.7. If no, set equal to 1. See Section 6.3.1.
4	Final Dilution Factor	300.0	Divide line 1 by line 2 and line 3
5	hs (m) =	2.90	Height above the top of intake
6	β =	1	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (m) =	0.36	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (m3/s) =	0.945	
9	Exhaust Temperature (Kelvin, K)	294.3	Default is set to ambient, K = C + 273.14
10	Ambient Temperature (Kelvin, K)	294.3	Default is 21.1 C , K = C + 273.14
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (m/s) =	9.1	**Ve = Qe/(πde²/4)**
13	F1	1131.7	**Equation 6.1**
14	F2	1127.7	**Equation 6.2**
15	UH (m/s) =	3.4	Vary unless pointed away. If pointed aways set UH = Ve
16	F1-F2	4.0	Maximize by changing UH between 1.5 and 10 m/s. Unless Pointed Away
17	$L_{initial}$ (m)	2.0	Equals zero if max F1-F2 is negative
18	L_{Final} (m)	2.0	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

Exhaust Type: Class 4. Commercial Kitchen Exhaust			I-P Units
1	Input Dilution Factor From Table 5-8	300	
2	Hidden Intake (Yes/No)	1.0	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.7	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
4	Final Dilution Factor	300.0	Divide line 1 by line 2 and line 3
5	hs (ft) =	9.5	Height above the top of intake
6	β =	1	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (ft) =	1.19	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (cfm) =	2000	
9	Exhaust Temperature (Rankine,R)	529.7	Default is set to ambient, R = F+ 459.67
10	Ambient Temperature (Rankine,R)	529.7	Default is 70 F, R = F+ 459.67
11	Heated Exhaust Factor, Bfac	1.00	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (fpm) =	1794.1	**Ve = Qe/(πde2/4)**
13	F1	12175.4	**Equation 6.1**
14	F2	12132.1	**Equation 6.2**
15	UH (fpm) =	670	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 295 fpm
16	F1-F2	43.3	Maximize by changing UH between 300 and 2000 fpm
17	$L_{initial}$ (ft)	6.6	Equals zero if max F1-F2 is negative
18	L_{Final} (ft)	6.6	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

6.4.5 Boiler Exhaust (Capped and Heated)

A 4.5 MMBTU Boiler is being installed with the following specifications: NO_x = 40 ppm, exhaust flow = 1270 cfm (0.6 m^3/s), diameter = 16 inches (0.406m), exhaust temperature = 300 F (422K), exhaust height = 4 ft (1.2 m), and capped. Using Table 5-8, the minimum Dilution factor is computed to be 40ppm x 2.8 =112. Using the capped heated exhaust method outlined in Section 6.3.4, the minimum separation distance is computed to be 9.2 ft (2.8m). Note, the exit diameter is multiplied by 10 which means the exit velocity is divided by 100. This accounts for the cap and plume rise due to a hot exhaust.

Table 6-6. Boiler Exhaust Example Calculation

Exhaust Type: Class 4. Commercial Kitchen Exhaust			SI Units
1	Input Dilution Factor From Table 5-8	112	
2	Hidden Intake (Yes/No)	1	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.0	If yes, set equal to 1.7. If no, set equal to 1. See Section 6.3.1.
4	Final Dilution Factor	112.0	Divide line 1 by line 2 and line 3
5	hs (m) =	1.22	Height above the top of intake
6	β =	1	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (m) =	4.06	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (m3/s) =	0.60	
9	Exhaust Temperature (Kelvin, K)	422.0	Default is set to ambient, K = C + 273.14
10	Ambient Temperature (Kelvin, K)	294.3	Default is 21.1 C , K = C + 273.14
11	Heated Exhaust Factor, Bfac	6.49	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (m/s) =	0.0	**Ve = Qe/(πde^2/4)**
13	F1	91.4	**Equation 6.1**
14	F2	83.9	**Equation 6.2**
15	UH (m/s) =	10.0	Vary unless pointed away. If pointed aways set UH = Ve
16	F1-F2	7.5	Maximize by changing UH between 1.5 and 10 m/s. Unless Pointed Away
17	$L_{initial}$ (m)	2.7	Equals zero if max F1-F2 is negative
18	L_{Final} (m)	2.7	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

