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FINAL REPORT

A WIND-TUNNEL STUDY OF AIR RE-ENTRAINMENT FROM AN ACCIDENTAL LABORATORY EXHAUST STACK RELEASE ON THE UC DAVIS WATERSHED SCIENCE RESEARCH CENTER

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EXECUTIVE SUMMARY

A wind-tunnel study of a laboratory exhaust stack, designated EF-2 and located on the roof of the new UC Davis Watershed Science Research Center, was conducted at the UC Davis Atmospheric Boundary Layer Wind Tunnel. The purpose of the study was to assess the stack's emissions reaching the three roof HVAC intakes of the Watershed Science building and 16 intakes of the neighboring building, Academic Surge. Three measurements were also made on the second floor windows along the northwest wall of the Watershed Science building. Thus, a total of 22 receptor sites were measured for stack emission concentrations. For the wind tunnel study, a 1-inch to 16-feet scaled model of the UCD Watershed Science Research Center site was constructed, including nearby buildings and surrounding trees. Stack effluent was modeled by releasing a neutrally buoyant tracer gas (ethane) from scaled model exhaust stacks. Over a wide range of wind speeds (i.e., from a few mph to approximately 25 mph), simulations were conducted under the "worst-case" scenario in which the exhaust stack was aligned directly upwind of the receptor being measured.

Physical characteristics defined that emissions from EF-2 were driven by a fan flowrate of 3750 CFM. However, with a tapered stack, the exhaust speed at the exit of the stack was increased, generating a final exhaust exit flowrate of 5820 CFM. EF-2 was also used to exhaust effluent from five source types: fume hoods, snorkels, a cabinet vent, a downdraft sink, and a general lab exhaust. Such sources provided a flowrate of 3550 CFM. This report presents a toxic dilution analysis presuming an accidental release from one fume hood. This accident source generates 900 CFM of toxic release, which is 25% of the total from all sources. With a pre-diluted tapered exhaust, this amount is actually 15% of the final exhaust release. A UC Davis campus minimum dilution standard of 1:1000 from a rooftop stack exhaust was then used to assess acceptable performance of the exhaust stack. According to results from a 10-foot and 15-foot height simulation, an accidental release from one toxic source generates high and passing dilution values for all receptor sites.

INTRODUCTION

This report documents a wind-tunnel study evaluating exhaust dilution levels and re-ingestion from a stack on the roof of the Watershed Science Research Center, to be located at the University of California, Davis. Tests were conducted in the Atmospheric Boundary Layer Wind Tunnel Laboratory, Department of Mechanical and Aeronautical Engineering, UC Davis, on behalf of Architects and Engineers, UC Davis. A detailed description of the wind tunnel test facility is given in Appendix A and Appendix B. The purpose of the study was to determine the extent to which exhaust from the building's exhaust stack would impinge on the building intakes of Watershed Science and the neighboring Academic Surge building. Wind tunnel simulations were conducted on a 1 inch equals 16 feet scaled model of the Watershed Science Research Center site. The wind tunnel replicated the wind conditions at the site while the exhaust flow patterns were monitored using a tracer gas measurement technique. General discussions on wind tunnel modeling parameters are presented in Appendix C, D, and E. A quantitative study was carried out using ethane as a neutrally buoyant tracer gas, which was emitted from the model exhaust stack. By monitoring hydrocarbon concentration levels, the dilution of emissions reaching critical receptor locations was determined.

Analysis of Near-field Air Toxics

The dispersion of potentially hazardous exhaust is of great concern. Several different methods for prediction and analysis of the atmosphere's ability to dilute pollutants before the gases impact sensitive receptors have been developed. In the environmental assessment of an exhaust stack, empirical or computer analysis may be employed, full-scale tests may be conducted, and/or wind-tunnel tests may be carried out. Choosing which of these methods to use depends on such factors as economic constraints, the physical region of interest, or the quality and accuracy of the desired results.

Various kinds of empirical-analytical methods have been developed to evaluate dispersion. However, each method generally applies only to specific areas of concern. For example, most numerical models are limited by failing to account adequately for local building wake effects or by requiring input of locally measured building wake and turbulence data, and consequently can be only used for down wind distances exceeding 50 to 100 meters which are free of building's effects.

Full-scale dispersion tests can provide useful concentration data. However, full-scale testing of different wind directions and speeds along with varied atmospheric stability is usually impractical. Changing atmospheric conditions complicates interpretation of full-scale data and the evaluation of a proposed structure is, of course, not possible.

Wind-tunnel tests can be conducted under ideal, steady wind conditions. Done properly, such tests can account for the effects of building aerodynamics and of site-specific wind-flow patterns created by the test facility and the surrounding buildings, trees, and topography. The results can be used to identify potential dilution problems. ASHRAE (1997) provides a good discussion of the validity of wind-tunnel modeling as a proven accurate means to simulate the dispersion of stack exhausts in the atmosphere. ASHRAE acknowledges the superiority of wind-tunnel data over that of empirically calculated predictions.

Wind-tunnel tests can precisely simulate critical conditions occurring in full scale. Wind-tunnel tests can simulate the average or mean wind speed dispersion of exhausts, as well as the so-called "worst-case" dispersion of exhausts, and other types of conditions that may be of interest. The "worst-case" dispersion of exhaust is generally used to determine the minimum level of dilution from an exhaust source that might occur under an accidental-release condition. This test represents a single wind direction at a single wind speed. This combination produces the minimum dilution of all possible wind directions and speeds. Usually, the occurrence of such a specific condition is statistically small and typically will comprise only a few hours or less of an annual meteorological data set. Thus, the "worst-case" dispersion case refers to an accident situation, which is used to determine if short-term exposure limits (e.g., 15 minutes, 1 hour, etc.) are exceeded at sensitive receptor locations. For the present study it was mutually agreed upon by the principal investigator Bruce R. White and the Environmental Health and Safety staff of UC Davis to use only the "worst-case" analysis.

In contrast to the "worst-case" analysis is the "routine release" analysis. Under routine release testing, the normally expected exposure of emissions over a specified time-period is estimated. Typically, the time-period is one year thus predicting annual exposure levels; although any time-period could be used (i.e., one month, etc.). For annual routine exposure analysis, the average concentration contribution from each of the 16 wind directions in 22.5-degree increments is measured (ASHRAE, 1997). The 16 major wind-direction measurement then can be integrated into the meteorological data for frequency and speed to estimate individual receptor annual exposure levels.

Accordingly, the worst-case dispersion of exhausts is assumed to occur when a given sensitive location is located directly downwind of the emission source for the so-called “critical wind speed.” The “critical wind speed” lies between lower wind speeds, which generally create a large exhaust dilution due to enhanced plume rise, and higher wind speeds, where the vertical exhaust stream is rapidly diffused horizontally and mixed with the turbulent moving air. At this single “critical” wind speed, the beneficial effects of plume rise (low speed) and mixing (high speeds) are compromised, and the minimal dilution of exhaust stack emissions results.

Critical Wind Speed

The “critical wind speed” represents the minimum dilution condition for a given exhaust emission at a specific receptor location. The value of the “critical wind speed” is not constant for all stacks; it depends on the size of the stack, the exhaust speed, and the distance between the emission source and the specific receptor location. Thus, for a single stack there will be as many critical wind speeds as there are receptor locations. ASHRAE (1997) provides an equation for theoretically calculating the “critical wind speed” which is given as follows.

$$\frac{U_{crit,0}}{V_e} = 3.6 B_1^{-0.5} A_e^{0.5} / S$$

Here, $U_{crit,o}$ is the critical wind speed producing the smallest minimum dilution for an uncapped vertical exhaust with negligible stack height. V_e is the exhaust speed of the stack. B_1 is called the distance dilution parameter. B_1 depends on the exhaust plume trajectory, turbulence intensity of the approach wind and turbulence generated by the building. Wilson and Lamb (1994) give the following equation for B_1.

$$B_1 = 0.027 + 0.0021 \sigma_\theta .$$

The upwind level of turbulence is given by σ_θ, the standard deviation (in degrees) of wind direction fluctuations averaged over a 10 minute period. The recommended design value for buildings in an urban terrain (Category B, α= 0.22, δ = 370 m) is σ_θ equals 15 degrees, which makes B_1 equal to 0.059 (ASHRAE, 1997). These values agree closely with the present study.

For the present case, the theoretical value was used to determine the theoretical critical wind speed of roof-level receptors. In addition, experimentally determined “critical wind speeds” were found from wind-tunnel testing by varying the ration of vertical exhaust speed to horizontal wind speed at stack height. The more conservative of the two values (i.e., the one that resulted in the lower value of minimum dilution) was used to assess the minimum dilution standard. This experimental technique should be used since the theoretical “critical wind speed” from the ASHRAE dilution equations addresses only simple building shapes and the equation was empirically determined from full-scale and wind-tunnel tests. The theoretical estimate of “critical wind speed” does not account for site-specific building geometry and surrounding topographic conditions, as does the wind tunnel testing. ASHRAE 97 estimates for this project is presented in Appendix F.

