ATMOSPHERIC DYNAMICS
METEOROLOGICAL AND AIR QUALITY MODELING

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November 24, 2009

Dr. Glen Long
Bay Area Air Quality Management District
939 Ellis St.
San Francisco, CA. 94109

Re: Wind Tunnel Modeling Protocol for the Oakley Generating Station

Dear Glen:

Attached for your review is the *Protocol for Wind Tunnel Modeling to Determine the Equivalent Building Dimensions for the Oakley Generating Station*. This protocol was developed by CPP, Inc. on behalf of Radback Energy, Inc. The purpose of the protocol is to determine Equivalent Building Dimensions (EBD) using wind tunnel modeling in place of the analytical methods typically used for inputs into the Building Profile Input Program (BPIP).

The attached Protocol describes the technical aspects and project plan for conducting the wind tunnel study. The only method the EPA has concurred with for determining EBD is through the use of wind tunnel modeling. The procedures described in this protocol for conducting EBD have been previously approved by EPA for numerous projects.

If you have any questions, please do not hesitate to call me at (805) 569-6555. Thank you for your attention in this matter.

Sincerely,

Atmospheric Dynamics, Inc.

Gregory Darvin

Gregory S. Darvin
Senior Meteorologist

cc:
Brewtser Birdsall, California Energy Commission
Carol Bohnenkamp, EPA Region 9

CERMAK
PETERKA
PETERSEN

WIND ENGINEERING AND AIR QUALITY CONSULTANTS

PROTOCOL

Wind Tunnel Modeling To Determine Equivalent Building Dimensions

For

The Oakley Generating Station

Prepared for:

Radback Energy, Inc.
145 Town and Country Dr.
Danville, CA 94526

CPP Project: 5153

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PROTOCOL

WIND TUNNEL MODELING TO DETERMINE EQUIVALENT BUILDING DIMENSIONS FOR THE OAKLEY GENERATING STATION

CPP Project 5153

November 2009

Prepared by:

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Anke Beyer-Lout, Atmospheric Scientist, M.S.

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AGL	Above Ground Level	(m)
A	Calibration Constant	(-)
B	Calibration Constant	(-)
B_o	Buoyancy Ratio	(-)
C	Concentration	(ppm or µg/m^3)
C_o	Tracer Gas Source Strength	(ppm or µg/m^3)
C_{max}	Maximum Measured Concentration	(ppm or µg/m^3)
C_s	Concentration of Calibration Gas	(ppm or µg/m^3)
	Concentration Estimate for Full-scale Sampling Time, t_s	(µg/m^3)
C_k	Concentration Estimate for Wind-tunnel Sampling Time, t_k	(µg/m^3)
Δ	Difference Operator	(-)
$\Delta\theta$	Potential Temperature Difference	(K)
δ	Boundary-Layer Height	(m)
d	Stack Diameter	(m)
E	Voltage Output	(Volts)
Fr	Froude Number	(-)
g	Acceleration Due to Gravity	(m/s^2)
h	Stack Height Above Roof Level	(m)
H	Stack Height Above Local Grade	(m)
H_t	Terrain Height	(m)
H_b	Building Height	(m)
I_s	Gas Chromatograph Response to Calibration Gas	(Volts)
I_{bg}	Gas Chromatograph Response to Background	(Volts)
k	von Kármán Constant	(-)
L	Length Scale	(m)
λ	Density Ratio	(-)
M_o	Momentum Ratio	(-)
n	Calibration Constant, Power Law Exponent	(-)
v	Kinematic Viscosity	(m^2/s)
m	Emission Rate	(g/s)
ρ_a	Density of Ambient Air	(kg/m^3)
ρ_s	Density of Stack Gas Effluent	(kg/m^3)
R	Velocity Ratio	(-)
R_i	Richardson Number	(-)
Re_b	Building Reynolds Number	(-)
Re_k	Roughness Reynolds Number	(-)
Re_s	Effluent Reynolds Number	(-)

T	Mean Temperature	(K)
t_s	Full-scale sampling time	(s)
t_k	Wind-tunnel sampling time	(s)
U_a	Wind Speed at Anemometer	(m/s)
U_H	Wind Speed at Stack Height	(m/s)
U_r	Wind Speed at Reference Height Location	(m/s)
U_∞	Free Stream Wind Velocity	(m/s)
U_*	Friction Velocity	(m/s)
U	Mean Velocity	(m/s)
U'	Longitudinal Root-Mean-Square Velocity	(m/s)
V	Volume Flow Rate	(m^3/s)
V_e	Exhaust Velocity	(m/s)
z	Height Above Local Ground Level	(m)
z_o	Surface Roughness Factor	(m)
z_r	Reference Height	(m)
z_∞	Free Stream Height – 600 m above ground level	(m)

<u>Subscripts</u>

m	pertaining to model
f	pertaining to full scale

1. INTRODUCTION

This protocol describes the wind-tunnel study that will be conducted by CPP, Inc. on behalf of Radback Energy, Inc. for the proposed Oakley Generating Station (OGS) in Oakley, California. The OGS is located near Oakley, California, as shown in Figures 1a and 1b. The OGS includes air cooled condensers that are basically elevated structural elements where the air can flow underneath. The wake created by this structure would be much smaller than if the structure were solid to ground level, which is the way BPIP treats the structure for input to AERMOD. Hence, the specific purpose of this study is to determine Equivalent Building Dimensions (EBD) for input into AERMOD to model the two turbine stacks associated with the generating station. The EBD values will be used in place of the BPIP inputs.

When a single solid rectangular building with the appropriate aspect ratio is adjacent or near a stack, the actual building dimensions are the appropriate model inputs. For more complicated situations, such as the OGS, the use of EBDs for model input will result in more accurate concentration estimates for assessing compliance.

The only method the Environmental Protection Agency (EPA) has concurred with for determining EBD is through the use of wind tunnel modeling. Petersen, et al (1991, 1992) describes the first such study for which a protocol was reviewed and accepted by the EPA (Region V and Research Triangle Park) and for which a permit was ultimately obtained (Blewitt, 1995). That study considered the effect of a nearby lattice type (porous) structure. Also, the EPA (Tikvart, 1994) has approved the equivalent building concept, based on a study conducted by CPP (Petersen and Cochran, 1993), for regulatory modeling use on the basis that it is a source characterization study, which is under the purview of the Regional Offices. Appendix C provides a copy of a paper that was presented at the 2007 A&WMA conference that summarizes the results of an EBD study reviewed and approved by EPA (approved in March 2007).

It should be pointed out that the EBD values determined in this study will, if anything, be conservative. In general, the EBD values should be insensitive to wind speed and plume rise. There will be a point, however, where this is not true. That point occurs when the plume rise is high enough such that the plume fully escapes any effect of the building wake. At that point, all building dimension inputs are effectively zero. The Tikvart (1994) memo presents some results of stack height (i.e., plume height) sensitivity tests conducted by CPP. That study showed that the EBD values are rather insensitive to stack height (plume height) and, if anything, they tend to decrease with taller stack heights (i.e., greater plume rise). Based on the above, the wind tunnel study has been designed to simulate a low plume rise condition where the plume is most likely to be captured by building wake and eddy effects. The first conservative (low plume rise) assumption is related to the method used to simulate plume rise as discussed in detail in Section 2.2. The stack gas exit parameters used in the model underestimate plume buoyancy and hence will produce lower plume rise than actual conditions. The second conservative assumption deals with the wind speed simulated in the wind tunnel. The wind speed that is exceeded 2% of the time will be simulated for all cases and as a result low plume rise will be simulated.

This protocol describes the technical aspects and project plan for conducting the wind tunnel study designed to meet the stated project objectives. It should be pointed out that the procedures described in this protocol for conducting EBD study have been approved by EPA on numerous occasions. Table 5 provides a list of past projects CPP has conducted of a related nature. Many of these projects have had protocols reviewed and approved by the appropriate State and/or EPA region.

2. TECHNICAL CONSIDERATIONS

2.1 DETERMINATION OF EQUIVALENT BUILDING DIMENSIONS

The basic modeling approach for determining equivalent building dimensions is to first document, in the wind tunnel, the dispersion characteristics as a function of wind direction at the site with all significant nearby structure wake effects included. Next, the dispersion is characterized, in the wind tunnel, with an equivalent building positioned at various locations upwind or downwind of the stack in place of all nearby structures as shown in Figure 2. This testing is conducted for various equivalent buildings until an equivalent building is found that provides a profile of maximum ground level concentration versus downwind distance that is similar (within the constraints defined below) to that with all site structures in place.

The criteria for defining whether or not two concentration profiles are similar is to determine the smallest building which: 1) produces an overall maximum concentration exceeding 90 percent of the overall maximum concentration observed with all site structures in place; and 2) at all other longitudinal distances, produces ground-level concentrations which exceed the ground-level concentration observed with all site structures in place less 20 percent of the overall maximum ground-level concentration with all site structures in place. These criteria have been accepted on past EPA approved EBD studies (Petersen and Cochran, 1995a, 1995b; McBee, 1995; Thornton, 1995) and is a suggested approach in the Tikvart (1994) memorandum.

To demonstrate the method for specifying the equivalent building, consider Figure 3 which shows a typical result from a previous study. The figure shows the maximum ground level concentration versus downwind distance for five different equivalent buildings and the maximum concentration measured with site structures in place. Within this figure, the concentration profile for EB2 meets the first criterion in that the maximum measured concentration is at least 90 percent of the maximum concentration measured with the site structures in place. However, the EB2 profile fails the second criterion at the third actual site data point (at approximately 200 m downwind) where the lower bound of the error bar exceeds the interpolated concentration value for EB2. Therefore, the equivalent building for the test case shown in Figure 3 is EB3, since EB3 is the smallest equivalent building which meets both criteria.

The 20 percent error bar is based on a statistical uncertainty analysis, which has been validated from past experience which has shown that wind tunnel maximum concentrations are generally repeatable within ±10 percent (Petersen and Cochran, 1993).

2.2 Similarity Requirements

General

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind tunnel study of diffusion from an industrial facility when *accurate* concentration estimates (i.e., ones that will compare with the real-world) are needed. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. A detailed discussion on these requirements is given in the EPA fluid modeling guideline (Snyder, 1981) and Appendix A. For EBD type studies, the criteria used for simulating plume trajectories and the ambient air flow are summarized below. These criteria maximize the accuracy of the building wake simulation and apply a conservative approach for simulating plume rise. These are the criteria that have been used on past EPA approved EBD type studies (Petersen and Cochran, 1993, 1995a, 1995b, Petersen and Ratcliff, 1991, Petersen et al., 2007).

Modeling Plume Trajectories

To model plume trajectories, the velocity ratio, R, and density ration, λ, will be matched in model and full scale. These quantities are defined as follows:

$$R = \frac{V_e}{U_h} \tag{1}$$

$$\lambda = \frac{\rho_s}{\rho_a} \tag{2}$$

U_h = wind velocity at stack top (m/s),

V_e = stack gas exit velocity (m/s),

ρ_s = stack gas density (kg/m^3),

ρ_a = ambient air density (kg/m^3).

In addition, the stack gas flow in the model will be fully turbulent upon exit as it is in the full scale. This criteria is met if the stack Reynolds number ($Re_s = dV_e/\nu_s$), where d is exhaust diameter and ν_s is the exhaust gas viscosity, is greater than 670 for buoyant plumes such as those simulated in this study (Arya and Lape, 1990). In addition, trips will be installed, if required, inside the model stacks to increase the turbulence level in the exhaust stream prior to exiting the stack.

Modeling the Airflow and Dispersion

To simulate the airflow and dispersion around the buildings, the following criteria will be met as recommended by EPA (1981) or Snyder (1981):

- all significant structures within a 691 m (2266.7 ft) radius of the stacks will be modeled at a 1:400 scale reduction (i.e. all structures whose critical dimension (lesser of height or width) exceeds 1/20th of the distance from the source are included in the model);
- the mean velocity profile through the entire depth of the boundary layer will be represented by a power law $U/U_\infty = (z/z_\infty)^n$ where U is the wind speed at height z, U_∞ is the freestream velocity at z_∞ and the power law exponent, n, is dependent on the surface roughness length, z_O, through the following equation:

$$n = 0.24 + 0.096 \log_{10} z_o + 0.016 (\log_{10} z_o)^2 \quad ; \qquad (3)$$

- Reynolds number independence will be ensured: the building Reynolds number ($Re_b = U_b H_b / v_a$; the product of the wind speed, U_b, at the building height, H_b, times the building height divided by the viscosity of air, v_a) should be greater than 3,000 to 11,000; since the upper criteria may not be met for all simulations, Reynolds number independence tests will be conducted to determine the minimum acceptable operating speed for the wind tunnel.
- a neutral atmospheric boundary layer will be established (Pasquill–Gifford C/D stability) by setting the bulk Richardson number (R_{ib}) equal to zero in model and full scale.

Summary

Using the above criteria and the source characteristics shown in Table 1, the model test conditions were computed for the stacks under evaluation. The model test conditions were computed for D stability at the 2% wind speed and are provided in the Tables included with Appendix A. Appendix A also includes a more detailed discussion on wind tunnel scaling issues.

2.3 Emission Rates

For this evaluation, emission rates are not needed. For convenience purposes, a 1 g/s emission rate will be used in reporting the measured concentration results of the study. With this convention, the concentration results presented in the report can be converted to full-scale concentrations by multiplying the reported concentrations by the actual emission rates for any pollutant.

2.4 Surface Roughness

To simulate full scale wind profiles in the wind tunnel it is necessary to match the surface roughness length used in the model to that of the actual site. The surface roughness lengths for the OGS site were specified using AERSURFACE (EPA, 2008). For this study it was necessary to define surface roughness values for the approach flow as well as for the OGS site model extents. The AERSURFACE tool with a radius of 5 km around the OGS site was used to determine the appropriate surface roughness length for the approach flow.

To calculate the mean roughness length characteristic of the area surrounding the OGS the AERSURFACE domain was set equal to the model extents, i.e. the area within a 691m (2266.7 ft) radius of the stacks of concern. This roughness will be installed in place of the OGS model for the EBD test setup.

Table 2 shows the AERSURFACE results for both radii used, in 30 degree intervals around the OGS site as well as the wind tunnel test sectors. It is evident that two approach flows are necessary to simulate the full scale wind profiles in the wind tunnel. For wind directions of 0 through 90 and 270 through 350 degrees the surface roughness values are small with a mean of 0.031 m representing the San Joaquin River to the north of the OGS. For wind directions of 100 through 260 degrees the mean surface roughness is 0.238 m because of the mix of industrial, residential and open areas to the south.

Meteorological surface and upper air input files for AERMOD were provided by the client. Upper air data from the Oakland International Airport (see Figure 1a), surface data from the Concord Buchanan Field (see Figure 1a) and meteorological on-site data, as well as land use characteristics from the nearby Contra Costa Power (CCP) Plant were merged and processed using AERMET. By merging all the available data AERMET creates a virtual anemometer and produces a surface and an upper air input file for AERMOD.

The surface roughness length around the virtual anemometer was estimated by averaging the specific surface roughness length for every wind direction provided in the meteorological surface input file for AERMOD. The average surface roughness length around the virtual anemometer is 0.22 m.

2.5 Test Wind Speed

For this study, the wind speed will be set to simulate the wind speed that is exceeded 2% of the time at the anemometer location, as has been the practice on past EBD studies. Using such a high wind speed will produce conservative results, as mentioned in the Introduction. The 2% wind speed for the OGS is based on the meteorological surface input file for AERMOD, which combines observations from the Oakland International Airport, the Concord Buchanan Field and the nearby Contra Costa Power (CCP) Plant for the period 2001-2006. Figure 4 shows that the 2% wind speed is 8.2 m/s (18.3 mph) at the virtual anemometer. All concentration tests to determine EBD will be conducted with speeds simulating the 2% wind speed.

Wind speeds in the tunnel will be set at a reference height of 400 m above stack grade. The speed at this reference height is determined by scaling the anemometer wind speed up to the freestream height, 600 m (Snyder, 1981) above ground level. At this height, is it assumed that wind speeds at the site and at the anemometer location are the same (i.e., local topographic effects are not important). Next, the wind speed over the site at the reference height is calculated using the wind speed at the freestream height and scaling down to the lower height using the following power law equation:

$$U_r = U_\infty \left(\frac{z_r}{z_\infty} \right)^{n_s} = U_{anem} \left(\frac{z_\infty}{z_{anem}} \right)^{n_a} \left(\frac{z_r}{z_\infty} \right)^{n_s} \tag{4}$$

where

U_r = wind speed at reference height (m/s),

z_r = reference height above plant grade (400 m),

U_∞ = wind speed at freestream height (m/s),

z_∞ = freestream height (600 m),

U_{anem} = wind speed at appropriate anemometer (m/s),

z_{anem} = height above grade for U_{anem} (10 m),

n_a = wind power law exponent at the anemometer (0.18 at the virtual anemometer)

n_s = wind power law exponent at the site (0.13 at OGS for the 0.031 m surface roughness and 0.19 for the 0.238 m surface roughness).

Tables A-1 through A-4 in Appendix A provide the calculated results using the above equations. It should be noted that the power law exponents were calculated using Equation (3) in Section 2.2 with z_o equal to 0.22 m at the airport and 0.031 or 0.238 m at the OGS. The surface roughness lengths for the site were specified using the site specific AERSURFACE information provided in Table 2, as discussed in Section 2.4.

2.6 Data Acquisition

Concentration, velocity, and volume flow measurements will be obtained following the methods outlined in Appendix B. Atmospheric Dispersion Comparability tests will not be conducted for this study as such measurements have been obtained on past studies at a similar scale.

2.7 Quality Control

To ensure that accurate and reliable data are collected for assessing the plume transport and dispersion, certain quality control steps will be taken. These include:

- use of blended mixtures or pure gases or certified mixtures for stack source gas;
- multipoint calibration of hydrocarbon analyzer with certified standard gas;
- calibration of stack flow measuring device with soap bubble meter;
- calibration of velocity measuring device against pitot tube;
- wind tunnel testing to show the Reynolds number independence of the concentration measurements.

3. PROJECT PLAN

To meet the project objectives, six tasks are planned. The six tasks, which are discussed in detail below, are: 1) test protocol development; 2) model construction; 3) wind tunnel testing—documentation tests; 4) visualization and meeting at CPP; 5) wind tunnel testing—equivalent building dimensions; and 6) analysis and reporting.

3.1 Test Protocol Development

During this phase of the project, this test protocol was developed. The protocol defines the methods used to conduct the study, the area and sources to be modeled, the wind directions and wind speeds to be simulated and the results that will be provided.

3.2 Model Construction

A 1:400 scale model of the OGS and surrounding structures will be constructed. The model will include all significant structures (i.e., structures whose critical dimension, lesser of height or width, exceeds 1/20th of the distance from the source) within a 691 m (2266.7 ft) radius of the center of the OGS stacks being modeled. The area to be modeled is shown in Figure 5a. A close-up view of the OGS showing the stack locations that will be evaluated is provided in Figure 5b. The model will be placed on a turntable so that different wind directions can be easily evaluated. Roughness elements, for positioning upwind and downwind of the turntable, will be constructed to represent the upwind roughness configuration. In this case two different approach roughness lengths are needed (i.e., 0.031 and 0.238 m) representing the open water to the north as well as the rougher terrain to the south (see Table 2). Flow conditioning devices, consisting of a 2-dimensional trip and spires, will be placed upwind of the model to aid in the development of the boundary layer. The setup for the low and high approach roughnesses is shown schematically in Figures 6a and 6b.

A set of solid structures, all with height to width ratios similar to those used by Huber and Snyder (1982) for development of the ISC downwash algorithm, will be fabricated for placement at directly upwind of each stack. These structures will be used to determine the equivalent building dimensions for many building configurations. Since AERMOD is not limited to this building shape or positioning, other building shapes/positions will also be investigated as appropriate to obtain the best match for the case when all site structures are present. These structures will be used to determine the equivalent building dimensions. The stacks in Table 1 and idealized buildings will be tested with the turntable model removed from the wind tunnel and a uniform roughness installed in its place. The uniform roughness will be constructed such that it provides the same surface roughness as the surroundings. Plan views of this setup in the wind tunnel for the low and high roughnesses are shown in Figures 6 c-d.

Stacks will be constructed of aluminum, plexiglass or brass tubes and will be supplied with a helium–hydrocarbon (or nitrogen-hydrocarbon) mixture of the appropriate density. The two combustion turbine stacks, each releasing a different hydrocarbon tracer, will be operated at the same time. Measures will be taken to ensure that the flow is fully turbulent upon exit. Precision gas flow meters will be used to monitor and regulate the discharge velocity.

For the EBD testing, concentration sampling taps will be installed on the surface of the model so that at least 45 locations will be sampled simultaneously for each simulation. A typical sampling grid will consists of 7 to 9 receptors located in each of 5 rows that are spaced perpendicular to the wind direction. Two background samples are located upwind of the stacks. The lateral and longitudinal spacing of receptors is designed so that the maximum concentration is defined in the lateral and longitudinal directions. Initial testing is conducted to confirm the grid design and to alter the design if necessary. A typical sampling grid is shown in Figure 7.

3.3 WIND TUNNEL TESTING – DOCUMENTATION TESTS

Before conducting the detailed wind tunnel testing, a limited series of documentation tests will be conducted. CPP has previously conducted atmospheric dispersion comparability (ADC) tests at a similar model scale and these tests will not be repeated for this study. However, Reynolds number independence tests will be conducted.