Exhaust Type: Class 4. Commercial Kitchen Exhaust			I-P Units
1	Input Dilution Factor From Table 5-8	112	
2	Hidden Intake (Yes/No)	1.0	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
3	Exhaust Pointed Away from Intake (Yes/No)	1.7	If yes, set equal to 2. If no, set equal to 1, see Section 6.3.3.
4	Final Dilution Factor	112.0	Divide line 1 by line 2 and line 3
5	hs (ft) =	4.0	Height above the top of intake
6	β =	1	Set = 0 for capped or horizontal, = 1 for vertical and non-capped or heated/capped
7	de (ft) =	13.33	For upblast/downblast exhaust see Section 6.3.2. For heated and capped see section 6.3.5.
8	Qe (cfm) =	1270	
9	Exhaust Temperature (Rankine,R)	759.6	Default is set to ambient, R = F+ 459.67
10	Ambient Temperature (Rankine,R)	529.7	Default is 70 F, R = F+ 459.67
11	Heated Exhaust Factor, Bfac	6.48	**Equations 6.3 and 6.4. See Section 6.3.4.**
12	Ve (fpm) =	9.1	**Ve = Qe/(πde2/4)**
13	F1	983.2	**Equation 6.1**
14	F2	902.0	**Equation 6.2**
15	UH (fpm) =	1968	Vary unless pointed away or capped. If pointed aways set UH = Ve. If capped, set = 295 fpm
16	F1-F2	81.2	Maximize by changing UH between 300 and 2000 fpm
17	$L_{initial}$ (ft)	9.0	Equals zero if max F1-F2 is negative
18	L_{Final} (ft)	9.0	L_{Final}=$L_{initial}$ unles pointed away. Then L_{Final}=$L_{initial}$ - 1.75d_e

7. CONCLUSIONS

The purpose of this Research Project was to provide a simple, yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid re-entrainment of exhaust gases. Accordingly, a new procedure was developed that addresses the technical deficiencies in the simplified equations and tables that are currently in Standard 62.1. The new procedure makes use of the knowledge provided in Chapter 45 of the 2015 ASHRAE Handbook—Applications, and various wind tunnel and full-scale studies discussed herein.

The updated methodology is suitable for standard HVAC engineering practice, and for regulatory use suitable for Standard 62.1, Standard 62.2, and model building codes. The new method has as independent variables: desired dilution factor; intake configuration relative to the exhaust (hidden/pointed away); height above or below the intake; exhaust outlet configuration (capped/uncapped/louvered); exhaust diameter (velocity); exhaust air volumetric flow rate; exhaust temperature; ambient temperature and wind speed.

The updated method was tested against several databases (field and wind tunnel) which demonstrated that the new method is more accurate than the existing Standard 62.1 equation in that is underpredicts and overpredicts observed dilution less frequently. In addition, the new method accounts for the following additional important variables: stack height, wind speed and hidden versus visible intakes. The new method also has theoretically justified procedures for addressing heated exhaust, louvered exhaust, capped heated exhaust and horizontal exhaust that is pointed away from the intake.

Included in the report are recommendations and documentation regarding minimum dilution factors for Class 1-4, wood burning kitchen, boiler, vehicle, emergency generator and cooling tower type exhaust.

8. REFERENCES

Amoore, J.E. 1985. The perception of hydrogen sulfide odor in relation to setting an ambient standard. Olfacto-Labs, Berkeley, CA: prepared for the CA Air Resources Board.

ANSI/ASHRAE. ASHRAE Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA, 30329, 2013.

ANSI/ASHRAE. Ventilation for acceptable indoor air quality. ANSI/ASHRAE standard 62.1. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA, 30329, 2013.

ANSIAIHA Standard Z9.5, Laboratory Ventilation, The American Industrial Hygiene Association, 2012

ASHRAE Standard 62.1-2010, "Ventilation for Acceptable Indoor Air Quality" American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA

ASHRAE Handbook 1993 – Chapter 14 - Fundamentals; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA

ASHRAE Handbook 1997 – Chapter 15 - Fundamentals; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA

ASHRAE Handbook 2015, Chapter 45 - HVAC Applications; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA

ASHRAE Handbook 2007, Chapter 44 - HVAC Applications; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Brode, R.W. 2015. Proposed updates to AERMOD modeling system. 11th Modeling Conference Presentation, Research Triangle Park, NC. August 12, 2015. http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5_Proposed_Updates_AERMOD_System.pdf

Cernansky, N.P. 1983. Diesel exhaust odor and irritants: a review. Journal of the Air Pollution Control Association, Vol. 33(2), pp. 97-104.

