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WIND ENGINEERING AND AIR QUALITY CONSULTANTS

Draft
Report

Final Test Results

Wind Tunnel Modeling Assessment
for the Integrated Waste Management Facilities

AECOM Asia Company Ltd
9/F Grand Central Plaza, Tower 2
Shatin Rural Committee Road, Shatin, Hong Kong

CPP Project: 4809

CPP, Inc.
1415 Blue Spruce Drive
Fort Collins, Colorado 80524, USA
Tel: 1 970 221 3371
Fax: 1 970 221 3124
info@cppwind.com
www.cppwind.com

FINAL TEST RESULTS

WIND TUNNEL MODELING ASSESSMENT FOR THE INTEGRATED WASTE MANAGEMENT FACILITIES

CPP Project 4809

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Prepared by:

Ronald L. Petersen, Principal, Ph.D., CCM
Anke Beyer-Lout, Atmospheric Scientist

CPP, INC.
WIND ENGINEERING AND AIR QUALITY CONSULTANTS
1415 Blue Spruce Drive
Fort Collins, Colorado 80524

Prepared for:

AECOM Asia Company Ltd
9/F Grand Central Plaza, Tower 2
Shatin Rural Committee Road, Shatin, Hong Kong

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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)

Subscripts

m	pertaining to model
f	pertaining to full scale

EXECUTIVE SUMMARY

This report documents the final phase of the wind-tunnel study conducted by CPP, Inc. on behalf of AECOM Asia Company Ltd (AECOM) for the Integrated Waste Management Facilities (IWMF) in Hong Kong. The overall objective of the study was to obtain concentration estimates under neutral, stable and unstable conditions at two potential sites; namely, the Shek Kwu Chau (SKC) and Tsang Tsui Ash Lagoons (TTAL) sites. The purpose of the final testing was to provide concentration estimates at 6 and 7 air sensitive receivers (ASRs) at the TTAL and SKC sites under neutral, stable and unstable conditions for a stack height of 150m and to confirm that the proposed stack height would not result in significant building or terrain wake effects.

To meet the objectives of the study, a 1:1000 scale model of IWMF and nearby surroundings within a 1728 m radius was constructed and placed in CPP's boundary-layer wind tunnel. Downwind terrain out to 5 km was constructed as needed to simulate the dispersion to each ASR. At each ASR, hourly concentrations were measured in the wind tunnel as a function of wind speed and direction for neutral atmospheric stability with a neutrally buoyant plume. For the final testing phase, the concentration data was corrected for plume buoyancy and atmospheric stability.

The overall predicted maximum concentrations for the averaging times of interest at each ASR are summarized in Table ES-1 for the two sites. The table shows that the SKC site has the overall highest predicted concentrations for all averaging periods except the daily (24-hour) averaging time. The highest concentrations are predicted at ASR A_S6 for the SKC site and ASR A_T6 for the TTAL site.

Table ES-1
Summary of Predicted Maximum Concentrations for Both Sites

Stack Height Above Base (m)	Receptor Identification	Predicted Maximum Normalized Concentration - Plume Rise, Buoyancy and Stability Correction (μg/m³)/(g/s)				
		1-hour average	8-hour average	24-hour average	3-month average	annual average
Shek Kwu Chau Site						
150	A_S1	0.038	0.017	0.006	0.000	0.000
150	A_S2	0.705	0.560	0.225	0.017	0.005
150	A_S3	0.624	0.473	0.186	0.016	0.005
150	A_S4	0.641	0.434	0.178	0.016	0.005
150	A_S5	0.459	0.342	0.165	0.020	0.007
150	A_S6	0.891	0.659	0.272	0.037	0.014
Tsang Tsui Ash Lagoons Site						
150	A_T1	0.611	0.366	0.140	0.015	0.004
150	A_T2	0.091	0.035	0.012	0.000	0.000
150	A_T3	0.043	0.006	0.002	0.000	0.000
150	A_T4	0.000	0.000	0.000	0.000	0.000
150	A_T5	0.006	0.002	0.001	0.000	0.000
150	A_T6	0.688	0.647	0.375	0.032	0.011
150	A_T7	0.374	0.257	0.069	0.003	0.002

Note:
The maximum normalized concentration for each site is highlighted in yellow.

1. INTRODUCTION

This report documents the final phase of the wind-tunnel study conducted by CPP, Inc. on behalf of AECOM Asia Company Ltd (AECOM) for the Integrated Waste Management Facilities (IWMF) in Hong Kong. The overall objective of the study was to obtain concentration estimates under neutral, stable and unstable conditions at two potential sites; namely, the Shek Kwu Chau (SKC) and Tsang Tsui Ash Lagoons (TTAL) sites. The purpose of the final testing was to provide concentration estimates at 6 and 7 air sensitive receivers (ASRs) at the TTAL and SKC sites under neutral, stable and unstable conditions for a stack height of 150m and to confirm that the proposed stack height would not result in significant building or terrain wake effects.

To meet the objectives of the study, a 1:1000 scale model of IWMF and nearby surroundings within a 1728 m radius was constructed and placed in CPP's boundary-layer wind tunnel. Downwind terrain out to 5 km was constructed as needed to simulate the dispersion to each ASR. At each ASR, hourly concentrations were measured in the wind tunnel as a function of wind speed and direction for neutral atmospheric stability with a neutrally buoyant plume. For the final testing phase, the concentration data was corrected for plume buoyancy and atmospheric stability.

Included in this report are a description of various site-specific issues, a discussion of the experimental methods and data post processing algorithms, and the final results of the study. The results are also summarized in an executive summary, which is located at the beginning of the report. More information on wind-tunnel modeling methods data listings and data fits can be found in Appendices A, B, C and D.

2. PROJECT SPECIFIC INFORMATION

2.1 DESCRIPTION OF SITES AND SURFACE ROUGHNESS

The two possible sites for the Integrated Waste Management Facilities are located in Hong Kong, as shown in Figures 1a and 1b. Figures 2a-d are detailed views of the areas modeled, showing surrounding ASR locations for both sites evaluated.

The surface roughness for the region surrounding the area modeled in the wind tunnel for both sites was set at 0.01m for areas covered with water and 0.6m for the stack and ASR locations.

2.2 EXHAUST SOURCES

The current IWMF design includes 6 incineration units, each connected to an exhaust flue. The 6 exhaust flues are grouped into two closely located stacks. For simulation purposes, one stack was modeled by setting the flow equal to the total flow for all exhaust flues. The exit velocity was set to 15 m/s and the corresponding exit area (and resulting diameter) was calculated by dividing the total flow by the exit velocity. The exit temperature was specified to be 413K.

The locations of the stack for the two sites are shown in Figures 2b and d. The full-scale exhaust parameters for all simulations are listed in Table 1.

2.3 AIR SENSITIVE RECEIVER LOCATIONS

To evaluate the air quality impact of the emissions from the IWMF, air sensitive receiver locations (ASRs) were specified by AECOM. The ASR locations are identified in Figures 2a and 2c. Table 2 provides a list of the ARS locations with abbreviated identifications.

2.4 METEOROLOGY

The meteorological information of primary interest for this evaluation is the hourly wind speed, wind direction, stability and temperature. AECOM provided CPP with MM5 data files for all the ASR's at stack height as well as MM5 data at 600 m at the stack locations for both sites. The following information was used for this study.

600 m MM5 Data at stack location

- Used to define the 1% wind speed and a wind rose – this information was used to specify a reasonable upper limit wind speed (i.e., 21 m/s) to be used for testing.
- Hourly wind speeds and wind directions were used to predict hourly concentrations at each ASR.

150m MM5 Data at stack location

- Used for plume buoyancy and atmospheric stability correction for the 150 m stack height results.

Figures 3a and b show the wind frequency distributions, in the form of a wind rose, at the 600m virtual anemometer at stack location for both sites. The wind rose indicates that for both sites the most frequent winds are from the northeast through east. The strongest winds, greater than 16 m/s, occur primarily from the east-northeast for the SKC site and from the northeast as well as south-southeast at the TTAL site.

Figures 4a and b show the cumulative frequency distribution of wind speed at the 600m virtual anemometer at stack location for both sites. The wind speed distribution was used to determine the wind speed at the anemometer that is exceeded 1% of the time (i.e., the 1% wind speed). The figure shows that the 1% wind speed at the SKC site is 21.3 m/s and the 1% wind speed at the TTAL site is 20.0 m/s. To ensure that concentration measurements were only obtained for likely wind conditions during the wind-tunnel testing, testing was restricted to wind speeds from 1 m/s to approximately the 1% wind speed (i.e., the maximum wind speed evaluated was 21 m/s).

2.5 EMISSION RATES

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.

2.6 AIR QUALITY OBJECTIVES

The principal legislation for the management of air quality in Hong Kong is the Air Pollution Control Ordinance (APCO). The Hong Kong Air Quality Objectives (AQOs) are summarized in

Table 4. For the purpose of this study CPP has used Table 4 to define the averaging periods of interest for presenting normalized concentrations. Table 4 shows that the averaging times of interest are 1-hour, 8-hour, daily (24-hour), 3 months and annual.

3. WIND-TUNNEL MODELING METHODOLOGY

3.1 WIND-TUNNEL SIMILARITY CRITERIA

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). For this study, the criteria used for simulating plume trajectories and the ambient air flow are summarized below. These criteria maximize the accuracy of the building and terrain wake simulations and apply a conservative approach for simulating plume rise. These are the criteria that have been used on past USEPA approved studies (Petersen and Cochran, 1993, 1995a, 1995b, Petersen and Ratcliff, 1991, Petersen et al., 2007). Model and full-scale parameters for the IWMF exhaust stack are presented in Appendix A.

Modeling Plume Trajectories

To model plume trajectories, the velocity ratio, R, and density ration, λ, were 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 v_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. It should be noted that Froude number similarity will not be used as it would require extremely low wind tunnel speeds and building and terrain wakes would be incorrectly modeled.

Modeling the Airflow and Dispersion

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

- all significant structures within a 1727 m (5667 ft) radius of the stacks were modeled at a 1:1000 scale reduction. This ensures that all structures whose critical dimension (lesser of height or width) exceeds 1/20th[1] of the distance from the source are included in the model; Terrain out to 5000m was also modeled.
- the mean velocity profile through the entire depth of the boundary layer were 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 was 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 was not met for all simulations,

[1] For the TTAL site, apart from IWMF, there are two other facilities planned in close proximity to IWMF namely the Sludge Treatment Facilities (STF) to the immediate east of IWMF and the site office of the WENT Landfill Extensions to the southeast of IWMF. The layout and detailed design of these 2 facilities are still under development but the general area of development is shown in Figure 2d. It is understood that the building heights for the STF will range from several meters up to about 20m above ground, whereas the building heights of the site offices for the WENT Landfill Extensions are likely to be about 10m or less. The buildings for the WENT Landfill Extension are likely to meet the 1/20th distance from source (i.e., the IWMF stack) criteria and do no need to be included in the model. Some of the buildings for the STF may not meet the 1/20th criteria; however, the design of the STF is yet to be developed and no information was available. Since the buildings will most likely be at least 10 building heights or more from the TTAL stack and the buildings on the TTAL site are much taller (e.g., 50 m), the wake effects of the TTAL buildings will dominate the dispersion and the effect of any missing buildings on the STF site is insignificant.

Reynolds number independence tests were 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 example source characteristics shown in Table 1, the model test conditions will be computed for the stack under evaluation. Tables A-1 through A-5 in Appendix A include more detailed information on the model and full scale parameters for one wind speed condition.

3.2 Scale Model and Wind Tunnel Setup

A 1:1000 scale model of the IWMF and nearby surroundings was constructed and placed on a 3.45 m diameter turntable. Terrain was also modeled upwind and downwind out distances of 5000 m. The areas modeled are depicted in Figures 2a and c. Close-up plan views of the test buildings showing the source location are provided in Figures 2b and d. Photographs of the model from various directions are shown in Figure 5.

3.2.1 Wind-tunnel Configuration

All testing was carried out in CPP's open-circuit wind tunnel shown in Figure 6. Photographs of the model installed in the wind tunnel are shown in Figures 7 and 8. Flow straighteners and screens at the tunnel inlet were used to create a homogenous, low turbulence entrance flow. A trip downwind of the flow straighteners begins the development of the atmospheric boundary layer. The long boundary layer development region between the trip and the site model is usually filled with roughness elements placed in the repeating roughness pattern to create an atmospheric boundary layer characteristic for the site. However, for this study the bare wind tunnel floor proved to be appropriate to simulate the very low roughness of the surrounding ocean. The target approach surface roughness length used in this study is specified in Table 1. The approach wind profile and surface roughness length are discussed in more detail in Appendix A.

3.2.2 Exhaust Sources

The exhaust source discussed in Section 2.2 was simulated by installing the stack constructed of a brass tube at the appropriate location for both sites. A trip was installed within the stack as required to ensure that the stack flow was fully turbulent upon exit. The stack was supplied with a tracer gas (ethane), helium and nitrogen mixture, so the model scale density ratio is equal to the one at full scale. Precision mass flow controllers were used to monitor and regulate the discharge velocities.

3.2.3 Air Sensitive Receivers (ASRs)

The ASR locations (concentration sampling points) discussed in Section 2.3 were evaluated by installing a small diameter brass tube at the specified location. This brass tube was then connected to the analysis instrumentation to determine the amount of tracer gas present at the ASR location.

3.3 Data Acquisition and Processing

3.3.1 Data Collection

The primary data of interest collected during the course of this study was concentration due to the tracer gas release from each source being simulated. Table 4 summarizes the various source/ASR combinations that were evaluated during the final phase of the study. The table also includes the overall maximum concentration measurement results for each source/ASR pair for a stack height of 150m.

Volume flow and wind speed measurements were also obtained for documentation and to set the wind tunnel operating conditions. The instrumentation and experimental procedures, including the general procedures used to collect the concentration data, are described in detail in Appendix B. Following is a summary of the general concentration data collection procedures.

1. The wind tunnel speed is set to the specified value.
2. A tracer gas mixture with the appropriate density is released from the specified stack at the specified flow rate.
3. Concentrations are measured at the ASR of interest and mean and root-mean-square normalized concentrations are displayed for the operator and saved to a computer file.
4. Step three is repeated for a range of wind directions and wind speeds such that the maximum normalized concentration is found and such that sufficient data is obtained to develop an equation to describe normalized concentration as a function of wind speed and direction.

5. The above process is repeated for every source/ASR combination identified in the concentration measurement test plan (see Table 4).
6. The saved data files are then used to generate summary tables and for additional analysis (i.e., total concentrations, annual averages, etc.).

3.3.2 Concentration Data Averaging Time

Throughout the study the samples were measured using a 120 second averaging time to provide a more accurate representation of steady-state conditions. The *C/m* values reported in Table 4 are 120-second averaging time values, which represent 15 minute to 1-hour average full-scale concentrations (i.e., steady-state conditions).

3.3.3 Concentration Data Post-processing

First, the concentration as a function of wind speed and wind direction is defined in the wind tunnel at all ASR locations of interest. The normalized concentrations (*C/m*) measured in the wind tunnel are then fit to an equation that is based on the Gaussian plume model equation for a point source.

$$\frac{C}{m} = \frac{1}{\pi\sigma_y\sigma_z U} \cdot \exp\left[-\frac{1}{2}\left(\frac{y-\bar{y}}{\sigma_y}\right)^2\right] \cdot \exp\left[-\frac{1}{2}\left(\frac{h_s+h_r}{\sigma_z}\right)^2\right] \cdot 10^6 \qquad (4)$$

The concentration C [µg/m^3], normalized by the emission rate m [g/s], at ground level $(z=0)$, is a function of the distance from the plume center line $(y-\bar{y})$, the effective stack height (h_s+h_r), and the wind speed U (at 600m). The dispersion coefficients σ_y and σ_z are functions of the downwind distance x. Using the above equation, the following fit equation was developed for the wind tunnel data:

$$\frac{C}{m} = \frac{A}{\pi\sigma_{y,WT}\sigma_{z,WT}U} \exp\left[-\frac{1}{2}\left(\frac{x\cdot\tan(WD-WDc)}{\sigma_{y,WT}}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{h_s}{\sigma_{z,WT}}+\frac{K}{\sigma_{z,WT}U^2}\right)^2\right] \cdot 10^6 \qquad (5)$$

where WD is the wind direction (in degrees), WDc is the critical wind direction (in degrees) where the peak concentration occurs. The values for A, $\sigma_{y,WT}$, $\sigma_{z,WT}$, WD_c, and K were found by minimizing the error of the fit. Correction factors were then applied for plume buoyancy and atmospheric stability using the following equation:

$$\frac{C}{m}=\frac{A}{\pi(\sigma_{y,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}S_{y}(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}S_{z}U}\cdot\exp\left[-\frac{1}{2}\left(\frac{x\cdot\tan(WD-WDc)}{(\sigma_{y,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}S_{y}}\right)^{2}\right]$$
$$\cdot\exp\left[-\frac{1}{2}\left(\left(\frac{h_{s}}{(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}}+\frac{K}{(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}U^{2}}\right)\frac{R}{S_{z}}\right)^{2}\right]\cdot 10^{6} \quad (6)$$

To account for increased plume rise due to buoyancy and decreased plumed rise due to stable stratification, a correction factor R is introduced. The dispersion coefficients $\sigma_{y,WT}$ and $\sigma_{z,WT}$ were corrected for buoyancy induced dispersion (σ_b) and for stability effects (S_y and S_z). These corrections are discussed in more detail in Appendix C.