For the Reynolds number tests, a scale model of the OGS and vicinity will be installed in the wind tunnel. A tracer gas will be emitted from CT-1 for the tests itemized in Table 4. Ground-level concentration measurements will then be taken downwind of the OGS for three different Reynolds numbers. If Reynolds number effects are negligible, the normalized concentration results should be equivalent (within 10 percent). The minimum test speed for the remaining tests will be chosen such that Reynolds number effects are negligible.

3.4 Meeting at CPP

Before detailed testing in the wind tunnel is carried out it is recommended that representatives from the client (and if possible, appropriate government officials) be present at CPP to inspect the model for accuracy and review the test plan. Visualizations of exhaust behavior are then conducted. The visualization will provide those present with a qualitative understanding of the effect of the structures on the dispersion and will provide information that can be used to finalize the test plan.

3.5 Wind Tunnel Testing – Equivalent Building Dimensions

The purpose of this phase of the testing is to define the Equivalent Building Dimensions that can be input into AERMOD for the two stacks listed in Table 1. Table 4 summarizes the concentration measurement test plan. The experimental methods are described in Appendix B.

A tracer gas will be released from the selected stacks and the maximum ground-level concentrations versus downwind distance will be determined for the 36 wind directions shown in Table 4 at the 2 % wind speed (8.2 m/s). After these tests are completed, tests will be conducted to determine the Equivalent Building Dimensions. For these tests, the turntable model will be removed from the wind tunnel and a uniform roughness representative of the plant surroundings will be installed in its place. Concentration measurements will then be conducted with various solid structures upwind of the stack under evaluation. The solid building that produces similar concentrations as with all structures in place is the equivalent building. The dimensions of these equivalent buildings can then be used for AERMOD model input. These dimensions will be used to assess maximum ground-level impact for the 36 wind directions evaluated.

3.6 Analysis and Reporting

The data will be analyzed shortly after it is collected and put in a form ready for report. The analyses will include:

- conversion of wind tunnel concentrations to full-scale hourly average normalized concentrations using the equation recommended by Snyder (1981); and
- tabulation of equivalent building dimensions for 36 wind directions for the two selected stacks.

The tabulated equivalent building dimensions can then be input directly into AERMOD. Upon completion of all analyses, a concise, comprehensive report will be prepared and submitted to the client for review and comment. After comments on the report are received, final bound copies will be provided.

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FIGURES

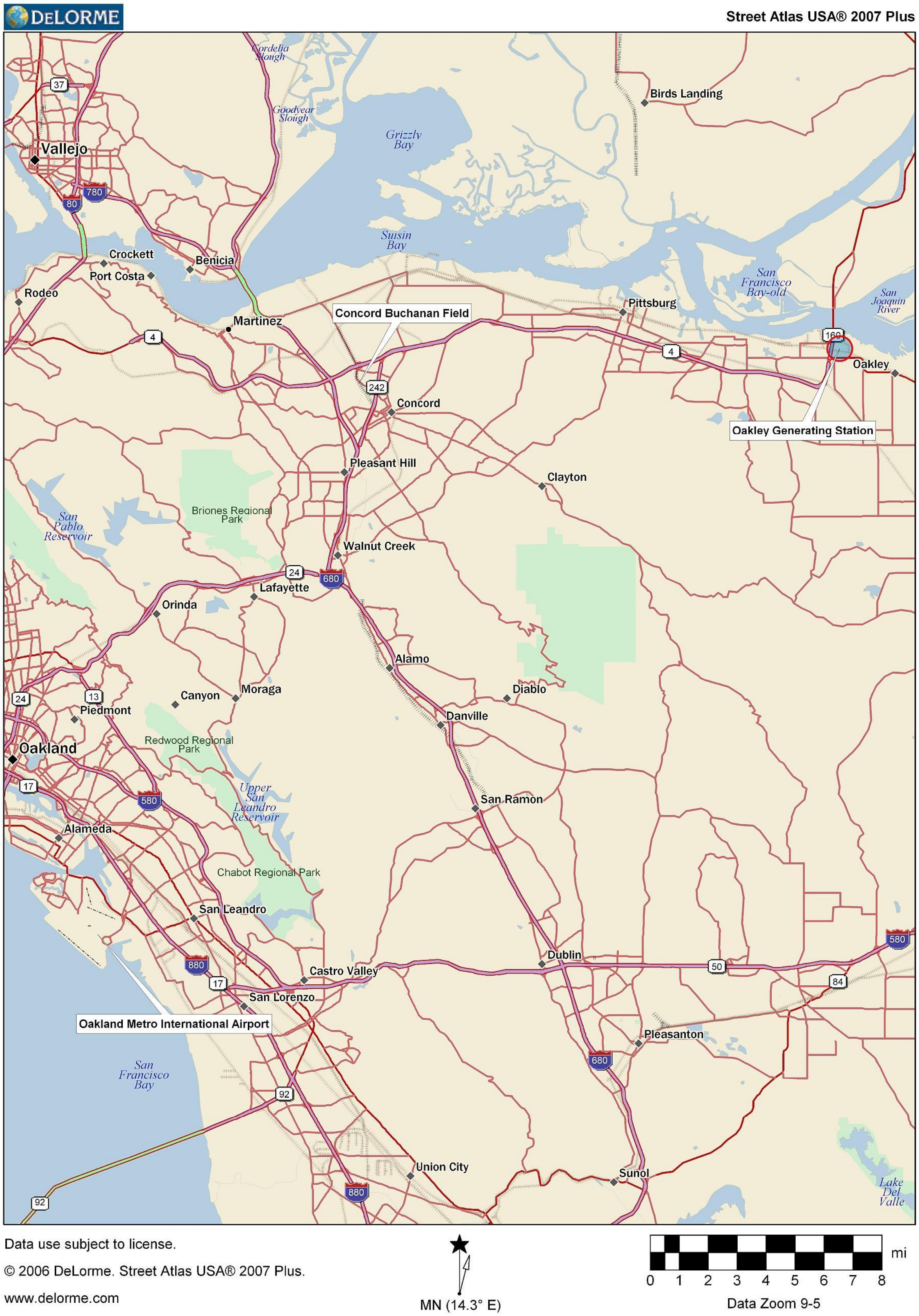


Figure 1. Site maps: a) site location and project anemometers.

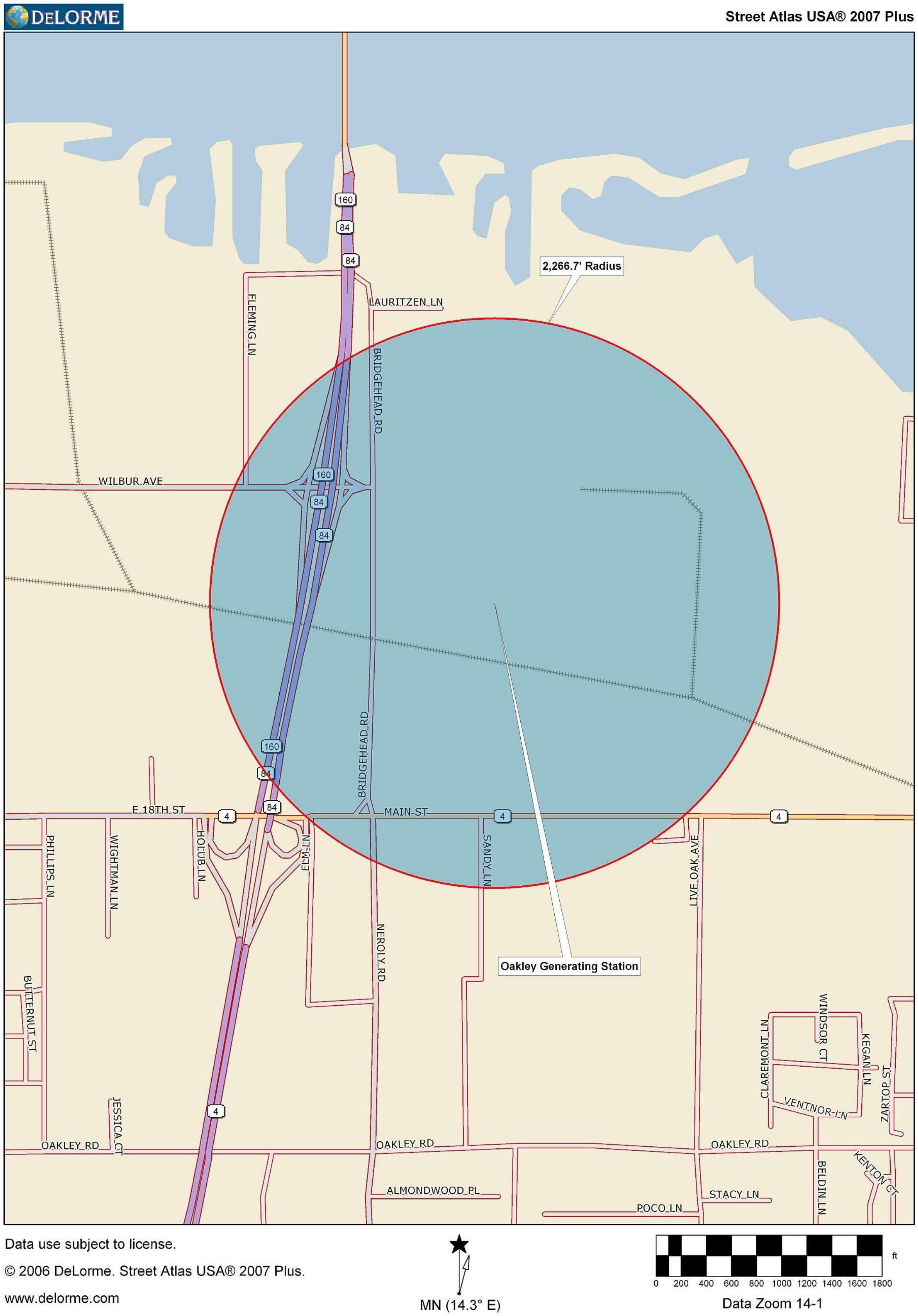


Figure 1. Site maps: b) extents of model turntable.

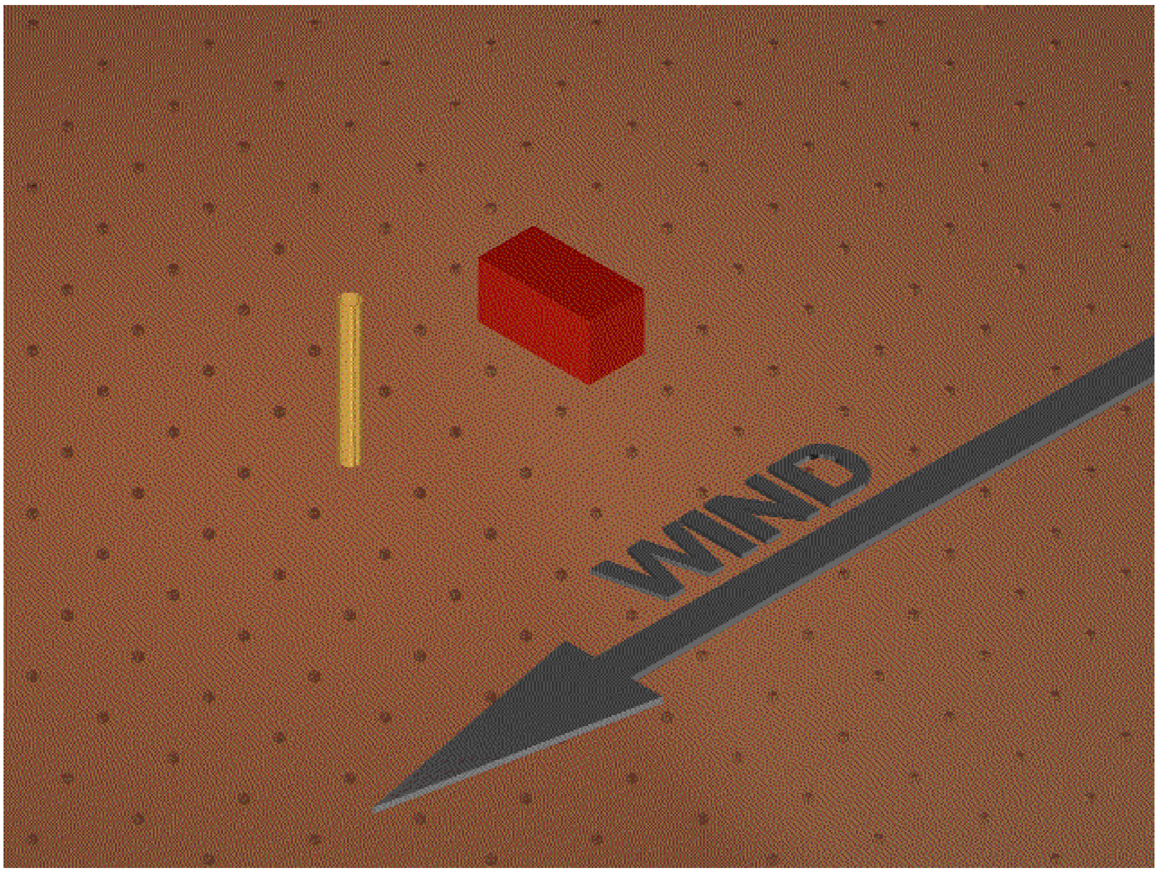


Figure 2. Idealized building and stack configuration for EBD wind tunnel setup.

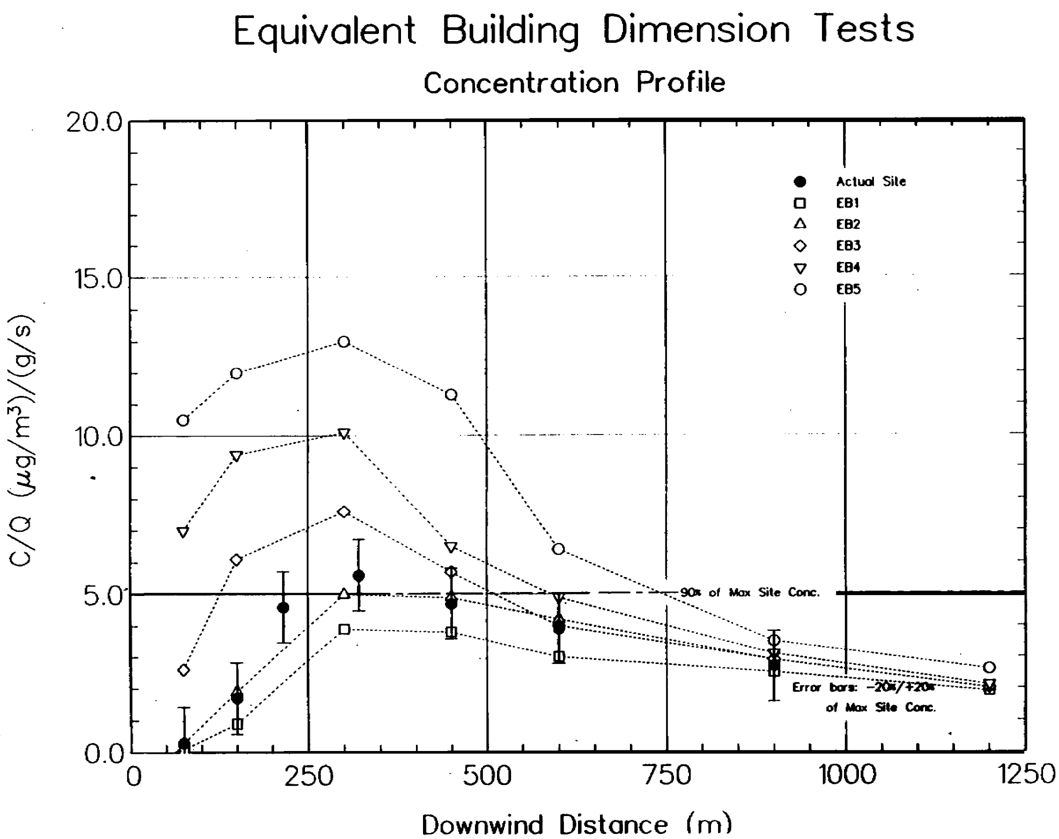
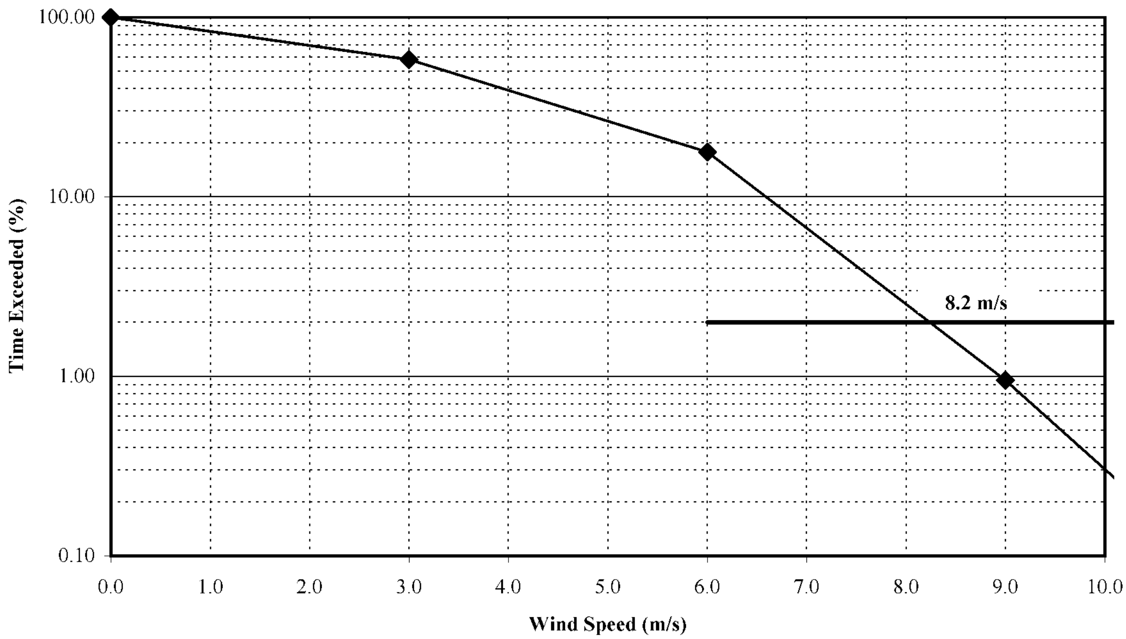


Figure 3. Typical results from a previous equivalent building determination. The figure shows the maximum concentration versus downwind distance with 20 percent error bar with the site structures in place, a horizontal line at 0.9 times the maximum concentration with site structures in place, and maximum concentration versus distance for various equivalent buildings.

2% Wind Speed Analysis
Wind data extracted from SFC input file for AERMOD
Data period: 2001-2006



Joint Probability Distribution of Wind Speed and Wind Direction

Category: Maximum Wind Speed (m/s):	1 3.0	2 6.0	3 9.0	4 12.0	5 >12	Totals by Direction (%)
N	1.280	0.249	0.073	0.002	0.000	**1.604**
NNE	0.859	0.112	0.009	0.000	0.000	**0.980**
NE	1.238	0.121	0.007	0.000	0.000	**1.366**
ENE	1.771	0.139	0.000	0.000	0.000	**1.910**
E	1.906	0.222	0.002	0.000	0.000	**2.130**
ESE	2.351	0.443	0.018	0.000	0.000	**2.812**
SE	3.073	1.737	0.439	0.128	0.011	**5.388**
SSE	2.029	0.761	0.123	0.014	0.000	**2.927**
S	1.067	0.393	0.023	0.000	0.000	**1.483**
SSW	0.907	0.448	0.043	0.000	0.000	**1.398**
SW	1.081	0.457	0.053	0.002	0.000	**1.593**
WSW	1.234	1.981	0.551	0.025	0.000	**3.791**
W	2.532	6.851	5.518	0.446	0.018	**15.365**
WNW	5.233	17.204	6.766	0.153	0.000	**29.356**
NW	4.022	7.655	2.395	0.048	0.000	**14.120**
NNW	2.852	1.540	0.802	0.103	0.002	**5.299**
Calm	8.500					
Totals by Category (%):	**41.935**	**40.313**	**16.822**	**0.921**	**0.031**	**100**
Time Exceeded (%):	**58.087**	**17.774**	**0.952**	**0.031**	**0.000**	

Figure 4. Wind speed and direction distribution for the AERMET virtual anemometer.