Cimorelli, A.J., S.G. Perry, A. Venkatram, J.C. Weil, R.J. Paine, R.B. Wilson, R.F. Lee, W.D. Peters, and R.W. Brode. AERMOD. 2005. A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization. Journal of Applied Meteorology, 44, 682-693. American Meteorological Society, Boston, MA.

Dravnieks, A., T. Masurat, and R.A. Lamm. 1984. Hedonics of odors and odor descriptors. Journal of the Air Pollution Control Association, Vol. 34 (7), pp. 752-755.

EPA. 2002. Health assessment document for diesel engine exhaust. Prepared by the National Center for Environmental Assessment, Washington, DC, for the Office of Transportation and Air Quality; EPA/600/8-90/057F.

EPA. 1995. User's guide for the Industrial Source Complex (ISC3) dispersion models, vol. 2: Description of model algorithms. U.S. Environmental Protection Agency, Research Triangle Park, OAQPS, Research Triangle Park, NC.,EPA-454/B-95003B.

EPA, 1999. Legionella: Human Health Criteria Document, Office of Science and Technology, Washington, DC, EPA-822-R-001, November, 1999.

EPA, 2004, AERMOD, Description of Model Formulation, U.S. Environmental Protection Agency, Research Triangle Park, OAQPS, Research Triangle Park, NC., EPA-454/R-03-004,

Grosch, W. 2001. Evaluation of the key odorants of foods by dilution experiments, aroma models and omission. Chemical Senses, Vol. 26, pp. 533545.

Gupta, A. T. Stathopoulos and P. Saathoff,. 2012. Wind tunnel investigation of the downwash effect of a rooftop structure on plume dispersion. Atmospheric Environment, Vol. 46. p 496-5

Gupta, A., 2009. Physical Modeling of the Downwash Effect of Rooftop Structure on Plume Dispersion. Ph.D. Thesis, Concordia University, Montreal, Quebec, Canada.

Hanna, S.R., O.R. Hansen, S. Dharmavaram, 2004. FLACS CFD air quality model performance evaluation with Kit Fox, MUST, Prairie Grass, and EMU observations, Atmospheric Environment, Vol 38.

Hajra, B. T. Stathopoulos. 2011. The effect of upstream buildings on near-field pollutant dispersion in the built environment. Atmospheric Environment. Vol. 45, pp.4930-4940

Hajra, B. T. Stathopoulos. 2012. A wind tunnel study of the effect of downstream buildings on near-field pollutant dispersion. Building and Environment. Vol. 52, 19-31

Hoydysh, W.G., and L.L. Schulman. 1987 "Fluid Modeling Study of the Contamination of Fresh Air Intakes From Rooftop Emissions," Paper 87-82A.9, 80th Annual Meeting of APCA, New York.

IAPMO/ANSI UMC 1-2012 Uniform Mechanical Code; International Association of Plumbing and Mechanical Officials; Ontario, CA

Mahin, T.D. 2001. Comparison of different approaches used to regulate odours around the world. Water Science and Technology, Vol. 44 (9), pp. 87–102.

Nicell, J.A. 2003. Expressions to relate population responses to odor concentration. Atmospheric Environment, Vol. 37, pp. 4955-4964.

NRC. 2013. Acute exposure guideline levels for selected airborne chemicals. Vol. 15. National Academies Press. ISBN 0-309-29122-4.

Pullen, J. 2007. Review of odor character and thresholds. Science Report SC030170/SR2. Environment Agency, Bristol U.K. ISBN 978-1-84432-719-5.

Petersen, R.L., J.J. Carter, and M.A. Ratcliff (1997). The Influence of Architectural Screens on Exhaust Dilution. ASHRAE 805-TRP, Final Report. 1997.

Petersen, R.L., M.A. Ratcliff, and J.J. Carter. 1999. Influence of architectural screens on rooftop concentrations due to effluent from short stacks. ASHRAE Transactions 105(1).

Petersen, R.L. D. Banks, T. Scott and J.D. Reifschneider. 2007. The effect of ganging on pollutant dispersion from building exhaust stacks. Final Report. ASHRAE RP 1167

Petersen, R.L., B.C. Cochran, and J.J. Carter. 2002. Specifying exhaust and intake systems. ASHRAE Journal.