Once the fit function and correction factors were determined normalized concentrations were predicted for every hour using the meteorological data described above. From these 1-hour average concentration predictions, the maximum normalized concentration was determined and running averages were calculated for every source/ASR combination for the following time periods: 1-hour, 8-hour, 3-month and annual. In addition, the maximum daily (24-hour) average concentration was calculated.

3.4 Quality Control

To ensure that accurate and reliable data were collected, the following quality control steps were taken.

1. A multi-point calibration of the flame ionization detector used to measure tracer gas concentrations was performed with a set of certified standard gases (see Appendix B).
2. The stack flow measuring devices used to supply the exhaust source were calibrated with a soap bubble meter (see Appendix B).
3. The velocity measuring device was calibrated against a certified standard (i.e., Pitot-static tube with a certified pressure transducer - see Appendix B).
4. Atmospheric Dispersion Comparability (ADC) tests have been performed on previous studies to ensure that plume dispersion coefficients measured in the wind tunnel replicate those experienced in field studies (EPA, 1981b).
5. Vertical velocity and turbulent intensity profiles approaching the turntable model were compared against those expected for the site (see Appendix A).

4. RESULTS

4.1 CONCENTRATION MEASUREMENTS

Normalized concentrations (*C/m*) due to emissions from the various sources were measured and evaluated following the procedures discussed in the earlier sections and the appendices. The concentration data tabulations for the simulations are provided in Appendix D. A compilation of the maximum steady-state *C/m* value for each source/receptor combination tested is presented in Table 4. It should be noted that the C/m values presented in Table 4 have not be corrected for plume buoyancy or atmospheric stability. The table shows that the SKC site has the overall highest measured concentrations. The highest concentrations for the SKC site were measured at ASR A_S6 and for the TTAL site at ASR A_T6.

4.2 CONCENTRATION PREDICTIONS - NEUTRAL STABILITY

The normalized concentrations (*C/m*) measured in the wind tunnel were fit to a function (see Section 2.4 and Appendix C). The complete results for the curve fit are provided in Appendix D. Using the fit function and meteorological data described previously, maximum normalized concentrations were predicted for each source/ASR combination and are presented in Table 5. In some cases the predicted concentrations are lower than the concentrations measured in the wind tunnel, because meteorological conditions favorable for high concentrations might not have occurred in the year of meteorological data provided. In some cases higher concentrations are reported than presented in Table 4 because the fit function predicted higher concentrations than observations. The table again shows that the SKC site has the highest predicted concentrations. The highest concentrations for the SKC site were predicted to occur at ASR A_S6 and for the TTAL site at ASR A_T6.

4.3 CONCENTRATION PREDICTIONS - CORRECTED FOR BUOYANCY AND STABILITY

Correction factors to adjust the data for plume rise, buoyancy and stability were determined. Using the fit function, correction factors and meteorological data described previously; maximum normalized concentrations were predicted for each source/ASR combination and are presented in Table ES-1 in the Executive Summary. Comparison of Table 5 with Table ES-1 shows that the plume rise and stability correction decreased the overall maximum concentrations by about a factor of two.

4.4 FLOW VISUALIZATION

Upon completion of the concentration testing, exhaust plume behavior was documented visually using still photographs. A dense white smoke was used to define the plume behavior.

The visualizations are usually conducted primarily at the wind directions and wind speeds corresponding to the worst case scenarios listed in Table 4. In some cases, alternate wind speeds and/or directions are included to illustrate an interesting airflow/plume behavior. The white smoke will tend to enhance the plume, thus, visually the plumes may look worse in the model than in full-scale. To properly interpret the visualizations, one should evaluate the portion of the plume that is impacting the receptor rather than the intensity of the smoke at the receptor. For a well-designed stack, the plume centerline should be well above the receptor. Photographs of selected cases are provided in Figure 9[1]. One should note that these photographs represent a snap shot in time and may not be representative of the steady-state conditions that are impacting the ASR location.

Based on the finding of the flow visualization for stack heights above 125m, significant building or terrain wake effect is not observed at both TTAL and SKC sites.

[1] Flow visualization photographs for a 150m stack height were not obtained for the SKC site. A photograph with a 125m stack is presented for illustrative purposes.

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FIGURES

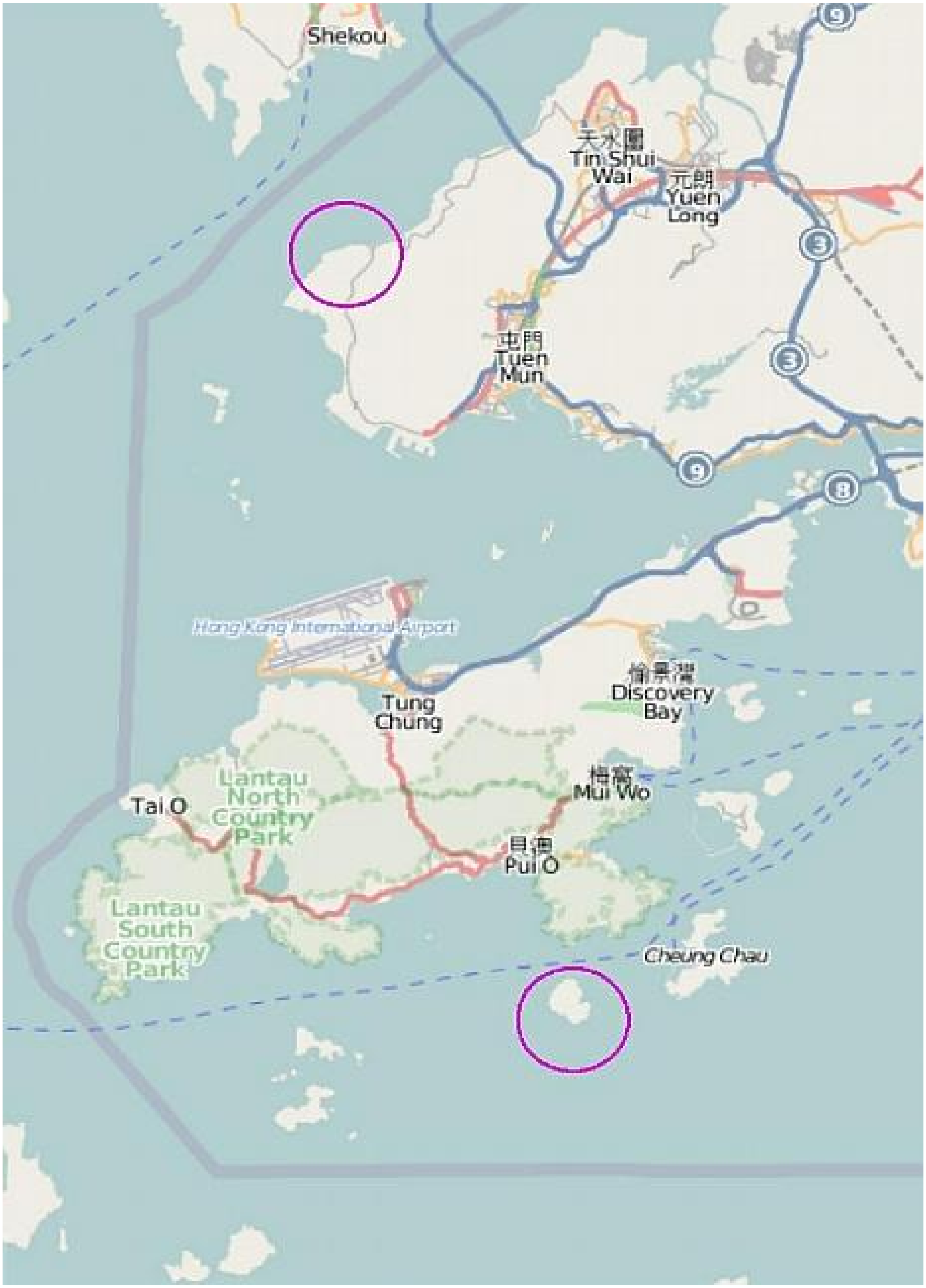


Figure 1. Site map showing the SKC and TTAL sites and turntable radii.

Figure 2. Plan view of: a) SKC terrain area modeled.

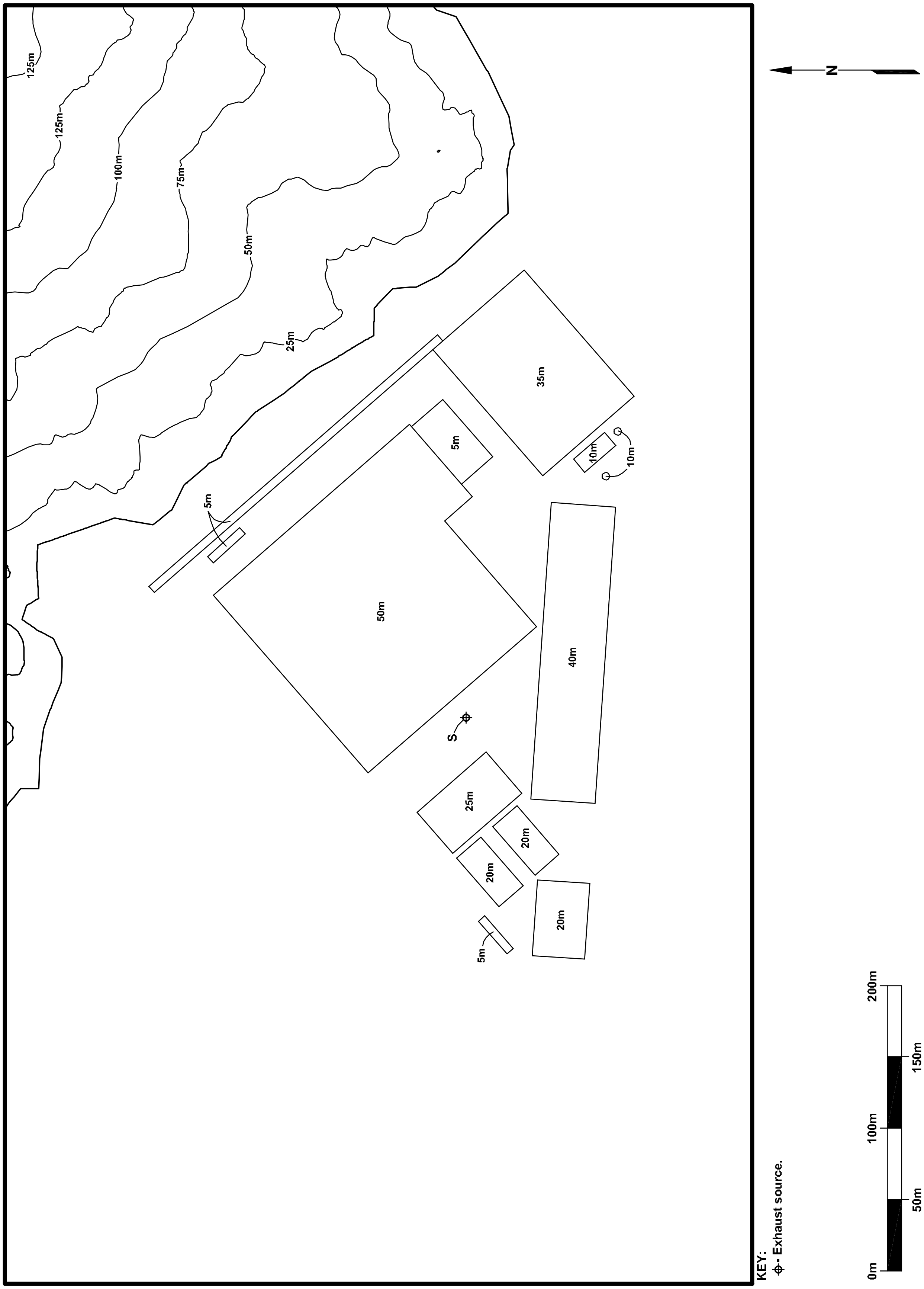


Figure 2. Plan view of: b) SKC IWMF site with building tier heights and stack location.

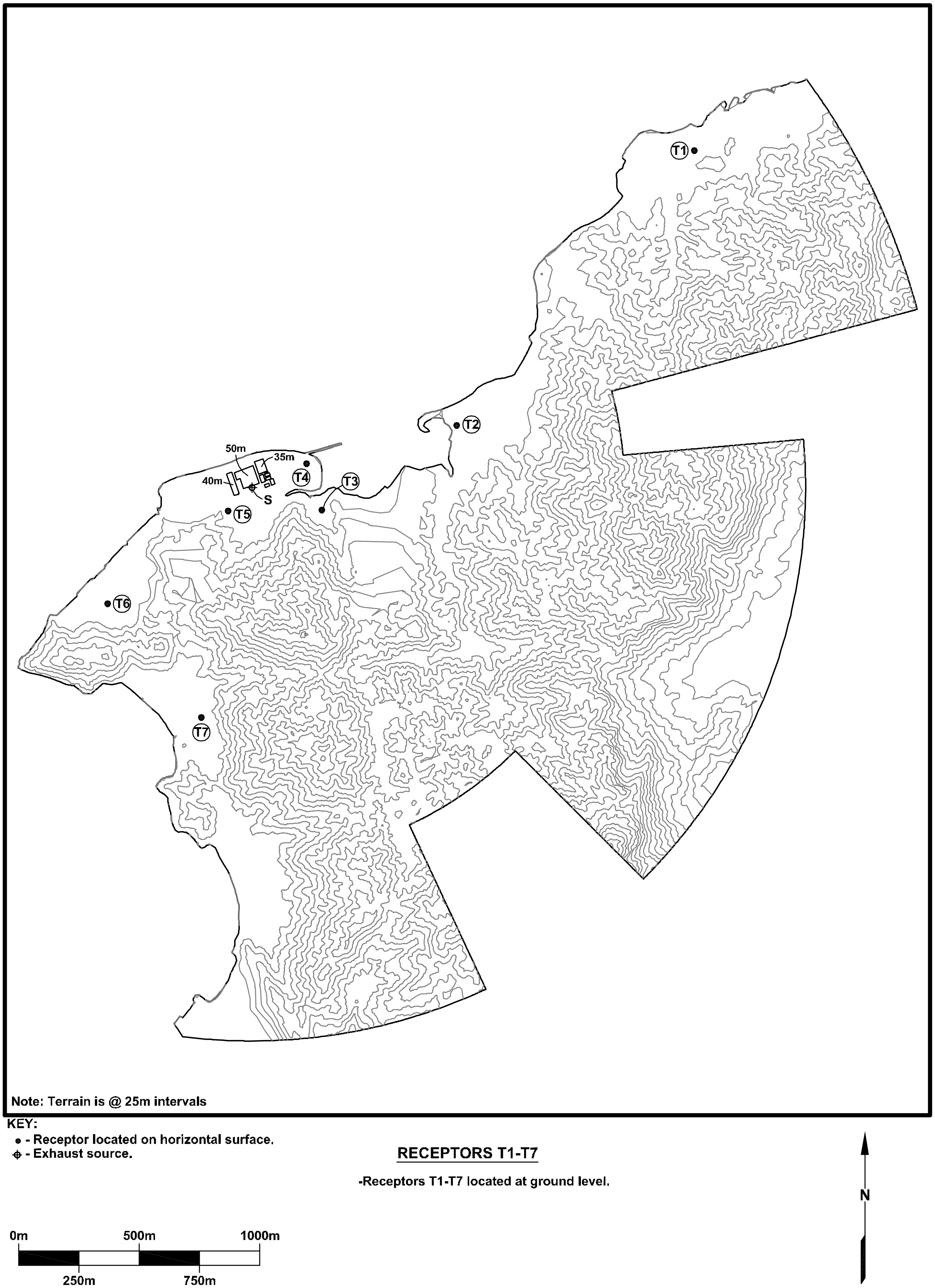


Figure 2. Plan view of: c) TTAL terrain area modeled.