TEST PROCEDURES

Wind-tunnel Simulation

A scaled model was centered about the UC Davis Watershed Science Research Center and Academic Surge, which encompassed a diameter of approximately 690 feet (see Figure 1). During the tests, the model was positioned on a turntable on the floor of the wind tunnel test section where it could be rotated and positioned to simulate any wind angle. The wind-tunnel flow was designed to simulate the mean and turbulent characteristics of wind flow approaching the modeled area. Details of this simulation technique can be found in Appendix D and Appendix E. Variation in the wind characteristics from one wind angle to another can be accounted for by varying the roughness of the wind tunnel floor upwind of the model. In the present case, the wind characteristics were considered typically urban terrain for all wind angles.

Figure 1: Wind tunnel turntable model of UC Davis Watershed Science Research Center.

The wind tunnel simulated the wind characteristics of a neutrally stable atmosphere. Although the dispersion of exhaust gases is generally not the same in stable (inversion) and unstable (convective) conditions as it is in neutral conditions, the differences are small in the case of rooftop exhaust fan dispersing within the building's influence, as in present case. In such cases, the behavior of the wind as it flows over and around the building is the most important parameter for gas dispersion. For these types of exhausts, therefore, the neutral atmosphere wind-tunnel simulation is considered appropriate.

Concentration Measurements

Dispersion analysis was conducted by injecting the ethane tracer gas through the model exhaust stack (source). For the existing design system, one model exhaust stack was used. Scaling was accomplished by maintaining the same momentum ratio of the exhaust plume to the wind at full scale and model scale. This results in the most accurate duplication of the shape and dispersion of exhaust plumes. A fully turbulent discharge was found to exist for the model exhaust stack tested. For details on the exhaust scaling methods, refer to Appendix F.

Quantitative dispersion analysis was carried out by emitting a controlled flow rate of ethane tracer gas for exhaust stack. The concentration of exhaust emissions reaching various receptor locations was determined by monitoring the level of hydrocarbons content of the air at those locations. The monitoring was achieved by drawing air samples through a sampling probe that could be controlled remotely once the wind-tunnel test commenced. The gas samples were drawn through the copper tubing to a hydrocarbon gas analyzer to determine the level of hydrocarbons in the sample. The ratio of hydrocarbons in the sample to the known release value resulted in the concentration level at the specific receptor. In the present study, the release gas contained 126,500 hydrocarbon-parts-per-million-parts.

The mean hydrocarbon concentration occurring at each receptor was recorded by the wind-tunnel data-acquisition system. Data are presented in the form of a dilution factor, which is determined from the concentration ration (C/C_0), where C represents the concentration of tracer gas in parts per million (PPM) at the receptor location and C_0 is the concentration emitted at the source. The resulting ratios are then scaled, as described in Appendix F, to represent full-scale concentration ratios, which are independent of the type and quality of contaminant emitted by the source. The dilution factors are directly calculated from the measured concentrations values. For example, for a measured concentration ratio, $C/C_{o,}$ of 500 ppm the dilution would be equal to 2000, i.e., $10^6/500 = 2000$.

Receptor Description

Tracer gas testing was conducted for a total of twenty-two locations for the rooftop stacks and windows nearest the stack. The following Table 1 presents a description of the test receptor locations.

Table 1: Descriptions of selected receptor locations.

Receptor Location	Brief description of receptor location
1	HVAC inlet 1 on Academic Surge
2	HVAC inlet 2 on Academic Surge
3	HVAC inlet 3 on Academic Surge
4	HVAC inlet 4 on Academic Surge
5	HVAC inlet 5 on Academic Surge
6	HVAC inlet 6 on Academic Surge
7	HVAC inlet 7 on Academic Surge
8	HVAC inlet 8 on Academic Surge
9	HVAC inlet 9 on Academic Surge
10	HVAC inlet 10 on Academic Surge
11	HVAC inlet 11 on Academic Surge
12	HVAC inlet 12 on Academic Surge
13	HVAC inlet 13 on Academic Surge
14	HVAC inlet 14 on Academic Surge
15	HVAC inlet 15 on Academic Surge
16	HVAC inlet 16 on Academic Surge
17	HVAC inlet 1 on Watershed
18	HVAC inlet 2 on Watershed
19	HVAC inlet 3 on Watershed
20	Window 1 on Watershed
21	Window 2 on Watershed
22	Window 3 on Watershed

Meteorology

Table 2 shows the wind frequency distribution, in the form of a wind rose, taken from the Executive Airport anemometer located in Sacramento, California. The cumulative wind frequency distribution from the Executive Airport anemometer was derived from the wind rose data. This wind distribution was used to determine the hours of occurrence for particular wind speeds and wind directions.

Table 2: Wind data collected between 1985 and 1989 from the Executive Airport meteorological tower ay Sacramento, California.

		Wind speed at 10m height given is knots, m/s, and MPH										
		0	3	6	10	16	21	27	31	40		*Knots*
Wind	Direction	0	1.542	3.084	5.14	8.224	10.794	13.878	15.934	20.56	Total	*m/s*
Direction	Azimuth	**0.00**	**3.47**	**6.94**	**11.57**	**18.50**	**24.29**	**31.23**	**35.85**	**46.26**	[hour]	***MPH***
N	0.0	95.79	22.80	102.19	56.60	35.80	7.00	1.00	0.20	0.00	321.38	
NNE	22.5	55.00	14.20	46.20	12.20	2.20	0.40	0.20	0.00	0.00	130.39	
NE	45.0	51.20	10.00	37.60	4.00	0.60	0.00	0.20	0.00	0.00	103.59	
ENE	67.5	47.40	11.60	26.00	4.20	0.80	0.20	0.00	0.00	0.00	90.20	
E	90.0	71.00	21.20	63.20	11.80	1.00	0.00	0.00	0.00	0.00	168.19	
ESE	112.5	153.19	35.80	172.59	45.80	11.60	1.40	0.00	0.00	0.00	420.38	
SE	135.0	176.59	49.00	371.78	137.39	40.80	9.00	4.20	0.20	0.00	788.96	
SSE	157.5	130.79	38.60	372.78	211.39	60.20	13.00	3.20	0.40	0.00	830.35	
S	180.0	145.99	47.20	412.78	401.98	103.79	5.80	0.60	0.00	0.00	1118.14	
SSW	202.5	112.19	27.20	291.38	471.17	277.98	16.00	2.00	0.00	0.20	1198.13	
SW	225.0	126.39	30.20	246.79	395.78	297.58	22.40	0.80	0.00	0.00	1119.94	
WSW	247.5	92.39	27.80	124.39	84.40	33.00	2.00	0.00	0.00	0.00	363.98	
W	270.0	77.80	22.20	109.39	44.40	7.00	0.60	0.00	0.00	0.00	261.39	
WNW	292.5	113.79	23.00	150.99	97.79	21.00	2.00	0.20	0.00	0.00	408.78	
NW	315.0	162.99	24.60	205.19	205.79	113.99	21.80	3.00	0.40	0.00	737.76	
NNW	337.5	164.99	22.60	173.39	171.59	127.39	35.20	7.40	0.20	0.00	702.76	
										Total	8764	

Expected wind speeds at the Watershed Science Research Center were calculated by relating the wind speeds at the Executive Airport anemometer to the following power law relationship.

$$\frac{U}{U_{ref}} = \left(\frac{z}{\delta}\right)^{\alpha}$$

Here, U is the mean velocity at a specific height, z, U_{ref} is a reference wind speed at the reference height, δ, and, α is a power-law exponent, which depends on the characteristic of roughness. In full-scale the reference wind speed is given by the gradient wind. Knowing a speed measured at the 20-foot high Executive Airport anemometer, the gradient wind speed over Sacramento (370 meters above grade) based on a power-law exponent of 0.2 (appropriate for the surroundings of the UC Davis campus). Since Davis is in close proximity, the gradient wind speed at Sacramento was then used to calculate the wind speed at the heights above grade of the Watershed Science Research Center in UC Davis using a power-law exponent of 0.2.

Dilution Criterion

The results given in this report are relative results of exhaust dilution or maximum concentration relative to mass emission rate. These relative results could be combined with full-scale usage rate information for evaluating designs. The analysis procedures vary with the type of exhaust studied. Unfortunately, the precise usage rates of the various chemicals used at the Watershed Science Research Center were not available. Consequently, it was mutually decided to use a dilution standard of 1:1000 that would be applied to all of the exhaust stacks. This approach is known to treat smaller diameter exhaust stacks liberally and large diameter exhaust stacks conservatively.

Generally, relative concentrations (concentrations divided by the effluent mass) are used to evaluate worst-case chemical concentrations from a health perspective for fume-hood exhausts. The source mass emission rate, *m*, and the health limit, *HL* are determined for each chemical of interest emitted. For a fume hood, there may be many chemicals of interest evaluated, thus the chemical with the lowest ratio of *HL/m* will provide the standard or limit of chemical usage for the basis of a stack-design criterion. However, without knowledge of the rate of chemical usage this approach is not possible.