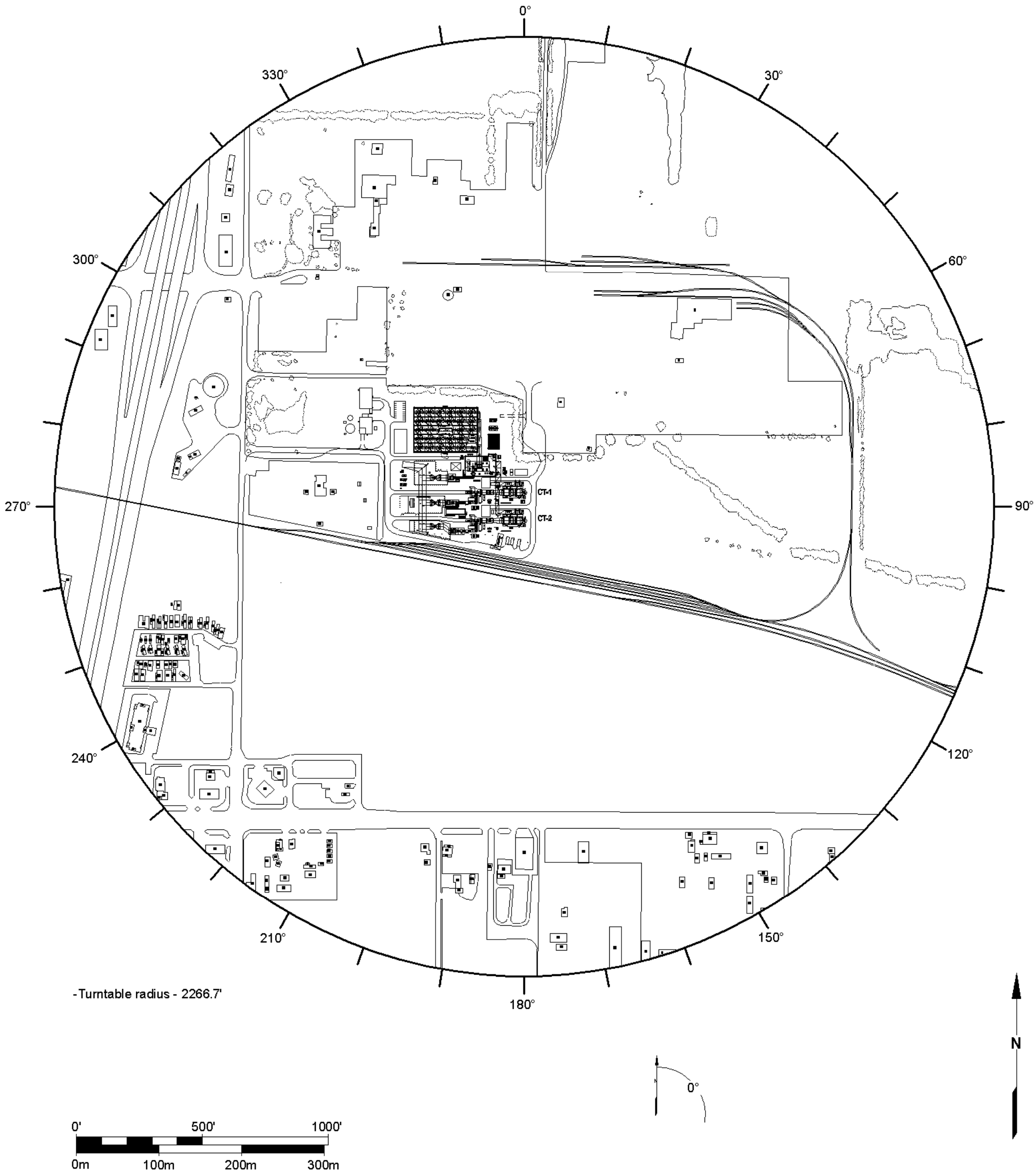


Figure 5. a) Site Plan of the area modeled in the wind tunnel.

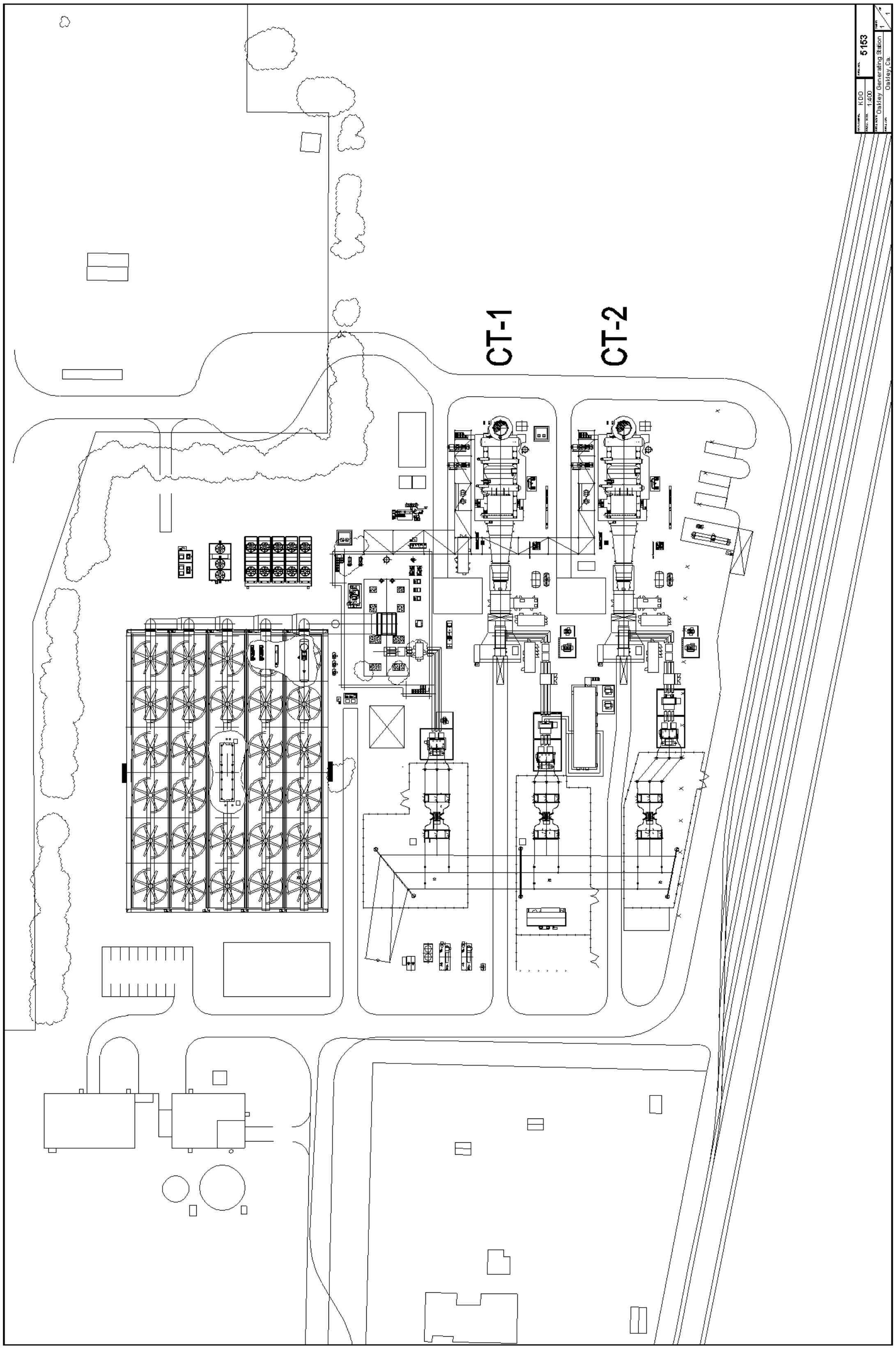


Figure 5. b) Close-up view of the area modeled in the wind tunnel showing locations of the sources to be modeled.

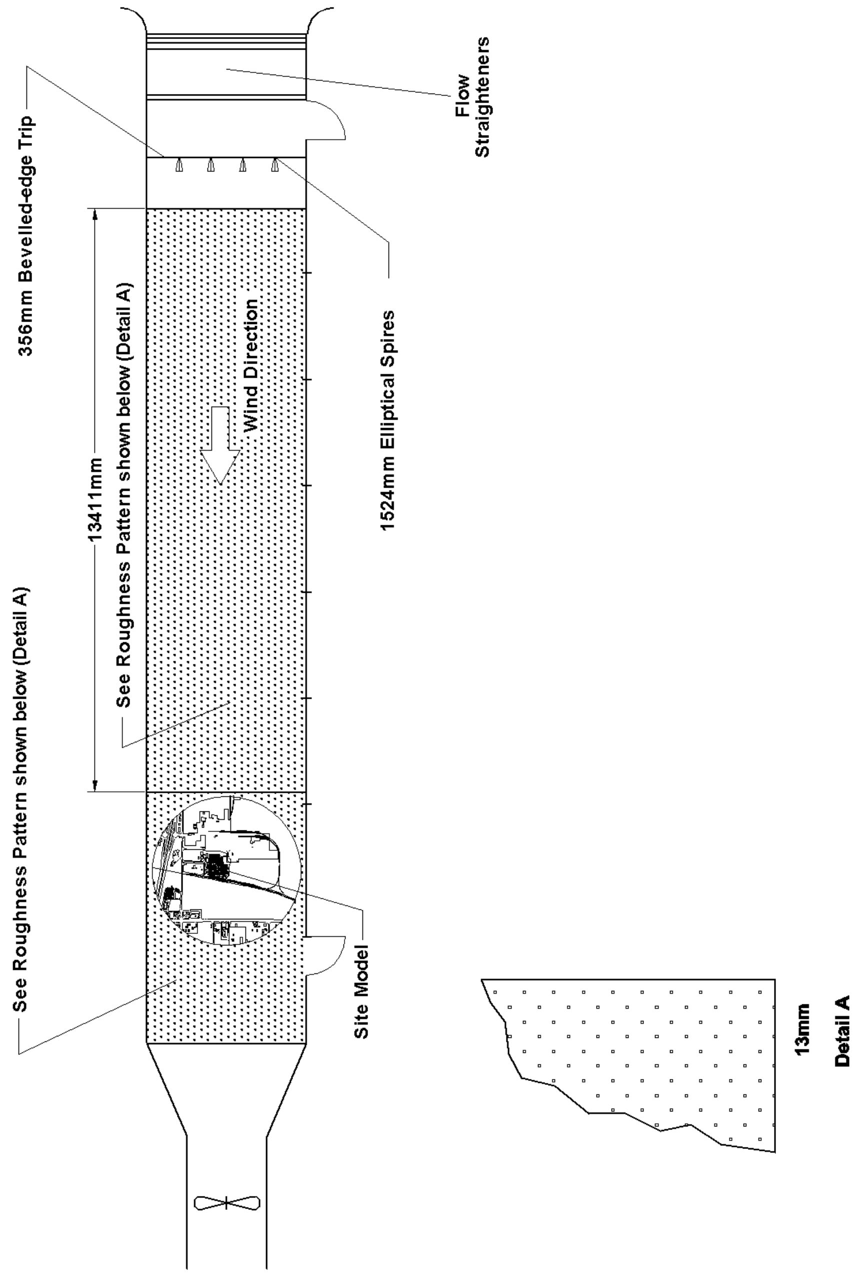


Figure 6. Wind tunnel setup for: a) tests with the site model - low roughness approach (0 through 90 and 270 through 350 degrees wind direction).

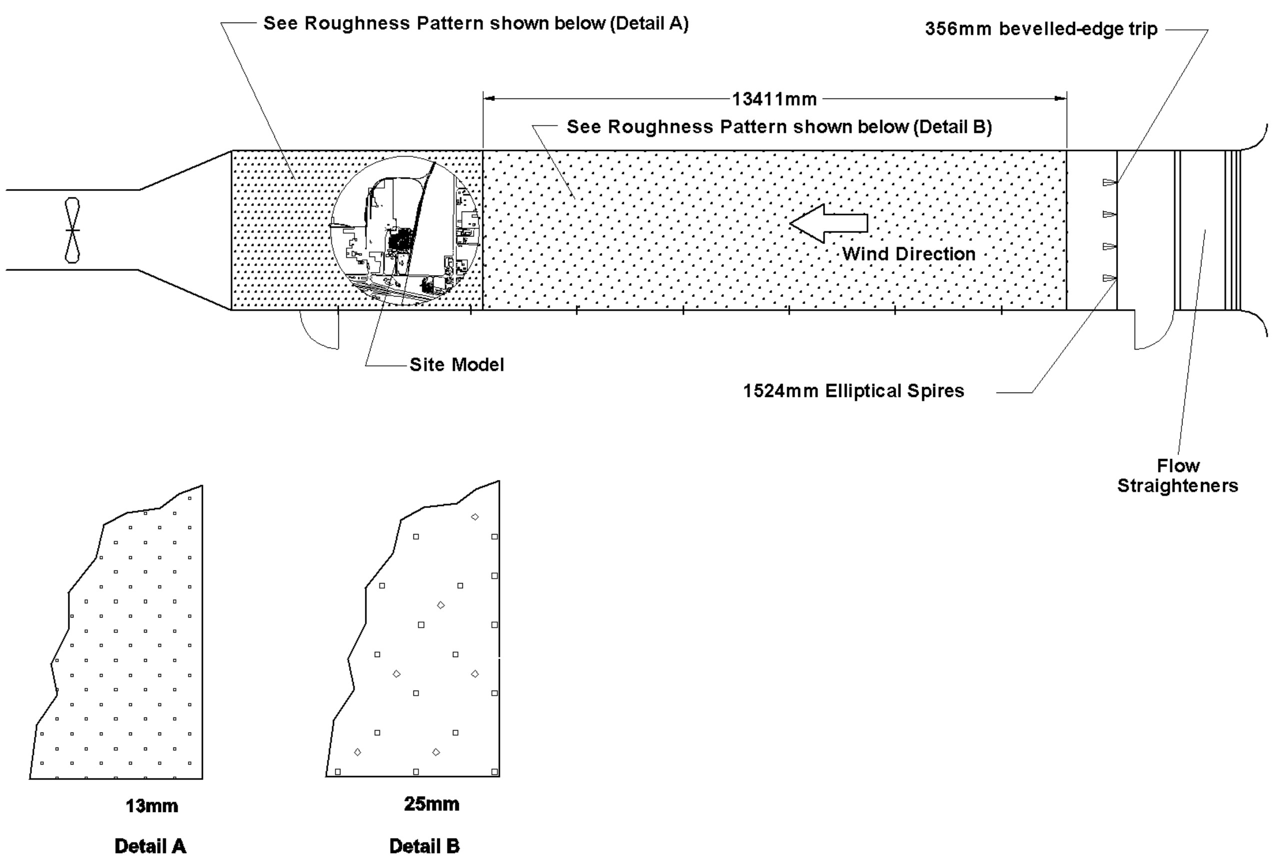


Figure 6. Wind tunnel setup for: b) tests with the site model - high roughness approach (100 through 260 degrees wind direction).

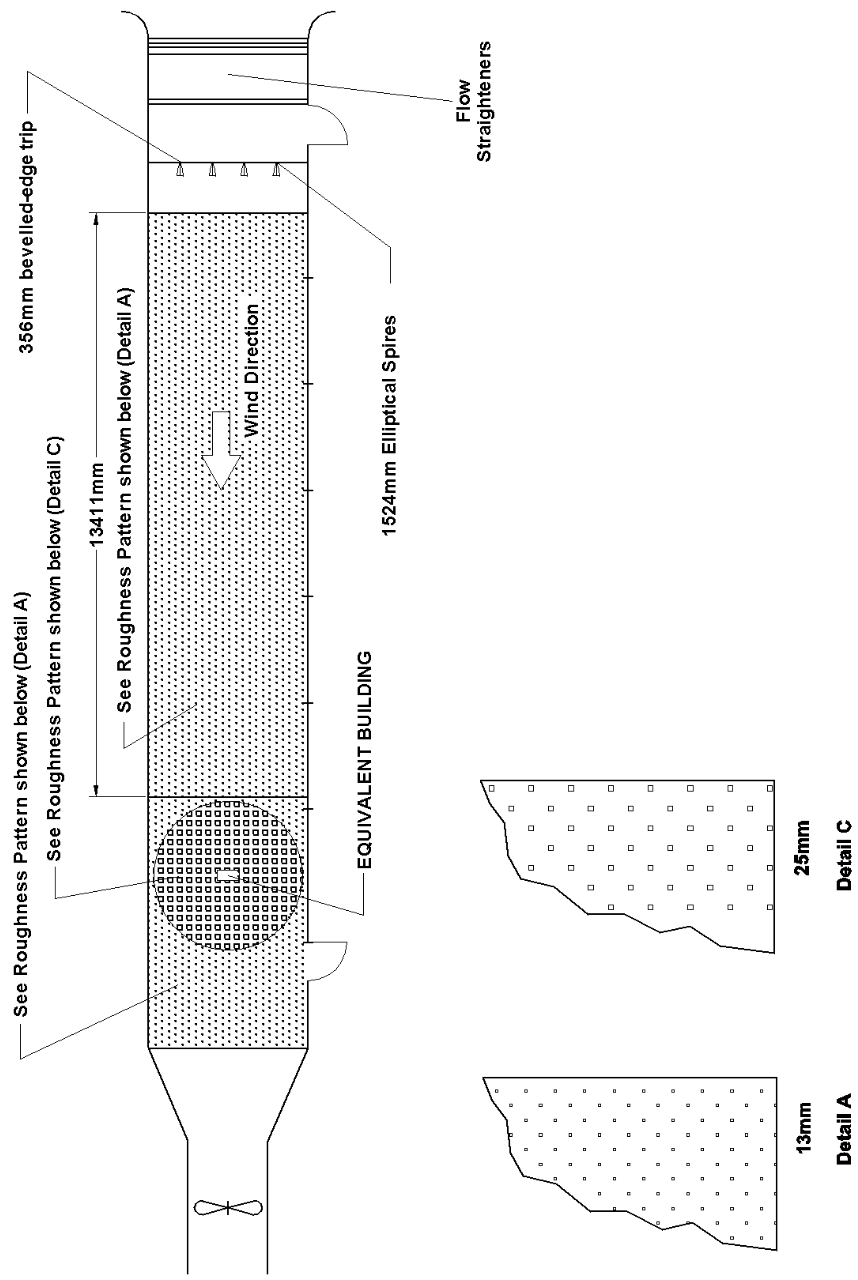


Figure 6. Wind tunnel setup for: c) tests with equivalent buildings - low roughness approach.

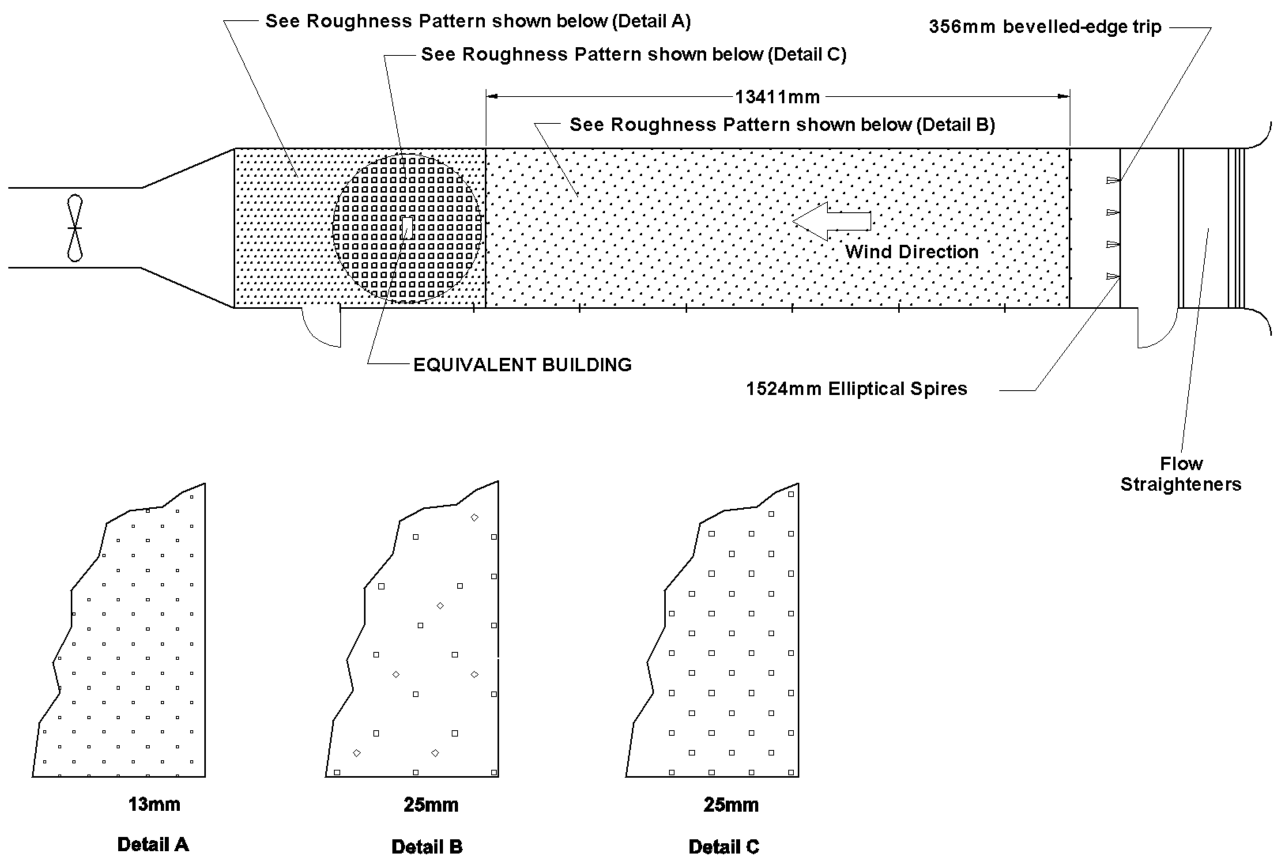


Figure 6. Wind tunnel setup for: d) tests with equivalent buildings - high roughness approach.