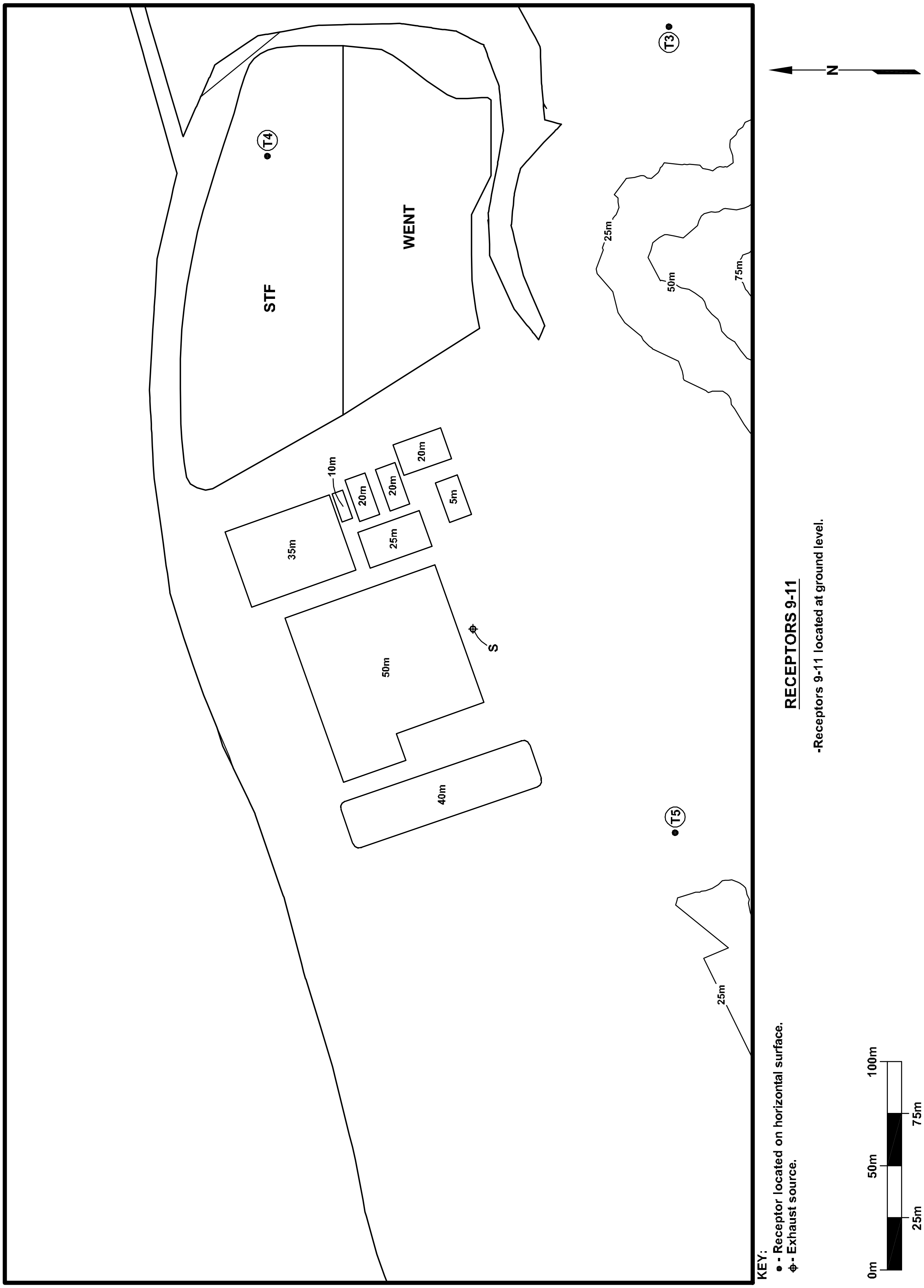


Figure 2. Plan view of: d) TTAL IWMF site with building tier heights and stack location.

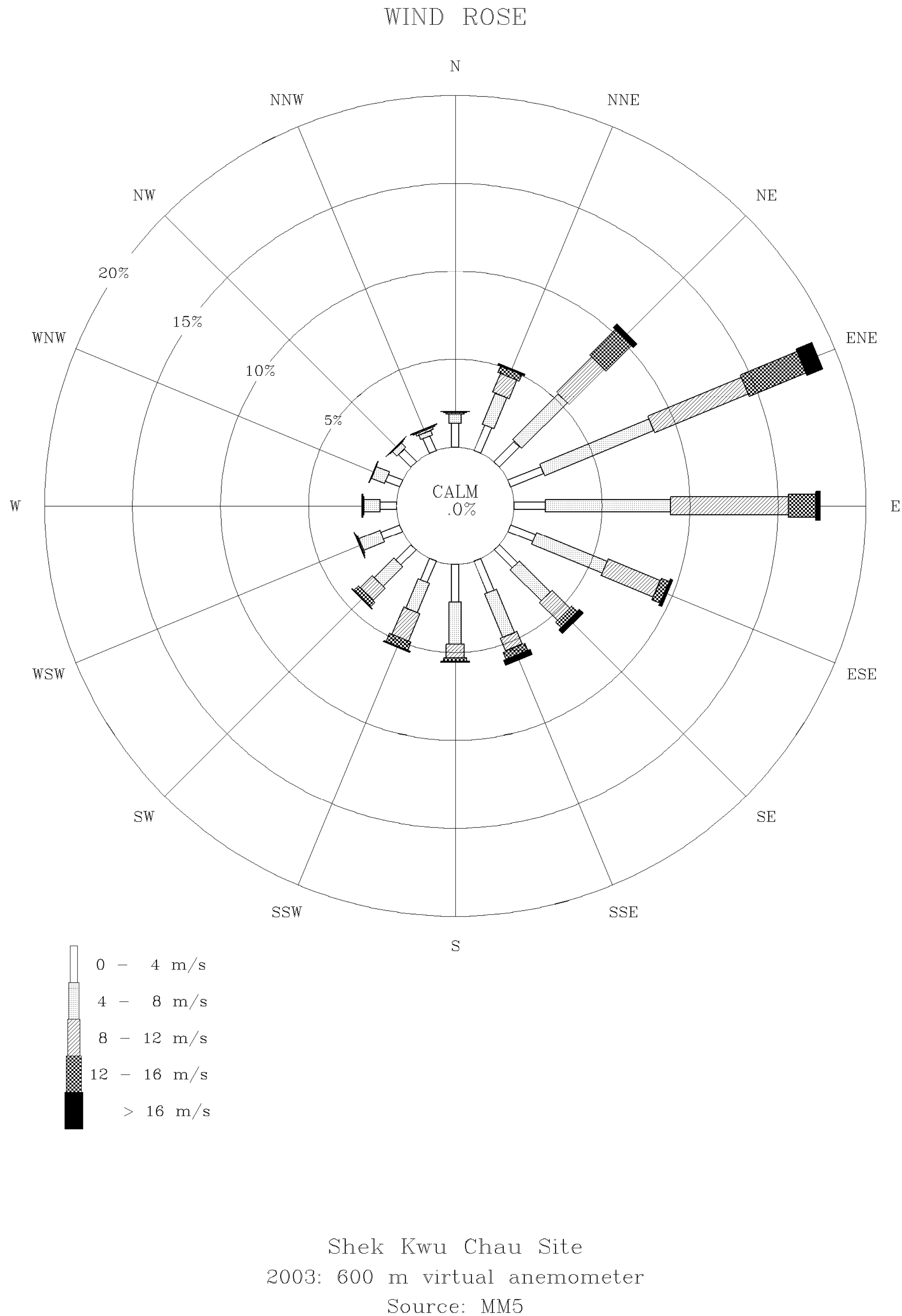


Figure 3. Wind rose for the 600m virtual anemometer at stack location: a) SKC site.

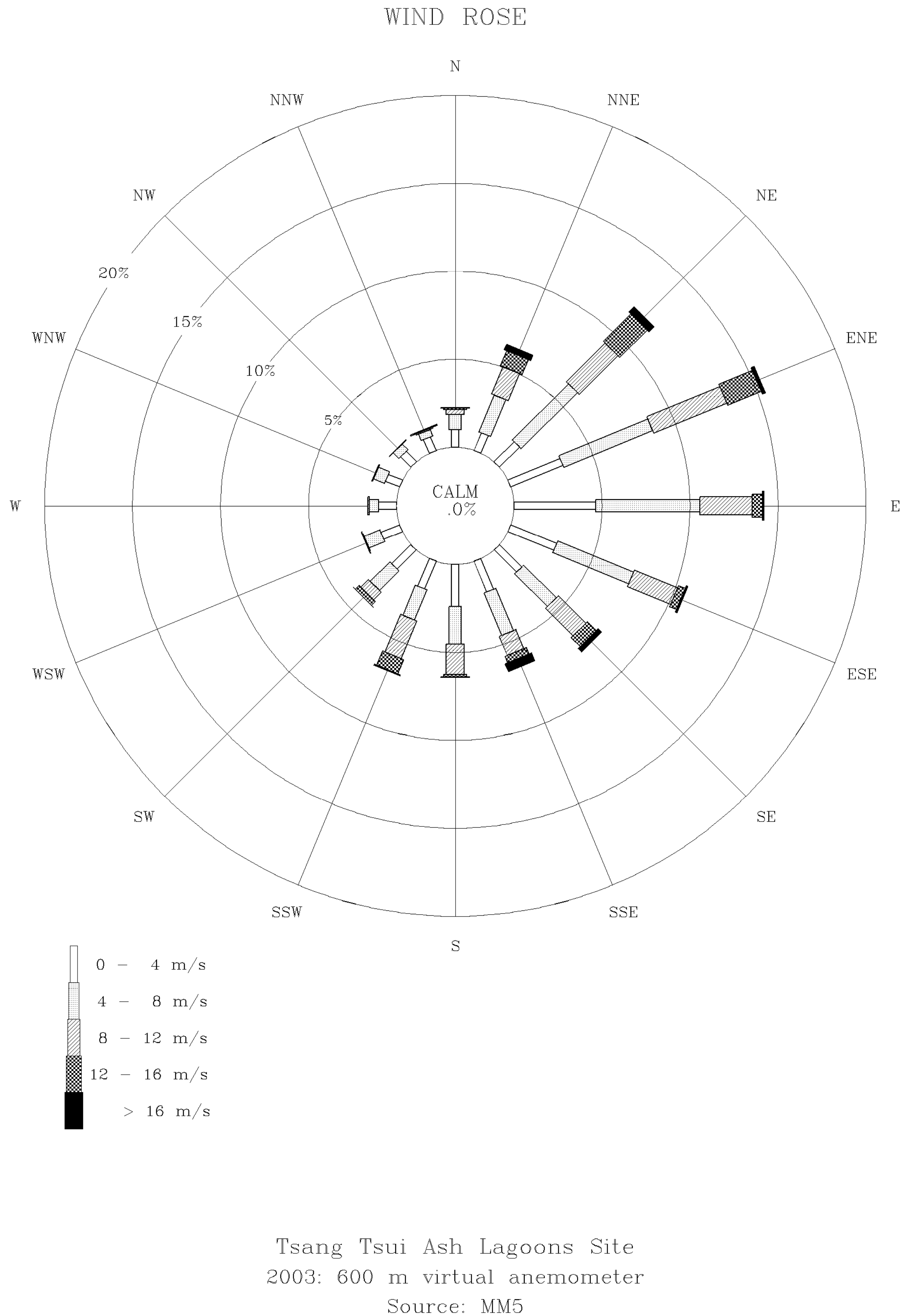


Figure 3. Wind rose for the 600m virtual anemometer at stack location: b) TTAL site.

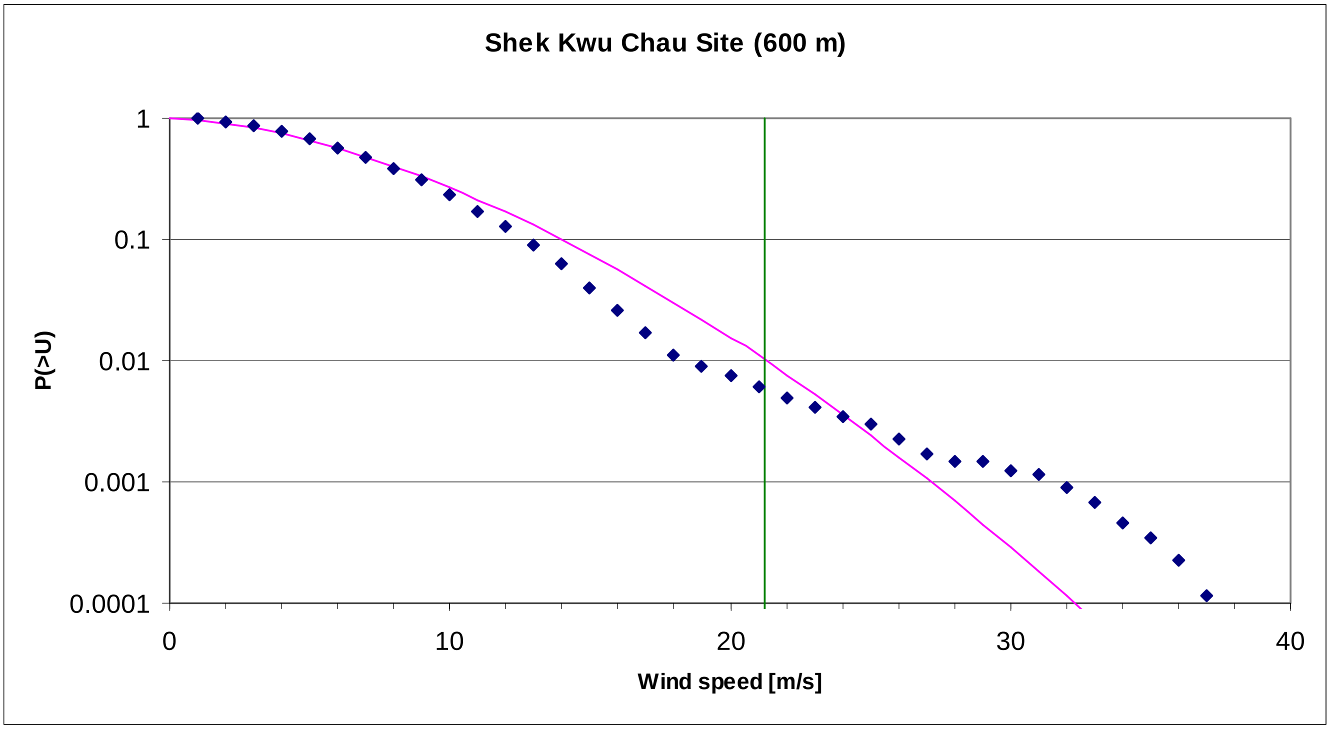


Figure 4. Percent time indicated wind speed is exceeded at the 600m virtual anemometer at stack location: a) SKC site.

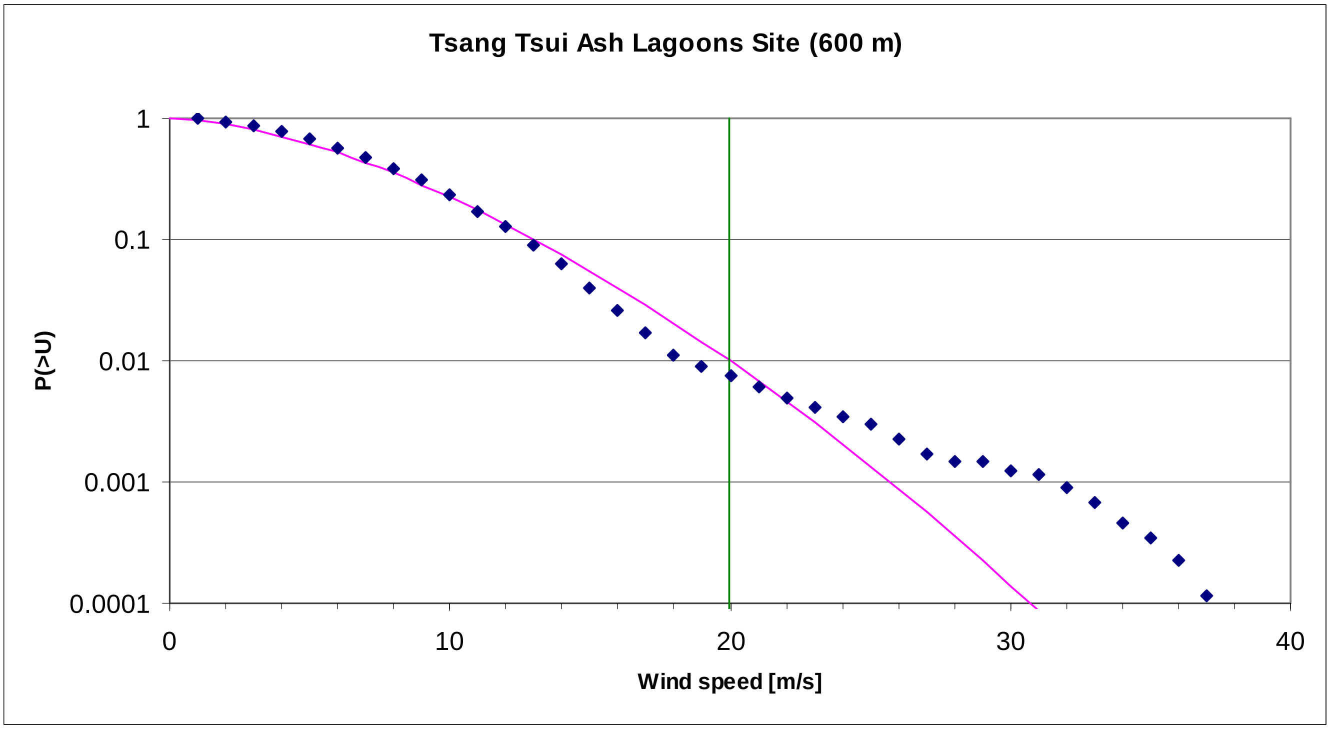
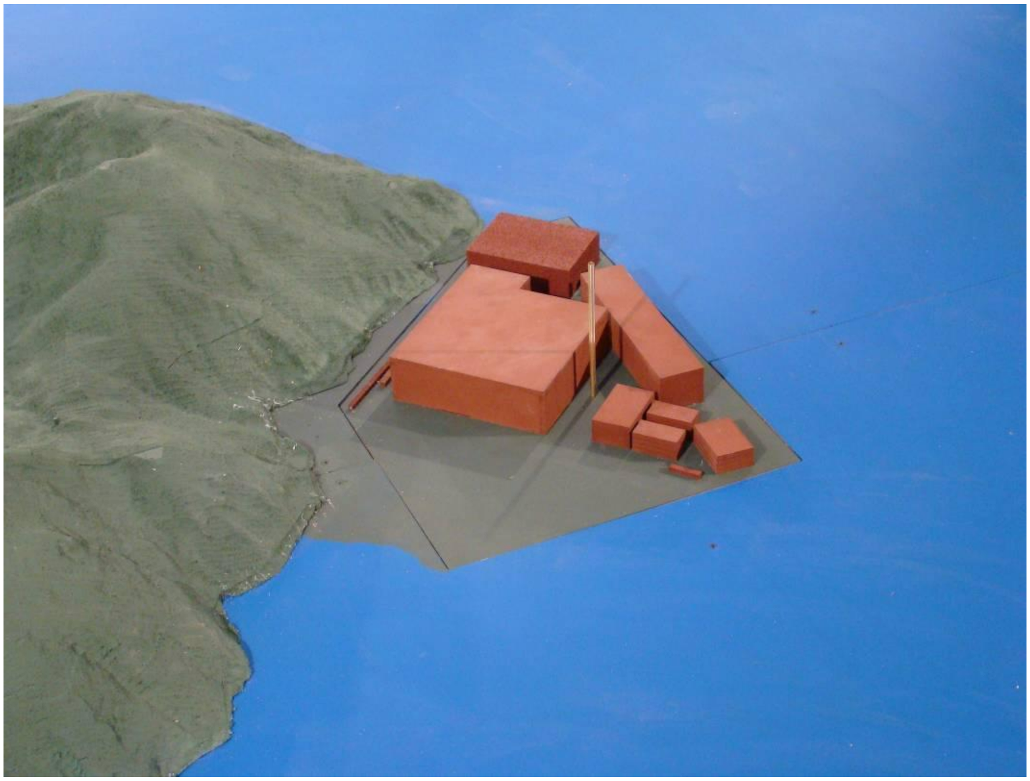