WIND-TUNNEL RESULTS AND ANALYSIS

Wind-tunnel concentration measurements were used to determine dilution factors at the chosen receptor locations. The meteorological and exhaust stack conditions were set for the worst-case scenario. Here, the exhaust stack was directly upwind of the receptor being measured. The simulated full-scale wind speed was varied to experimentally determine the poorest dilution factor and its associated conditions. From the meteorological record, then estimates of how frequent and for what duration these conditions would occur on an annual basis. Advanced analysis methods were also made use based on available with knowledge of chemical usage and inventory analysis. Thus, results in this report were based on an accidental release from one toxic source. Using the dilution criterion of 1:1000 for the laboratory stack as the acceptability standard, an assessment of the effectiveness of each individual exhaust stack was made.

The data and results for the individual stack are presented in Appendix G. The exhaust stack results are presented on two pages. The first page presents the modeling and full-scale variables and flow characteristics. Also, the dilution factors as a function of receptor location and equivalent full-scale wind speed (at 10 meter height in mph) are given. Key parameters are the total flow rate in cubic feet per minute (CFM) and the percentage of toxic gas assumed to be contained in the release. The table at the bottom of the first page presents the calculated dilution factors for the exhaust stack. It has two threshold values. Values less than the minimum passing dilution factor are given in darkly shaded and bolded numerical presentation.

The second page of data presentation displays the graphical results of dilution factor as a function of wind speed for each measurement location. The key aspect of this presentation is to determine the minimum dilution wind speed (e.g., the critical speed) and the functional trend of dilution as a function wind speed, i.e., is the minimum dilution factor rapidly achieved or slowly achieved. The basic nature of these trends provides fundamental performance information of each individual stack being considered.

In this wind tunnel test, the worst-case scenario was evaluated. This condition will lead to the lowest level of effluent for the various combinations of wind direction and wind speed. In cases where the minimum dilution factors are low, these conditions (wind speed and direction) may be correlated with the full-scale meteorological data to estimate the number of hours per year that these conditions would occur. If the number of occurrence hours per year is small (less than 1% of the time or about 88 hours/year) and the minimum dilution is not unusually small, then there is little concern, because the nature variability of the direction of the full-scale wind would minimize the actual exposure level at the receptor. However, if the occurrence hours are large, then the exposure at the receptor could be substantial and mitigation measures may be necessary.

The worst-case scenario is the case where the emission source or exhaust stack is located directly upwind of the particular receptor being measured. The centerline of plume trajectory then impacts the receptor leading to the highest concentrations (or lowest dilutions) that would be encountered at the receptor. This process is a function of the ratio of effluent speed and mean wind speed at stack height. Therefore, this ratio was varied in the wind-tunnel testing to experimentally determine the so-called “worst-case scenario” since it is highly site specific and governed by the local building geometry resulting wind flow and turbulence characteristics. In the present study, since the exhaust speeds are constant, the varying of this ratio is equivalent to varying only the full-scale wind speed.

This approach to analysis of wind-tunnel data is often referred to as the accident scenario since it considers the worst-case effects that might occur in an accident or spillage of toxic chemical. It is assumes that this situation would occur under the most adverse meteorological conditions. This is how the minimum dilution factor is derived (Seabury 1991 a, b, c and d and White et al, 1991). This information also may be used to evaluate the routine usage of the exhaust stack. Since it is known and generally accepted that if the minimum dilution standard for the accident scenario is met then the routine operation standard is also met because the accident standard is more stringent than the routine operation standard. These assumptions are built into the calculation of accident dilution standard. All of this assumes that only routine or common chemicals are used. If unusually highly toxic chemicals are used then the accident minimum dilution standard must be re-calculated to a higher value.

CONCLUSION

A wind-tunnel study of an accidental release from the UC Davis Watershed Science Research building laboratory stack was conducted. The purpose of the study was to assess the effluents reaching the various inlets not only on this building but also on the roof of Academic Surge. This was accomplished by determining to what extent the exhaust effluent from the stack would impinge on the two buildings. Stack effluent was modeled by releasing a neutrally buoyant tracer gas (ethane) from the scaled model exhaust stack and measuring the concentration (or dilution) level downwind at a number of specified receptor locations. Simulations were conducted for a wide range of wind speeds (i.e., from a few mph to 30-40 mph). The "worst-case" scenario was modeled in which the exhaust stack was aligned directly upwind of the receptor being measured. This approach is known to result in conservative estimates of concentration (i.e., larger concentrations than would be expected in full scale, due to the changeable directions of natural wind). A minimum dilution standard of 1:1000 was used to assess acceptable performance of individual exhaust stacks. Based on analysis of an accidental release from one toxic source, dilution results revealed no violations for any stack height simulation tested. A 1:1000 dilution standard is typical of many university-type chemical laboratory guidelines (i.e., the University of California at Davis and San Francisco, San Marcos State University and University of California at Davis Medical Center, located in Sacramento, all use a 1:1000 dilution standard).

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APPENDIX A:

THE ATMOSPHERIC BOUNDARY LAYER WIND TUNNEL AT UNIVERSITY OF CALIFORNIA, DAVIS

In the present investigation, the Atmospheric Boundary Layer Wind Tunnel (ABLWT) located at University of California, Davis was used (Figure B-1). Built in 1979 the wind tunnel was originally designed to simulate turbulent boundary layers comparable to wind flow near the surface of the earth. In order to achieve this effect, the tunnel requires a long flow-development section such that a mature boundary-layer flow is produced at the test section. The wind tunnel is an open-return type with an overall length of 21.3 m and is composed of five sections: the entrance, the flow-development section, the test section, the diffuser section, and the fan and motor.

The entrance section is elliptical in shape with a smooth contraction area that minimizes the free-stream turbulence of the incoming flow. Following the contraction area is a commercially available air filter that reduces large-scale pressure fluctuations of the flow and filters larger-size particles out of the incoming flow. Behind the filter, a honeycomb flow straightener is used to reduce large-scale turbulence.

The flow development section is 12.2 m long with an adjustable ceiling for longitudinal pressure-gradient control. For the present study, the ceiling was diverged ceiling so that a zero-pressure-gradient condition is formed in the stream wise direction. At the leading edge of the section immediately following the honeycomb flow straightener, four triangularly shaped spires are stationed on the wind-tunnel floor to provide favorable turbulent characteristics in the boundary-layer flow. Roughness elements are then placed all over the floor of this section to artificially thicken the boundary layer. For a free-stream wind speed of 4.0 m/s, the wind-tunnel boundary layer grows to a height of one meter at the test section. With a thick boundary layer, larger models could be tested and thus measurements could be made at higher resolution.

Dimensions of the test section are 2.44 m in stream wise length, 1.66 m high, and 1.18 m wide. Similar to the flow-development section, the test section ceiling can also be adjusted to obtain the desired stream wise pressure gradient. Experiments can be observed from both sides of the test section through framed Plexiglas windows. One of the windows is also a sliding door that allows access into the test section. When closed twelve clamps distributed over the top and lower edges are used to seal the door. Inside the test section, a three-dimensional probe-positioning system is installed at the ceiling to provide fast and accurate sensor placement. The traversing system scissor-type extensions, which provide vertical probe motion, are also made of aerodynamically shaped struts to minimize flow disturbances.

The diffuser section is 2.37 m long and has an expansion area that provides a continuous transition from the rectangular cross-section of the test section to the circular cross-sectional area of the fan. To eliminate upstream swirl effects from the fan and avoid flow separation in the diffuser section, fiberboard and honeycomb flow straighteners are placed between the fan and diffuser sections.

The fan consists of eight constant-pitch blades 1.83 m in diameter and is powered by a 56 kW (75 hp) variable-speed DC motor. A dual belt and pulley drive system is used to couple the motor and the fan.