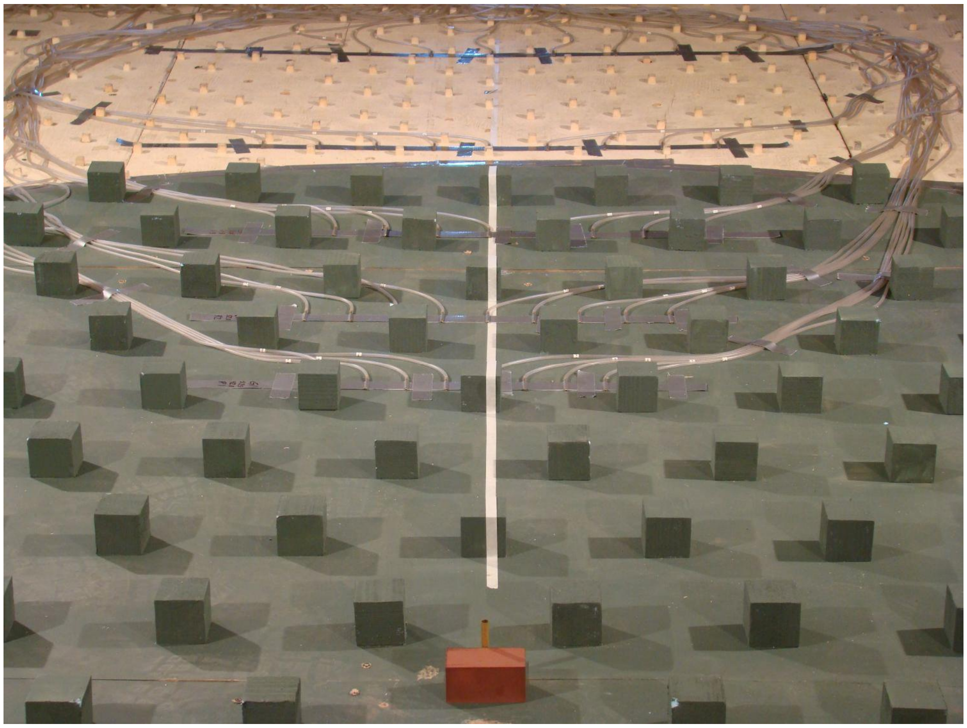


Figure 7. Photograph of a typical ground-level concentration sampling grid.

TABLES

Table 1
Full-scale Exhaust and Modeling Information

english units:

Source Description	Source ID	Initial Source Height Above Base (ft)	Exit Diameter (in)	Exit Temp. (^{o}F)	Mass Flow (lb/hr)	Volume Flow Rate (cfm)	Exit Velocity (fpm)	Source Orientation	Source Base Height Above Grade (ft)	Comment
Oakley Generating Station										
Combustion Turbine Stack 1	CT-1	155.5	220.0	192.0	4,287,931	1,156,237	4,380	Vertical	0.0	Local Grade
Combustion Turbine Stack 2	CT-2	155.5	220.0	192.0	4,287,931	1,156,237	4,380	Vertical	0.0	Local Grade

metric units:

Source Description	Source ID	Initial Source Height Above Base (m)	Exit Diameter (m)	Exit Temp. (K)	Mass Flow (kg/s)	Volume Flow Rate (m^3/s)	Exit Velocity (m/s)	Source Orientation	Source Base Height Above Grade (m)	Comment
Oakley Generating Station										
Combustion Turbine Stack 1	CT-1	47.41	5.59	362.0	541.41	546.10	22.26	Vertical	0.0	Local Grade
Combustion Turbine Stack 2	CT-2	47.41	5.59	362.0	541.41	546.10	22.26	Vertical	0.0	Local Grade

Site Parameters:

Scale Reduction:	400	
Grade Elevation (m):	5.3	17.5 ft msl
Typical Building Height (m):	37.8	
Ambient Temperature (^{o}K):	294.3	Concord Buchanan Field (70 F Average)
Anemometer Height (m):	20.0	Concord Buchanan Field
Anemometer Surface Roughness (m):	0.22	Concord Buchanan Field
Site Anemometer Height (m):	20.0	
2% Wind Speed (m/s):	8.2	Concord Buchanan Field (Period of Record: 2001 to 2006)

Table 2
Surface Roughness Values Determined by AERSURFACE for the OGS Site and Values Used in Wind Tunnel Simulation

AERSURFACE Sector (Degrees)	0.691 km AERSURFACE Zo (m)	5 km AERSURFACE Zo (m)	Wind Tunnel Test Sector (Degrees)	5 kmWind Tunnel Test Zo (m)
0-30	0.328	0.02		
30-60	0.537* (0.25)	0.01	0-90	0.031
60-90	0.318	0.01		
90-120	0.182	0.18		
120-150	0.143	0.27		
150-180	0.14	0.18		
180-210	0.385	0.19	100-260	0.238
210-240	0.398	0.25		
240-270	0.305	0.36		
270-300	0.311	0.08		
300-330	0.346	0.02	270-360	0.031
330-360	0.287	0.04		
Mean	0.283	0.134		

* Aerial Photographs indicate that AERSURFACE overestimates the roughness of the 30-60 degree sector (see Table 3). A surface roughness of 0.25 is used for this sector.

Table 3
Surface Roughness Classification
(Davenport Method Updated by Wieringa, 1992)

Class	Surface Roughness - z_o (m)	Landscape Description
1	0.0002 Sea	Open sea or lake (irrespective of wave size)*, tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
2	0.005 Smooth	Featureless land surface without any noticeable obstacles and ridges, morass, and snow-covered or fallow open country.
3	0.03 Open	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacles heights; e.g. grazing land without windbreaks, heather, moor and tundra, runway area of airports.
4	0.10 Roughly Open	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g. low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights.
5	0.25 Rough	Recently-developed "young" landscape with high crops or crops of varying height, and scattered obstacles (e.g. dense shelterbelts, vineyards) at relative distances of about 15 obstacle heights.
6	0.5 Very Rough	"Old" cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights. Also low large vegetation with small interspaces, such as bush land, orchards, young densely-planted forest.
7	1.0 Closed	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights; e.g. mature regular forests, homogeneous cities or villages.
8	>2.0 Chaotic	Centers of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.

Notes:

* CPP believes that wave height does influence surface roughness.

Table 4
Concentration Measurment Test Plan

Run No.	Source 1 ID	Stack Height Above Base (ft)	Tracer Gas	Source 2 ID	Stack Height Above Base (ft)	Tracer Gas	Wind Direction (Deg.)	Model Reference Wind Speed (m/s)	2% Airport Wind Speed (m/s)	Approach Zo (m)
Reynolds Number Independence Tests										
1	CT-1	155.5	Ethane				150	4.00	8.20	0.238
2	CT-1	155.5	Ethane				150	3.00	8.20	0.238
3	CT-1	155.5	Ethane				150	2.00	8.20	0.238
Tests with Site Structure Present										
101	CT-1	155.5	Methane	CT-2	155.5	Ethane	0	4.00	8.20	0.031
102	CT-1	155.5	Methane	CT-2	155.5	Ethane	10	4.00	8.20	0.031
103	CT-1	155.5	Methane	CT-2	155.5	Ethane	20	4.00	8.20	0.031
104	CT-1	155.5	Methane	CT-2	155.5	Ethane	30	4.00	8.20	0.031
105	CT-1	155.5	Methane	CT-2	155.5	Ethane	40	4.00	8.20	0.031
106	CT-1	155.5	Methane	CT-2	155.5	Ethane	50	4.00	8.20	0.031
107	CT-1	155.5	Methane	CT-2	155.5	Ethane	60	4.00	8.20	0.031
108	CT-1	155.5	Methane	CT-2	155.5	Ethane	70	4.00	8.20	0.031
109	CT-1	155.5	Methane	CT-2	155.5	Ethane	80	4.00	8.20	0.031
110	CT-1	155.5	Methane	CT-2	155.5	Ethane	90	4.00	8.20	0.031
111	CT-1	155.5	Methane	CT-2	155.5	Ethane	270	4.00	8.20	0.031
112	CT-1	155.5	Methane	CT-2	155.5	Ethane	280	4.00	8.20	0.031
113	CT-1	155.5	Methane	CT-2	155.5	Ethane	290	4.00	8.20	0.031
114	CT-1	155.5	Methane	CT-2	155.5	Ethane	300	4.00	8.20	0.031
115	CT-1	155.5	Methane	CT-2	155.5	Ethane	310	4.00	8.20	0.031
116	CT-1	155.5	Methane	CT-2	155.5	Ethane	320	4.00	8.20	0.031
117	CT-1	155.5	Methane	CT-2	155.5	Ethane	330	4.00	8.20	0.031
118	CT-1	155.5	Methane	CT-2	155.5	Ethane	340	4.00	8.20	0.031
119	CT-1	155.5	Methane	CT-2	155.5	Ethane	350	4.00	8.20	0.031
120	CT-1	155.5	Methane	CT-2	155.5	Ethane	100	3.91	8.20	0.238
121	CT-1	155.5	Methane	CT-2	155.5	Ethane	110	3.91	8.20	0.238
122	CT-1	155.5	Methane	CT-2	155.5	Ethane	120	3.91	8.20	0.238
123	CT-1	155.5	Methane	CT-2	155.5	Ethane	130	3.91	8.20	0.238
124	CT-1	155.5	Methane	CT-2	155.5	Ethane	140	3.91	8.20	0.238
125	CT-1	155.5	Methane	CT-2	155.5	Ethane	150	3.91	8.20	0.238
126	CT-1	155.5	Methane	CT-2	155.5	Ethane	160	3.91	8.20	0.238
127	CT-1	155.5	Methane	CT-2	155.5	Ethane	170	3.91	8.20	0.238
128	CT-1	155.5	Methane	CT-2	155.5	Ethane	180	3.91	8.20	0.238
129	CT-1	155.5	Methane	CT-2	155.5	Ethane	190	3.91	8.20	0.238
130	CT-1	155.5	Methane	CT-2	155.5	Ethane	200	3.91	8.20	0.238
131	CT-1	155.5	Methane	CT-2	155.5	Ethane	210	3.91	8.20	0.238
132	CT-1	155.5	Methane	CT-2	155.5	Ethane	220	3.91	8.20	0.238
133	CT-1	155.5	Methane	CT-2	155.5	Ethane	230	3.91	8.20	0.238
134	CT-1	155.5	Methane	CT-2	155.5	Ethane	240	3.91	8.20	0.238
135	CT-1	155.5	Methane	CT-2	155.5	Ethane	250	3.91	8.20	0.238
136	CT-1	155.5	Methane	CT-2	155.5	Ethane	260	3.91	8.20	0.238
EBD Tests										
201	CT-1	155.5	Ethane				no EB	4.00	8.20	0.031
202	CT-1	155.5	Ethane				EB1	4.00	8.20	0.031
203	CT-1	155.5	Ethane				EB2	4.00	8.20	0.031
204	CT-1	155.5	Ethane				EB3	4.00	8.20	0.031
205	CT-1	155.5	Ethane				EB4	4.00	8.20	0.031
206	CT-1	155.5	Ethane				EB5	4.00	8.20	0.031
207	CT-1	155.5	Ethane				EB6	4.00	8.20	0.031
208	CT-1	155.5	Ethane				no EB	3.91	8.20	0.238
209	CT-1	155.5	Ethane				EB1	3.91	8.20	0.238
210	CT-1	155.5	Ethane				EB2	3.91	8.20	0.238

Table 5
List of Past EPA and/or State Approved EBD Studies

Project Name	Client	Project Location	EPA Region	EBD Approved	Year	Model Used
Amoco Whiting Refinery	Amoco	IN	5	Yes	1990	ISC
Public Service Electric and Gas	PSE&G	NJ	2	Yes	1993	ISC
Celco Plant	ENSR and Hoechst Celanese	VA	3	Yes	1994	ISC
Gilbert Station	Jersey Central Power and Light	NJ	2	Yes	1993	ISC
Cape Industries	Radian Corp	NC	4	Yes	1993	ISC
Cambridge Electric Plant	Com Electric	MA	1	Yes	1993	ISC
District Energy	Labno Environmental	MN	5	Yes	1993	ISC
Astoria Station	Consolidated Edison	NY	2	Yes	1996	ISC
Hawaiin Electric Waiau Facility	Jim Clary and Associates	HI	9	Yes	1998	ISC-PRIME
Pleasants Power Station	Allegheny Power	WV	3	Yes	2002	ISC
Mirant Potomac River Generating Station	ENSR and Mirant	VA	3	Yes	2006	AERMOD
Cheswick Power Plant	ENSR and Reliant Energy	PA	3	Yes	2006	AERMOD
Alcoa Davenport Works	Alcoa	IA	7	Pending	2008	AERMOD

APPENDIX

A

WIND-TUNNEL SIMILARITY REQUIREMENTS

TABLE OF CONTENTS

A.1. EXACT SIMILARITY REQUIREMENTS

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind-tunnel study of diffusion. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. The basic equations governing atmospheric and plume motion (conservation of mass, momentum and energy) may be expressed, using Einstein notation, in the following dimensionless form (Cermak, 1975; Petersen, 1978):

$$\frac{\partial \rho^*}{\partial t^*} + \frac{\partial\left(\rho^* U_i^*\right)}{\partial x_i^*} = 0 \tag{A.1}$$

$$\begin{aligned} &\frac{\partial U_i^*}{\partial t^*} + U_j^* \frac{\partial U_i^*}{\partial x_j^*} - \left[\frac{L_o \Omega_o}{U_o}\right] 2 \in_{ijk} \Omega_j^* U_k^* = \\ &- \frac{\partial \rho^*}{\partial x_i^*} - \left[\frac{\Delta T_o L_o g_o}{T_o U_o^2}\right] \Delta T^* g^* \delta_{i3} + \left[\frac{v_o}{U_o L_o}\right] \frac{\partial^2 U_i^*}{\partial x_k^* \partial x_k^*} + \frac{\partial}{\partial x_k^*} + (\overline{-U'^*_i U'^*_j}) \end{aligned} \tag{A.2}$$

and

$$\begin{aligned} &\frac{\partial T^*}{\partial t^*} + \frac{U_i^* \partial T^*}{\partial x_i^*} = \\ &\left[\frac{K_o}{\rho_o C_{Po} v_o}\right] \left[\frac{v_o}{L_o U_o}\right] \frac{\partial^2 T^*}{\partial x_k^* \partial x_k^*} + \frac{\partial}{\partial x_i^*} (\overline{- T'^* U'^*_i}) + \left[\frac{v_o}{U_o L_o}\right] \left[\frac{U_o}{C_{po} (\Delta T)_o}\right] \phi \end{aligned} \tag{A.3}$$

where

T	=	temperature;
ρ	=	density;
U	=	velocity;
L	=	length scale;
g	=	acceleration due to gravity;
C_p	=	specific heat at constant pressure;
x_i	=	Cartesian coordinates in tensor notation;
v	=	kinematic viscosity;

K = thermal conductivity;

Ω = angular acceleration of earth;

Φ = dissipation;

and the subscript "*o*" denotes a reference quantity. The dependent and independent variables have been made dimensionless (indicated by an "*") by choosing the appropriate reference values. The prime (′) refers to a fluctuating quantity and $\in_{\mathrm{ijk}}$ is the alternating unit tensor.

For exact similarity, the bracketed quantities and boundary conditions must be the same in the wind tunnel as they are in the corresponding full-scale case. The complete set of requirements for similarity is:

- undistorted geometry;
- equal Rossby number:

$$Ro = \frac{U_o}{L_o \Omega_o} \tag{A.4}$$

- equal gross Richardson number:

$$Ri = \frac{\Delta T_o g_o L_o}{T_o U_o^2} \tag{A.5}$$

- equal Reynolds number:

$$\mathrm{Re} = \frac{U_o L_o}{v_o} \tag{A.6}$$

- equal Prandtl number:

$$\mathrm{Pr} = \frac{v_o \rho_o C_{po}}{K_o} \tag{A.7}$$

- equal Eckert number:

$$Ec = \frac{U_o^2}{L_o \Omega_o} \tag{A.8}$$

- similar surface-boundary conditions; and

- similar approach-flow characteristics.

For exact similarity, each of the above dimensionless parameters must be matched in the model and in full scale for the exhaust flow and ambient flow separately. To ensure that the exhaust plume dispersion is similar relative to the air motion, three additional similarity parameters are required (EPA, 1981) for modeling plume trajectories:

- velocity ratio:

$$R = \frac{U_s}{U_a} \tag{A.9}$$

- densimetric Froude number:

$$Fr = \frac{U_s}{\sqrt{(g\gamma L)}} \tag{A.10}$$

where

$$\gamma = \frac{\rho_s - \rho_a}{\rho_s} \tag{A.11}$$

and

- density ratio:

$$\lambda = \frac{\rho_s}{\rho_a} \tag{A.12}$$

where the subscripts "*s*" and "*a*" denote source and ambient quantity, respectively. All of the above requirements cannot be simultaneously satisfied in the model and full scale. However, some of the quantities are not important for the simulation of many flow conditions. The parameters that can be neglected and those which are important will be discussed in the next section.

A.2. SCALING PARAMETERS THAT CANNOT BE MATCHED

For most studies, simultaneously equalizing Reynolds number, Rossby number, Eckert Number and Richardson number for the model and the prototype is not possible. However, these inequalities are not serious limitations, as will be discussed below.

Reynolds number independence is an important feature of turbulent flows which allows wind-tunnel modeling to be used. The Reynolds number describes the relative importance of inertial forces to viscous forces in fluid flow. Atmospheric wind flows around buildings are characterized by high Reynolds numbers ($>10^6$) and turbulence. Matching high Reynolds numbers in the wind tunnel for the scale reduction of this study would require tunnel speeds 180 to 300 times typical outdoor wind speeds; an impossibility because of equipment limitations and since such speeds would introduce compressible flow (supersonic) effects. Beginning with Townsend (1956), researchers have found that in the absence of thermal and Coriolis (earth rotation) forces, the turbulent flow characteristics are independent of Reynolds number provided the Reynolds number is high enough. EPA (1981) specifies a Reynolds number criterion of about 11,000 for sharp-edged building complexes.

The Reynolds number related to the exhaust gas is defined by

$$\mathrm{Re}_s = \frac{V_e d}{\nu_s} \tag{A.13}$$

Plume rise becomes independent of the exhaust Reynolds number if the plume is fully turbulent at the stack exit (Hoult and Weil, 1972; EPA, 1981). Hoult and Weil (1972) reported that plumes appear to be fully turbulent for stack Reynolds numbers greater than 300. Their experimental data showed that the plume trajectories were similar for Reynolds numbers above this critical value. In fact, the trajectories appeared similar down to $Re_s = 28$ if only the buoyancy dominated portion of the plume trajectory was considered. Hoult and Weil's study was in a laminar cross flow (water tank) with low ambient turbulence levels, and, hence, the rise and dispersion of the plume was primarily dominated by the plume's own self-generated turbulence. Arya and Lape (1990) showed similar plume trajectories for Reynolds numbers greater than 670 for buoyant plumes and greater than 2000 for neutrally buoyant plumes. Care should be taken to ensure Re_s exceeds the minimum values or trips should be installed in the stack to augment the turbulence.

The mean flow field will become Reynolds number independent and characteristic of the atmospheric boundary layer if the flow is fully turbulent (Schlichting, 1978). The critical Reynolds number for this criterion to be met is based on the work of Nikuradse, as summarized by Schlichting (1978), and is given by:

$$\mathrm{Re}_{z_o} = \frac{z_o u_*}{\nu} > 2.5 \tag{A.14}$$

In this relation, z_o is the surface roughness factor. If the scaled down roughness gives a Re_{zo} less than 2.5, then exaggerated roughness would be required. The roughness elements must be larger than about 11 z_f where z_f is the friction length ν/u^*. Below this height, the flow is smooth.

In the event the Reynolds numbers are not sufficiently high, testing should be conducted to establish the expected errors. Recent arguments suggest that Re_{zo} can be as low as 1.0 without introducing serious errors into the simulations. It should be noted that this guidance is based on a neutral atmosphere. For stable stratification, it has been often assumed that a similar limit applies, but no systematic studies have been conducted to confirm this assumption.

Another scaling parameter that has been shown to be important is the Peclet-Richardson number ratio, *Pe/Ri*. The Peclet-Richardson number measures the relative rates of turbulent entrainment and molecular diffusion. If the wind-tunnel simulation is affected by molecular diffusion, the concentrations measured in the wind tunnel will be lower than those in the atmosphere for the same condition. Meroney (1987) reported that researchers at Shell concluded that molecular diffusion may play an important role in the laboratory when the scaled turbulent diffusivity is very small. They found that when the *Pe/Ri* number is less than a critical value, simulations were inaccurate. Their parameter was defined as follows:

$$\frac{Pe}{Ri} = \frac{U_r^3}{(g^{/} \in)} \tag{A.15}$$

where U_r is the reference wind speed, $\in$ is a molecular diffusivity, and $g' = g(\rho_s - \rho_a)/\rho_a$. The criterion has a problem in that two flows with the same reference speed but different turbulence (i.e., neutral versus stable or grassland versus an urban area) will have the same criterion which does not seem appropriate. For this reason, Meroney (1987) suggests the following criterion:

$$\frac{Pe^*}{Ri^*} = \frac{U^{*3}}{(g^{/} \in)} > 2.0 \tag{A.16}$$

Meroney (1987) found that errors in wind-tunnel simulations were noticed when P_e*/R_i* was less than 0.2; hence, all tests should be designed to meet or exceed this value. If tests are needed such that this restriction must be violated, additional tests should be conducted to assess the potential errors when using lower $Pe*/Ri*$ values.