Figure 4. Percent time indicated wind speed is exceeded at the 600m virtual anemometer at stack location: b) TTAL site.

a) 

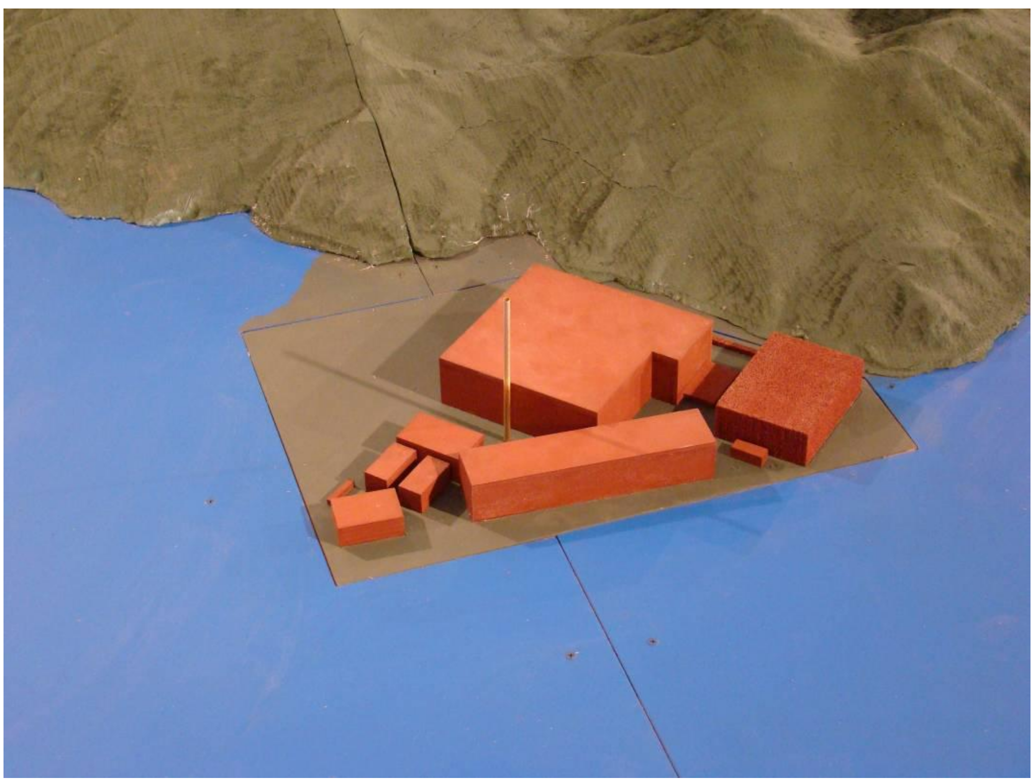
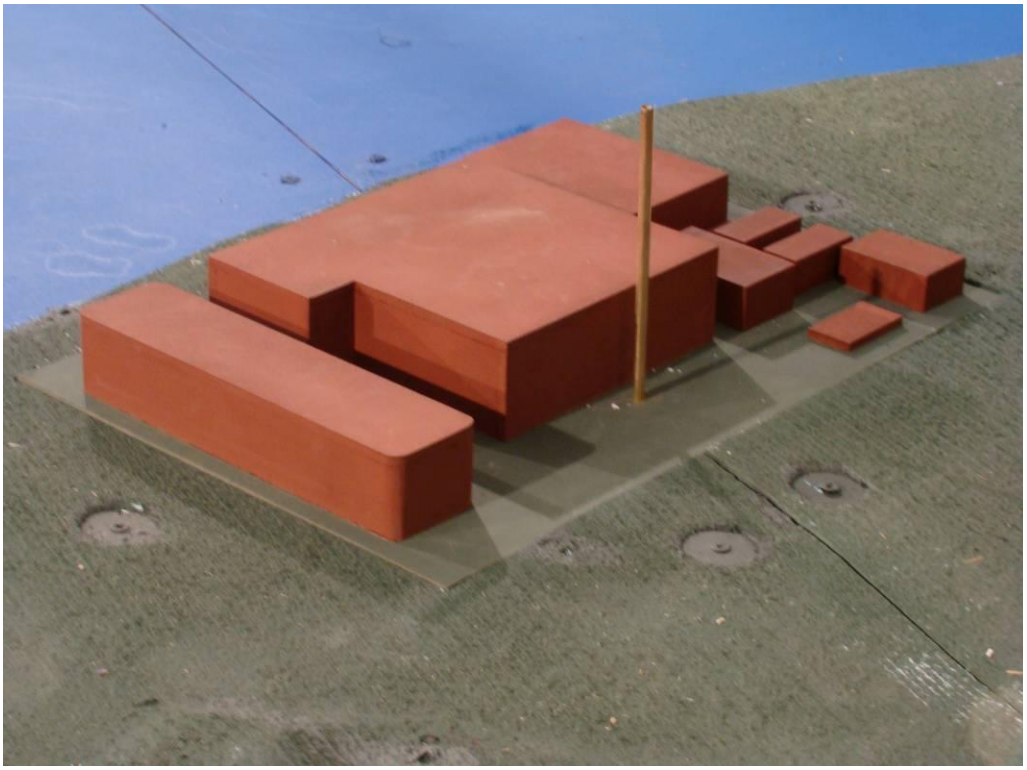
b) 

Figure 5. Close-up photographs of the IWMF: a) SKC site looking from the northwest; b) SKC site looking from the southwest.

c)



d)

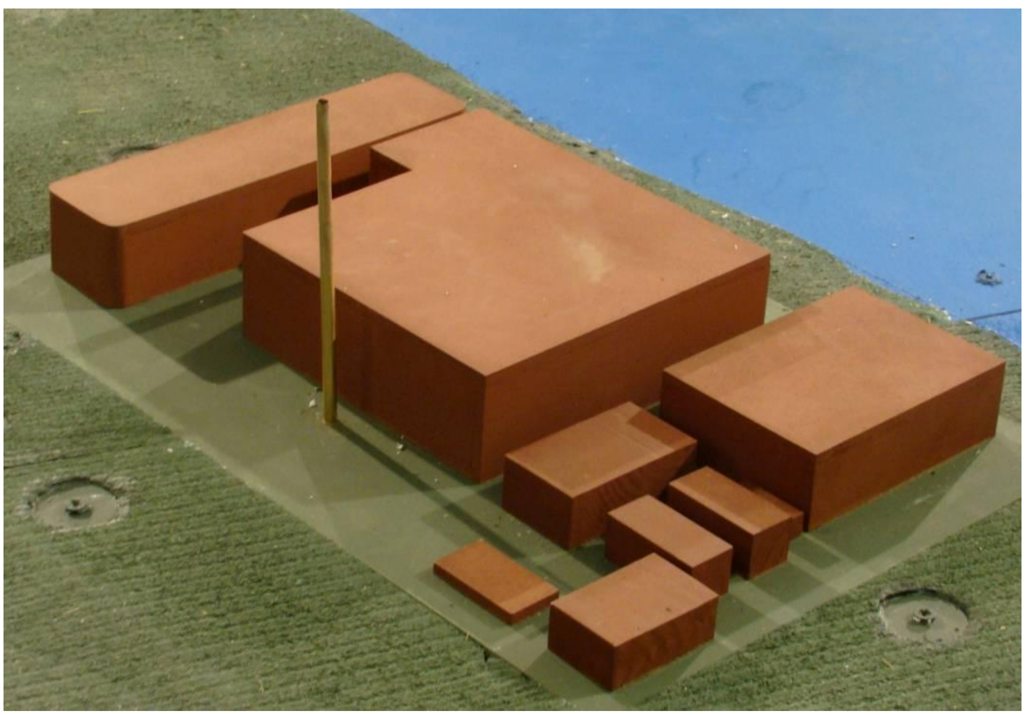
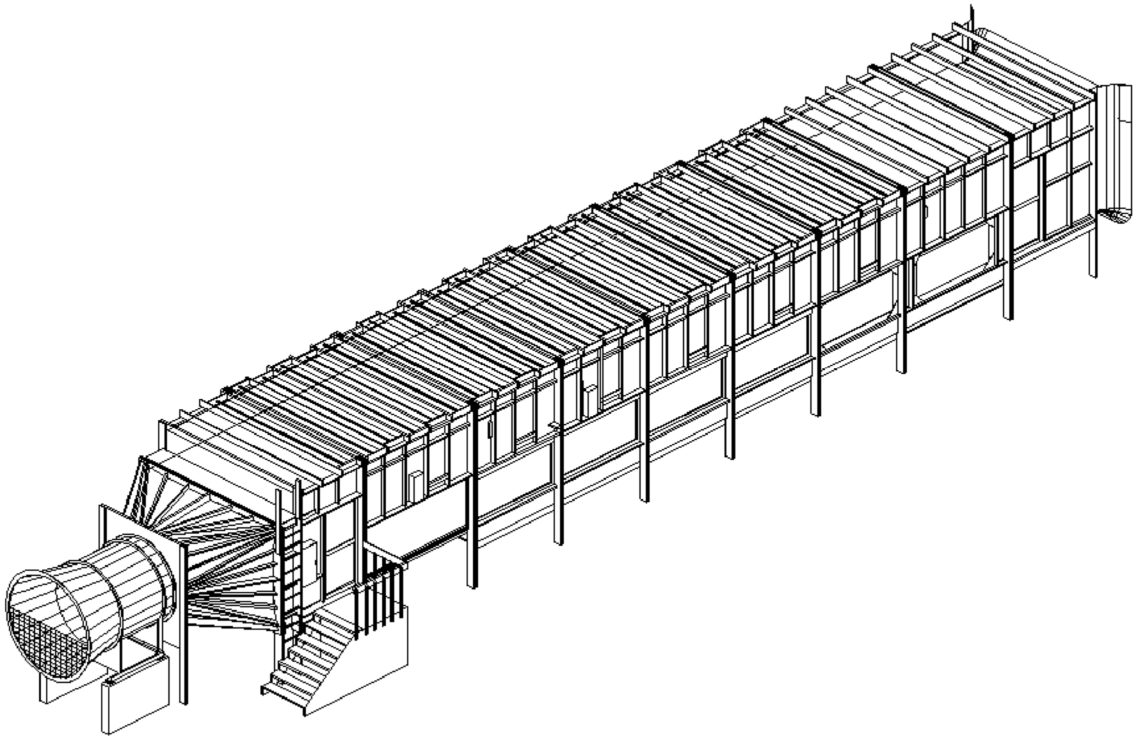


Figure 5. Close-up photographs of the IWMF: c) TTAL looking from the southwest; d) TTAL looking from the southeast.



CPP's Open-Circuit Wind Tunnel Performance Specifications

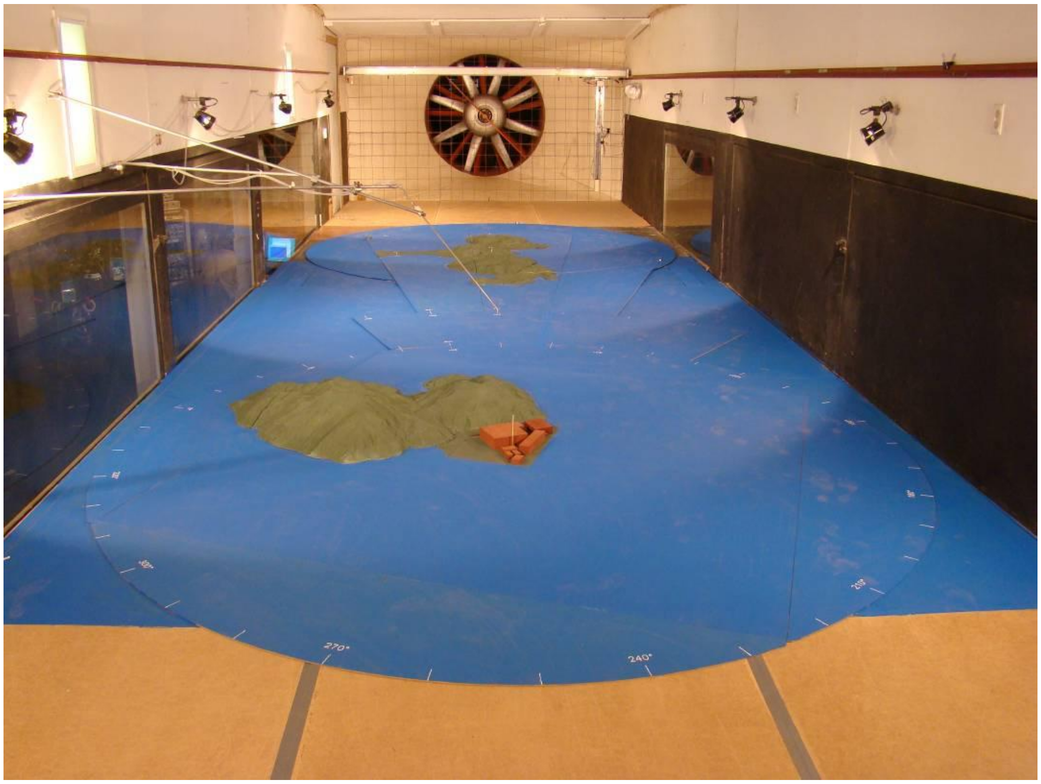
1.	**Dimensions**	
	Test Section Length	*74.5 ft (22.7 m)*
	Test Section Width	*12 ft (3.7 m)*
	Ceiling Height	*Variable from 5.5 ft to 8.5 ft (1.7 m to 2.6 m)*
2.	**Wind-Tunnel Fan**	
	Horse Power	*20 hp (15 kW)*
	Drive Type	*8 blade axial fan, two-speed motor*
	Speed Control	*Coarse: 900/600 rpm, 2 speed motor*
		Fine: blade pitch control
3.	**Temperature**	
	Ambient Air	*Not Controlled*
	Test Section Surface	*-50 ^{o}F to 120 ^{o}F (-46 ^{o}C to 49 ^{o}C)*
4.	**Boundary-Layer**	
	Free Stream Velocities	*0.0 fps to 30.0 fps (0.0 to 9.1 m/s)*
	Boundary-Layer Thickness	*Up to 6.0 ft (1.8 m)*
5.	**Stream wise Pressure Gradient**	*Zeroed by ceiling adjustment*

Figure 6. CPP's open-circuit wind tunnel used for testing.

a)

b)

Figure 7. Photographs of the wind-tunnel configuration for the SKC site: a) 180 degree wind direction, downwind view; b) 180 degree wind direction, upwind view.



c)

d)

Figure 7. Photographs of the wind-tunnel configuration for the SKC site: c) 250 degree wind direction, downwind view; d) 250 degree wind direction, upwind view.

a)

b)

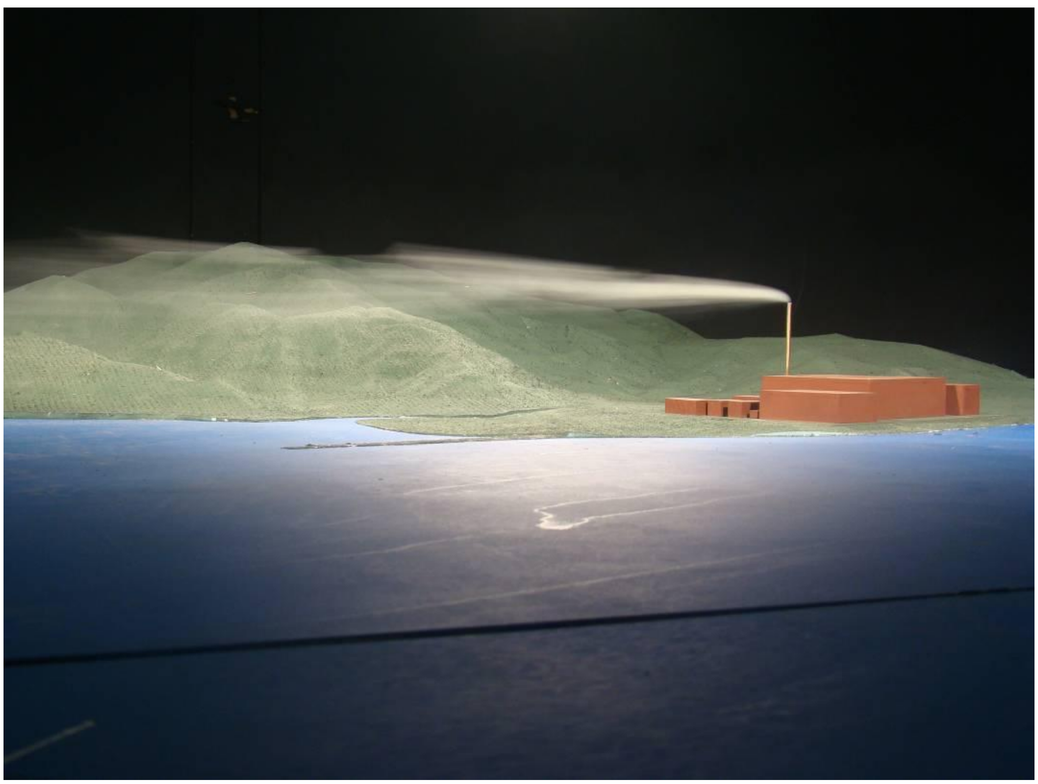
Figure 8. Photographs of the wind-tunnel configuration for the TTAL site: a) 355 degree wind direction, downwind view; b) 355 degree wind direction, upwind view.

c) 

d) 

Figure 8. Photographs of the wind-tunnel configuration for the TTAL site: c) 295 degree wind direction, downwind view; d) 295 degree wind direction, upwind view.

a)



b)

Figure 9. Photographs of selected plume flow visualizations: a) SKC Site, 125 m stack, 175 degree wind direction, 4 m/s wind speed at 600 m; b) TTAL Site, 150 m stack, 295 degree wind direction, 14 m/s wind speed at 600 m.