Petersen, R.L. and J.W. LeCompte. 2002. Exhaust contamination of hidden versus visible air intakes. Final Report, ASHRAE RP-1168.

Petersen, R.L., J.J. Carter, and J.W. LeCompte. 2004. Exhaust contamination of hidden vs. visible air intakes. ASHRAE Transactions, 110 (1)

Petersen, R.L., J.J. Carter, B.C. Cochran. 2005. Modeling exhaust dispersion for specifying acceptable exhaust/intake designs. US EPA Laboratories for the 21st Century Best Practices Guide, DOE/GO-102005-2104.

Petersen, R.L. and B.C. Cochran. 2008. Air quality modeling: Chapter 24A: Wind tunnel modeling of pollutant dispersion. The EnviroComp Institue and Air and Waste Management Association.

Petersen, R.L. 1987. Performance evaluation of integral and analytical plume rise algorithms, JAPCA, Vol 37, No. 11, November.

Petersen, R.L. and J.D. Reifschneider. 2008. The effect of ganging on pollutant dispersion from building exhaust stacks. ASHRAE Transactions 114 (1)

Peterson, K. 2011. Odour measurments in a kitchen exhaust duct at Burger King. Report U3117. IVL Swedish Environmental Research Institute. Accessed online on 24 Nov, 2014, at http://www.interzon.com/wp-content/uploads/2014/10/U3117-lukt-Burger-King-2010-och-2011-2.pdf

Public Review Draft, ASHRAE Standard 62-1989R; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA, August 1996

Roy, M.M., and Mustafi, N.N. 2001. Investigation of odorous components in the exhaust if DI diesel engines. *Proceedings of* the 4th International Conference on Mechanical Engineering, December 26-28, 2001, Dhaka, Bangladesh/pp. II 31-36.

Ruth, J.H. 1986. Odor Thresholds and Irritation Levels of Several Chemical Substances: A Review. American Industrial Hygiene Association Journal. Vol. 47, pp. A142-A151.

Schulman, L.L and J.S. Scire. 1991. “The Effect of Stack Height, Exhaust Speed, and Wind Direction on Concentrations From a Rooftop Stack,” ASHRAE Transactions, Vol. 97, Pt. 2.

Snyder, W. H., 1981. “Guideline for Fluid Modeling of Atmospheric Diffusion,” USEPA, Environmental Sciences Research Laboratory, Office of Research and Development, Research Triangle Park, North Carolina, Report No. EPA600/8–81–009.

Suarez, F.L., Springfield, J., Levitt, M.D. 1998. Identification of gases responsible for the odour of Human flatus and evaluation of a device purported to reduce this odour. Gut. Vol. 43, pp. 100-104.

Tangerman, A. 2009. Measurement and biological significance of the volatile sulfur compounds hydrogen sulfide, methanethiol and dimethyl sulfide in various biological matrices. Journal of Chromatography B. Vol. 877, pp. 3366-3377

Vanderheyden, M.D., D.S. Chadder, and A.E. Davies. 1994. "A novel methodology for predicting the impact of model sources on air quality," presented at the 87th Annual Meeting of the Air & Waste Management Association.

Vanderheyden, M.D., and G.D. Schuyler. 1994. Evaluation and quantification of the impact of cooling tower emissions on indoor air quality, Paper #: OR-94-01-3, ASHRAE Transactions.

Wagner, R.K, and Grosch, W. 1998. Key odorants of french fries. Journal of the American Oil Chemists Society, Vol. 75 (10), pp. 1385-1392.

Wilson, D.J., I. Fabris, and M.Y. Ackerman. 1998a. Measuring adjacent building effects on laboratory exhaust stack design. ASHRAE Transactions 104(2):1012-1028.

Wilson, D.J., I. Fabris, J. Chen, and M.Y. Ackerman. 1998b. Adjacent building effects on laboratory fume hood exhaust stack design. Final Report, ASHRAE RP-897.

Wilson, D.J., B.K. Lamb. 1994. Dispersion of exhaust gases from roof-level stacks and vents on laboratory building, Atmospheric Environment, Volume 28, Issue 19, Pages 3099-3111

Wilson, D.J., and E.H. Chui. 1994. Influence of building size on rooftop dispersion of exhaust gas, Atmospheric Environment, Volume 28, No. 14, Pages 2325-2334