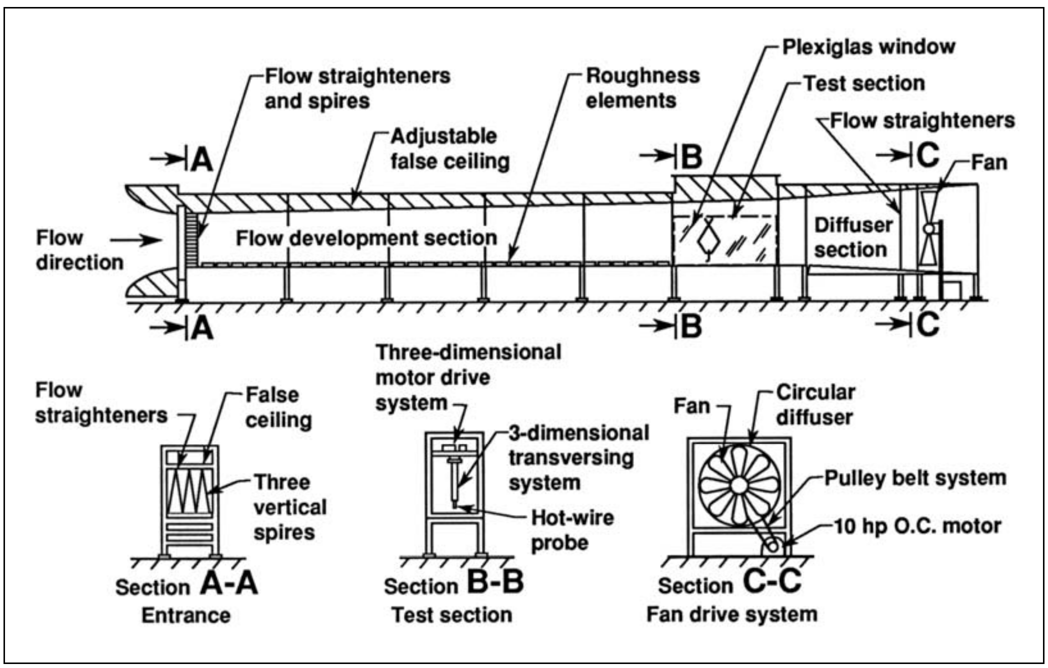


Figure B-1: Schematic diagram of the UC Davis Atmospheric Boundary Layer Wind Tunnel.

APPENDIX B:
INSTRUMENTATION AND MEASUREMENT SYSTEMS

Wind tunnel measurements of the mean velocity and turbulence characteristics were performed using hot-wire anemometry. A standard Thermo Systems Inc. (TSI) single hot-wire sensor model 1210-60 was used to measure the wind quantities. The sensor was installed at the end of a TSI model 1150 50-cm probe support, which was secured onto the support plate of the three-dimensional sensor positioning system in the U.C. Davis Atmospheric Boundary Layer Wind Tunnel (ABLWT) test section. A 10-m shielded tri-axial cable was then used to connect the probe support and sensor arrangement to a TSI model IFA 100 constant temperature thermal-anemometry unit with signal conditioner.

Hot-wire sensor calibrations were conducted in the ABLWT test section over the range of common velocities measured in the wind-tunnel boundary layer. Signal-conditioned voltage readings of the hot-wire sensor were then matched against the velocity measurements from a Pitot-static tube connected to a Meriam model 34FB2 oil micro-manometer, which had a resolution of 25.4 μm of oil level. The specific gravity of the oil was 0.934. The Pitot-static tube was secured to an aerodynamically shaped stand and was positioned so that its flow-sensing tip is normal to the flow and situated near the volumetric center of the test section. Normal to the flow, the end of the hot-wire sensor was then traversed to a position 10 cm next to the tip of the Pitot-static tube.

Concentration measurements of an ethane tracer gas were conducted with the use of a Rosemount Analytical model 400A hydrocarbon analyzer. This instrument uses a flame-ionization detection method to determine trace concentrations in the air. Operation of this analyzer involves iso-kinetically aspirating ethane-air samples into a burner where the sample is burned with a mixture of medical-rated air and 40% hydrogen and 60% nitrogen. Figure C-1 displays a schematic of the concentration measurement system. A 1/4-inch-diameter, copper refrigeration-grade tubing, 12 inches in length, was used as the gas-analyzer sensing probe, mitered 45° at the end. This copper probe was secured to the test-section traverse-system mounting plate, where an additional length of the same type tubing was used to connect the probe to a pressure-regulated vacuum pump, which sends samples into the analyzer at a constant pressure of 5 psig.

Calibration of the hydrocarbon analyzer system was accomplished with two known samples of ethane-air mixtures, one certified with 52.4 parts per million (ppm) and the other with 524.8 ppm. Calibration gas samples were accurate to less than 0.5% of the stated value. The precision of the gas analyzer was within 1% of full scale. Prior to the calibration, the analyzer voltage output was first mechanically zeroed using a sample of pure air (hydrocarbon-free).

Ethane tracer gas emissions from the stacks were controlled by a model B-250-1 ball-type flow meter. Flow meter volumetric flow rates for a tracer gas of some ethane mixture are calibrated by measuring the time elapsed for the tracer gas to fill a container of known volume. Since the ethane mixture was virtually invisible, the gas level needs to be monitored by using a traceable substance such as water. This was done by first filling and completely submerging the calibration container in a water tank. The ethane gas mixture is released in the container by inserting a tube extension from the flow meter into the water-drowned container. A complete fill of tracer gas can then be detected when the decreasing water level reaches the mark corresponding to a known volume. For a thorough calibration, elapsed times are collected for at least three height settings on the flow meter gage. Dividing these times by the known volume gives a volumetric flow rate for a corresponding flow meter height setting.

Raw voltage data sets of hot-wire velocity measurements and of tracer gas concentrations were digitally collected using a LabVIEW data acquisition system, which was installed in a Gateway personal computer with a Pentium 166Mhz processor. Concentration voltages were collected from the hydrocarbon analyzer analog output, while hot wire voltages were obtained from the signal conditioner output of the IFA 100 anemometer. The two outputs were connected to a multi-channel daughter board linked to a United Electronics Inc. (UEI) analog-to-digital (A/D) data acquisition board, which is installed in one of the ISA motherboard slots of the Gateway PC. LabVIEW software was used to develop virtual instruments (VI) that would initiate and configure the A/D board, then collect the voltage data given by the measurement equipment, display appropriately converted results on the computer screen, and finally save the raw voltage data into a designated filename.

Since velocity and concentration measurements were individually performed, a VI was developed for each type of acquisition. For the hot-wire acquisition, the converted velocity data and its histogram is displayed along with the mean voltages, mean velocity, root-mean-square velocity, and turbulence intensity. In the concentration VI, the converted concentration data is shown with the corresponding mean voltage and mean concentration. For both programs, the raw voltage data can be saved in the computer hard drive. For both hot-wire and concentration acquisition 30,000 samples were collected at a sampling rate of 1000 Hz. This acquisition setting greatly satisfies the Nyquist sampling theorem such that the average tunnel turbulence signal was 300 Hz.

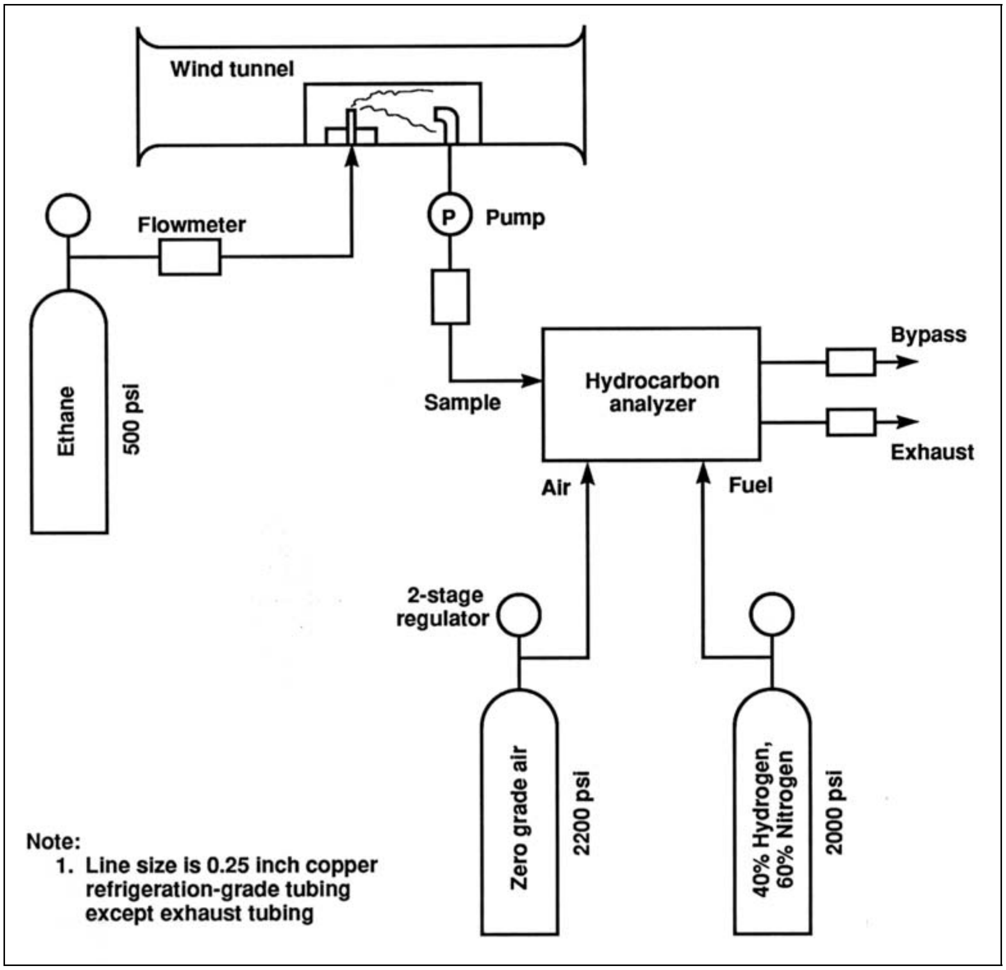


Figure C-1: Schematic diagram of gas dispersion concentration measurement system.