TABLES

Table 1
Full-scale Exhaust and Modeling Information

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 Base Height Above Grade (m)	Comment
The Integrated Waste Management Facility									
6 individual flues	F 1-6	150.00	2.03	413.0	42.19	48.55	15.00	0.0	Local Grade
Combined Stack	S	150.00	4.97	413.0	252.90	291.00	15.00	0.0	Local Grade

Site Parameters:

Scale Reduction:	1,000	
Typical Building Height (m):	50.0	
Ambient Temperature (°K):	295	stack location
Anemometer Height (m):	600.00	virtual anemometer at stack location
Anemometer Surface Roughness (m):	0.60	virtual anemometer at stack location
Wind Tunnel Approach Surface Roughness (m):	0.01	

Table 2
Air Sensitive Receiver Descriptions

Receptor Number	ASR Identification	Additional Explanation
S1	A_S1	Shek Kwu Chau Treatment and Rehabilitation Centre
S2	A_S2	Sai Wan Care Village
S3	A_S3	Don Basco Youth Centre
S4	A_S4	Cheung Fung House, Cheung Kwai Estate
S5	A_S5	Block 19-20, Sea Ranch, Yi Long Wan
S6	A_S6	Mong Tung Wan Hostel
T1	A_T1	Sheung Pak Nai
T2	A_T2	Ha Pak Nai
T3	A_T3	EPD WENT Landfill Site Office
T4	A_T4	Sludge Treatment Facilities Site Office
T5	A_T5	Tin Hau Temple
T6	A_T6	Black Point Power Station (Office)
T7	A_T7	Lung Kwu Sheung Tan

Table 3
Hong Kong Air Quality Objectives

Pollutant	Concentration in Microgrammes per Cubic Metre (i) Averaging Time					Health Effects of Pollutant at Elevated Ambient Levels
	1hr (ii)	8hrs (iii)	24hrs (iii)	3mths (iv)	1yr (iv)	
Sulphur Dioxide	800	--	350	--	80	Respiratory illness; reduced lung function; morbidity and mortality rates increase at higher levels.
Total Suspended Particulates	--	--	260	--	80	Respirable fraction has effects on health.
Respirable Suspended Particulates (v)	--	--	180	--	55	Respiratory illness; reduced lung function; cancer risk for certain particles; morbidity and mortality rates increase at higher levels.
Nitrogen Dioxide	300	--	150	--	80	Respiratory irritation; increased susceptibility to respiratory infection; lung development impairment.
Carbon Monoxide	30000	10000	--	--	--	Impairment of co-ordination; deleterious to pregnant women and those with heart and circulatory conditions.
Photochemical Oxidants (as ozone) (vi)	240	--	--	--	--	Eye irritation; cough; reduced athletic performance; possible chromosome damage.
Lead	--	--	--	1.5	--	Affects cell and body processes; likely neuro-psychological effects, particularly in children; likely effects on rates of incidence of heart attacks, strokes and hypertension.

Table 4
Concentration Measurement Test Plan and Summary of
Maximum Normalized Concentrations at each Receptor versus Wind Direction
No Buoyancy or Stability Correction

Run No.	Source ID	Stack Height Above Base (ft)	Stack Height Above Base (m)	Receptor Identification	Model Reference Speed (m/s)	Test Wind Direction (degrees)	Critical Wind Speed (m/s)	(1) Max Normalized WT-Measured Concentration (µg/m³)/(g/s)
Reynolds Number Independence tests								
901	S_3	328.0	100	A_S2	3	250	16.0	0.68
902	S_3	328.0	100	A_S3	3	250	16.0	0.48
903	S_4	328.0	100	A_S2	4	250	16.0	0.79
904	S_4	328.0	100	A_S3	4	250	16.0	0.50
905	S_5	328.0	100	A_S2	5	250	16.0	0.83
906	S_5	328.0	100	A_S3	5	250	16.0	0.48
Shek Kwu Chau Site								
304A	S	491.8	150	A_S1	4	170	21.0	0.02
305A	S	491.8	150	A_S1	4	175	21.0	0.04
306A	S	491.8	150	A_S1	4	180	21.0	0.07
307A	S	491.8	150	A_S1	4	185	21.0	0.01
301A	S	491.8	150	A_S1	4	187.5	21.0	0.01
302A	S	491.8	150	A_S1	4	190	21.0	0.00
312A	S	491.8	150	A_S2	4	240	4.0	0.01
318A	S	491.8	150	A_S2	4	242.5	4.0	0.00
313A	S	491.8	150	A_S2	4	245	4.0	0.26
311A	S	491.8	150	A_S2	4	247.5	4.0	0.54
314A	S	491.8	150	A_S2	4	250	4.0	1.11
316A	S	491.8	150	A_S2	4	252.5	4.0	0.66
315A	S	491.8	150	A_S2	4	255	4.0	0.12
317A	S	491.8	150	A_S2	4	257.5	4.0	0.01
321A	S	491.8	150	A_S3	4	242.5	4.0	0.03
323A	S	491.8	150	A_S3	4	245	4.0	0.04
322A	S	491.8	150	A_S3	4	247.5	4.0	0.27
324A	S	491.8	150	A_S3	4	250	4.0	1.06
326A	S	491.8	150	A_S3	4	252.5	4.0	0.71
325A	S	491.8	150	A_S3	4	255	4.0	0.13
327A	S	491.8	150	A_S3	4	257.5	4.0	0.01
337A	S	491.8	150	A_S4	4	227.5	4.0	0.07
336A	S	491.8	150	A_S4	4	230	4.0	0.16
331A	S	491.8	150	A_S4	4	232.5	4.0	0.72
332A	S	491.8	150	A_S4	4	235	4.0	1.14
333A	S	491.8	150	A_S4	4	237.5	4.0	0.80
334A	S	491.8	150	A_S4	4	240	4.0	0.12
335A	S	491.8	150	A_S4	4	245	4.0	0.00
341A	S	491.8	150	A_S5	4	170	4.0	0.06
348A	S	491.8	150	A_S5	4	172.5	4.0	0.04
342A	S	491.8	150	A_S5	4	175	6.0	0.08
343A	S	491.8	150	A_S5	4	177.5	6.0	0.09
344A	S	491.8	150	A_S5	4	180	6.0	0.26
345A	S	491.8	150	A_S5	4	182.5	6.0	0.57
346A	S	491.8	150	A_S5	4	185	6.0	0.63
347A	S	491.8	150	A_S5	4	187.5	6.0	0.31
349A	S	491.8	150	A_S5	4	190	6.0	0.08

Table 4
Concentration Measurement Test Plan and Summary of
Maximum Normalized Concentrations at each Receptor versus Wind Direction
No Buoyancy or Stability Correction

Run No.	Source ID	Stack Height Above Base (ft)	Stack Height Above Base (m)	Receptor Identification	Model Reference Speed (m/s)	Test Wind Direction (degrees)	Critical Wind Speed (m/s)	(1) Max Normalized WT-Measured Concentration (μg/m³)/(g/s)
352A	S	491.8	150	A_S6	4	167.5	4.0	0.14
353A	S	491.8	150	A_S6	4	170	4.0	0.44
354A	S	491.8	150	A_S6	4	172.5	4.0	1.01
355A	S	491.8	150	A_S6	4	175	4.0	1.51
356A	S	491.8	150	A_S6	4	177.5	4.0	1.15
357A	S	491.8	150	A_S6	4	180	4.0	0.46
351A	S	491.8	150	A_S6	4	182.5	4.0	0.08
Tsang Tsui Ash Lagoons Site								
801A	S	491.8	150	A_T1	4	225	4.0	0.02
802A	S	491.8	150	A_T1	4	227.5	4.0	0.24
803A	S	491.8	150	A_T1	4	230	4.0	0.92
804A	S	491.8	150	A_T1	4	232.5	4.0	0.80
805A	S	491.8	150	A_T1	4	235	4.0	0.35
806A	S	491.8	150	A_T1	4	237.5	4.0	0.07
807A	S	491.8	150	A_T1	4	240	4.0	0.09
811A	S	491.8	150	A_T2	4	240	21.0	0.01
812A	S	491.8	150	A_T2	4	245	21.0	0.04
813A	S	491.8	150	A_T2	4	247.5	21.0	0.31
814A	S	491.8	150	A_T2	4	250	21.0	0.44
815A	S	491.8	150	A_T2	4	252.5	21.0	0.46
816A	S	491.8	150	A_T2	4	255	21.0	0.38
817A	S	491.8	150	A_T2	4	260	21.0	0.02
821A	S	491.8	150	A_T3	4	275	21.0	0.00
822A	S	491.8	150	A_T3	4	280	21.0	0.00
823A	S	491.8	150	A_T3	4	285	21.0	0.00
824A	S	491.8	150	A_T3	4	287.5	21.0	0.23
825A	S	491.8	150	A_T3	4	290	21.0	0.59
828A	S	491.8	150	A_T3	4	292.5	21.0	0.16
826A	S	491.8	150	A_T3	4	295	21.0	0.03
827A	S	491.8	150	A_T3	4	300	21.0	0.02
831A	S	491.8	150	A_T4	4	240	21.0	0.00
832A	S	491.8	150	A_T4	4	245	21.0	0.00
833A	S	491.8	150	A_T4	4	247.5	21.0	0.00
834A	S	491.8	150	A_T4	4	250	21.0	0.00
835A	S	491.8	150	A_T4	4	252.5	21.0	0.00
836A	S	491.8	150	A_T4	4	255	21.0	0.01
837A	S	491.8	150	A_T4	4	260	21.0	0.00

Table 4
Concentration Measurement Test Plan and Summary of
Maximum Normalized Concentrations at each Receptor versus Wind Direction
No Buoyancy or Stability Correction

Run No.	Source ID	Stack Height Above Base (ft)	Stack Height Above Base (m)	Receptor Identification	Model Reference Speed (m/s)	Test Wind Direction (degrees)	Critical Wind Speed (m/s)	(1) Max Normalized WT-Measured Concentration (µg/m³)/(g/s)
841A	S	491.8	150	A_T5	4	35	21.0	0.02
842A	S	491.8	150	A_T5	4	40	21.0	0.00
844A	S	491.8	150	A_T5	4	45	21.0	0.00
845A	S	491.8	150	A_T5	4	47.5	21.0	0.00
846A	S	491.8	150	A_T5	4	50	21.0	0.00
847A	S	491.8	150	A_T5	4	55	21.0	0.00
857A	S	491.8	150	A_T6	4	35	21.0	0.07
856A	S	491.8	150	A_T6	4	40	21.0	0.09
851A	S	491.8	150	A_T6	4	45	21.0	0.79
855A	S	491.8	150	A_T6	4	47.5	21.0	1.03
852A	S	491.8	150	A_T6	4	50	21.0	1.08
854A	S	491.8	150	A_T6	4	55	21.0	0.20
853A	S	491.8	150	A_T6	4	60	21.0	0.03
868A	S	491.8	150	A_T7	4	0	14.0	0.08
861A	S	491.8	150	A_T7	4	5	14.0	0.42
862A	S	491.8	150	A_T7	4	10	14.0	0.71
863A	S	491.8	150	A_T7	4	12.5	14.0	0.56
864A	S	491.8	150	A_T7	4	15	14.0	0.39
865A	S	491.8	150	A_T7	4	17.5	14.0	0.18
866A	S	491.8	150	A_T7	4	20	14.0	0.09
867A	S	491.8	150	A_T7	4	25	14.0	0.00

Table 5
Summary of Predicted Maximum Normalized Concentrations at each Receptor
No Buoyancy or Stability Correction

Stack Height Above Base (m)	Receptor Identification	Maximum Normalized Concentration Prediced from Fit and Hourly Met Data (µg/m³)/(g/s)				
		1-hour average	8-hour average	24-hour average	3-month average	annual average
Shek Kwu Chau Site						
150	A_S1	0.052	0.026	0.009	0.000	0.000
150	A_S2	1.301	0.916	0.366	0.023	0.006
150	A_S3	1.179	0.745	0.304	0.023	0.007
150	A_S4	1.351	0.850	0.265	0.027	0.008
150	A_S5	0.737	0.554	0.233	0.021	0.009
150	A_S6	1.762	1.358	0.424	0.059	0.025
Tsang Tsui Ash Lagoons Site						
150	A_T1	0.918	0.433	0.235	0.019	0.006
150	A_T2	0.359	0.109	0.036	0.000	0.000
150	A_T3	0.003	0.000	0.000	0.000	0.000
150	A_T4	0.000	0.000	0.000	0.000	0.000
150	A_T5	0.000	0.000	0.000	0.000	0.000
150	A_T6	1.223	1.205	0.914	0.104	0.034
150	A_T7	0.683	0.536	0.154	0.007	0.004

Note:
The maximum normalized concentration for each site is highlighted in yellow.

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):

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

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

and

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

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;
ν	=	kinematic viscosity;

K = thermal conductivity;

Ω = angular velocity 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 $\in_{ijk}$ 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:

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

- equal Prandtl number:

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

- equal Eckert number:

$$Ec = \frac{U_o^2}{C_{po} \Delta T_o} \tag{A.8}$$

- 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:

$$\mathrm{Re}_{z_o} = \frac{z_o u_*}{\nu} > 2.5 \qquad \text{(A.14)}$$

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:

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

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:

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

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. WIND-TUNNEL SCALING METHODS

This section discusses the methods commonly used to set up wind-tunnel model operating conditions. Based on CPP's past experience with diffusion studies (Petersen, 1991, 1989, 1987, and 1978) and the requirements in the EPA fluid modeling guideline (EPA, 1981; 1985), the criteria that are used for conducting these wind-tunnel simulations are:

- match (equal in model and full scale) momentum ratio, M_o:

$$M_o = \lambda \left(\frac{V_e}{U_H} \right)^2 \tag{A.17}$$

- match buoyancy ratio, B_o:

$$B_o = \frac{g d V_e (\rho_a - \rho_s)}{\rho_a U_h^3} = \left(\frac{\rho_s}{\rho_a} \right) \left(\frac{(V_e / U_h)^3}{Fr_s^2} \right) \left(\frac{d}{z_r} \right) \tag{A.18}$$

where

$$Fr_s^2 = \frac{\rho_s V_e^2}{g(\rho_a - \rho_s) d} \tag{A.19}$$

- ensure a fully turbulent stack gas flow [stack Reynolds number ($Re_s = V_e d/\nu$) greater than 670 for buoyant plumes or 2000 for turbulent jets (Arya and Lape, 1990), or in-stack trip];
- ensure a fully turbulent wake flow [terrain or building Reynolds number ($Re_b = U_H H_b/\nu$) greater than 11,000 or conduct Reynolds number independence tests];
- identical geometric proportions;
- equivalent stability [Richardson number [$Ri = (g\Delta\theta H_b)/(T\, U_H^2)$] in model equal to that in full scale, equal to zero for neutral stratification]; and
- equality of dimensionless boundary and approach flow conditions;

where

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

U_H = ambient velocity at building top (m/s);

d = stack diameter (m);

ρ_a = ambient air density (kg/m^3);

$\Delta\theta$ = potential temperature difference between H_b and the ground (K);

T = mean temperature (K);

ρ_s = stack gas density (kg/m^3);

ν = viscosity (m^2/s);

H_b = typical building height (m); and

λ = density ratio, ρ_s/ρ_a (-).