The Rossby number, *Ro*, is a quantity which indicates the effect of the earth's rotation on the flow field. In the wind tunnel, equal Rossby numbers between model and prototype cannot be achieved without a spinning wind tunnel. The effect of the earth's rotation becomes significant if the distance scale is large. EPA (1981) set a conservative cutoff point at 5 km for diffusion studies. For most air quality studies, the maximum range over which the plume is transported is less than 5 km in the horizontal and 100 m in the vertical.

When equal Richardson numbers are achieved, equality of the Eckert number between model and prototype cannot be attained. This is not a serious compromise since the Eckert number is equivalent to a Mach number squared. Consequently, the Eckert number is small compared to unity for laboratory and atmospheric flows and can be neglected.

A.3. DEFINITION OF PARAMETERS IN SIMILARITY TABLE

[1] *Building Height, H_b (Terrain Height, H_t) m*

This is the height of the dominating building (terrain peak) relative to the grade (z=0) which is used for all entries.

Full scale value: Input.

Model scale value: Computed by dividing H_b (or H_z) [1_f] by SF [29_f].

[2] *Base Elevation Above Mean Sea Level, z = 0 (m)*

This is the altitude of the grade (z = 0) relative to mean sea level.

Full scale value: Input.

Model scale value: Constant for CPP's facility in Fort Collins, Colorado: 1524 m.

[3] *Stack Height Above Grade, h (m)*

This is the height of the stack top relative to the grade (z = 0) which is used for all height entries.

Full scale value: Input.

Model scale value: Computed by dividing h [3_f] by SF [29_f].

[4] *Stack Inside Diameter, d (m)*

This is the inside diameter at the stack exit.

Full scale value: Input or Computed.

Model scale value: Computed by dividing d [4_f] by SF [29_f]. Actual modeled stack diameters are rounded to the nearest 1/32nd of an inch due to the restrictions of commercially available brass tubing. Minimum value is 2/32nds to ensure turbulent exhaust.

[5] *Stack Inside Area, A_e (m^2)*

This is the inside area of the stack exit, which is computed from d [4] using the following equation:[1]

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[1] Only two of the three parameters d[4], V_e [6] *or* V [8] are input. The third parameter is then computed using Equations (A.24) and (A.25).

$$A_e = \frac{\pi\, d^2}{4} \tag{A.17}$$

Full scale value: Computed using Equation A.24 with d equal to [4_f].

Model scale value: Computed using Equation A.24 with d equal to [4_m].

This parameter is related to V [8] and V_e [6] by the following equation:

$$A_e = \frac{V}{V_e} \tag{A.18}$$

[6] *Exit Velocity, V_e (m/s)*

This is the exit velocity of the stack gas effluent.

Full scale value: Input or Computed.[1]

Model scale value: Computed by multiplying U_r [18_m] by R [33_m].

[7] *Exit Temperature, T_s (K)*

This is the temperature of the stack gas effluent at the stack exit.

Full scale value: Input.

Model scale value: Constant at the laboratory room temperature ~293K.

[8] *Volume Flow Rate, V (m^3/s)*

This is the actual volume flow rate through the stack at the pressure and temperature given by P_a [10] and T_a [11], respectively.

Full scale value: Input or Computed.[1]

Model scale value: Computed by multiplying A_e [5_m] by V_e [6_m].

[9] *Emission Rate, m (g/s)*

This is the emission rate of any chemical species or gas component. This value is used to compute full scale concentrations based on concentration measurements made in the wind tunnel.

Full scale value: Input.

Model scale value: Since only a tracer gas is used in the wind tunnel, the emission rate of the chemical species or gas component is not applicable (#*NA*) at the model scale.

[10] *Ambient Pressure, P_a (hPa)*

This is the ambient atmospheric pressure at the site (model) location.

Full scale value: Estimated based on the grade elevation of the site z = 0 [2_f]. For sites at mean sea level, P_a is ≈ 1013 hPa. The ambient pressure for sites at other locations is determined using the following equation which was obtained by fitting a curve to the U.S. Standard Atmosphere (1962):

$$P_a = 1013 \exp\left[\frac{x}{-8350}\right] \tag{A.19}$$

where x (m) is the base elevation of the site above mean sea level z = 0 [2_f].

Model scale value: Estimated using Equation A.26 and the elevation of CPP's facility in Fort Collins, Colorado, z = 1524 m [2_m].

[11] *Ambient Temperature, T_a (K)*

This is the ambient annual average temperature at the site (model) location.

Full scale value: Input.

Model scale value: Constant at the laboratory room temperature ~293K.

[12] *Air Density, ρ_a (kg/m^3)*

This is the density of the ambient air. Assuming air behaves as an ideal gas, the following relationship can be used to relate the density of air to temperature and pressure:

$$P_a = 28.96\frac{g}{mole} \div 22.4\frac{1}{mole} \times 273.15K \div T\ (K) \times P\ (atm) \tag{A.20}$$

Full scale value: Computed using Equation A.27 with P equal to [10_f] and T equal to [11_f].

Model scale value: Computed using Equation A.27 with P equal to [10_m] and T equal to [11_m].

[13] *Exhaust Density, ρ_s (kg/m^3)*

This is the density of the stack effluent.

Full scale value: Computed, treating the effluent as air, using Equation A.27 with P equal to [10_f] and T equal to [7_f].

Model scale value: Computed using the following equation, where ρ_a is [12_m], λ is [40_m]:

$$\rho_s = \rho_a\ \lambda \tag{A.21}$$

[14] *Air Viscosity, v_a (m^2/s)*

This is the viscosity of the ambient air. It is computed using the following equation from Vasserman *et al*. (1966):

$$V = \frac{145.8\ T^{3/2}}{\rho\ (T + 110.4)\ 10^8} \tag{A.22}$$

Full scale value: Computed using Equation A.29 where T is equal to [11_f] and ρ is equal to [12_f].

Model scale value: Computed using Equation A.29 where T is equal to [11_m] and ρ is equal to [12_m].

[15] *Gas Viscosity, ν_s (m^2/s)*

This is the viscosity of the stack effluent.

Full scale value: Computed using Equation A.29 where T is equal to [7_f] and ρ is equal to [13_f].

Model scale value: Computed based on the composition of the simulant gas mixture, using the following equations by Wilke (1950):

$$\mu_{mix} = \sum_{i=1}^{n}\left[\frac{X_i \mu_i}{\sum_{j=1}^{n} X_j \Phi_{ij}}\right] \tag{A.23}$$

$$\Phi_{ij} = \frac{1}{\sqrt{8}}\left(1+\frac{M_i}{M_j}\right)^{-1/2}\left[1+\left(\frac{\mu_i}{\mu_j}\right)^{1/2}\left(\frac{M_j}{M_i}\right)^{1/4}\right]^2 \tag{A.24}$$

where n is the number of chemical species in the mixture; X_i and X_j are the mole fractions of species i and j; μ_i and μ_j are the viscosities of species i and j at 1 atm and ~293K; and M_i and M_j are the corresponding molecular weights. Note that Φ_{ij} is dimensionless, and when $i = j$, $\Phi_{ij} = 1$.

[16] *Free Stream Wind Speed, U_∞ (m/s)*

This is the wind speed found at the top of the atmospheric boundary layer where ground based obstructions have no significant influence on the mean wind speed.

Full scale value: Computed using the power law equation which is as follows:

$$U_{z_1} = U_{z_2}\left(\frac{z_1}{z_2}\right)^n \tag{A.25}$$

Where U_{z_2} is [20_f], z_1 is [17_f], z_2 is [21_f] and n is [31_f].

Model scale value: Computed using Equation A.32 where U_{z_2} is [18_m], z_1 is [17_m], z_2 is [19_m] and n is [32_m].

[17] *Free Stream Height, z_∞ (m)*

This is the height above the grade (z = 0) where ground based obstructions have no significant influence on the mean wind speed.

Full scale value: Constant at 600 m (Counihan, 1975).

Model scale value: Computed by dividing z_∞ [17_f] by SF [29_f].

[18] *Reference Wind Speed, U_r (m/s)*

This is the wind speed measured by the instrumentation CPP uses to monitor the wind tunnel speed.

Full scale value: Computed using Equation A.32 where U_{z_2} is [16_f], z_1 is [19_f], z_2 is [17_f] and n is [32_f].

Model scale value: Input.

[19] *Reference Height, z_r (m)*

This is the height above grade where the instrumentation CPP uses to monitor the wind-tunnel speed is mounted in the wind tunnel.

Full scale value: Computed by multiplying z_r [19_m] by *SF* [29_f].

Model scale value: Input.

[20] *Anemometer Wind Speed, U_a (m/s)*

This is the wind speed which would be measured by the anemometer referenced in the study.

Full scale value: Input.

Model scale value: Computed using Equation A.32 where U_{z_2} is [16_m], z_1 is [21_m], z_2 is [17_m] and n is [31_m].

[21] *Anemometer Height, z_a (m)*

This is the height above grade at which the anemometer referenced in the study is mounted.

Full scale value: Input.

Model scale value: Computed by dividing z_a [21_f] by *SF* [29_f].

[22] *Site Wind Speed, U_s (m/s)*

This is the wind speed which would be measured by an anemometer located at the site, at the height given by [23_f] relative to the grade (z = 0).

Full scale value: Computed using Equation A.32 where U_{z_2} is [16_f], z_1 is [23_f], z_2 is [17_f] and n is [32_f].

Model scale value: Computed using Equation A.32 where U_{z_2} is [16_m], z_1 is [23_m], z_2 is [17_m] and n is [32_m].

[23] *'Site Anemometer' Height, z_s (m)*

This is the height above the grade (z = 0) at which a hypothetical anemometer exists at the site. This value differs from [21] only when there is a significant difference in elevation between the anemometer and site locations.

Full scale value: Input.

Model scale value: Computed by dividing z_s [23_f] by *SF* [29_f].

[24] *Stack Height Speed, U_h (m/s)*

This is the wind speed at the top of the stack.

Full scale value: Computed using Equation A.32 where U_{z_2} is [16_f], z_1 is [3_f], z_2 is [17_f] and n is [32_f].

Model scale value: Computed using Equation A.32 where U_{z_2} is [16_m], z_1 is [3_m], z_2 is [17_m] and n is [32_m].

[25] *Building Height Speed, U_b (Terrain Height Speed, U_t) (m/s)*

This is the wind speed at the top of the dominating building (terrain peak).

Full scale value: Computed using Equation A.32 where U_{z_2} is [16_f], z_1 is [1_f], z_2 is [17_f] and n is [32_f].

Model scale value: Computed using Equation A.32 where U_{z_2} is [16_m], z_1 is [1_m], z_2 is [17_m] and n is [32_m].

[26] *Anemometer Surface Roughness Length, $z_{o,a}$ (m)*

This is the surface roughness length estimated for the area surrounding the anemometer referenced in the study.

Full scale value: Input.

Model scale value: Computed by dividing $z_{o,a}$ [26_f] by *SF* [29_f].

[27] *Site Surface Roughness Length, $z_{o,s}$ (m)*

This is the surface roughness length estimated for the site and surrounding area.

Full scale value: Input.

Model scale value: Computed by dividing $z_{o,s}$ [27_f] by *SF* [29_f].

[28] *Surface Friction Velocity, U^* (m/s)*

This is defined as the square root of the surface shear stress divided by the flow density and is determined empirically from the ratio of U^*/U_∞ [45].

Full scale value: Computed by multiplying U^*/U_∞ [45_f] by U_∞ [18_f].

Model scale value: Computed by multiplying U^*/U_∞ [45_m] by U_∞ [18_m].

[29] *Length Scale, SF*

This is the ratio of the full scale to model scale length units. For example, a model scale of 1:300 indicates that 300 m at full scale is represented by 1 m at model scale.

Full scale value: Input.

Model scale value: Constant equal to unity.

[30] *Time Scale, TS*

This is the ratio of the full scale (real world) to model scale (wind-tunnel) time units. Because of the reduced model scale used in the wind tunnel, time based observations (such as video of a looping plume) appear faster than would the same observations made in the real world. For example, in viewing a video of wind-tunnel visualization tests, the observations will appear realistic if the playback speed of the video is slowed down by this factor.

Full scale value: Computed using the following equation:

$$t_f = t_m\, SF \left(\frac{U_{\infty_m}}{U_{\infty_f}} \right) \tag{A.26}$$

Model scale value: Input.

[31] *Anemometer Power Law Exponent, n_a*

This is the power law exponent based on the surface roughness length estimated for the area surrounding the anemometer referenced in the study, computed using the following equation (Counihan, 1975):

$$n = 0.24 + 0.096 \log_{10} z_o + 0.016 \left(\log_{10} z_o \right)^2 \tag{A.27}$$

Full scale value: Computed using Equation A.34 with z_o equal to [26_f].

Model scale value: Equal to n_a [31_f].

[32] *Site Power Law Exponent, n_s*

This is the power law exponent based on the surface roughness length estimated for the site and surrounding area.

Full scale value: Computed using Equation A.34 with z_o equal to [27_f].

Model scale value: Equal to n_s [32_f].

[33] *Velocity Ratio, R*

This is the ratio of the stack exit velocity to the reference wind speed.

Full scale value: Computed by dividing V_e [6_f] by U_r [18_f].

Model scale value: Computed using the following equation:

$$R = \left[\frac{M_o}{\lambda \left(\frac{d}{h} \right)} \right]^{1/2} \tag{A.28}$$

where M_o is [37_m], λ is [40_m], d is [4_m] and h is [3_m].

[34] *Stack Velocity Ratio, R_s*

This is the ratio of the stack exit velocity to the wind speed at the top of the stack.

<u>Full scale value</u>: Computed by dividing V_e [6_f] by U_h [24_f].

<u>Model scale value</u>: Computed by dividing V_e [6_m] by U_h [24_m].

[35] *Stack Height to Building Height Ratio, h/H_b*

(Stack Height to Terrain Height Ratio, h/H_t)

This is the ratio of the stack height to the dominating building (terrain peak) height, where both heights are determined relative to the same grade (z = 0).

<u>Full scale value</u>: Computed by dividing h [3_f] by H_b (or H_t) [1_f].

<u>Model scale value</u>: Computed by dividing h [3_m] by H_b (or H_t) [1_m].

[36] *Diameter to Stack Height Ratio, d/h*

This is the ratio of the inside stack diameter to the height of the stack above grade.

<u>Full scale value</u>: Computed by dividing d [4_f] by h [3_f].

<u>Model scale value</u>: Computed by dividing d [4_m] by h [3_m].

[37] *Momentum Ratio, M_o*

This factor is computed using the following equation:

$$M_o = \left(\frac{V_e}{U_r} \right)^2 \lambda \left(\frac{d}{h} \right)^2 \tag{A.29}$$

<u>Full scale value</u>: Computed using Equation A.36 where (V_e/U_r) is [33_f], λ is [40_f], d is [4_f] and h is [3_f].

<u>Model scale value</u>: Computed using Equation A.36 where (V_e/U_r) is [33_m], λ is [40_m], d is [4_m] and h is [3_m].

[38] *Froude Number, Fr_s*

This factor is computed using the following equation:

$$Fr_s = \left[\frac{V_e^2}{d\ g\left(\frac{1}{\lambda} - 1\right)} \right]^{1/2} \tag{A.30}$$

Full scale value: Computed using Equation A.37 where V_e is [6_f], d is [4_f], g is gravitational acceleration (9.81 m/s^2), and λ is [40_f].

Model scale value: Computed using Equation A.37 where V_e is [6_m], d is [4_m], g is gravitational acceleration (9.81 m/s^2), and λ is [40_m].

[39] *Buoyancy Ratio, B_o*

This factor is computed using the following equation:

$$B_o = \frac{1}{4}\frac{\lambda R^3 d}{Fr_s^2 h} \tag{A.31}$$

Full scale value: Computed using Equation A.38 where λ is [40_f], R is [33_f], d is [4_f], Fr_s is [38_f] and h is [3_f].

Model scale value: Computed using Equation A.38 where λ is [40_m], R is [33_m], d is [4_m], Fr_s is [38_m] and h is [3_m].

[40] *Density Ratio, λ*

This factor is the ratio of the density of the ambient air to the density of the stack effluent.

Full scale value: Computed by dividing ρ_s [13_f] by ρ_a [12_f].

Model scale value: Input based on actual gas mixture used in the wind tunnel.

[41] *Stack Reynolds Number (Exterior), $d\ U_h/\nu_a$*

The Reynolds number is given by the following equation:

$$\mathrm{Re} = \frac{L\ U}{\nu} \tag{A.32}$$

Full scale value: Computed using Equation A.39 where L is [4_f], U is [24_f] and ν is [14_f].

Model scale value: Computed using Equation A.39 where L is [4_m], U is [24_m] and ν is [14_m].

[42] *Stack Flow Reynolds (Interior) Number, Re_s*

Full scale value: Computed using Equation A.39 where L is [4_f], U is [6_f] and ν is [15_f].

Model scale value: Computed using Equation A.39 where L is [4_m], U is [6_m] and ν is [15_m].

[43] *Building Reynolds Number, Re_b (Terrain Reynolds Number, Re_t)*

Full scale value: Computed using Equation A.39 where L is [1_f], U is [25_f] and ν is [14_f].

Model scale value: Computed using Equation A.39 where L is [1_m], U is [25_m] and ν is [14_m].

[44] *Surface Reynolds Number, $z_{o,s}\,U^*/\nu_a$*

Full scale value: Computed using Equation A.39 where L is [27_f], U is found as the product of U^*/U_∞ [45_f] and U_∞ [16_f], and ν is [14_f].

Model scale value: Computed using Equation A.39 where L is [27_m], U is found as the product of U_*/U_∞ [45_m] and [16_m], U_∞ and ν is [14_m].

[45] *Site Friction Velocity Ratio, U^*/U_∞*

This factor is computed using the following equation:

$$\frac{U_*}{U_\infty} = \sqrt{0.00275 + 0.0006\log\left(z_o\right)} \qquad \text{(A.33)}$$

Full scale value: Computed using Equation A.40 where z_o is equal to [27_f].

Model scale value: Set equal to U^*/U_∞ [45_f].

For Atmospheric Dispersion Comparability (ADC) tests, the following distinctions apply to the definitions given above:

- H_b (or H_t) [1] is not applicable since ADC tests are conducted in the absence of buildings, elevated terrain, or other obstructions;
- h [3], the height of the ADC stack, is usually chosen to be an even increment of 50 m (i.e., 50, 100, 150, 200 m…);
- d [4] is chosen by first computing 0.05h or 0.025h (whichever stack to diameter ratio will be more representative of the stack being evaluated in the study). Using the procedure previously described for d [4_m], an actual size of tubing is selected for the model. The equivalent full scale diameter which is exactly equal to the actual model diameter (tubing size) is then input as d [4_f];
- V_e [6] is set equal to 1.5 U_h, where U_h is given by [24_f];
- T_s [7] is set equal to T_a, where T_a is [11];
- V [8] is computed from d [4] and V_e [6] using Equations A.24 and A.25;
- m [9] is set equal to unity; and
- $z_{o,s}$ [27] is set equal to 0.1 m for a “rural” ADC test, and 1 m for an “urban” ADC test.

For Reynolds number independence tests, the following distinctions apply to the definitions given above:

- according to the EPA guideline (1985), h [3] should be set equal to H_b (or H_t) [1];
- V_e [6] is set equal to 1.5 U_h, where U_h is given by [24_f];
- T_s [7] is set equal to T_a, where T_a is [11];
- V [8] is computed from d [4] and V_e [6] using Equations A.24 and A.25; and
- m [9] is set equal to unity.