APPENDIX C:
WIND-TUNNEL ATMOSPHERIC FLOW SIMILARITY PARAMETERS

Wind-tunnel models of a particular test site are typically several orders of magnitude smaller than the full-scale size. In order to appropriately simulate atmospheric winds in the U.C. Davis Atmospheric Boundary Layer Wind Tunnel (ABLWT), certain flow parameters must be satisfied between a model and its corresponding full-scale equivalent. Similitude parameters can be obtained by non-dimensionalizing the equations of motion, which build the starting point for the similarity analysis. Fluid motion can be described by the following time-averaged equations.

Conservation of mass:

$$\frac{\partial \overline{U}_i}{\partial t_i} = 0 \text{ and } \frac{\partial \rho}{\partial t} + \frac{\partial (\rho \overline{U}_i)}{\partial x_i} = 0$$

Conservation of momentum:

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{u}\ \frac{\partial \overline{U}_i}{\partial x_j} + 2\varepsilon_{ijk}\Omega_j \overline{U}_k = -\frac{1}{\rho_0}\frac{\partial \overline{\delta P}}{\partial x_i} - \frac{\overline{\delta T}}{T_0} g\delta_{i3} + \nu_0 \frac{\partial^2 \overline{U}_i}{\partial x_j} + \frac{\partial(\overline{-u_j u_i})}{\partial x_j}$$

Conservation of energy:

$$\frac{\partial \overline{\delta T}}{\partial t} + \overline{U}_i \frac{\partial \overline{\delta T}}{\partial x_i} = \left[\frac{\kappa_0}{\rho_0 c_{p_0}}\right] \frac{\partial^2 \overline{\delta T}}{\partial x_k \partial x_k} + \frac{\partial(\overline{-\theta u_i})}{\partial x_i} + \frac{\overline{\phi}}{\rho_0 c_{p_0}}$$

Here, the mean quantities are represented by capital letters while the fluctuating values by small letters. δP is the deviation of pressure in a neutral atmosphere. ρ_0 and T_0 are the density and temperature of a neutral atmosphere and ν_0 is the kinematic viscosity. In the equation for the conservation of energy, ϕ is the dissipation function, $\overline{\delta T}$ is the deviation of temperature from the temperature of a neutral atmosphere, κ_0 is the thermal diffusivity, and c_{p_o} is the heat capacity.

Applying the Boussinesq density approximation, application of the equations is then restricted to fluid flows where $\overline{\delta T} << T_0$. Defining the following non-dimensional quantities and then substituting into the above equations.

$$\overline{U}_i' = \overline{U}_i' / U_0 \;;\; u_i' = u_i / U_0 \;;\; x_i' = x_i / L_0 \;;\; t' = tU_0 / L_0 \;;\; \Omega_j' = \Omega_j / \Omega_0 \;;\; \overline{\delta P}' = \overline{\delta P} / \rho_0 U_0^2 \;;$$

$$\overline{\delta T}' = \overline{\delta T} / \delta T_0 \;;\; g' = g / g_0 \;;\; \overline{\varphi}' = \overline{\varphi} / \varphi_0$$

The equations of motion can be presented in the following dimensionless forms.

Continuity Equation:

$$\frac{\partial u_i'}{\partial k_i'} = 0 \text{ and } \frac{\partial \rho'}{\partial t'} + \frac{\partial(\rho' u_i')}{\partial x_i'} = 0$$

Momentum Equation:

$$\frac{\partial \overline{U}_i'}{\partial t'} + \overline{U}_j' \frac{\partial \overline{U}_i'}{\partial x_j'} + \frac{2}{Ro}\varepsilon_{ijk}\overline{U}_k'\Omega_j' = -\frac{\partial \overline{\delta P}'}{\partial x_i'} + \frac{1}{Fr^2}\overline{\delta T}'\delta_{3i} + \frac{1}{Re}\frac{\partial^2 \overline{U}_i'}{\partial x_j' \partial x_j'} + \frac{\partial(\overline{-u_j' u_i'})}{\partial x_j'}$$

Turbulent Energy Equation:

$$\frac{\partial \overline{\delta T}'}{\partial t'} + \overline{U}_i' \frac{\partial \overline{\delta T}'}{\partial x_i'} = Pr \cdot \frac{1}{Re}\frac{\partial^2 \overline{\delta T}'}{\partial x_k' \partial x_k'} + \frac{\partial(-\overline{\theta' u_i'})}{\partial x_i'} + \frac{1}{Re} \cdot Ec \cdot \overline{\varphi}'$$

Although the continuity equation gives no similarity parameters, coefficients from both other equations do provide the following desired similarity parameters.

1. Rossby number: $R_0 \equiv U_0 / L_0\Omega_0$
2. Densimetric Froude number: $Fr \equiv U_0 / (gL_0\delta T_0 / T_0)^{1/2}$
3. Prandtl number: $Pr \equiv \rho_0 c_{p_0} \nu_0 / \kappa_0$
4. Eckert number: $Ec \equiv U_0^2 / c_{p_0}\delta T_0$
5. Reynolds number: $Re \equiv U_0 L_0 / \nu_0$

In the dimensionless momentum equation, the Rossby number is extracted from the denominator of the third term on the left hand side. The Rossby number represents the ratio of advective acceleration to Coriolis acceleration due to the rotation of the earth. If the Rossby number is large, Coriolis accelerations are small. Since UC Davis ABLWT is not rotating, the Rossby number is infinite allowing the corresponding term in the dimensionless momentum equation to approach zero. In nature, however, the rotation of the earth influences the upper layers of the atmosphere; thus, the Rossby number is small and becomes important to match, and the corresponding term in the momentum equation is sustained.

Most modelers have assumed the Rossby number to be large, thus, neglecting the respective term in the equations of motion and ignoring the Rossby number as a criterion for modeling. Snyder (1981) showed that the characteristic length scale, L_0, must be smaller than 5 km in order to simulate diffusion under neutral or stable conditions in relatively flat terrain. Other researchers discovered similar findings. Since UC Davis ABLWT produces a boundary layer with a height of about one meter, the surface layer vertically extends 10 to 15 cm above the ground. In this region the velocity spectrum would be accurately modeled. The Rossby number can then be ignored in this region. Since testing is limited to the lower 10% to 15% of the boundary layer, the length in longitudinal direction, which can be modeled, has to be no more than a few kilometers.

Derived from the denominator of the second term on the right hand side of the dimensionless momentum equation, the square of the Froude number represents the ratio of inertial forces to buoyancy forces. High values of the Froude number infer that the inertial forces are dominant. For values equal or less than unity, thermal effects become important. Since the conditions inside the UC Davis ABLWT are inherently isothermal, the wind tunnel generates a neutrally stable boundary layer; hence, the Froude number is infinitely large allowing the respective term in the momentum equation to approach zero.

The third parameter is the Prandtl number, which is automatically matched between the wind-tunnel flow and full-scale winds if the same fluid is been used. The Eckert number criterion is important only in compressible flow, which is not of interest for a low-speed wind tunnel.

Reynolds number represents the ratio of inertial to viscous forces. The reduced scale of a wind tunnel model results in a Reynolds number several orders of magnitude smaller than in full scale. Thus, viscous forces are more dominant in the model than in nature. No atmospheric flow could be modeled, if strict adherence to the Reynolds number criterion was required. However, several arguments have been made to justify the use of a smaller Reynolds number in a model. These arguments include laminar flow analogy, Reynolds number independence, and dissipation scaling. With the absence of thermal and Coriolis effects, several test results have shown that the scaled model flow will be dynamically similar to the full-scale case if a critical Reynolds number is larger than a minimum independence value. The gross structure of turbulence is similar over a wide range of Reynolds numbers. Nearly all modelers use this approach today.

APPENDIX D:
WIND-TUNNEL ATMOSPHERIC BOUNDARY-LAYER SIMILARITY

Wind-tunnel simulation of the atmospheric boundary layer under neutrally stable conditions must also meet non-dimensional boundary-layer similarity parameters between the scaled-model flow and its full-scale counterpart. The most important conditions are:

1. The normalized mean velocity, turbulence intensity, and turbulent energy profiles.
2. The roughness Reynolds number, $Re_z = z_0 u_* / \nu$.
3. Jensen's length-scale criterion of z_0/H.
4. The ratio of H/δ for H greater than $H/\delta > 0.2$.