For certain simulations it is advantageous to conduct simulations at model scale Reynolds numbers less than 11,000. When this situation arises, Reynolds number sensitivity tests are conducted. The Reynolds number independence tests consist of setting up a simulation with a neutral density exhaust and an approach wind speed to exit velocity ratio of 1.50. Initial tests are conducted with a high model approach wind speed so that the building Reynolds number meets or exceeds 11,000. The simulation is subsequently repeated at incrementally lower approach wind speeds, thus incrementally lower building Reynolds numbers. Concentrations during each of these simulations are measured at one or more receptor locations. The concentration distribution measured for the simulation with a building Reynolds number at or greater than 11,000 is used as the baseline. The concentration distribution from the subsequent, lower building Reynolds number simulations, are then compared to this baseline distribution. If the two distributions are within ±10% of the maximum measured value, the two simulations are assumed to be equivalent. The building Reynolds number for the simulation with the lowest approach wind speed which meets this criterion is established as the site specific critical building Reynolds number. All subsequent simulations are conducted with building Reynolds numbers at least as great as this site specific building Reynolds number.

For buoyant sources, the ideal modeling situation is to simultaneously match the stack exit Froude number, momentum ratio and density ratio. Achieving such a match requires that the wind speed in the tunnel be equal to the full scale wind speed divided by the square root of the length scale. For example, for a 1:180 length scale reduction, the wind speed ratio would be approximately 1:13, meaning the tunnel speeds would be 13 times lower than the full scale wind speeds. Such a low tunnel speed would produce low Reynolds numbers and is operationally difficult to achieve. Hence, Froude number scaling is typically not used. Instead, for buoyant sources, the buoyancy ratio defined above is matched between model and full scale. Using this criterion, the exhaust density of the source can be distorted which allows higher wind-tunnel speeds.

Even with distorting the density, there may still be situations in which the buoyancy ratio can not be matched without lowering the wind-tunnel speed below the value established for the critical building Reynolds number. When this conflict exists, the buoyancy ratio is distorted and the building Reynolds number criterion is not relaxed. The impact of distorting the buoyancy ratio will result in lower plume rise which in turn will result in higher predicted concentrations. Hence, the results of the study will be conservative.

Testing is typically performed under neutral stability ($Ri = 0$). Meroney (1990) cites a Colorado State University report which determined that the effect of atmospheric stability on dispersion within five building heights of a building complex is relatively small due to the dominance of mechanical turbulence generated within the building complex.

Another factor to consider when setting up a wind-tunnel simulation is the blockage (model cross-sectional area perpendicular to the flow divided by wind tunnel cross-sectional area). EPA (1981) states that blockage should be limited to 5% unless the roof can be adjusted. In the later case a 10% blockage is acceptable. The model-scale reduction factor used for CPP studies are established to ensure that the blockage is less than 10%, since CPP's wind-tunnel roof is adjustable.

Using the above criteria and source parameters supplied by the client, as noted in the main body of this report, the model test conditions were computed for each of the exhaust sources under evaluation. CPP has developed a spreadsheet to facilitate the design of wind-tunnel tests based on full-scale source parameters and pertinent modeling restrictions. A description of each of the parameters shown on the similarity tables included at the end of this appendix is presented Section A.5. Values shown in square brackets are parameter numbers which correspond to the number of the parameter in the similarity table. Depending upon the type of wind-tunnel study being conducted, building or terrain effects may dominate the flow patterns on the model. For parameters which may have this distinction, the terrain parameter description is contained in parentheses following the first description. Parameter subscripts f and m indicate reference to the full scale or model scale parameter value, respectively.

A.4. EVALUATION OF SIMULATED BOUNDARY LAYER

An important similarity criterion discussed in Section A.1 is the similarity of the approaching wind conditions, particularly the variation of mean wind speed and turbulence intensity with height. The atmospheric boundary-layer wind tunnels employed by CPP are specifically designed to simulate the mean wind speed and turbulence intensity profiles which occur in the atmosphere. The boundary layer is achieved with the use of screens, flow straighteners, trips, and roughness elements. The screens and flow straighteners (long horizontal tubes) are located at the entrance of the wind tunnel to produce a homogeneous flow across the entrance region. Development of the boundary layer is initiated with a series of vertical spires and a horizontal trip located downwind of the entrance region. The floor of the boundary-layer development region, which resides between the trip and the test section, is filled with roughness elements that are specifically designed to simulate the atmospheric boundary layer approaching the project site. When the approach conditions vary with wind direction, i.e., a site which is partially bounded by a large body of water or a site which is located on the outskirts of a large city, multiple roughness configurations may be necessary. Figure A.1 shows the wind-tunnel configuration(s) utilized during this study.

In order to document the appropriateness of the wind-tunnel configuration(s), vertical profiles of mean velocity and longitudinal turbulence intensity were obtained upwind of the model test area. The profiles were collected using a hot-film anemometer mounted on a vertical traverse device. The procedures for measuring the velocity profiles are discussed in Appendix B.

Figure A.2 shows the mean velocity and longitudinal turbulence intensity profiles that were collected upwind of the turntable model for the wind-tunnel configuration(s) shown in Figure A.1. Each of the plots include the measured data along with curves of the predicted profiles developed from the analysis described below.

An analysis of the mean velocity profile was conducted to determine whether the shape was characteristic of that expected in the atmosphere. The starting point in any analysis of the mean velocity profile characteristics is to consider the equations which are commonly used to predict the distribution of wind and turbulence in the atmosphere. The most common equation, which has a theoretical basis, is referred to as the "log-law" and is given by:

$$\frac{U}{U_*} = \frac{1}{k} \ln\left(\frac{z}{z_o}\right) \tag{A.20}$$

where

U	=	the velocity at height z;
z	=	elevation above ground-level;
z_o	=	the surface roughness length;
U_*	=	the friction velocity; and
k	=	the von Kàrmàn's constant (which is generally taken to be 0.4).

Another equation which is commonly used to characterize the mean wind profile is referred to as the "power-law" and is given by:

$$\frac{U}{U_r} = \left(\frac{z}{z_r}\right)^n \tag{A.21}$$

where

z_r	=	is some reference height;
U_r	=	is the wind speed at the reference height; and
n	=	is the "power-law" exponent.

Figure A.1 shows the computed U^* and z_o values obtained from the analysis of the mean velocity profiles. The analysis was undertaken using a least-squares technique to find the n, U^* and z_o values which gave the least error to the above equations. The measured "power-law" exponent and the surface roughness length values are shown within the figure.

Another consistency check is to relate the power-law exponent, n, to the surface roughness length, z_o. Counihan (1975) presents a method for computing the "power-law" from the surface roughness length, z_o, using the following equation:

$$n = 0.24 + 0.096 \log_{10} z_o + 0.016 (\log_{10} z_o)^2 \tag{A.22}$$

When the value for z_o shown in Figure A.1 is substituted in to the above equation a "power-law" exponent, n, is obtained. The power law wind profile was computed using this exponent and the result is shown in Figure A.1. The figure indicates that there is a strong agreement between the power-law profile and the measured velocity profile.

The variation of longitudinal turbulence intensity with height has been quantified by EPA (1981). EPA gives the following equation for predicting the variation of longitudinal turbulence intensity in the surface layer:

$$\frac{U'}{U} = n \frac{\ln\left(\frac{30}{z_o}\right)}{\ln\left(\frac{z}{z_o}\right)} \tag{A.23}$$

where all heights are in full-scale meters. This equation is only applicable between 5 and 100 m (16 and 330 ft). Above 100 m, the turbulence intensity is assumed to decrease linearly to a value of 0.01 at a height of roughly 600 m (2000 ft) above ground level. The observed z_o and computed power law exponent were input into the above equation to define the turbulence intensity profile. Figure A.1 shows that the observed turbulence intensity profile compares well with the profile estimated using the above equation (denoted “Snyder’s Approximation” in the figure).

In summary, the mean velocity and turbulence intensity profiles established in the wind tunnel are representative of those expected for the site evaluated during this study. Thus, the profiles meet the approach similarity requirements for wind-tunnel modeling.

A.5. 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 1/32^nd of an inch due to the restrictions of commercially available brass tubing. Minimum value is 2/32^nds 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]

[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).

$$A_e = \frac{\pi d^2}{4} \tag{A.24}$$

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:

$$A_e = \frac{V}{V_e} \tag{A.25}$$

[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):

$$P_a = 1013 \exp\left[\frac{x}{-8350}\right] \quad \text{(A.26)}$$

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:

$$P_a = 28.96\frac{g}{mole} \div 22.4\frac{1}{mole} \times 273.15K \div T\ (K) \times P\ (atm) \quad \text{(A.27)}$$

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]:

$$\rho_s = \rho_a\ \lambda \quad \text{(A.28)}$$

[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):

$$V = \frac{145.8\, T^{3/2}}{\rho\,(T + 110.4)\, 10^8} \quad \text{(A.29)}$$

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):

$$\mu_{mix} = \sum_{i=1}^{n} \left[\frac{X_i \mu_i}{\sum_{j=1}^{n} X_j \Phi_{ij}} \right] \tag{A.30}$$

$$\Phi_{ij} = \frac{1}{\sqrt{8}} \left(1 + \frac{M_i}{M_j} \right)^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j} \right)^{1/2} \left(\frac{M_j}{M_i} \right)^{1/4} \right]^2 \tag{A.31}$$

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:

$$U_{z_1} = U_{z_2} \left(\frac{z_1}{z_2} \right)^n \tag{A.32}$$

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:

$$t_f = t_m \, SF \left(\frac{U_{\infty_m}}{U_{\infty_f}} \right) \tag{A.33}$$

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):

$$n = 0.24 + 0.096 \log_{10} z_o + 0.016 \left(\log_{10} z_o \right)^2 \tag{A.34}$$

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:

$$R = \left[\frac{M_o}{\lambda \left(\frac{d}{h} \right)^2} \right]^{1/2} \tag{A.35}$$

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.

Full scale value: Computed by dividing V_e [6_f] by U_h [24_f].

Model scale value: 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 ($z = 0$).

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

Model scale value: 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.

Full scale value: Computed by dividing d [4_f] by h [3_f].

Model scale value: Computed by dividing d [4_m] by h [3_m].

[37] *Momentum Ratio, M_o*

This factor is computed using the following equation:

$$M_o = \left(\frac{V_e}{U_r} \right)^2 \lambda \left(\frac{d}{h} \right)^2 \tag{A.36}$$

Full scale value: 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].

Model scale value: 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:

$$Fr_s = \left[\frac{V_e^2}{d\ g \left(\frac{1}{\lambda} - 1 \right)} \right]^{1/2} \quad \text{(A.37)}$$

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:

$$B_o = \frac{1}{4} \frac{\lambda R^3 d}{Fr_s^2 h} \quad \text{(A.38)}$$

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:

$$\mathrm{Re} = \frac{L\ U}{\nu} \quad \text{(A.39)}$$

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 v is [14_f].

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

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

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 v 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 v is [14_m].

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

This factor is computed using the following equation:

$$\frac{U_*}{U_\infty} = \sqrt{0.00275 + 0.0006 \log\left(z_o\right)} \tag{A.40}$$

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.6. REFERENCES

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FIGURES

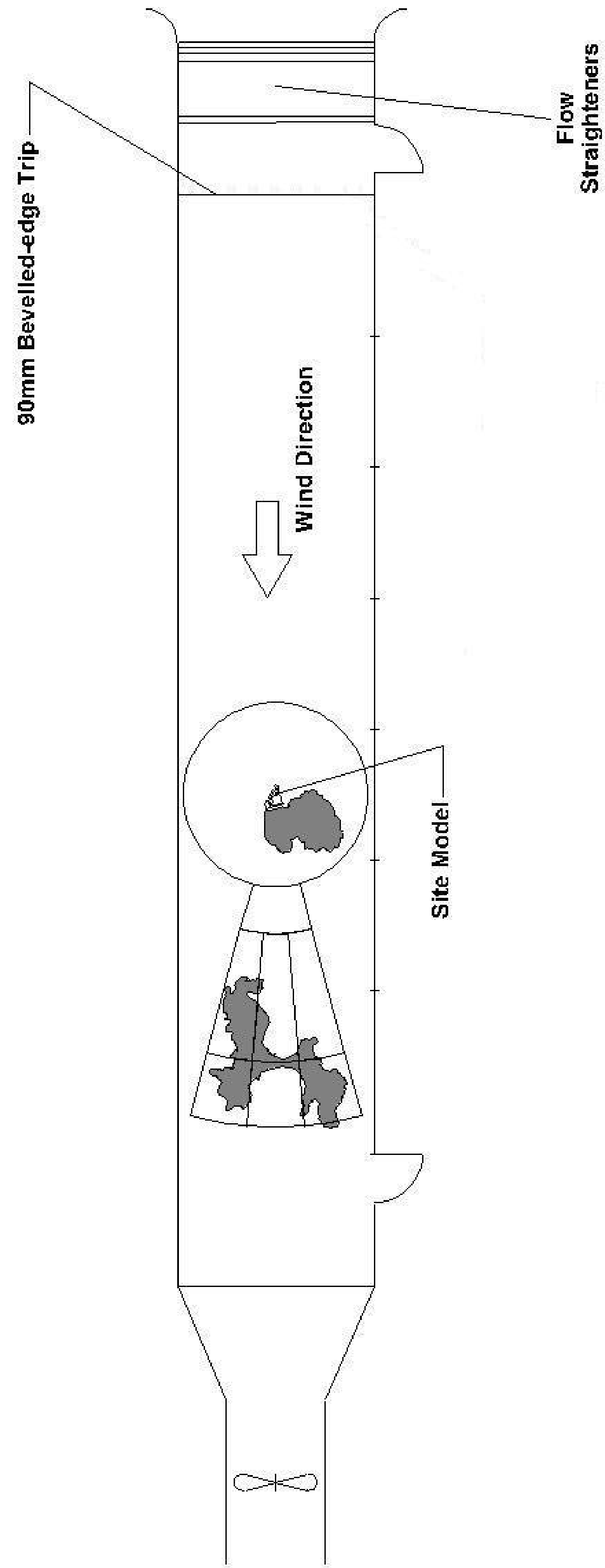


Figure A.1.a. Schematic of the wind-tunnel configuration - SKC site.

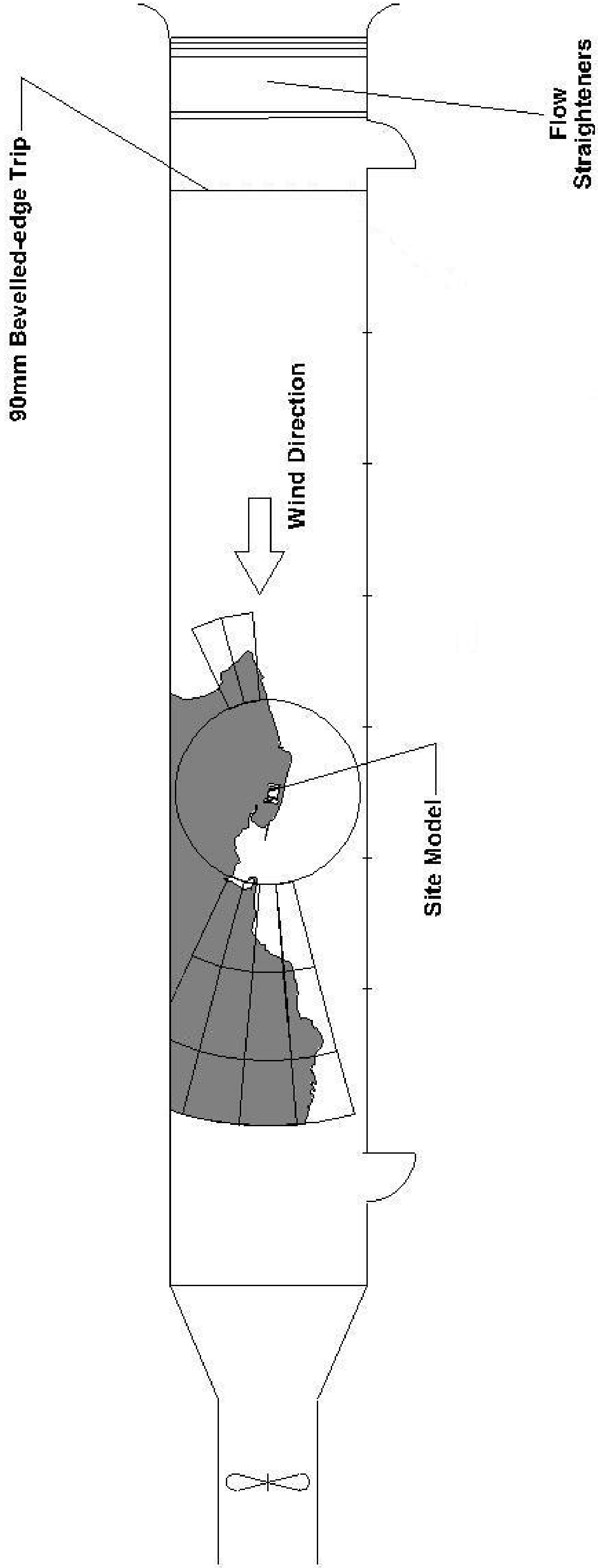
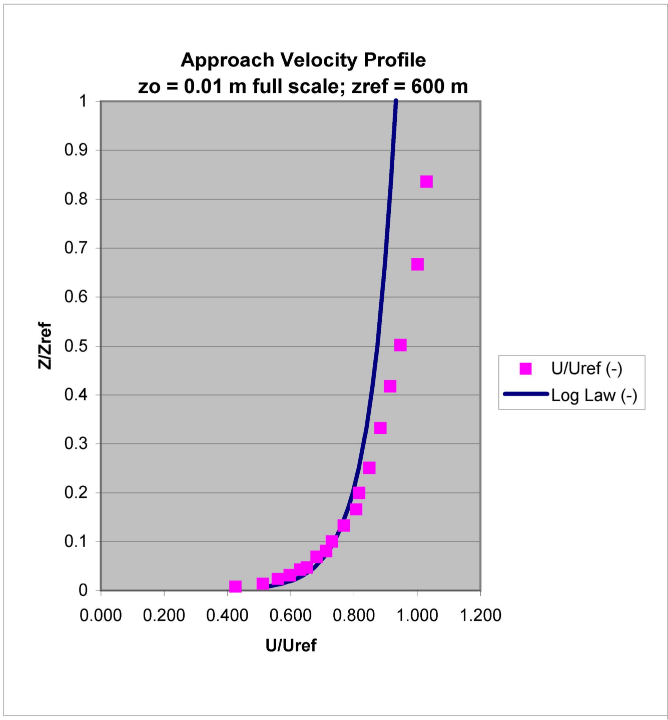


Figure A.1.b. Schematic of the wind-tunnel configuration - TTAL site.