A.4. REFERENCES

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TABLES

Table A-1 (Low roughness approach, Zo=0.031m)
Full and Model Scale Similarity Parameters
Combustion Turbine Stack 1 (CT-1)
Anemometer Wind Speed =8.2 m/s

Dimensional Parameters	**Full Scale**	**Model Scale**
1 . Typical Building Height, Hb (m)	37.80	0.09
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	5.34	1,524.00
3 . Stack Height above grade, h (m)	47.41	0.12
4 . Stack Inside Diameter, d (m)	5.59	1.429E-02
5 . Stack Inside Area, A_e (m^2)	24.54	1.603E-04
6 . Exit Velocity, V_e (m/s)	22.26	6.00
7 . Exit Temperature, T_s (K)	362.04	293.15
8 . Volume Flow Rate, V (m^3/s)	546.10	9.613E-04
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	1,012.35	844.00
11 . Ambient Temperature, T_a (K)	294.26	293.15
12 . Air Density, ρ_a (kg/m^3)	1.20	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.97	0.82
14 . Air Viscosity, ν_a (m^2/s)	1.52E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	2.18E-05	1.42E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	15.32129938	4.22
17 . Free Stream Height, z_{inf} (m)	600.00	1.50
18 . Reference Wind Speed, U_{ref} (m/s)	14.53	4.00
19 . Reference Height, z_{ref} (m)	400.00	1.00
20 . Anemometer Wind Speed, U_a (m/s)	8.20	2.26
21 . Anemometer Height, z_a (m)	20.00	0.05
22 . Site Wind Speed, U_s (m/s)	9.79	2.70
23 . Site Anemometer' Height, z_s (m)	20.00	0.05
24 . Stack Height Speed, U_h (m/s)	10.97	3.02
25 . Building Height Speed, Ub (m/s)	10.65	2.93
26 . Anemometer Surface Roughness Length, $z_{o,a}$ (m)	0.22	5.50E-04
27 . Site Surface Roughness Length, $z_{o,s}$ (m)	0.03	7.75E-05
28 . Site Surface Friction Velocity, U_* (m/s)	0.66	0.18
Dimensionless Parameters		
29 . Length Scale, SF	400.00	1.00
30 . Time Scale, TS	110.18	1.00
31 . Anemometer Power Law Exponent, n_a	0.18	0.18
32 . Site Power Law Exponent, n_s	0.13	0.13
33 . Velocity Ratio, $R = V_e/U_r$	1.53	1.50
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	2.03	1.98
35 . Stack Height to Building Height Ratio, h/Hb	1.25	1.25
36 . Diameter to Stack Height Ratio, d/h	0.12	0.12
37 . Momentum Ratio, M_o	2.65E-02	2.65E-02
38 . Froude Number, Fr_s	6.26	33.37
39 . Buoyancy Ratio, B_o	2.20E-03	7.40E-05
40 . Density Ratio, λ	0.81	0.81
41 . Stack Reynolds Number (Exterior), $d\ U_h / \nu_a$	4.04E+06	2,388.35
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\ V_e / \nu_s$	5.70E+06	6,021.64
43 . Building Reynolds Number, Reb = Hb Ub / Nua	2.65E+07	15,335.32
44 . Surface Reynolds Number, $z_{o,s}\ U_* / \nu_a$	1.34E+03	0.78
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.04	0.04

Table A-2 (Low roughness approach, Zo=0.031m)
Full and Model Scale Similarity Parameters
Combustion Turbine Stack 2 (CT-2)
Anemometer Wind Speed =8.2 m/s

Dimensional Parameters	**Full Scale**	**Model Scale**
1 . Typical Building Height, Hb (m)	37.80	0.09
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	5.34	1,524.00
3 . Stack Height above grade, h (m)	47.41	0.12
4 . Stack Inside Diameter, d (m)	5.59	1.429E-02
5 . Stack Inside Area, A_e (m^2)	24.54	1.603E-04
6 . Exit Velocity, V_e (m/s)	22.26	6.00
7 . Exit Temperature, T_s (K)	362.04	293.15
8 . Volume Flow Rate, V (m^3/s)	546.10	9.613E-04
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	1,012.35	844.00
11 . Ambient Temperature, T_a (K)	294.26	293.15
12 . Air Density, ρ_a (kg/m^3)	1.20	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.97	0.82
14 . Air Viscosity, ν_a (m^2/s)	1.52E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	2.18E-05	1.42E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	15.32	4.22
17 . Free Stream Height, z_{inf} (m)	600.00	1.50
18 . Reference Wind Speed, U_{ref} (m/s)	14.53	4.00
19 . Reference Height, z_{ref} (m)	400.00	1.00
20 . Anemometer Wind Speed, U_a (m/s)	8.20	2.26
21 . Anemometer Height, z_a (m)	20.00	0.05
22 . Site Wind Speed, U_s (m/s)	9.79	2.70
23 . Site Anemometer' Height, z_s (m)	20.00	0.05
24 . Stack Height Speed, U_h (m/s)	10.97	3.02
25 . Building Height Speed, Ub (m/s)	10.65	2.93
26 . Anemometer Surface Roughness Length, $z_{o,a}$ (m)	0.22	5.50E-04
27 . Site Surface Roughness Length, $z_{o,s}$ (m)	0.03	7.75E-05
28 . Site Surface Friction Velocity, U_* (m/s)	0.66	0.18
Dimensionless Parameters		
29 . Length Scale, SF	400.00	1.00
30 . Time Scale, TS	110.18	1.00
31 . Anemometer Power Law Exponent, n_a	0.18	0.18
32 . Site Power Law Exponent, n_s	0.13	0.13
33 . Velocity Ratio, $R = V_e/U_r$	1.53	1.50
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	2.03	1.98
35 . Stack Height to Building Height Ratio, h/Hb	1.25	1.25
36 . Diameter to Stack Height Ratio, d/h	0.12	0.12
37 . Momentum Ratio, M_o	2.65E-02	2.65E-02
38 . Froude Number, Fr_s	6.26	33.37
39 . Buoyancy Ratio, B_o	2.20E-03	7.40E-05
40 . Density Ratio, λ	0.81	0.81
41 . Stack Reynolds Number (Exterior), $d\ U_h / \nu_a$	4.04E+06	2,388.35
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\ V_e / \nu_s$	5.70E+06	6,021.83
43 . Building Reynolds Number, Reb = Hb Ub / Nua	2.65E+07	15,335.32
44 . Surface Reynolds Number, $z_{o,s}\ U_* / \nu_a$	1.34E+03	0.78
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.04	0.04

Table A-3 (High roughness approach, Zo=0.238m)
Full and Model Scale Similarity Parameters
Combustion Turbine Stack 1 (CT-1)
Anemometer Wind Speed =8.2 m/s

Dimensional Parameters	**Full Scale**	**Model Scale**
1 . Typical Building Height, Hb (m)	37.80	0.09
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	5.34	1,524.00
3 . Stack Height above grade, h (m)	47.41	0.12
4 . Stack Inside Diameter, d (m)	5.59	1.429E-02
5 . Stack Inside Area, A_e (m^2)	24.54	1.603E-04
6 . Exit Velocity, V_e (m/s)	22.26	5.99597
7 . Exit Temperature, T_s (K)	362.04	293.15
8 . Volume Flow Rate, V (m^3/s)	546.10	9.613E-04
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	1,012.35	844.00
11 . Ambient Temperature, T_a (K)	294.26	293.15
12 . Air Density, ρ_a (kg/m^3)	1.20	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.97	0.82
14 . Air Viscosity, ν_a (m^2/s)	1.52E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	2.18E-05	1.42E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	15.32129938	4.22
17 . Free Stream Height, z_{inf} (m)	600.00	1.50
18 . Reference Wind Speed, U_{ref} (m/s)	14.21	3.91
19 . Reference Height, z_{ref} (m)	400.00	1.00
20 . Anemometer Wind Speed, U_a (m/s)	8.20	2.26
21 . Anemometer Height, z_a (m)	20.00	0.05
22 . Site Wind Speed, U_s (m/s)	8.13	2.24
23 . Site Anemometer' Height, z_s (m)	20.00	0.05
24 . Stack Height Speed, U_h (m/s)	9.55	2.63
25 . Building Height Speed, Ub (m/s)	9.15	2.52
26 . Anemometer Surface Roughness Length, $z_{o,a}$ (m)	0.22	5.50E-04
27 . Site Surface Roughness Length, $z_{o,s}$ (m)	0.24	5.95E-04
28 . Site Surface Friction Velocity, U_* (m/s)	0.75	0.21
Dimensionless Parameters		
29 . Length Scale, SF	400.00	1.00
30 . Time Scale, TS	110.18	1.00
31 . Anemometer Power Law Exponent, n_a	0.18	0.18
32 . Site Power Law Exponent, n_s	0.19	0.19
33 . Velocity Ratio, $R = V_e/U_r$	1.57	1.53
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	2.33	2.28
35 . Stack Height to Building Height Ratio, h/Hb	1.25	1.25
36 . Diameter to Stack Height Ratio, d/h	0.12	0.12
37 . Momentum Ratio, M_o	2.77E-02	2.77E-02
38 . Froude Number, Fr_s	6.26	33.37
39 . Buoyancy Ratio, B_o	2.35E-03	7.91E-05
40 . Density Ratio, λ	0.81	0.81
41 . Stack Reynolds Number (Exterior), $d\, U_h / \nu_a$	3.52E+06	2,078.31
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\, V_e / \nu_s$	5.70E+06	6,021.64
43 . Building Reynolds Number, Reb = Hb Ub / Nua	2.28E+07	13,180.13
44 . Surface Reynolds Number, $z_{o,s}\, U_* / \nu_a$	1.17E+04	6.77
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.05	0.05

Table A-4 (High roughness approach, Zo=0.238m)
Full and Model Scale Similarity Parameters
Combustion Turbine Stack 2 (CT-2)
Anemometer Wind Speed =8.2 m/s

Dimensional Parameters	**Full Scale**	**Model Scale**
1 . Typical Building Height, Hb (m)	37.80	0.09
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	5.34	1,524.00
3 . Stack Height above grade, h (m)	47.41	0.12
4 . Stack Inside Diameter, d (m)	5.59	1.429E-02
5 . Stack Inside Area, A_e (m^2)	24.54	1.603E-04
6 . Exit Velocity, V_e (m/s)	22.26	6.00
7 . Exit Temperature, T_s (K)	362.04	293.15
8 . Volume Flow Rate, V (m^3/s)	546.10	9.613E-04
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	1,012.35	844.00
11 . Ambient Temperature, T_a (K)	294.26	293.15
12 . Air Density, ρ_a (kg/m^3)	1.20	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.97	0.82
14 . Air Viscosity, ν_a (m^2/s)	1.52E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	2.18E-05	1.42E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	15.32	4.22
17 . Free Stream Height, z_{inf} (m)	600.00	1.50
18 . Reference Wind Speed, U_{ref} (m/s)	14.21	3.91
19 . Reference Height, z_{ref} (m)	400.00	1.00
20 . Anemometer Wind Speed, U_a (m/s)	8.20	2.26
21 . Anemometer Height, z_a (m)	20.00	0.05
22 . Site Wind Speed, U_s (m/s)	8.13	2.24
23 . Site Anemometer' Height, z_s (m)	20.00	0.05
24 . Stack Height Speed, U_h (m/s)	9.55	2.63
25 . Building Height Speed, Ub (m/s)	9.15	2.52
26 . Anemometer Surface Roughness Length, $z_{o,\,a}$ (m)	0.22	5.50E-04
27 . Site Surface Roughness Length, $z_{o,\,s}$ (m)	0.24	5.95E-04
28 . Site Surface Friction Velocity, U_* (m/s)	0.75	0.21
Dimensionless Parameters		
29 . Length Scale, SF	400.00	1.00
30 . Time Scale, TS	110.18	1.00
31 . Anemometer Power Law Exponent, n_a	0.18	0.18
32 . Site Power Law Exponent, n_s	0.19	0.19
33 . Velocity Ratio, $R = V_e/U_r$	1.57	1.53
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	2.33	2.28
35 . Stack Height to Building Height Ratio, h/Hb	1.25	1.25
36 . Diameter to Stack Height Ratio, d/h	0.12	0.12
37 . Momentum Ratio, M_o	2.77E-02	2.77E-02
38 . Froude Number, Fr_s	6.26	33.37
39 . Buoyancy Ratio, B_o	2.35E-03	7.91E-05
40 . Density Ratio, λ	0.81	0.81
41 . Stack Reynolds Number (Exterior), $d\ U_h / \nu_a$	3.52E+06	2,078.31
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\ V_e / \nu_s$	5.70E+06	6,021.83
43 . Building Reynolds Number, Reb = Hb Ub / Nua	2.28E+07	13,180.13
44 . Surface Reynolds Number, $z_{o,\,s}\ U_* / \nu_a$	1.17E+04	6.77
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.05	0.05

APPENDIX

B

EXPERIMENTAL METHODS

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EXPERIMENTAL METHODS

B.1. Concentration Measurements

After the desired atmospheric condition is established in the wind tunnel, a mixture of inert gas and a tracer (ethane, methane and/or propane) of predetermined concentration is released from the stacks at the required rate to simulate prototype plume rise. Samples of gas are withdrawn from the sampling points and analyzed. The flow rate of the gas mixture is controlled by a pressure regulator at the supply cylinder outlet and monitored by a precision flow meter.

The test procedure consists of: 1) setting the proper tunnel wind speed; 2) releasing a metered mixture of source gas of the required density from the stacks; 3) withdrawing samples of air from the tunnel at designated locations; and 4) analyzing the samples with a flame ionization gas chromatograph (FIGC). The samples are collected simultaneously over a 200 s (approximate) time using CPP's sampling system and consecutively injected into a FIGC. The sampling system is tested periodically to insure all gas syringes and tubing connections are operating properly. The linearity of the FIGC is checked periodically.

B.2. Analysis Procedure

The procedure for analyzing the air samples from the tunnel is as follows: 1) the 30 cc sample volume drawn from the wind tunnel is introduced into a 2 cc gas sampling loop; 2) the 2cc sample is injected into the FIGC column; 3) the flame ionization detector (FID) indicates the presence and measures the amount of components in the column effluent; 4) the voltage output from the FID is captured by a computer-based analog-to-digital converter; 5) the digitized signal is analyzed for the peak height which is proportional to the amount of hydrocarbon present in the sample; 6) the peak heights and pertinent run information are stored in a computer file; and 7) a data reduction program converts peak voltages to full scale concentrations.

B.3. Calculation of Full-Scale Concentrations

Measured model concentrations are converted to full-scale normalized concentrations by equating the non-dimensional concentration, $K = CUL^2/m$, in both model and full scale, as noted in the following equation presented in the Guideline for Use of Fluid Modeling of Atmospheric Diffusion (EPA 1981):

$$\left(\frac{C}{m}\right)_f = \left(\frac{CU_r}{m}\right)_m \left(\frac{1}{U_r}\right)_f \left(\frac{L_m}{L_f}\right)^2 \tag{B.1}$$

where

$$C_m = \left[\left(\frac{E_{meas} - E_o}{E_{cal}}\right)_{rec} - \left(\frac{E_{meas} - E_o}{E_{cal}}\right)_{bg}\right] x \left(\frac{C_{cal}}{C_o}\right) \times \frac{1}{V_m} \times 10^6 \tag{B.2}$$

C_f	=	full scale concentration of pollutant (µg/m^3);
C_m	=	model scale concentration of tracer gas (µg/m^3);
C_{cal}	=	calibration gas concentration (ppm);
C_o	=	tracer gas concentration at source (ppm);
E_{meas}	=	voltage reading from HFFID for measured sample (V);
E_o	=	zero offset voltage reading from HFFID (V);
E_{cal}	=	voltage reading from HFFID for calibration gas sample (V);
L	=	length scale (m);
m	=	chemical mass emission rate (g/s);
U_r	=	reference wind speed (m/s);
V_m	=	model volume flow rate (m^3/s);
10^6	=	conversion from g to µg; and

the subscripts *rec* and *bg* denote measurements at the receptor and background, respectively.

The 200 second sample, discussed in Section B.1.1.1 is representative of a steady-state average. In the full scale, a steady-state average concentration corresponds to a 15 minute to 1 hour average concentration due to the natural fluctuations in both wind speed and wind direction present within the atmosphere.

Full scale concentration estimates for averaging times less than 24 hours can be obtained using the following power law relationship defined by Turner (1974):

$$\left(\frac{C}{m}\right)_s = \left(\frac{C}{m}\right)_k \times \left(\frac{t_k}{t_s}\right)^p \qquad \text{(B.3)}$$

where:

$(C/m)_s$ = normalized concentration estimate for averaging time t_s;

$(C/m)_k$ = normalized concentration estimate for averaging time t_k; and

p = power law exponent between 0.17 and 0.20.

B.4. Error Analysis

The full-scale concentration results have certain experimental errors associated with them. To estimate the experimental error, referred to as uncertainty interval, the technique outlined by Kline and McClintock (1953) is used, which results in the following error equation:

$$\left(\frac{\Delta C}{C}\right)_f = \left[\left(\frac{\Delta C}{C}\right)_m^2 + \left(\frac{\Delta C_{cal}}{C_{cal}}\right)_m^2 + \left(\frac{\Delta C_o}{C_o}\right)_m^2 + \left(\frac{\Delta L}{L}\right)_m^2 + \left(\frac{\Delta U_r}{U_r}\right)_m^2 + \left(\frac{\Delta V}{V}\right)_m^2\right]^{1/2} \qquad \text{(B.4)}$$

where

$(\Delta C/C)_m$ = uncertainty in measured concentration, ± 0.15 for low concentrations, and ± 0.05 for high concentrations;

$(\Delta C_{cal}/C_{cal})_m$ = uncertainty in calibration gas concentration, ± 0.02;

$(\Delta C_o/C_o)_m$ = uncertainty in initial tracer gas concentration, ± 0.02;

$(\Delta L/L)_m$ = uncertainty in length scale reduction, ± 0.01;

$(\Delta U_r/U_r)_m$ = uncertainty in reference wind speed, ± 0.05, and

$(\Delta V/V)_m$ = uncertainty in volume flow setting, ± 0.02.

Substituting the above uncertainty estimates into Equation B.4 gives the following uncertainty for the full-scale concentrations:

$(\Delta C/C)_f$ = ± 0.16 for low concentrations ($C_f < 100$ μg/m^3),

= ± 0.08 for high concentrations ($C_f > 100$ μg/m^3).

B.5. Quality Control

To ensure that the data collected is accurate and reliable, certain quality control steps are taken. To summarize, these include:

- multi point calibration of hydrocarbon analyzer using certified standard gases;
- calibration of flow measuring devices with a soap bubble meter;
- adjustment of tunnel roof so that blockage effects (i.e., reduction of cross-sectional area) are less than 5 percent; and
- periodical testing of the linearity of the voltage response of the HFFID.

B.6. Velocity Measurements

Split-film (dual hot-film sensor) and hot-film or hot-wire (single sensor) probes are used to measure velocities. The dual sensor probe is used to measure mean velocity (*U*), longitudinal turbulence intensity (*U'*), vertical turbulence intensity (*W'*) and surface friction velocity (*U**) while the single sensor probe was used to measure *U* and *U'*. The theory of operation for split-film and hot-film sensors is based on the physical principle that heat transferred from a sensor equals heat supplied to that sensor by an anemometer. This physical principle can be represented by the following equations.

For the hot-film sensor:

$$\frac{E_1^2}{K_1} = A + BU^C \tag{B.5}$$

and for the split-film sensor:

$$\left(\frac{E_1{}^2}{K_1}\right) + \left(\frac{E_2{}^2}{K_2}\right) = \left[A + B(U_n)^C\right] \tag{B.6}$$

and

$$\left(\frac{E_1{}^2}{K_1}\right) - \left(\frac{E_2{}^2}{K_1}\right) = (a + bU_n)(\theta_o - \theta) + c \tag{B.7}$$

where

E_i	=	output voltage from a sensor;
K_i	=	$R_{Hot,\,i}\,(R_{Hot,\,i} - R_{Cold,i})$;
U, U_n	=	the velocity sensed;
A, B, C, a, b, c	=	constants determined by calibration;
R_{Cold}	=	Resistance across hot film with baseline voltage applied;
θ	=	angle formed by plane of sensor splits and the velocity vector;
θ_o	=	change in θ;
R_{Hot}	=	resistance across hot film with overheat ratio applied $\left(\frac{R_{Hot}}{R_{Cold}} = 1.5\right)$.

Sensor calibrations are accomplished immediately prior to each velocity measurement activity. For low flow calibrations (<1.5 m/s) the sensor is placed within a Thermo–Systems, Inc. calibration nozzle and a Hastings Mass Flow meter is used to provide a metered air flow through the calibrator. High flow calibrations (> 1.5 m/s) are accomplished by placing the sensor adjacent to a pitot-static tube mounted in the wind tunnel. The constants *A*, and *C* (or *A, B, C, a, b, c* and θ_o) are obtained by calibrating the sensors over a range of known velocities (or velocities and angles) and determined by a least squares analysis utilizing the appropriate previously referenced equations.

A hot-film probe (TSI Model No. 121020) is used to obtain one-dimensional measurements of mean (*U*) and fluctuating (*U'*) wind speed (i.e., turbulence). A split-film probe (TSI Model No.

1287) is used to obtain the two-dimensional measurements of mean (*U* and *W* or *V*) and fluctuating (*U'* and *W'* or *V'*) wind speed. Lateral and vertical profiles of mean velocity and turbulence are obtained by affixing the probe to a traversing carriage which relates height (*z*) or lateral position (*y*) to voltage output. All data are obtained by sampling the probe output at sample rates ranging from 30 Hz to 400 Hz depending upon the approach wind speed. The data is then reduced by the computer in real-time and stored in files for later analysis.

B.7. REFERENCES

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Kline, S.J., and F.A. McClintock, "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, Vol. 75, January 1953.

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APPENDIX
C

IMPROVED BUILDING DIMENSION INPUTS FOR AERMOD MODELING OF THE MIRANT POTOMAC RIVER GENERATING STATION

Improved Building Dimension Inputs for AERMOD Modeling of the Mirant Potomac River Generating Station

Paper # 276

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ABSTRACT

This paper describes a wind tunnel modeling study conducted for the Mirant Potomac River Generating Station (MPRGS) located in Alexandria, Virginia. The study was commissioned because a screening-level model indicated potential for plume impacts at a nearby uniquely-shaped high-rise building within a few hundred meters of the station, constructed long after the station started operation in 1949. Due to the complex interaction between the two buildings, both a computer dispersion modeling study using AERMOD and a wind-tunnel modeling study were undertaken to help answer questions about potential impacts. The wind-tunnel study was conducted to obtain a better understanding of the concentration spatial distribution on and around the high-rise building and to provide site-specific building dimension inputs (i.e., Equivalent Building Dimensions or EBD) for AERMOD, to account for the complex building interactions in a form that AERMOD could handle. The study also had the important goal to help MPRGS design modifications to the plant that would help reduce potential ambient impacts on the high-rise building and other areas in the vicinity of the plant.