In the turbulent core of a neutrally stable atmospheric boundary layer, the relationship between the local flow velocity, U, versus its corresponding height, z, may be represented by the following velocity-profile equation.

$$\frac{U}{U_\infty} = \left(\frac{z}{\delta}\right)^\alpha$$

Here, U_∞ is the mean velocity of the inviscid flow above the boundary layer, δ is the height of the boundary layer, and α is the power-law exponent, which represents the upwind surface conditions. Wind-tunnel flow can be shaped such that the exponent α will closely match its corresponding full-scale value, which can be determined from field measurements of the local winds. The required power-law exponent, α, can then be obtained by choosing the appropriate type and distribution of roughness elements over the wind tunnel flow-development section.

Full-scale wind data suggest that the atmospheric wind profile at the site of the Lawrence Berkeley National Laboratory yields a nominal value of α = 0.3. This condition was closely matched in the UC Davis Atmospheric Boundary Layer Wind Tunnel by systematically arranging an pattern of 2” x 4” wooden blocks of 12” in length along the entire surface of the flow-development section. The pattern generally consisted of alternating sets of four and five blocks in one row. A typical velocity profile is presented in Figure 23, where the simulated power-law exponent is α = 0.33.

In the lower 20% of the boundary layer height, the flow is then governed by a rough-wall or "law-of-the-wall" logarithmic velocity profile.

$$\frac{U}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{z_o}\right)$$

Here, u_* is the surface friction velocity, κ is von Karman's constant, and z_o is the roughness height. This region of the atmospheric boundary layer is relatively unaffected by the Coriolis force, the only region that can be modeled accurately by the wind tunnel (i.e., the lowest 100 m of the atmospheric boundary layer under neutral stability conditions). Thus, it is desirable to have the scaled-model buildings and its surroundings contained within this layer.

The geometric scale of the model should be determined by the size of the wind tunnel, the roughness height, z_o, and the power-law index, α. With a boundary-layer height of 1 m in the test section, the surface layer would be 0.2 m deep for the U.C. Davis ABLWT. For the current study, this boundary layer corresponds to a full-scale height of the order of 800 m. Since the highest elevation of the modeled site investigated in this study is about 160 m full-scale, a majority of the model is contained in this region of full-scale similarity.

Due to scaling effects, full-scale agreement of simulated boundary-layer profiles can only be attained in wind tunnels with long flow-development sections. For full-scale matching of the normalized mean velocity profile, an upwind fetch of approximately 10 to 25 boundary-layer heights can be easily constructed. To fully simulate the normalized turbulence intensity and energy spectra profiles, the flow-development section needs to be extended to about 50 and 100 to 500 times the boundary-layer height, respectively. These profiles must at least meet full-scale similarities in the surface layer region. However, with the addition of spires and other flow tripping devices, the flow development length can be reduced to less than 20 boundary layer heights for most engineering applications.

In the U.C. Davis Atmospheric Boundary Layer Wind Tunnel, the maximum values of turbulence intensity near the surface range from 35% to 40%, similar to that in full scale. Thus, the turbulent intensity profile, u'/u versus z, should agree reasonably with the full-scale, particularly in the region where testing is performed. Figure 24 displays a typical turbulence intensity profile of the boundary layer in the ABLWT test section.

The second boundary-layer condition involves the roughness Reynolds number, Re_z. According to the criterion given by Sutton (1949), Reynolds number independence is attained when the roughness Reynolds number is defined as follows.

$$Re_z = \frac{u_* z_0}{\nu} \geq 2.5$$

Here, u_* is the friction speed, z_0 is the surface roughness length and ν is the kinematic viscosity. Re_z larger than 2.5 ensures that the flow is aerodynamically rough. Therefore, wind tunnels with a high enough roughness Reynolds numbers simulate full-scale aerodynamically rough flows exactly. To generate a rough surface in the wind tunnel, roughness elements are placed on the wind tunnel floor. The height of the elements must be larger than the height of the viscous sub-layer in order to trip the flow. The UC Davis ABLWT satisfies this condition, since the roughness Reynolds number is about 40, when the wind tunnel free stream velocity, $U_{\infty,}$ is equal 3.8 m/s, the friction speed, u_*, is 0.24 m/s, and the roughness height, z_o, is 0.0025 m. Thus, the flow setting satisfies the Re number independence criterion and dynamically simulates the flow.

To simulate the pressure distribution on objects in the atmospheric wind, Jensen (1958) found that the surface roughness to object-height ratio in the wind tunnel must be equal to that of the atmospheric boundary layer, i.e., z_o/H in the wind tunnel must match the full-scale value. Thus, the geometric scaling should be accurately modeled.

The last condition for the boundary layer is the characteristic scale height to boundary layer ratio, H/δ. There are two possibilities for the value of the ratio. If $H/\delta \geq 0.2$, then the ratios must be matched. If $(H/\delta)_{F.S.} < 0.2$, then only the general inequality of $(H/\delta)_{W.T.} < 0.2$ must be met (F.S. stands for full-scale and W.T. stands for wind tunnel). Using the law-of-the-wall logarithmic profile equation, instead of the power-law velocity profile, this principle would constrain the physical model to the 10% to 15% of the wind tunnel boundary layer height.

Along with these conditions, two other constraints have to be met. First, the mean stream wise pressure gradient in the wind tunnel must be zero. Even if high- and low-pressure systems drive atmospheric boundary layer flows, the magnitude of the pressure gradient in the flow direction is negligible compared to the dynamic pressure variation caused by the boundary layer. The other constraint is that the model should not take up more than 5% to 15% of the cross-sectional area at any down wind location. This assures that local flow acceleration affecting the stream wise pressure gradient will not distort the simulation flow.

Simulations in the U.C. Davis ABLWT were not capable of producing stable or unstable boundary layer flows. In fact, proper simulation of unstable boundary layer flows could be a disadvantage in any wind tunnel due to the artificial secondary flows generated by the heating that dominate and distort the longitudinal mean-flow properties, thus, invalidating the similitude criteria. However, this is not considered as a major constraint, since the winds that produce annual an average dispersion are sufficiently strong, such that for flow over a complex terrain, the primary source of turbulence is due to mechanical shear and not due to diurnal or heating and cooling effects in the atmosphere.

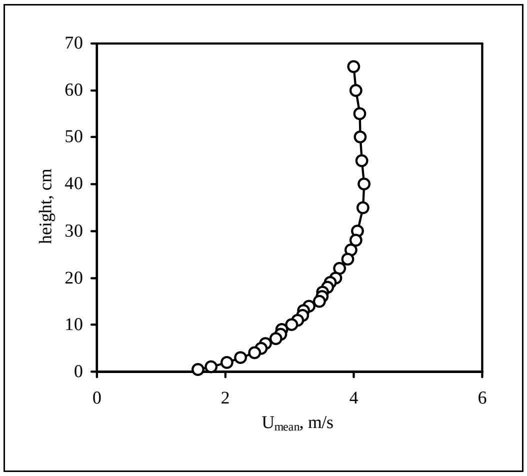


Figure D-1: Mean velocity profile for a typical wind direction in the wind tunnel. The power law exponent α is 0.33. The reference velocity at 65 cm height is 3.55 m/s.

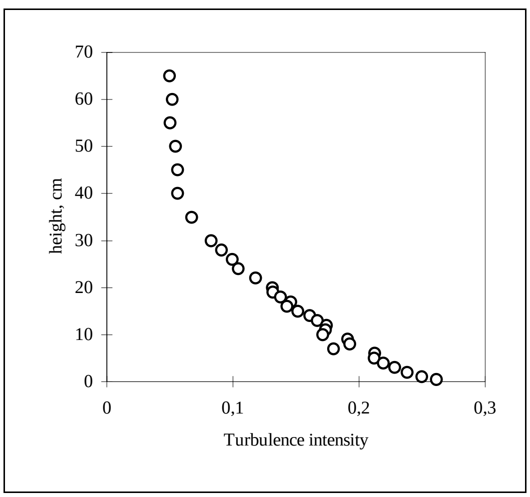


Figure D-2: Turbulence intensity profile for a typical wind direction in the wind tunnel.

APPENDIX E:
WIND-TUNNEL STACK MODELING PARAMETERS

Wind-tunnel simulations use the same fluid, air, as in the full scale. The building Reynolds number, Re, represents a ratio of inertial to viscous forces per unit area and it is often used as a parameter that must be matched between the full scale and the model to insure similarity. Full-scale building Re numbers exceed the tunnel building Re number by several orders of magnitude due to scale reductions, however for the purpose of concentration-profile measurements, flow above a critical building Re number of 11,000 (Snyder, 1981) is essentially Re number independent. The Re number is given by:

$$\mathrm{Re} = \frac{U_H H}{\nu}$$

For lower building Re numbers the critical value for flow independence must be determined experimentally. This was accomplished by repeating tests of ground-level concentration at increased tunnel free-stream velocity and stack flow rate.