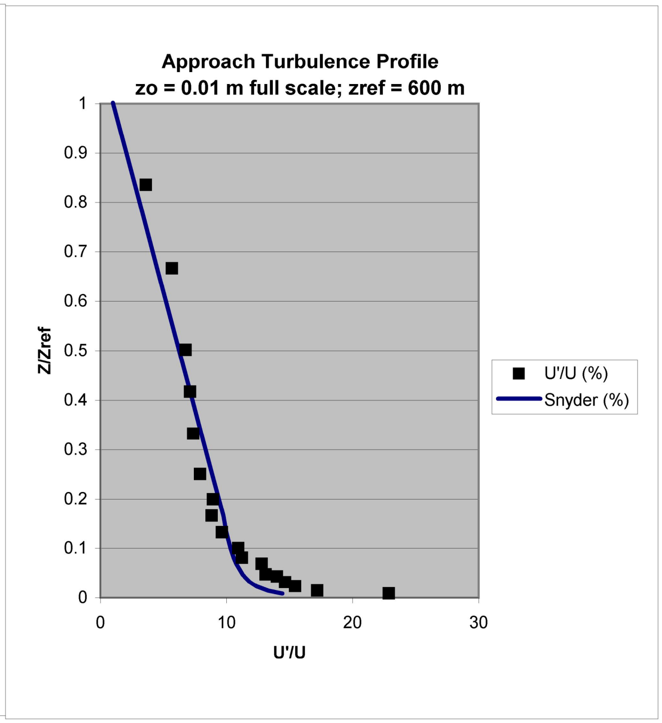


Figure A.2. Mean velocity and turbulence intensity profile approaching the model.

TABLES

Table A-AB

Full and Model Scale Similarity Parameters

Combined Stack (S)

Anemometer Wind Speed =21.25 m/s

Dimensional Parameters	**Full Scale**	**Model Scale**
1 . Terrain Height, Ht (m)	50.00	0.05
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	-	1,524.00
3 . Stack Height above grade, h (m)	150.00	0.15
4 . Stack Inside Diameter, d (m)	4.97	4.969E-03
5 . Stack Inside Area, A_c (m^2)	19.40	1.939E-05
6 . Exit Velocity, V_c (m/s)	15.00	2.83
7 . Exit Temperature, T_s (K)	413.00	293.15
8 . Volume Flow Rate, V (m^3/s)	291.00	5.478E-05
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	1,013.00	844.00
11 . Ambient Temperature, T_a (K)	295.37	293.15
12 . Air Density, ρ_a (kg/m^3)	1.19	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.85	0.72
14 . Air Viscosity, ν_a (m^2/s)	1.53E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	2.74E-05	1.77E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	21.25	4.00
17 . Free Stream Height, z_{inf} (m)	600.00	0.60
18 . Reference Wind Speed, U_{ref} (m/s)	21.25	4.00
19 . Reference Height, z_{ref} (m)	600.00	0.60
20 . Anemometer Wind Speed, U_a (m/s)	21.25	4.00
21 . Anemometer Height, z_a (m)	600.00	0.60
22 . Site Wind Speed, U_s (m/s)	21.25	4.00
23 . Site Anemometer' Height, z_s (m)	600.00	0.60
24 . Stack Height Speed, U_h (m/s)	18.19	3.43
25 . Terrain Height Speed, Ut (m/s)	16.09	3.03
26 . Anemometer Surface Roughness Length, $z_{o,a}$ (m)	0.01	1.00E-05
27 . Site Surface Roughness Length, $z_{o,s}$ (m)	0.01	1.00E-05
28 . Site Surface Friction Velocity, U_* (m/s)	0.84	0.16
Dimensionless Parameters		
29 . Length Scale, SF	1,000.00	1.00
30 . Time Scale, TS	188.29	1.00
31 . Anemometer Power Law Exponent, n_a	0.11	0.11
32 . Site Power Law Exponent, n_s	0.11	0.11
33 . Velocity Ratio, $R = V_c/U_r$	0.71	0.71
34 . Stack Velocity Ratio, $R_s = V_c/U_h$	0.82	0.82
35 . Stack Height to Terrain Height Ratio, h/Ht	3.00	3.00
36 . Diameter to Stack Height Ratio, d/h	0.03	0.03
37 . Momentum Ratio, M_o	3.91E-04	3.91E-04
38 . Froude Number, Fr_s	3.40	20.28
39 . Buoyancy Ratio, B_o	1.80E-04	5.07E-06
40 . Density Ratio, λ	0.72	0.72
41 . Stack Reynolds Number (Exterior), $d\ U_h / \nu_a$	5.92E+06	941.52
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\ V_c / \nu_s$	2.72E+06	791.90
43 . Terrain Reynolds Number, Ret = Ht Ut / Nua	5.27E+07	8,377.58
44 . Surface Reynolds Number, $z_{o,s}\ U_* / \nu_a$	5.48E+02	0.09
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.04	0.04

Table A-AC

Full and Model Scale Similarity Parameters

Combined Stack (S_3)

Anemometer Wind Speed =21 m/s

Dimensional Parameters	**Full Scale**	**Model Scale**
1 . Terrain Height, Ht (m)	50.00	0.05
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	-	1,524.00
3 . Stack Height above grade, h (m)	100.00	0.10
4 . Stack Inside Diameter, d (m)	4.97	4.969E-03
5 . Stack Inside Area, A_c (m^2)	19.40	1.939E-05
6 . Exit Velocity, V_e (m/s)	15.00	2.14
7 . Exit Temperature, T_s (K)	413.00	293.15
8 . Volume Flow Rate, V (m^3/s)	291.00	4.157E-05
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	1,013.00	844.00
11 . Ambient Temperature, T_a (K)	295.37	293.15
12 . Air Density, ρ_a (kg/m^3)	1.19	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.85	0.72
14 . Air Viscosity, ν_a (m^2/s)	1.53E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	2.74E-05	1.77E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	21.00	3.00
17 . Free Stream Height, z_{inf} (m)	600.00	0.60
18 . Reference Wind Speed, U_{ref} (m/s)	21.00	3.00
19 . Reference Height, z_{ref} (m)	600.00	0.60
20 . Anemometer Wind Speed, U_a (m/s)	21.00	3.00
21 . Anemometer Height, z_a (m)	600.00	0.60
22 . Site Wind Speed, U_s (m/s)	21.00	3.00
23 . Site Anemometer' Height, z_s (m)	600.00	0.60
24 . Stack Height Speed, U_h (m/s)	14.17	2.03
25 . Terrain Height Speed, Ut (m/s)	12.17	1.74
26 . Anemometer Surface Roughness Length, $z_{o, a}$ (m)	0.60	6.00E-04
27 . Site Surface Roughness Length, $z_{o, s}$ (m)	0.60	6.00E-04
28 . Site Surface Friction Velocity, U_* (m/s)	1.07	0.15
Dimensionless Parameters		
29 . Length Scale, SF	1,000.00	1.00
30 . Time Scale, TS	142.90	1.00
31 . Anemometer Power Law Exponent, n_a	0.22	0.22
32 . Site Power Law Exponent, n_s	0.22	0.22
33 . Velocity Ratio, R = V_e/U_r	0.71	0.71
34 . Stack Velocity Ratio, R_s = V_e/U_h	1.06	1.06
35 . Stack Height to Terrain Height Ratio, h/Ht	2.00	2.00
36 . Diameter to Stack Height Ratio, d/h	0.05	0.05
37 . Momentum Ratio, M_o	9.01E-04	9.01E-04
38 . Froude Number, Fr_s	3.40	15.39
39 . Buoyancy Ratio, B_o	2.79E-04	1.37E-05
40 . Density Ratio, λ	0.72	0.72
41 . Stack Reynolds Number (Exterior), d U_h / ν_a	4.61E+06	556.58
42 . Stack Flow Reynolds Number (Interior), Re_s = d V_e / ν_s	2.72E+06	601.00
43 . Terrain Reynolds Number, Ret = Ht Ut / Nua	3.99E+07	4,810.37
44 . Surface Reynolds Number, $z_{o, s}$ U_* / ν_a	4.22E+04	5.09
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.05	0.05

Table A-AD

Full and Model Scale Similarity Parameters

Combined Stack (S_4)

Anemometer Wind Speed =21 m/s

Dimensional Parameters	**Full Scale**	**Model Scale**
1 . Terrain Height, Ht (m)	50.00	0.05
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	-	1,524.00
3 . Stack Height above grade, h (m)	100.00	0.10
4 . Stack Inside Diameter, d (m)	4.97	4.969E-03
5 . Stack Inside Area, A_c (m^2)	19.40	1.939E-05
6 . Exit Velocity, V_e (m/s)	15.00	2.86
7 . Exit Temperature, T_s (K)	413.00	293.15
8 . Volume Flow Rate, V (m^3/s)	291.00	5.543E-05
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	1,013.00	844.00
11 . Ambient Temperature, T_a (K)	295.37	293.15
12 . Air Density, ρ_a (kg/m^3)	1.19	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.85	0.72
14 . Air Viscosity, ν_a (m^2/s)	1.53E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	2.74E-05	1.77E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	21.00	4.00
17 . Free Stream Height, z_{inf} (m)	600.00	0.60
18 . Reference Wind Speed, U_{ref} (m/s)	21.00	4.00
19 . Reference Height, z_{ref} (m)	600.00	0.60
20 . Anemometer Wind Speed, U_a (m/s)	21.00	4.00
21 . Anemometer Height, z_a (m)	600.00	0.60
22 . Site Wind Speed, U_s (m/s)	21.00	4.00
23 . Site Anemometer' Height, z_s (m)	600.00	0.60
24 . Stack Height Speed, U_h (m/s)	14.17	2.70
25 . Terrain Height Speed, Ut (m/s)	12.17	2.32
26 . Anemometer Surface Roughness Length, $z_{o,a}$ (m)	0.60	6.00E-04
27 . Site Surface Roughness Length, $z_{o,s}$ (m)	0.60	6.00E-04
28 . Site Surface Friction Velocity, U_* (m/s)	1.07	0.20
Dimensionless Parameters		
29 . Length Scale, SF	1,000.00	1.00
30 . Time Scale, TS	190.53	1.00
31 . Anemometer Power Law Exponent, n_a	0.22	0.22
32 . Site Power Law Exponent, n_s	0.22	0.22
33 . Velocity Ratio, $R = V_e/U_r$	0.71	0.71
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	1.06	1.06
35 . Stack Height to Terrain Height Ratio, h/Ht	2.00	2.00
36 . Diameter to Stack Height Ratio, d/h	0.05	0.05
37 . Momentum Ratio, M_o	9.01E-04	9.01E-04
38 . Froude Number, Fr_s	3.40	20.52
39 . Buoyancy Ratio, B_o	2.79E-04	7.70E-06
40 . Density Ratio, λ	0.72	0.72
41 . Stack Reynolds Number (Exterior), d U_h / ν_a	4.61E+06	742.11
42 . Stack Flow Reynolds Number (Interior), Re_s = d V_e / ν_s	2.72E+06	801.33
43 . Terrain Reynolds Number, Ret = Ht Ut / Nua	3.99E+07	6,413.83
44 . Surface Reynolds Number, $z_{o,s}$ U_* / ν_a	4.22E+04	6.79
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.05	0.05

Table A-AE

Full and Model Scale Similarity Parameters

Combined Stack (S_5)

Anemometer Wind Speed =21 m/s

Dimensional Parameters		Full Scale	Model Scale
1 .	Terrain Height, Ht (m)	50.00	0.05
2 .	Grade Elevation Above Mean Sea Level, z=0 (m)	-	1,524.00
3 .	Stack Height above grade, h (m)	100.00	0.10
4 .	Stack Inside Diameter, d (m)	4.97	4.969E-03
5 .	Stack Inside Area, A_c (m^2)	19.40	1.939E-05
6 .	Exit Velocity, V_c (m/s)	15.00	3.57
7 .	Exit Temperature, T_s (K)	413.00	293.15
8 .	Volume Flow Rate, V (m^3/s)	291.00	6.929E-05
9 .	Exhaust rate, Q (kg/s)	#N/A	#N/A
10 .	Ambient Pressure, P_a (hPa)	1,013.00	844.00
11 .	Ambient Temperature, T_a (K)	295.37	293.15
12 .	Air Density, ρ_a (kg/m^3)	1.19	1.00
13 .	Exhaust Density, ρ_s (kg/m^3)	0.85	0.72
14 .	Air Viscosity, ν_a (m^2/s)	1.53E-05	1.81E-05
15 .	Gas Viscosity, ν_s (m^2/s)	2.74E-05	1.77E-05
16 .	Free Stream Wind Speed, U_{inf} (m/s)	21.00	5.00
17 .	Free Stream Height, z_{inf} (m)	600.00	0.60
18 .	Reference Wind Speed, U_{ref} (m/s)	21.00	5.00
19 .	Reference Height, z_{ref} (m)	600.00	0.60
20 .	Anemometer Wind Speed, U_a (m/s)	21.00	5.00
21 .	Anemometer Height, z_a (m)	600.00	0.60
22 .	Site Wind Speed, U_s (m/s)	21.00	5.00
23 .	Site Anemometer' Height, z_s (m)	600.00	0.60
24 .	Stack Height Speed, U_h (m/s)	14.17	3.38
25 .	Terrain Height Speed, Ut (m/s)	12.17	2.90
26 .	Anemometer Surface Roughness Length, $z_{o,a}$ (m)	0.60	6.00E-04
27 .	Site Surface Roughness Length, $z_{o,s}$ (m)	0.60	6.00E-04
28 .	Site Surface Friction Velocity, U_* (m/s)	1.07	0.26
	Dimensionless Parameters		
29 .	Length Scale, SF	1,000.00	1.00
30 .	Time Scale, TS	238.16	1.00
31 .	Anemometer Power Law Exponent, n_a	0.22	0.22
32 .	Site Power Law Exponent, n_s	0.22	0.22
33 .	Velocity Ratio, R = V_c/U_r	0.71	0.71
34 .	Stack Velocity Ratio, $R_s = V_c/U_h$	1.06	1.06
35 .	Stack Height to Terrain Height Ratio, h/Ht	2.00	2.00
36 .	Diameter to Stack Height Ratio, d/h	0.05	0.05
37 .	Momentum Ratio, M_o	9.01E-04	9.01E-04
38 .	Froude Number, Fr_s	3.40	25.65
39 .	Buoyancy Ratio, B_o	2.79E-04	4.93E-06
40 .	Density Ratio, λ	0.72	0.72
41 .	Stack Reynolds Number (Exterior), d U_h / ν_a	4.61E+06	927.63
42 .	Stack Flow Reynolds Number (Interior), Re_s = d V_c / ν_s	2.72E+06	1,001.66
43 .	Terrain Reynolds Number, Ret = Ht Ut / Nua	3.99E+07	8,017.29
44 .	Surface Reynolds Number, $z_{o,s}$ U_* / ν_a	4.22E+04	8.49
45 .	Site Friction Velocity Ratio, U_*/U_{inf}	0.05	0.05

APPENDIX

B

DATA COLLECTION

TABLE OF CONTENTS

B.1. DATA COLLECTION TECHNIQUES

B.1.1 CONCENTRATION MEASUREMENTS

B.1.1.1 Data Collection Procedure

After the desired atmospheric condition has been established in the wind tunnel, a mixture of inert gas and a tracer (ethane, methane and/or propane) of predetermined concentration is released from an emission source at the required rate to simulate the prototype plume rise. The flow rate of the gas mixture is controlled and monitored by a precision mass flow controller. The concentration of the tracer gas at each sampling point is analyzed using a high frequency flame ionization detector (HFFID).

Using the HFFID allows for real-time concentrations measurements to be obtained. For every wind direction outlined in the test plan, a 120 second sample is collected for multiple wind speeds and wind directions.

B.1.1.2 Calculation of Full-scale Normalized 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):

$$\left(\frac{C}{m}\right)_f = \left(\frac{CU_r}{C_o V}\right)_m \left(\frac{1}{U_r}\right)_f \left(\frac{L_m}{L_f}\right)^2 \times 10^6 \qquad \text{(B.1)}$$

where

$$C_m = \left[\left(\frac{E_{meas} - E_o}{E_{cal}}\right)_{rec} - \left(\frac{E_{meas} - E_o}{E_{cal}}\right)_{bg}\right] x\ C_{cal} \qquad \text{(B.2)}$$

C_f	=	full scale concentration of pollutant (µg/m^3);
C_m	=	model scale concentration of tracer gas (ppm);
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 120 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.