INTRODUCTION

This paper describes a wind tunnel study conducted for the Mirant Potomac River Generating Station (MPRGS) located as shown in Figure 1. The study was commissioned by Mirant because a USEPA recommended computer dispersion model, AERMOD[1], predicted high impacts of plant emissions on a nearby high-rise tower (Marina Towers) as shown in Figure 2. The tower was built near the plant without the benefit of site-specific modeling or a wind tunnel study in the 1970s, long after the MPRGS was built in 1949. The heights of the stacks at MPRGS were restricted due to the proximity of the power plant to Reagan National Airport.

Since AERMOD was predicting high concentration levels on the Marina Towers (MT) and at various ground level locations surrounding MPRGS, a wind tunnel study was undertaken to obtain a better understanding of the concentration spatial distribution on and around MT and to provide site-specific building dimension inputs for AERMOD.[2]

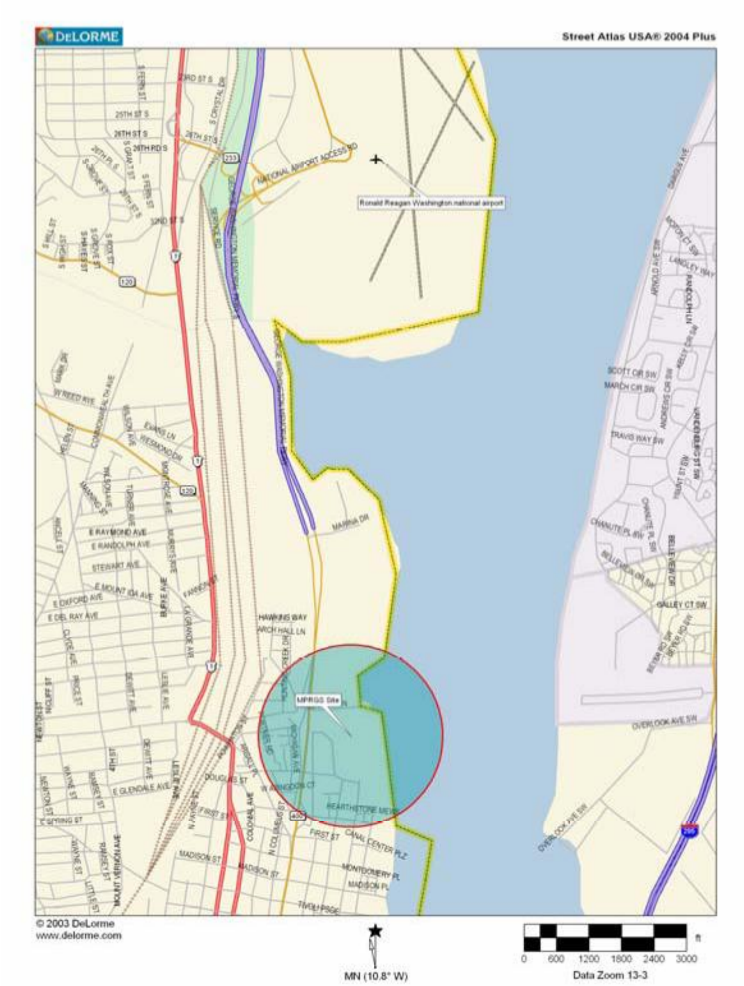

Figure 1. Location of area modeled in wind tunnel

Since AERMOD has advanced building downwash and plume rise modeling capabilities, it was anticipated that if the "correct" building dimensions are input into the model it will produce accurate concentrations estimates. The EBD values are the building height, width, length and position that should be input into AERMOD to allow the model to produce an accurate representation of concentration spatial distributions due to all site building wake effects. When a single solid rectangular building is adjacent to a stack and the wind flow is perpendicular to a building face, the actual building dimensions are the appropriate inputs. An estimate of these dimensions for each wind direction is normally determined using the Building Profile Input Program (BPIP). For more complicated situations, such as for this application, the use of EBD values for model input will result in more accurate concentration estimates, and hence, an optimal determination of any required mitigation.

The only practical manner for determining EBD is through the use of wind tunnel modeling.[3,4,5,6,7] To conduct the wind tunnel simulations, a detailed physical model of MPRGS and nearby structures (including MT) was created to test their impacts on plume dispersion. The wind tunnel testing was divided into two main phases for both the current and future design of the MPRGS: EBD determination for predicting ground-level impacts; and EBD determination for determining MT impacts. For the first phase of testing, EBD values were determined to account for the combined effect of MT and the MPRGS. The second phase of testing involved obtaining EBD values for characterizing the impact on MT due to the effect of MPRGS. These EBD values were used as an input for AERMOD to obtain a better representation of building effects on concentration estimates on MT and at ground level.

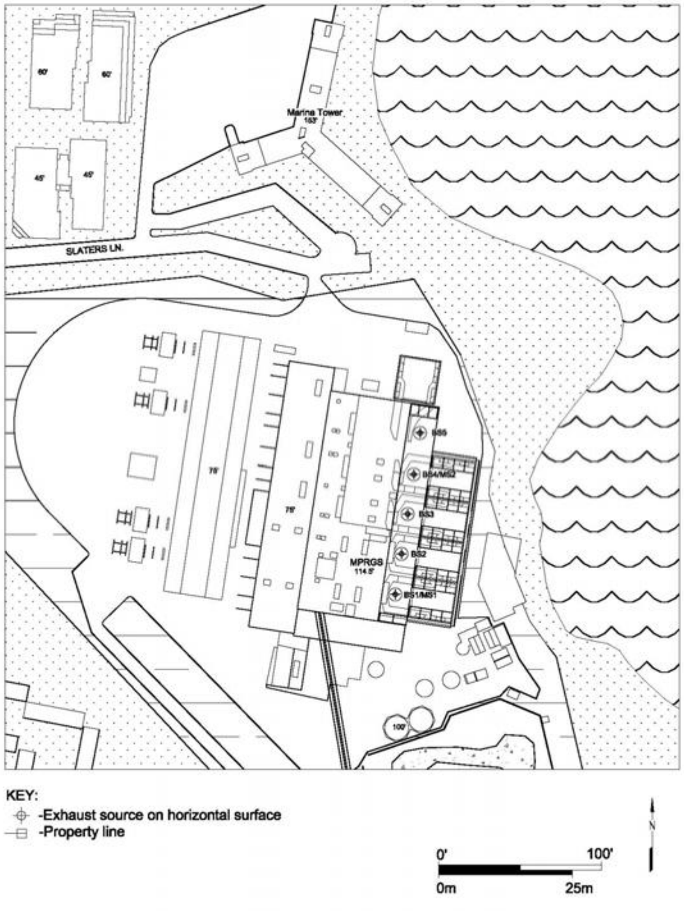

Figure 2. Close up view of area modeled

This paper focuses on the methods used to obtain the EBD and provides a comparison between the EBD and BPIP determined building dimension inputs values. The general use of the EBD values in AERMOD is discussed in a paper by Petersen.[8] The use of the EBD values developed in this study for AERMOD application is discussed in Shea.[9]

SIMILARITY REQUIREMENTS

To model plume trajectories for the EBD determinations, the velocity ratio, $R\ (V_e/U_h)$, and density ratio, $\lambda\ (\rho_s/\rho_a)$ were matched in model and full scale where U_h = wind velocity at stack top (m/s), V_e = stack gas exit velocity (m/s), ρ_s = stack gas density (kg/m^3), and ρ_a = ambient air density (kg/m^3). In addition, the stack gas flow in the model was fully turbulent upon exit as it is in the full scale.

To simulate the airflow and dispersion around the buildings, the following criteria were met as recommended by EPA[10]: 1) all structures within a 518-m (1700-ft) radius of the stacks were modeled at a 1:300 scale reduction; 2) appropriate mean and turbulent approach boundary layer was established; 3) building Reynolds number independence was verified through testing; 4) a neutral atmospheric boundary layer was established simulating an approach surface roughness of 0.79 m for wind directions of 175-360 (urbanized sector) and 0.15 m for all other wind directions (water and low roughness sector).

The above scaling parameters were used to determine the model operating conditions. It should be noted that the use of these scaling parameters is the recommended method for determining GEP stack heights by EPA[11] and have been used on past EBD studies. The use of these scaling parameters does not include an exact simulation of full buoyancy, and as a result, full-scale plume rise is underestimated (i.e., a conservative scaling approach). If one wants to compare the wind tunnel results with AERMOD, the full scale source parameters have to be back calculated from the conditions set in the wind tunnel by using the appropriate buoyancy and momentum scaling method.[10] These full scale conditions are provided in Table 1.

Table 1. Model Inputs

Exhaust Stack Parameters

Source ID:	Existing Boilers		Future Merged Boilers*	
	BS1, BS2	BS3, BS4, BS5	MS1	MS2
Exit Diameter, d (m)	2.59	2.44	2.59	3.05
Stack Height, H_s (m)	48.2	48.2	48.2	48.2
Exit Temperature, T_s (K)	304.9	303.7	304.9	303.7
Volume Flow Rate, V (m^3/s)	111.5	86.0	223.1	257.9
Exit Velocity, U_s (m/s)	21.2	18.4	42.3	35.4
* MS1 consists of merging the BS1 and BS2 exhaust in to the BS1 exhaust flue and MS2 consists of merging BS3, BS4 and BS5 exhausts into the BS4 exhaust flue.				

Ambient Parameters

Wind Direction	1-174	175-360
Stack Height Wind Speed, U_h (m/s)	12.52	10.8
Approach Roughness, z_o (m)	0.15	0.79
Ambient Temperature, T_a (K)	298.15	298.15

DETERMINATION OF EBD VALUES

Ground Level

The basic modeling approach for determining EBD values is to first document, in the wind tunnel, the dispersion characteristics as a function of wind direction at the site with all significant nearby structure wake effects included. Next, the dispersion is characterized, in the wind tunnel, with an equivalent building positioned directly upwind of the stack in place of all nearby structures. This testing is conducted for various equivalent buildings until an equivalent building is found that provides a profile of maximum ground-level concentration versus downwind distance that is similar (within the constraints defined below) to that with all site structures in place.

The criteria for defining whether or not two concentration profiles are similar is to determine the smallest building which: 1) produces an overall maximum concentration exceeding 90 percent of the overall maximum concentration observed with all site structures in place; and 2) at all other longitudinal distances, produces ground-level concentrations which exceed the ground-level concentration observed with all site structures in place less 20 percent of the overall maximum ground-level concentration with all site structures in place.

To demonstrate the method for specifying the EBD values, consider Figure 3 which shows a typical result from this study. The figure shows the maximum ground-level concentration versus downwind distance for five different equivalent buildings and the maximum concentration measured with site structures in place. Within this figure, the concentration profile for EBD 11.5 meets the first criterion in that the maximum measured concentration is at least 90 percent of the maximum concentration measured with the site structures in place. (Note, the 11.5 is building height in model centimeters. Multiple by 3 to obtain the full-scale height in meters). However, the EBD 11.5 profile fails the second criterion at the third actual site data point (at approximately 180 m downwind) where the lower bound of the error bar exceeds the interpolated concentration value for EBD 11.5. Therefore, the equivalent building for the test case shown in Figure 3 is EBD 12, since EBD 12 is the smallest equivalent building which meets both criteria.

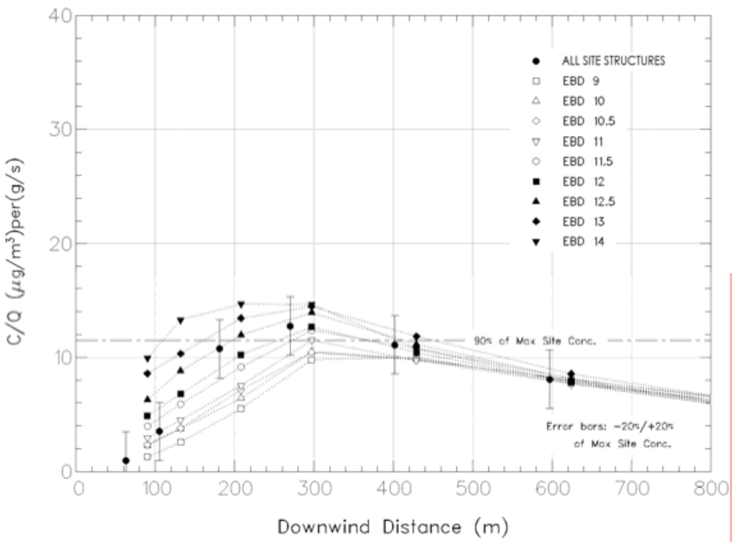

Figure 3. Typical Ground Level EBD Results for BS4

Marina Towers

In addition to traditional ground-level EBD values for the purpose of predicting ground-level impacts, EBD values were also determined to serve as an AERMOD input when the impact of MPRGS on MT is being evaluated. In this case, the approach for determining EBD values was to first document, in the wind tunnel, the concentration levels as a function of wind direction on MT with all significant nearby structure wake effects included. For testing with the EBD structures, the MPRGS and MT were removed, but the rest of the site remained the same (i.e., surrounding buildings, terrain, etc.) MT was replaced with a "flag pole" receptor grid with sampling points at the same locations as those obtained when MT was in place to replicate the way the receptors are represented in the AERMOD model. Then, the stack under evaluation was placed in its respective location with the same height above grade. Various EBD structures were then placed directly upwind of the stack of interest.

The determination of EBD values for the impact on MT is similar to that described in the previous section with the exception of the type of data profile evaluated. For this phase of EBD determination, the data points were ranked from largest to smallest for the site structures and EBD tests. The site structure profiles were then compared with the EBD profiles for EBD determination. The criteria for defining whether two-ranked concentration profiles were similar was the same as that described above.

Figure 4 shows typical results from this study. Within this figure, the profiles for the EBD 8 1:4:1, EBD 9 1:2:1, EBD 9 1:4:1, and EBD 10 1:4:1 meet the first criterion in that the maximum measured concentration is at least 90 percent of the maximum concentration measured with all site structures in place. (Note: the three numbers following the building height, specify the building height to width to length ratios.)

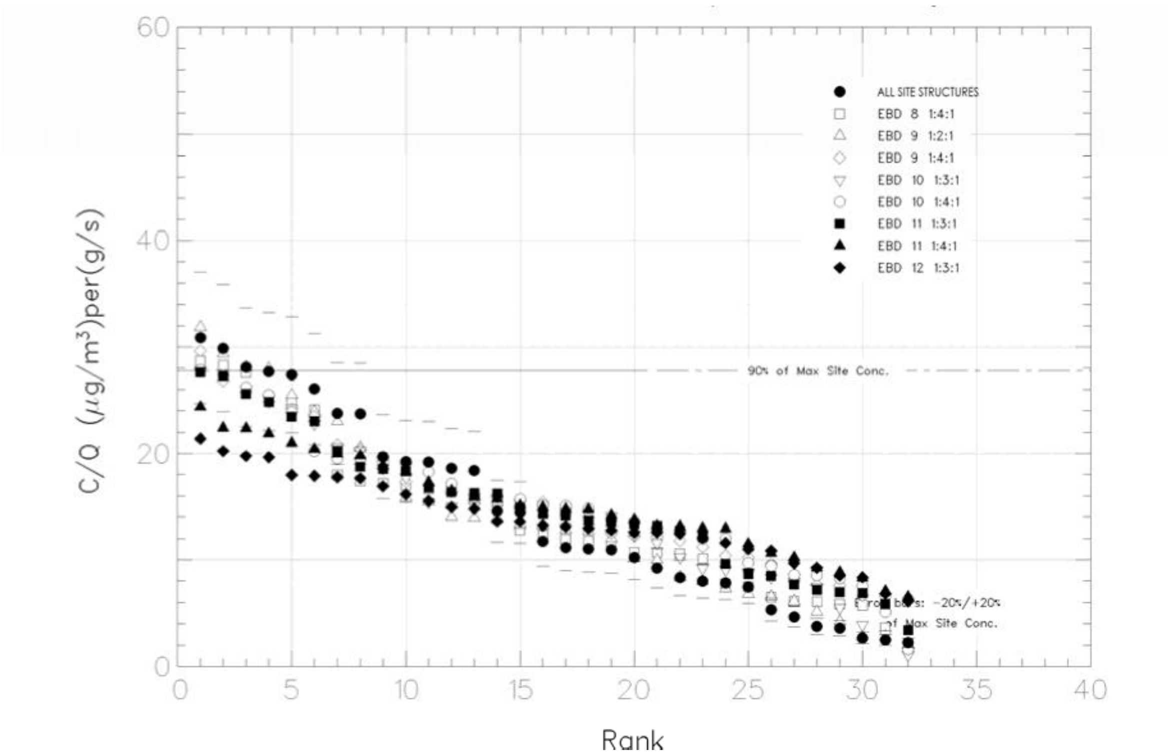

Figure 4. Typical Flagpole EBD Results for BS4 Stack with BS5 operating, 160 degree wind direction

However, EBD 8 1:4:1 and EBD 9 1:2:1 both fail the second criterion of 20 percent of the overall maximum ground-level concentration with all site structures in place. Of the two profiles that meet both criteria, the lowest value can be chosen as the EBD structure. Therefore, the EBD for this case is EBD 9 1:4:1 denoted by a white diamond.

MODEL CONSTRUCTION AND SETUP

A 1:300 scale model of the MPRGS and surrounding structures and terrain was constructed. The model included all significant structures within a 518-m (1700-ft) radius of the center of the MPRGS. A close-up of a portion of the area modeled is shown in Figure 2. The model was placed on a turntable so that different wind directions could be easily evaluated. Photographs of the model are provided in Figures 5, 6 and 7. Stacks were constructed of plastic and were supplied with a helium–hydrocarbon (or nitrogen-hydrocarbon) mixture of the appropriate density. Measures were taken to ensure that the flow was fully turbulent upon exit. Precision gas flow meters were used to monitor and regulate the discharge velocity.

A set of solid rectangular structures was fabricated for placement directly upwind of each stack for EBD testing. The structure shapes evaluated had height-to-width-to-length ratios of: 1:2:1; 1:3:1; and 1:4:1. For the ground-level EBD tests, the stacks in Table 1 and idealized buildings were tested with the turntable model removed from the wind tunnel and a uniform roughness installed in its place. The uniform roughness was constructed such that it provided the same surface roughness as the surroundings (i.e., 0.79 m for the urbanized approach, and 0.15 m for the water and lower roughness approach). For the ground-level EBD testing, concentration sampling taps were installed on the surface of the model so that at least 46 locations were sampled simultaneously for each simulation. A typical sampling grid consisted of 5 to 7 receptors located in each of 7 rows that were spaced perpendicular to the wind direction. Two background samples were located upwind of the stacks. The lateral and longitudinal spacing of receptors was designed so that the maximum concentration was defined in the lateral and longitudinal directions.

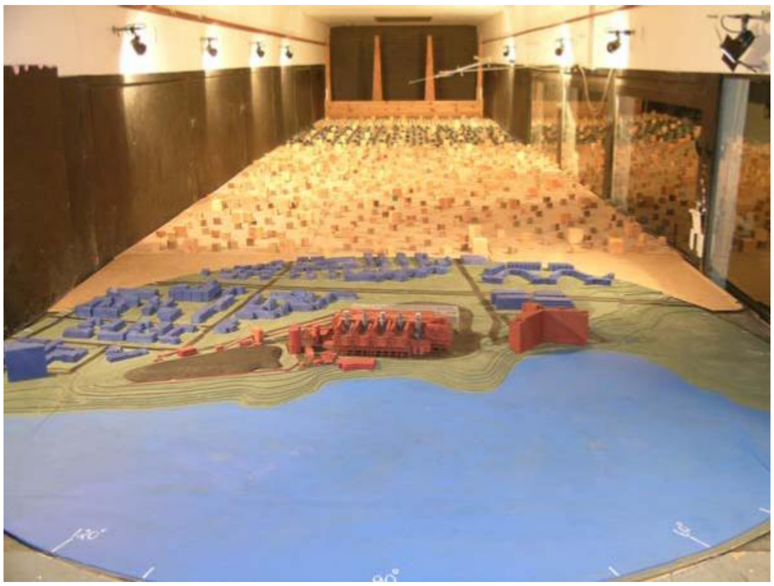

Figure 5. Photograph of model

For the site structures portion of MT testing, MT was instrumented with 46 sampling taps that closely matched the locations modeled with AERMOD (see Figure 6). Roof-top, side-wall and ground-level locations were evaluated. For the EBD portion of MT testing, a "flagpole" receptor grid was constructed such that sampling locations were the same as when MT was in place (see Figure 7). The same EBD structures were used for the EBD portion of MT testing, and were placed directly upwind of the stack evaluated on the model turntable with the MPRGS removed.