Stack emissions in full-scale are turbulent. However, in the wind-tunnel simulations, matching the full-scale stack Re number, Re_s, to that of the model is not possible. In wind- tunnel simulations, adequate similarity is achieved by ensuring that the tunnel stack flow also is turbulent (Snyder, 1981). This condition is generally achieved (for neutral stability conditions) for stack Re number, Re_s, greater than:

$$\mathrm{Re}_s = \frac{U_s D_s}{\nu} > 2300$$

Values as low as 530 may be adequate if trips are used to enhance turbulence. The tunnel stack, for concentration-measurement experiments, has an inside diameter, D_s, of 0.81 cm; for expected stack velocities, U_s, of 12.9 m/s and 2.0 m/s, the stack Re numbers are 6970 and 1080, respectively. The criteria for turbulent stack flow will be achieved if trips are used to enhance the turbulence. For smoke tests the stack inside diameter was exaggerated to 0.25 cm and for a tunnel stack velocity of 5.2 m/s, the stack Re number was 867. The stack again will be tripped to enhance turbulence.

Maintaining a correct ratio of plume momentum to ambient flow requires that (Isyumov and Tanaka, 1980):

$$\frac{\rho_s D_s^2 U_s^2}{\rho_a L^2 U_w^2} = \text{constant}$$

Here, L is a vertical length scale, and U_w is the wind speed at the stack height. For non-buoyant stack exhausts, the stack exhaust density, ρ_s, equals that of the ambient air, ρ_a, and the above relation reduces to:

$$\frac{D_s^2 U_s^2}{L^2 U_w^2} = \text{constant}$$

For a free-stream wind-tunnel air speed of 3.8 m/s, U_w is equal to 2.6 m/s. Thus, for a tunnel stack velocity of 13.7 m/s, satisfaction of the above relation corresponds to a full-scale wind speed at the stack of 5.4 m/s (12 mph) while the full-scale stack velocity, U_s, is 16.3 m/s. For tests with a tunnel stack velocity of 30 m/s, the corresponding full-scale wind speed at the stack outlet is 2.5 m/s (6 mph).

Concentrations measured in the tunnel, C, may be related to full-scale values by the relation

$$\left(\frac{CU_w}{C_s U_s A_s}\right)_{FS} S^2 = \left(\frac{CU_w}{C_s U_s A_s}\right)_{WT}$$

Under similar atmospheric conditions, concentrations measured in the wind tunnel may be related to those in full-scale by this relationship.

APPENDIX F:
ASHRAE 97 ESTIMATES

UCD Watershed Science Lab Exhaust ASHRAE 97 Dilution Estimates on UCD Academic Surge Rooftop Intakes

UCD Watershed Science Building and Stack Information

Building height, H =	**30**	ft		
Rectangular stack exhaust, w =	**19.25**	in		
Rectangular stack exhaust, d =	**14.50**	in		
Stack exhaust area, A_e =	1.94	ft^2		
Stack height, h_s =	**10**	ft		
Stack fan flowrate before end taper, Q_t =	**3550**	CFM		
Stack exhaust velocity before end taper, V_t =	30.52	ft/s		
Stack exhaust velocity at exit of end taper, V_e =	50	ft/s	**3000**	ft/min
Stack exhaust flowrate at exit of end taper, Q_e =	5820	CFM		

ASHRAE 97 Boundary Layer Parameters

MET Tower Site Boundary Layer Conditions

Boundary layer height, π_{MET} (ft) =	**1000**
Power law coefficient, π_{MET} =	**0.16**

Local Boundary Layer Conditions

Boundary layer height, π (ft) =	**1200**
Power law coefficient, π =	**0.2**

Annual MET Tower Wind Conditions

Mean wind speed, U_{MET} (ft/s) =	**10**
MET tower height, H_{MET} (ft) =	**33**
Wind speed at building height, U_H (ft/s) =	8.3

ASHRAE 97 Required Parameters for Stack Dilution Estimates to Air Intakes

S_{WT} (in) = stretch distance to receptor from UCD Academic Surge wind tunnel model

S_{FS} (ft) = stretch distance to receptor in full scale dimension

π_z (ft) = vertical plume spread standard deviation

π_{π} (deg) =	**15**	wind direction fluctuation standard deviation (15 deg for urban terrain)
B_1 =	0.059	distance dilution parameter
$\pi\leq$	**1.0**	stack capping factor (1.0 for uncapped, 0 for capped, louvered, or down-facing)
$\pi_p\pi\leq$	**1.0**	plume orientation parameter (1.0 for minimum dilution from plume centerline)
M =	**2.0**	intake location factor

M = 1.5 for stack & intake on same roof
M = 2.0 for stack & intake on different buildings
M = 4.0 when intake is much lower than stack

ASHRAE 97 Stack Dilution Estimates to Air Intakes

Step 1	EQ-20	$U_{crit,o}$ (ft/s) = critical wind speed at zero stack height
Step 2	EQ-21	$D_{crit,o}$ = minimum dilution at zero stack height
Step 3	EQ-34	Y = height-to-spread parameter
Step 4	EQ-31	U_{crit} (ft/s) = critical wind speed at stack height
Step 5	EQ-32	D_{crit} = minimum dilution for stack height
Step 6	EQ-17	D_o = 478 dilution due to exhaust jet internal turbulence
Step 7	EQ-18	D_s = dilution due to building and atmospheric turbulence
Step 8	EQ-14	$D_{min,r}$ = dilution from strong jets in flow recirculation cavity
Step 9	EQ-15	$D_{min,m}$ = dilution from strong jets on multiwinged buildings
Step 10	EQ-16	$D_{min,f}$ = dilution from a stack at zero height on a flat roof

UCD Academic Surge Wind Tunnel Model Scale: 1 in = 16 ft

Receptor	S_{WT} (in)	S_{FS} (ft)	π_z (ft)	$U_{crit,o}$ (ft/s)	$D_{crit,o}$	Y	U_{crit} (ft/s)	D_{crit}	D_s	$D_{min,r}$	$D_{min,m}$	$D_{min,f}$
1	17.75	284	26.4	3.65	713	0.0036	3.87	806	402	780	1110	1757
2	18.25	292	27.2	3.55	733	0.0034	3.76	826	425	823	1165	1804
3	18.75	300	27.9	3.45	753	0.0032	3.66	846	448	867	1221	1852
4	19.125	306	28.5	3.39	768	0.0031	3.58	861	466	901	1264	1889
5	18	288	26.8	3.60	723	0.0035	3.82	816	413	801	1137	1780
6	18.125	290	27.0	3.57	728	0.0034	3.79	821	419	812	1151	1792
7	18.375	294	27.3	3.52	738	0.0033	3.73	831	431	834	1179	1816
8	18.5	296	27.5	3.50	743	0.0033	3.71	836	436	845	1193	1828
9	18.5	296	27.5	3.50	743	0.0033	3.71	836	436	845	1193	1828
10	18.25	292	27.2	3.55	733	0.0034	3.76	826	425	823	1165	1804
11	20	320	29.8	3.24	803	0.0028	3.41	896	510	982	1367	1976
12	19.75	316	29.4	3.28	793	0.0029	3.46	886	497	959	1337	1951
13	20.5	328	30.5	3.16	823	0.0027	3.33	915	536	1030	1428	2026
14	20.25	324	30.1	3.20	813	0.0028	3.37	906	523	1006	1397	2001
15	20.375	326	30.3	3.18	818	0.0027	3.35	911	529	1018	1412	2014
16	20.25	324	30.1	3.20	813	0.0028	3.37	906	523	1006	1397	2001

APPENDIX G:

WIND TUNNEL TEST RESULTS

Stack EF-2-10

Modeling variables		Geometric scaling factor :	192	1"= 16 '
		Full Scale		Wind-tunnel Scale
Stack	Length	10.00 feet		0.63 inch
	Roof Elevation	30.00 feet		1.88 inch
	Internal Diameter	18.9 inch		0.10 inch
	Internal Area	279.37 $inch^2$		0.0079 $inch^2$
	Exhaust flowrate	5820 CFM		varies *(see following table)*
	Flowspeed	15.24 m/s		varies *(see following table)*
Wind	α in power law	0.23		0.23
	Speed at reference height	varies *(see following table)*		3.25 m/s
		10.00 m		70.00 cm
	Speed at stack height	varies *(see following table)*		1.87 m/s
		12.19 m		6.35 cm

Equivalent wind speed calculation

Flowmeter Reading [cm]	Tube flow rate of model [CCPM]	Tube flow speed [m/s]	Speed ratio Vs/Uw	Equivalent wind speed at stack height [m/s]	Equivalent wind speed at stack height [MPH]	Equivalent wind speed 10 m above ground level [m/s]	Equivalent wind speed 10 m above ground level [MPH]
3.75	839.3	2.8	1.5	10.3	23.2	9.9	22.2
4.5	1130.2	3.7	2.0	7.7	17.3	7.3	16.5
7.5	1782.5	5.9	3.1	4.9	10.9	4.6	10.5
10	2342.6	7.7	4.1	3.7	8.3	3.5	8.0
15	3422.0	11.3	6.0	2.5	5.7	2.4	5.4
27.5	5959.4	19.6	10.5	1.5	3.3	1.4	3.1
57.5	12188.6	40.1	21.4	0.7	1.6	0.7	1.5

Exhaustion condition

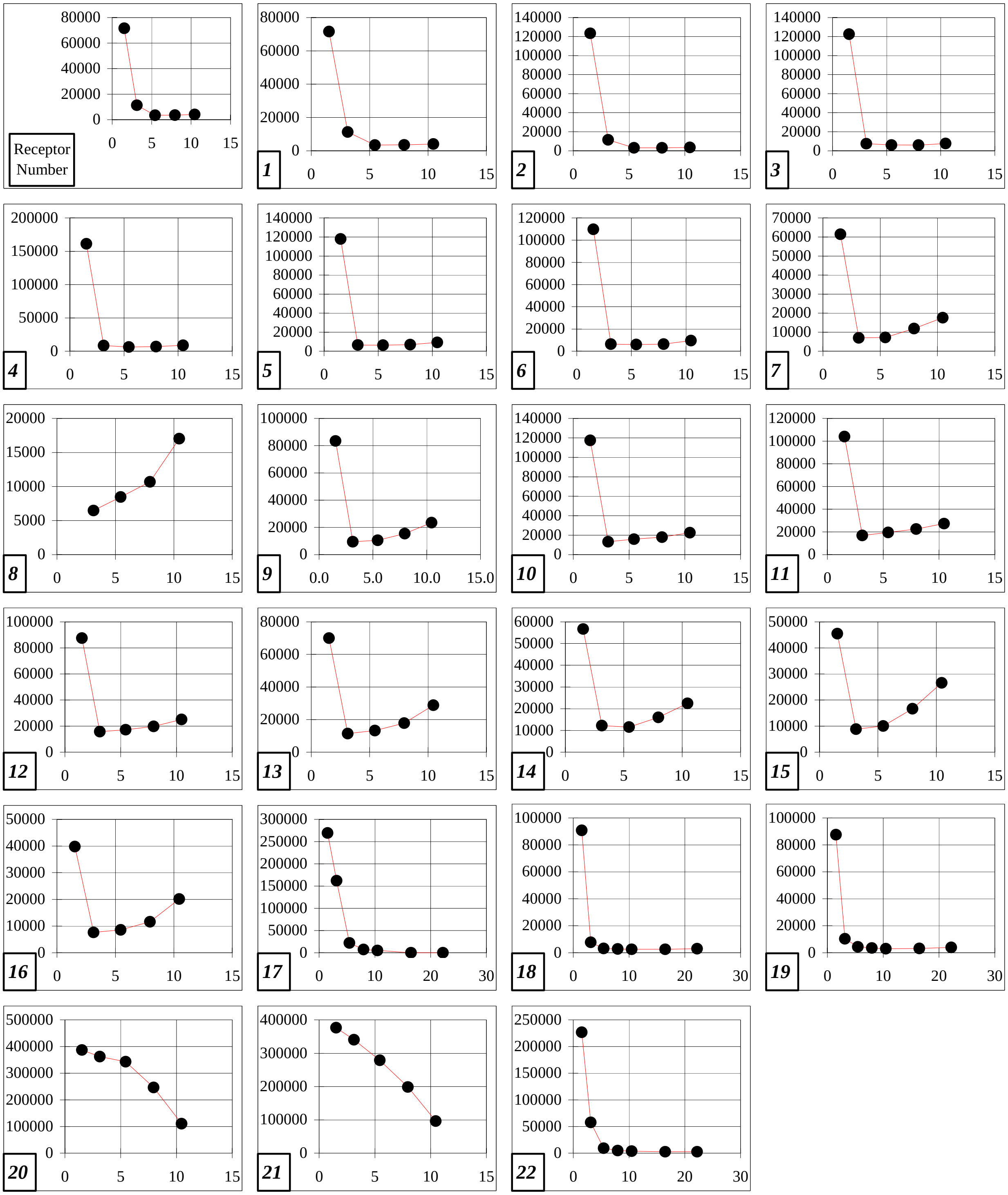
Total Flow Rate =	5820.0	CFM
Toxic Gas Flow Rate =	900.0	CFM
Toxic Gas Ratio =	15	%

Threshold = **1000** ***failed***
Warning range = **2000** **caution**

Resulting Dilution Factors

Receptor ID.	Wind Speed at 10 m height [MPH] 22.2	16.5	10.5	8.0	5.4	3.1	1.5	*Ethane %*
1			4052	3519	3392	11290	71604	*12.65*
2			3500	3098	3050	11492	123405	*12.65*
3			7631	5905	6079	7470	122514	*12.65*
4			8782	6915	6365	8452	161177	*12.65*
5			9348	6913	6313	6574	117913	*12.65*
6			9598	6421	6003	6411	109818	*12.65*
7			17589	11866	7273	6985	61434	*12.65*
8			17027	10677	8469	6478	86686	*12.65*
9			23465	15448	10582	9404	83444	*12.65*
10			22506	17966	15915	13224	117423	*12.65*
11			27366	22536	19485	16976	104024	*12.65*
12			25053	19689	17172	15779	87492	*12.65*
13			28817	17785	13280	11377	70008	*12.65*
14			22488	16008	11568	12193	56709	*12.65*
15			26627	16659	10046	8824	45482	*12.65*
16			20123	11602	8562	7582	39803	*12.65*
17			4941	7103	22038	162102	269141	*12.65*
18	2946	2504	2529	2815	3117	7666	90770	*12.65*
19	3968	3149	3003	3464	4351	10330	87582	*12.65*
20			110823	246452	343236	362305	387120	*12.65*
21			96122	198546	278879	340479	376797	*12.65*
22	2628	2752	3683	4886	9341	57752	226683	*12.65*

Dilution Results for Stack EF-2-10



Stack EF-2-15

Modeling variables		Geometric scaling factor :	192	1"=	16 '
		Full Scale		Wind-tunnel Scale	
Stack	Length	15.00 feet		0.94 inch	
	Roof Elevation	30.00 feet		1.88 inch	
	Internal Diameter	18.9 inch		0.10 inch	
	Internal Area	279.37 $inch^2$		0.0079 $inch^2$	
	Exhaust flowrate	5820 CFM		varies *(see following table)*	
	Flowspeed	15.24 m/s		varies *(see following table)*	
Wind	α in power law	0.23		0.23	
	Speed at reference height	varies *(see following table)*		3.25 m/s	
	reference height	10.00 m		70.00 cm	
	Speed at stack height	varies *(see following table)*		1.92 m/s	
	stack height	13.72 m		7.14 cm	

Equivalent wind speed calculation

Flowmeter Reading [cm]	Tube flow rate of model [CCPM]	Tube flow speed [m/s]	Speed ratio Vs/Uw	Equivalent wind speed at stack height [m/s]	Equivalent wind speed at stack height [MPH]	Equivalent wind speed 10 m above ground level [m/s]	Equivalent wind speed 10 m above ground level [MPH]
3.5	749.7	2.5	1.3	11.9	26.7	11.1	24.9
4.25	1029.8	3.4	1.8	8.7	19.5	8.0	18.1
5.75	1675.8	5.5	2.9	5.3	12.0	4.9	11.1
7.75	2652.5	8.7	4.5	3.4	7.6	3.1	7.0
13.75	5414.7	17.8	9.3	1.6	3.7	1.5	3.4
50	10507.8	34.6	18.0	0.8	1.9	0.8	1.8
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Exhaustion condition

Total Flow Rate =	5820.0	CFM
Toxic Gas Flow Rate =	900.0	CFM
Toxic Gas Ratio =	15	%

Threshold =	***1000***	***failed***
Warning range =	**2000**	**caution**

Resulting Dilution Factors

Receptor ID.	Wind Speed at 10 m height [MPH] 24.9	18.1	11.1	7.0	3.4	1.8	0.0	*Ethane %*
1	9204	5604	4185	5475				*12.65*
2		5149	3869	4212	23426			*12.65*
3		14071	8008	7954	15005			*12.65*
4		14433	9349	8418	15320			*12.65*
5		19748	10432	7813	12728			*12.65*
6		19423	10173	7879	9693			*12.65*
7		21253	14615	10196	8126	136741		*12.65*
8		21998	12671	8955	7890	114258		*12.65*
9		29622	19521	14302	10557	163983		*12.65*
10		33457	22304	18228	13526	190944		*12.65*
11		34351	24652	18983	16294	159360		*12.65*
12		30908	20483	17027	17082	123946		*12.65*
13		30171	19090	12120	11407	97898		*12.65*
14		26118	15502	13343	12607	98581		*12.65*
15		36829	15697	11022	9743	58108		*12.65*
16		26803	14191	9166	6942	44715		*12.65*
17	4096	6760	21436	54346				*12.65*
18	4264	3624	3994	4212				*12.65*
19	5164	4477	5444	6453				*12.65*
20	66808	137183	347456	550515				*12.65*
21	75026	144675	450954	618827				*12.65*
22	4463	5450	7356	11232				*12.65*

Dilution Results for Stack EF-2-15