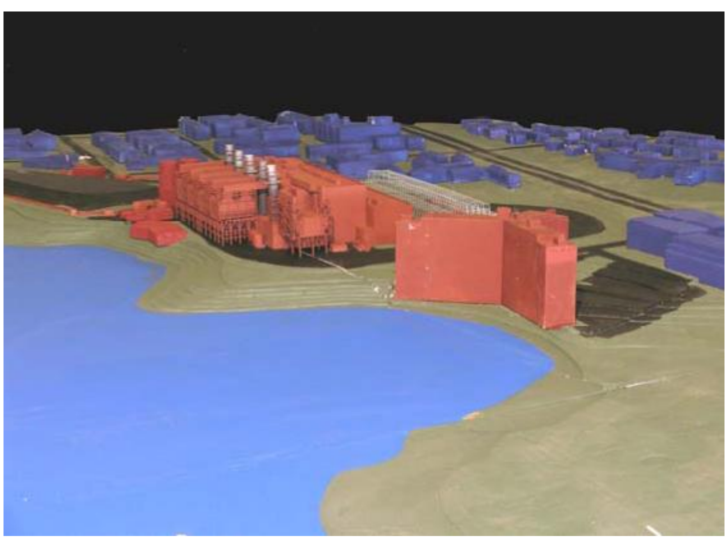

Figure 6. Close-up of all Site Structures

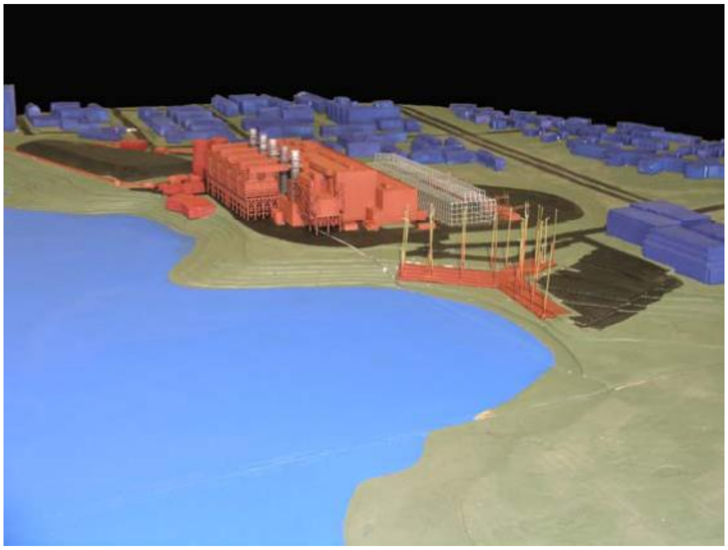

Figure 7. Close-up of Power Plant and Flagpole Receptor Grid

RESULTS

EBD Results - Ground Level

For the ground-level EBD portion of the study, wind tunnel tests were first conducted for the existing and merged exhaust stacks for the wind directions of interest with all site structures in place as shown in Figure 6. The full-scale exhaust information for the various exhausts is listed in Table 1. The MPRGS consists of five boiler exhaust stacks with stack identification labels of BS1, BS2, BS3, BS4, and BS5 representing stacks one through five as shown in Figure 2. The stacks, BS1/BS2, were simulated with the same source parameters (i.e., exit diameter, volume flow, temperature, etc.) while BS3/BS4/BS5 were simulated with the same source parameters.

Due to the proximity of the airport, MPRGS cannot significantly raise the stack heights to increase the plume height and escape building wake effects. However, it is possible to merge the exhaust streams to accomplish the desired objective of redesigning the plant to reduced impacts on the Marina Towers. Therefore, merged exhausts were evaluated at the stack positions normally occupied by stacks BS1 and BS4 having the stack identification labels of MS1 and MS2, as shown in Figure 2. MS1 represents combining the BS1 and BS2 exhausts through one merged-flue stack, while MS2 represents combining the BS3, BS4, and BS5 exhausts through another merged-flue stack.

Ground-level concentrations were measured at a minimum of 46 locations for each test. The receptor grid was designed so the maximum ground-level concentration versus downwind distance could be defined within acceptable uncertainty. The stacks, BS1/MS1 and BS4/MS2 were evaluated for wind directions of 10 through 360 degrees at ten degree increments.

For the next phase of the EBD determination for the various stacks, the site model was removed from the wind tunnel and replaced with a uniform roughness representative of the surface roughness of the actual site. Since this site has two roughness approaches, EBD had to be determined for both. For each test, a single rectangular building was placed upwind of the stack under evaluation and the maximum ground-level concentrations versus downwind distance were measured as described above. This process was repeated for various building shapes until an EBD was found that had a similar ground-level concentration profile as with all buildings present. The idealized rectangular structures (EBD structures) initially tested had height-to-width-to-length ratios similar to those used by Huber and Snyder[12,13] for development of the ISC2 downwash algorithm (H:W:L = 1:2:1). For cases where the traditional EBD did not provide an adequate concentration profile, alternate EBD configurations were assessed. For example, wider EBD structures with the ratios of “1:3:1”,”1:4:1”, etc. were very effective. For certain cases, the best EBD configuration that resulted in the proper profile was with the EBD turned at a 45-degree angle to the approach flow resulting in a corner vortex bringing the exhaust plume downward. Unfortunately, AERMOD does not allow this type of configuration for input. Petersen[2] provides a listing of building dimensions that were evaluated and the values chosen for each exhaust stack and wind direction scenario evaluated.

To illustrate the difference between the BPIP and EBD determined building dimension inputs, only the results for BS4 will be discussed in detail. The variation in building dimensions and building location versus wind direction for the two methods are shown in Figures 8-12.

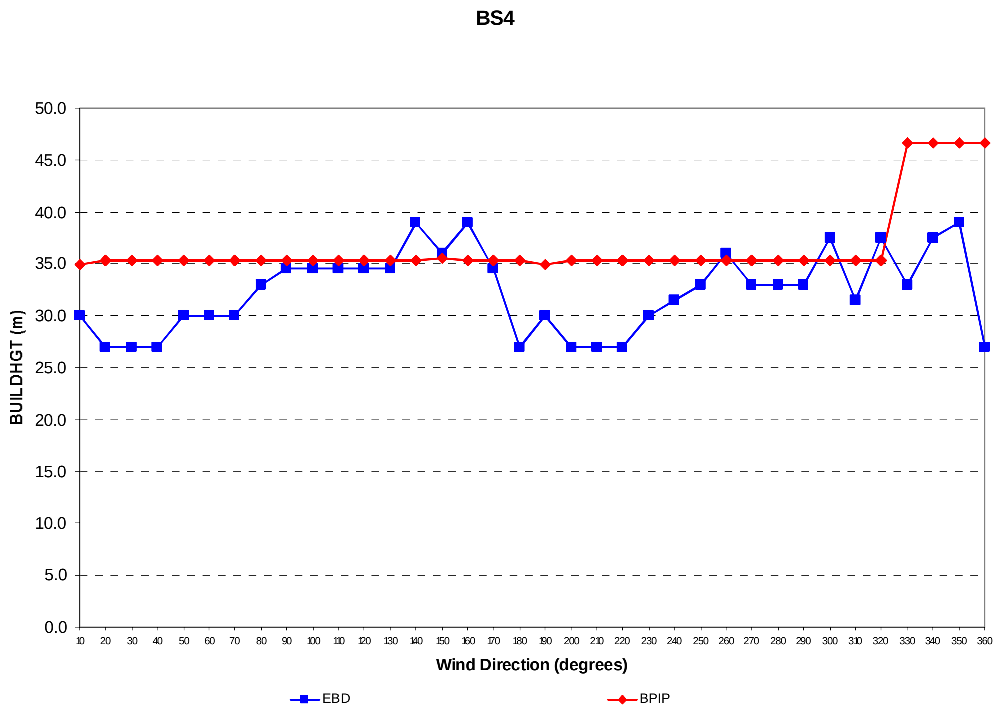

Figure 8. Building height, BUILDHGT, determined using BPIP and EBD methods

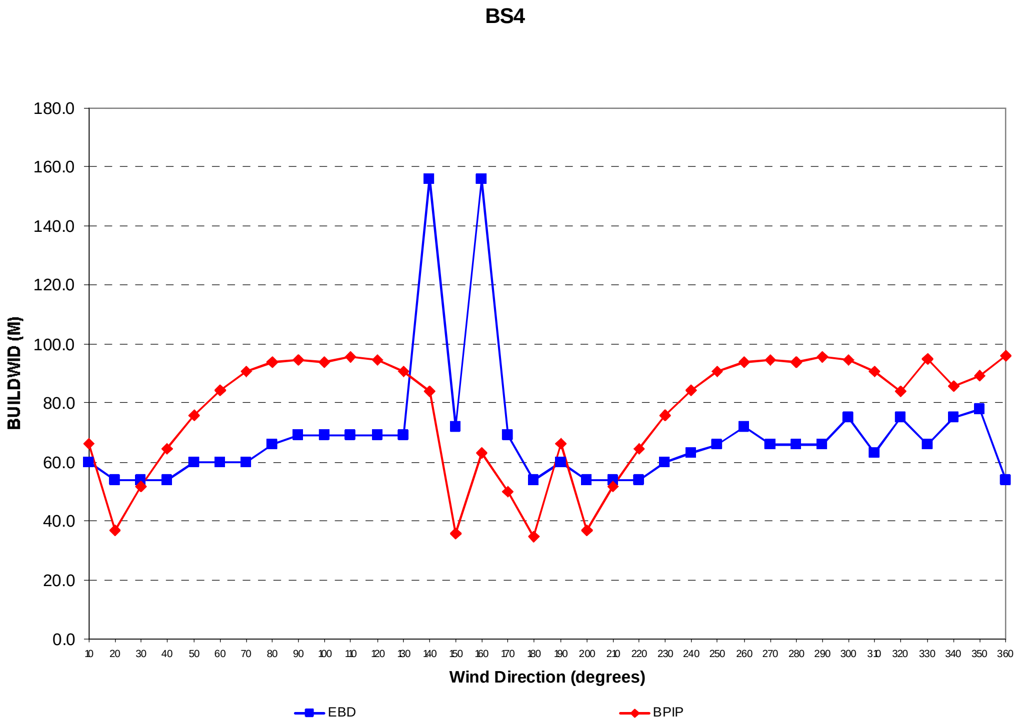

Figure 9. Building width, BUILDWID, determined using BPIP and EBD methods

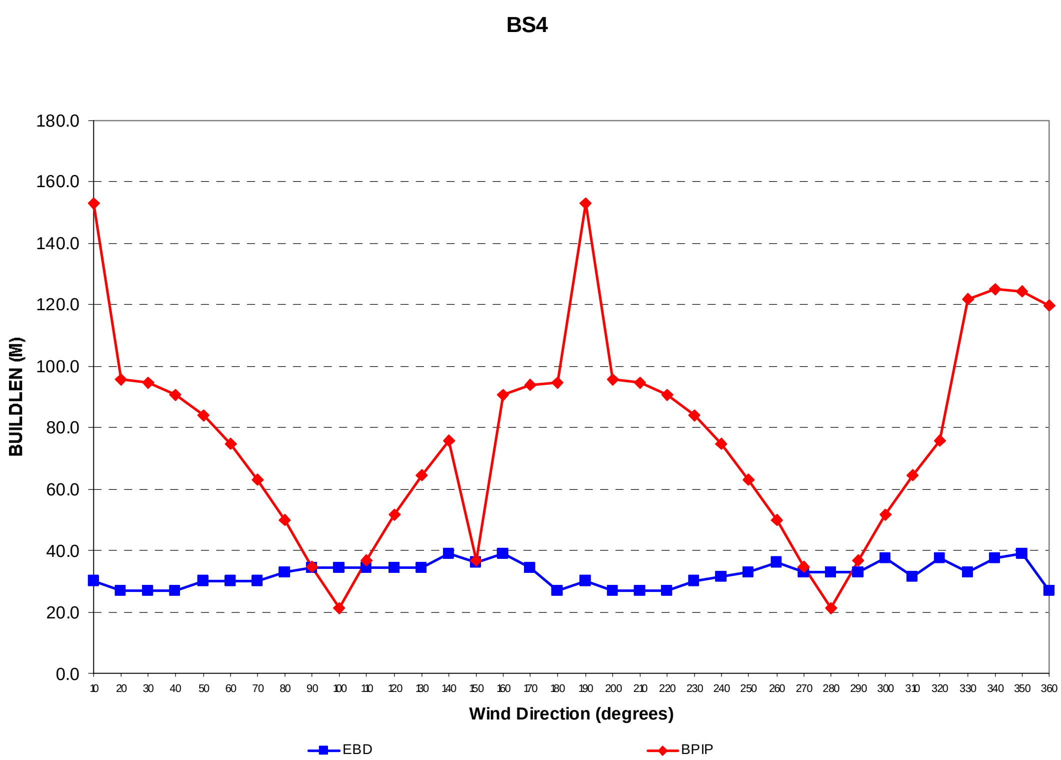

Figure 10. Building length, BUILDLEN, determined using BPIP and EBD methods

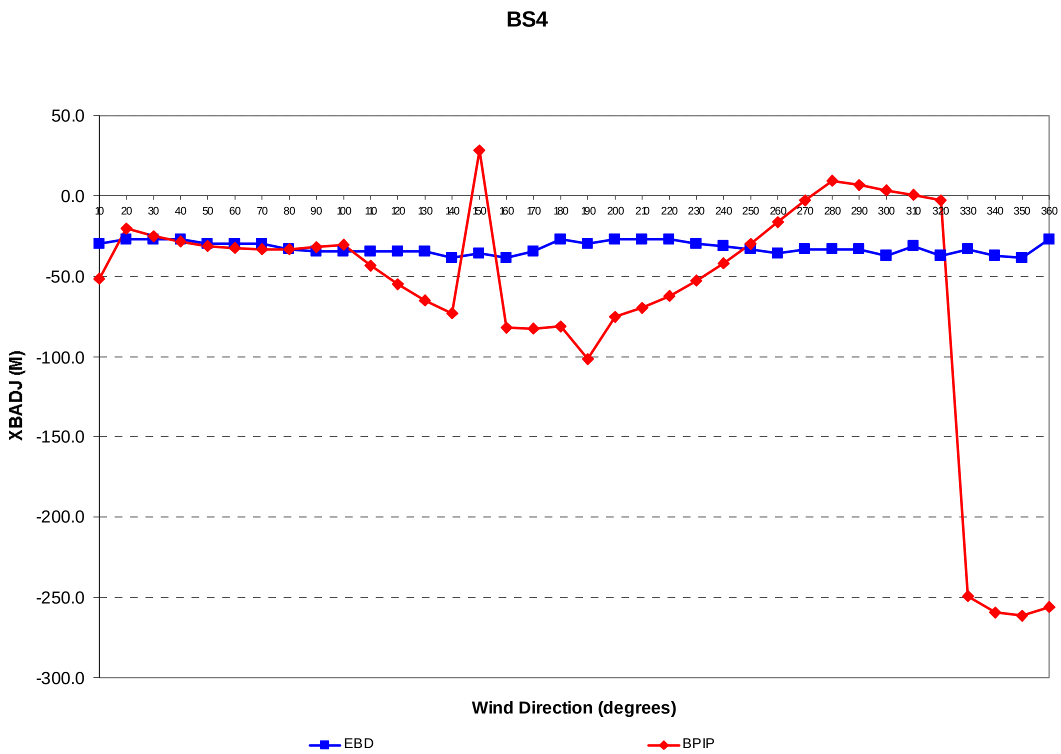

Figure 11. Building position in X direction, XBADJ, determined using BPIP and EBD methods

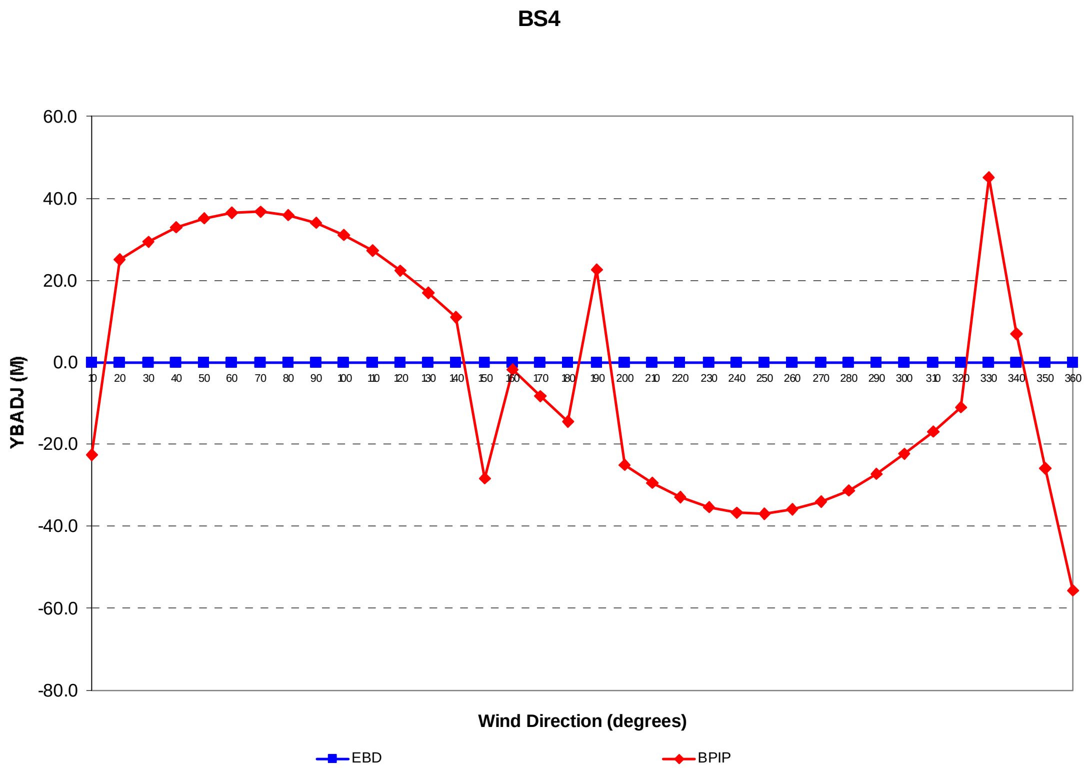

Figure 12. Building position in Y direction, YBADJ, determined using BPIP and EBD methods

For the building height comparison, shown in Figure 8, BPIP designates the same dimension for all wind directions with the exception of 330 to 360 degrees which show an increased dimension that corresponds with the height of the Marina Tower structure that is upwind of the power plant. The EBD values change by wind direction which reflects the true variation of downwash based on the wakes created by all site structures and structure angular positions relative to the wind.

Figure 9 shows the building width comparisons for BPIP and EBD. It is apparent that BPIP is using the long dimension of the power plant for winds from the east and west and the short dimension for winds from the north and south. From this plot, inclusion of the Marina Tower structure upwind of the power plant is not apparent. The BPIP and EBD values show similar trends, with the exception of the 140 and 160 degree wind directions. For these cases, wider EBD dimensions were necessary to replicate the downwash attributed to corner vortex shedding on the power plant structure.

Figure 10 shows significantly different values for the building length component produced by BPIP and EBD. In this plot, BPIP appears to be choosing the long dimension of the power plant when winds are from the north and south and the short dimension when winds are from the east and west. Again, from this plot, inclusion of the Marina Tower structure upwind of the power plant is not apparent. The EBD values do not demonstrate a drastic change in the dominate length component as represented by BPIP.

Figure 11 is an excellent indicator that BPIP is choosing the structure to the north of the power plant as the dominant structure when winds are from 330 to 360 degrees. From 20 to 100 degrees, the BPIP and EBD values are similar. For all other wind directions, the BPIP values are slightly greater or less than the EBD values depending upon wind direction.

Figure 12 shows that all EBD structures were centered on the exhaust stack for all wind directions. The BPIP values, on the other hand shift depending on wind direction. At the 330 through 360 directions, it is likely the values are attributed to the structure upwind of the power plant.

EBD Results - Marina Towers

In addition to traditional EBD values for predicting ground-level concentrations, EBD values were also determined to serve as an AERMOD input when the impact of MPRGS on MT is being evaluated. For these wind tunnel tests, concentrations were measured at 46 locations. These locations correspond to those locations evaluated during AERMOD evaluations of the site[1]. Measurements were obtained for various exhaust stack and wind direction combinations as specified in Petersen.[2]. The wind directions of interest were 150, 160, 170, and 180 degrees as these encompass the wind directions with impacts due to MPRGS on MT.

To determine the EBD, the MPRGS and MT were removed, but the rest of the site remained the same (i.e., surrounding buildings, terrain, etc.) MT was replaced with a “flag pole” receptor grid with collection points at the same locations as those obtained when MT was in place as shown in Figure 7. Then, the stack under evaluation was placed in its respective location with the same stack height above grade. Various EBD structures were then placed upwind of the stacks of interest until a ranked data profile was obtained that was similar to those measured when MPRGS and MT were in place. For these cases, traditional EBD values with the “1:2:1” relationships were initially evaluated and if necessary, other types of EBD configurations were evaluated. The values chosen for each exhaust stack and wind direction scenario are listed in Petersen.[2] Shea[9] discusses the use of these values in AERMOD for estimating the impacts on Marina Tower and also compares the results of the estimates to field observations.

CONCLUSIONS

This analysis has demonstrated that EBD and BPIP determined building dimension inputs are significantly different. The EBD building dimension inputs are based on a characterization of the wake effects created by all site structures. The BPIP determined building inputs are based on logic algorithms that consider building tiers, building spacings, building angles to the flow and from that information a set of building dimension inputs are computed. The problem with these inputs is that they may or may not be appropriate to characterize building wake effects for the site under evaluation. These inputs may cause concentrations to be over or underestimated when utilized in AERMOD.

For this particular study, the impact of the EBD values on concentration estimates is discussed in a companion paper.[9]

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