B.1.1.3 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:

$$\left(\frac{\Delta C}{C}\right)_f = \left[\left(\frac{\Delta C}{C}\right)_m^2 + \left(\frac{\Delta C_{cal}}{C_{cal}}\right)_m^2 + \left(\frac{\Delta C_o}{C_o}\right)_m^2 + \left(\frac{\Delta L}{L}\right)_m^2 + \left(\frac{\Delta U_r}{U_r}\right)_m^2 + \left(\frac{\Delta V}{V}\right)_m^2\right]^{1/2} \quad \text{(B.3)}$$

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.1.1.4 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.1.2 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:

$$\frac{E_1^2}{K_1} = A + BU^C \tag{B.4}$$

and for the split-film sensor:

$$\left(\frac{E_1^{\ 2}}{K_1}\right) + \left(\frac{E_2^{\ 2}}{K_2}\right) = \left[A + B(U_n)^C\right] \tag{B.5}$$

and

$$\left(\frac{E_1{}^2}{K_1}\right)-\left(\frac{E_2{}^2}{K_1}\right)=\left(a+bU_n\right)\left(\theta_o-\theta\right)+c \tag{B.6}$$

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 representative calibration curve of sensor output voltage versus sensed velocity is included as Figure B.1.

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.1.3 VOLUME FLOW MEASUREMENTS

The volume flow rate of tracer gas from the model stack is an important variable in any wind-tunnel study of atmospheric dispersion. Various volume flow rates are calculated prior to testing to simulate multiple wind speeds or source flow rates. Tylan General and/or Porter mass flow controllers are calibrated using a Gillian Air Flow Calibrator to determine the settings necessary to obtain the calculated volume flows at stack exit. The gases used for the calibration are the same as those used in the study tests. Figure B.2 contains a typical mass flow controller calibration.

B.1.4 COLLECTION SOFTWARE PROGRAM SPECIFICATION AND PROCEDURES

B.1.4.1 Introduction

The collection of tracer gas concentrations and the subsequent calculation of full scale concentrations is accomplished through an in-house developed software program. The program specification for this software collection program (vbDIFCOLLECT) is described below. The primary features of the program are:

- recording of data and settings into output files;
- output in the form of full scale *C/m* and voltages;
- determination of mean and standard deviation *C/m* values for each wind condition;
- prompting of the operator when collection is completed;
- monitoring of wind tunnel speed;
- well-defined zero and calibration stages;
- over-voltage detection;
- background concentrations recorded during data collection; and
- input of flow calibrations to determine mass flow meter settings.

B.1.4.2 Program Logic

The program starts with a main screen, Figure B.3. Note the grayed-out Option buttons on the left. These program features cannot be accessed until all program settings are entered and reviewed, as shown in Figure B.4, the settings screen. Each Option accesses the input screens for the appropriate data set. All settings are updated as changes are made. When all settings are input and reviewed, the user is returned to the main screen, where the remaining buttons in the top half of the Options menu are now active. The Zero, Check Cal, and Set Velocity options are used according to the Quality Control (QC) schedule defined in the Settings screen.

When all of the settings have been input and validated, the user proceeds to the Define Run Parameters screen, Figure B.5a. Within each run, many wind conditions can be evaluated for a given stack/receptor combination. These conditions are input at the Define Trial screen, Figure B.5b. Figure B.6 shows the Sampling Concentrations screen, which displays the full scale *C/m* values during data collection, as well as the current Run Definition and the conditions for the current maximum *C/m* value. The tunnel speed is monitored during each trial. After a wind condition is tested (i.e., a trial is collected), the operator can either collect more data (i.e., more trials) or finalize the run by taking a longer steady-state average of the worst case. The Main screen, containing the current results for the active run, is displayed after each trial is collected, as shown in Figure B.7. After the long average has been collected, the results are saved to an output file using the End + Save button. The program then returns to the Main screen, with the top buttons in the main menu active.

When the run is over, a new run can be started with the old calibration, or a new calibration can be taken. The tunnel speed can be set again if needed.

B.1.4.3 Mean *C/m* Calculations

The goal of a run is to find the full scale maximum normalized concentration *C/m* for a given stack/receptor combination, where *C* is concentration in $\mu g/m^3$ and *m* is the mass emission rate in g/sec. Concentrations are calculated point by point from the measured voltage output from the HFFID using the equations defined in Section B.1.1. Mean concentrations are calculated as the average calculated concentration over a specified averaging window.

B.1.4.4 Calculations for Averaging and Windowing

Averages for the HFFID readings during an actual run are typically 120 seconds. However, an updated value is reported every 3 to 5 seconds. The reported value on the screen applies to a window extending for the last 120 seconds. Voltages recorded before the window are discarded.

The following example of this averaging window procedure assumes a 30-second window and a 3-second reporting interval. The 30-second window can be viewed as having ten 3-second blocks. Previous blocks of 3 seconds are discarded, and a new block of 3 seconds is recorded while the most recent result is displayed. When computing 30-second averages, all data for the 30 seconds could be made available to compute mean and standard deviation, but this is computationally intensive. Instead, subsequent values of the mean and standard deviation can be calculated by saving the means and the sums of squares from each 3-second block. The mean of the window is:

$$V_{\text{mean},window} = \frac{1}{\#blocks} \times \left(V_{\text{mean},1} + V_{\text{mean},2} + \cdots\right) \tag{B.7}$$

where the individual block means are means of voltages with the zeros subtracted.

B.1.4.5 Tunnel Speed Computations with the Pitot-static Tube

Tunnel wind speed $U_{m,ref}$ is computed from the pitot-static tube dynamic pressure, Δp, as follows:

$$\Delta p = \frac{1}{2}\rho_{atmos} U^{z}_{m_{ref}} \tag{B.8}$$

Δp	=	pitot-static tube dynamic pressure; i.e., [total pressure – static pressure] (Pa);
ρ_{atmos}	=	atmospheric density (kg/m^3); and
$U_{n,ref}$	=	mean wind speed (m/s).

A calibration constant is needed for computation of Δp from voltages. The calibration factor is presented in units of psi/volt, which is not SI but is compatible with other programs. The pitot dynamic pressure is computed from:

$$\Delta p\left[V_{pitot} - V_{pitot,zero}\right] \times Calfactor \times 6897.4 \tag{B.9}$$

where

Δ_p	=	pitot static tube total pressure-static pressure (Pa);
V_{pitot}	=	voltage out from pressure transducer connected to the pitot tube (volt);
$V_{pitot,\ zero}$	=	voltage obtained with no input to the pressure transducer (volt);
Calfactor	=	calibration factor to relate pressure transducer output to pressure (lbf/in^2)/ volt; and
6894.7	=	factor to convert (lbf/in^2) to Pa.

Density is computed from barometric pressure, ρ_{atmos}, and tunnel air temperature with the ideal gas law:

$$\rho_{atmos}\ (kg/m^3) = \frac{\rho_{atmos}(in.Hg)\ x\ 3377}{RT} \tag{B.10}$$

ρ_{atmos}	=	atmospheric density (kg/m^3) (inches Hg);
3377	=	factor to inches Hg to Pa.
R	=	ideal gas constant for air,
	=	287 (Pa) / [(Kg/m^3) x K];

On the user screen, 5-second, 1-minute, and 3-minute averages are displayed. Five second means can be computed from the voltage data with Equation B.10. In principle, the U should be computed from the square root of Δp with each voltage point before averaging, but for small variations in tunnel speed, averaging Δp first is acceptable and is done in this program. The 1-minute average is computed from the simple average of the last twelve 5-second averages. Similarly, the 3-minute average is the average of the last three 1-minute averages. Standard deviations of the wind tunnel speed are not computed.

B.1.4.6 Flow Meter Calibration Data and Curve Fits

Flow meter settings are calculated as follows:

$$Setting = A \times V^{B} \tag{B.11}$$

where *Setting* is the flow metering device setting, and A and B are fit parameters, assuming volume flow rate V is in ml/s.

B.1.4.7 Input and Output Files

There are four input files required to run vbDIFCOLLECT and three output files are created. The four input files are ppppPROJ.INP, ppppFLOW.INP, ppppFCAL.INP and ppppVSET.INP, where pppp is the four-digit project number. The PROJ.INP file is shown in Figure B.8 and consists of basic project information. The FLOW.INP file, shown in Figure B.9, consists of source flow settings and tunnel speeds for each stack/approach/anemometer-wind-speed combination, as determined by the test plan. The FCAL.INP file, shown in Figure B.10, contains flow calibrations for the flow meters to be used. The VSET.INP file, shown in Figure B.11, stores variable information generated by the user when the program is initialized.

The output files consist of a large file to document all trial information (the trial log), a file containing all of the run definition information, including a time stamp recording the date and time the run was completed (the run log) and a smaller text file for every run.

The trial log and run log files are used for "book keeping" so that vbDIFCOLLECT can keep track of what runs have been conducted to date. Along with the run numbers and run letters, the log file also tracks the source and receptor identifications, the tracer concentration of the source exhaust gas, the source gas density ratio, the stack height and other information of interest.

B.1.4.8 Hardware Environment

The program assumes the use of a high frequency flame ionization detector HFFID. Background concentrations are collected on one HFFID channel, while concentrations at various receptor locations are collected on the other channels (currently up to two receptor locations). The background concentrations are measured using the most sensitive settings, while the sensitivity settings for the receptor channels may vary according to the amount of signal available.

Tunnel speed is monitored with a pitot-static tube using an electronic pressure measuring device to measure dynamic pressures. The voltage outputs from the various instruments are input into the computer through use of an Analog to Digital (A/D) conversion card. The A/D channels used for the HFFID and pressure measurements are listed in from the VSET.INP file. The source gas flow meters operate manually with no electronic monitoring by the program.

B.1.4.9 Quality Assurance

Several subprograms or program units are individually checked with shell programs which provide sample inputs and record outputs. The individual program units checked are:

- the four subroutines reading and checking ranges of the four input files;
- the *C/m* computation;
- the tunnel speed computation and display;
- flow settings calculations from the flow calibration inputs;
- the HFFID zero; and
- the HFFID calibration.

The integrity of the final compiled version of vbDIFCOLLECT is evaluated using a defined bench test. The bench tests consists of running the program with predefined input files (as shown in Figures B.8 through B.11). Voltage inputs for each A/D channel are set at specified levels to artificially set the measured reference wind speed, the HFFID calibration voltages, and the receptor and background concentration voltages. To pass, the "measured" concentrations must be equivalent to those values calculated independently from the program.

B.2. REFERENCES

EPA, *Guideline for Use of Fluid Modeling of Atmospheric Diffusion*. U.S. Environmental Protection Agency, Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA-600/8-81-009, April 1981.

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

Turner, B.D., "Workbook of Atmospheric Dispersion Estimates," Air Resources Field Office, Environmental Science Services Administration, Environmental Protection Agency, Office of Air Programs, Research Triangle Park, North Carolina, No. AP-26, January 1974

FIGURES

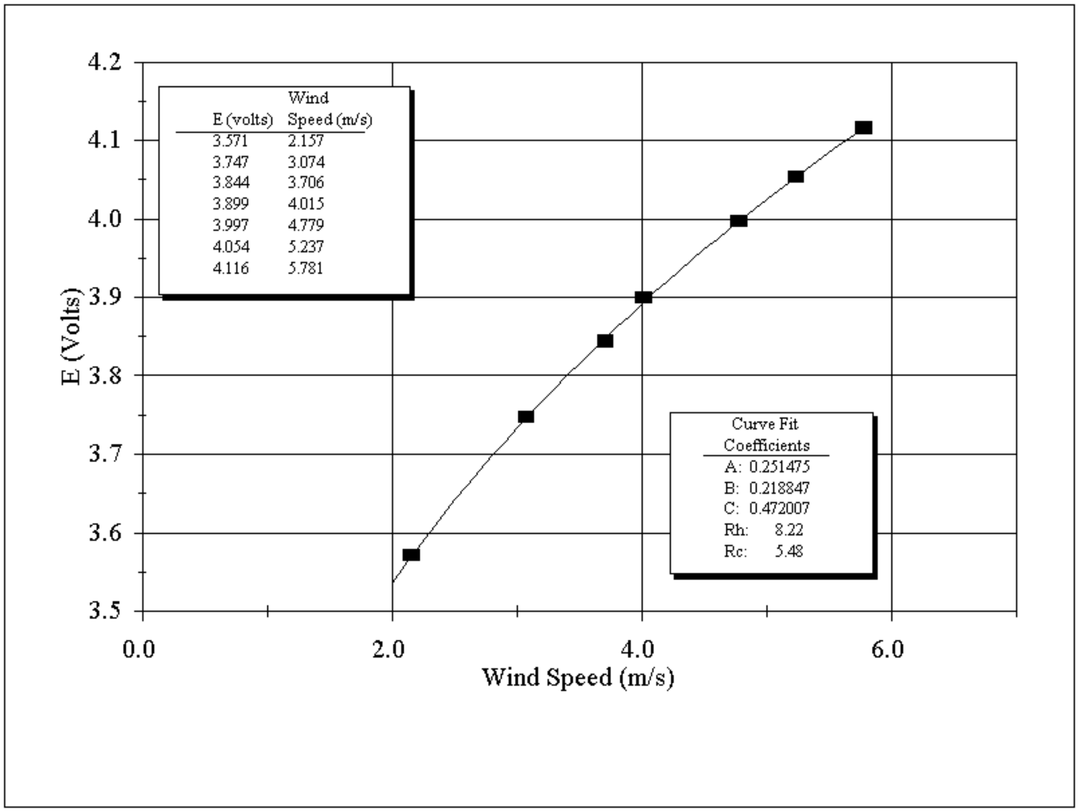


Figure B.1. Sample hot-film calibration curve.

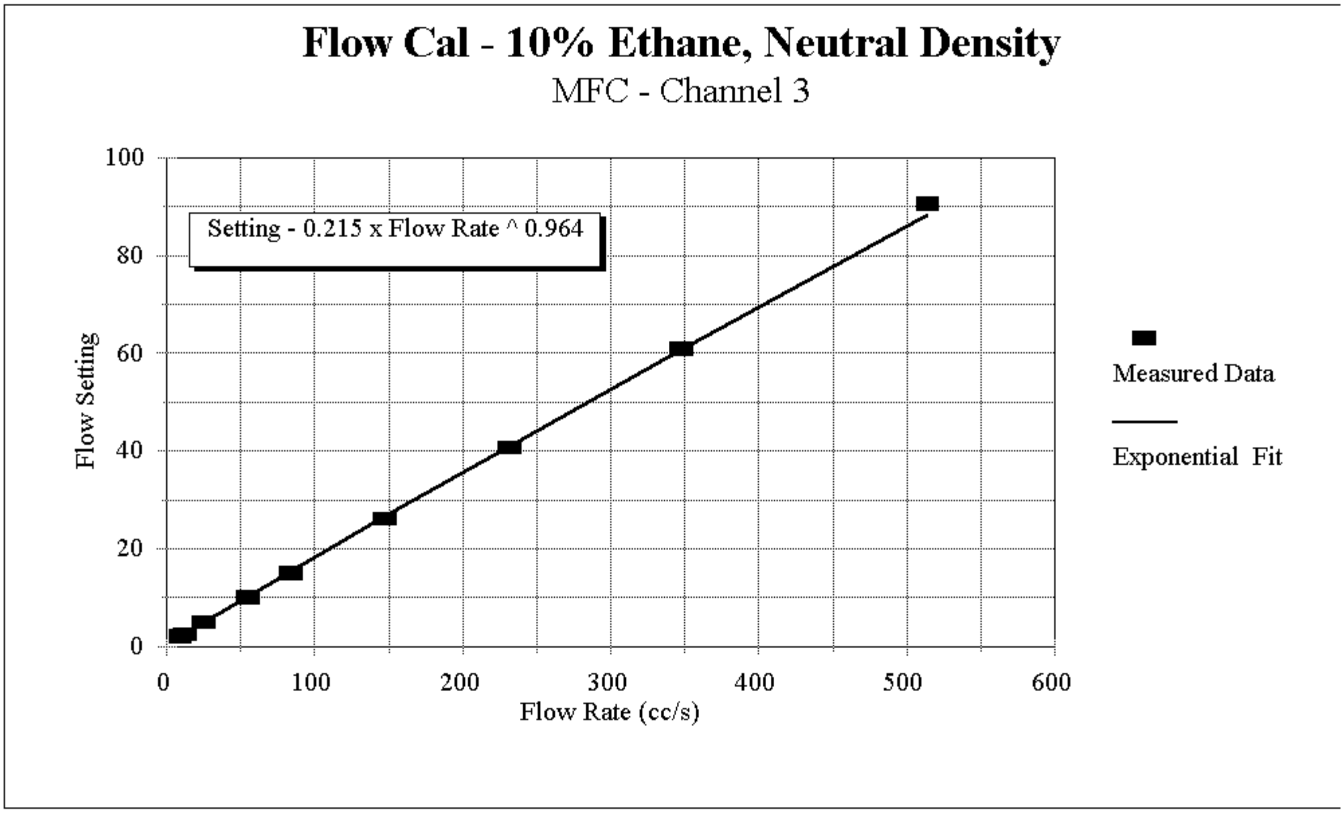


Figure B.2. Sample mass flow controller calibration curve.

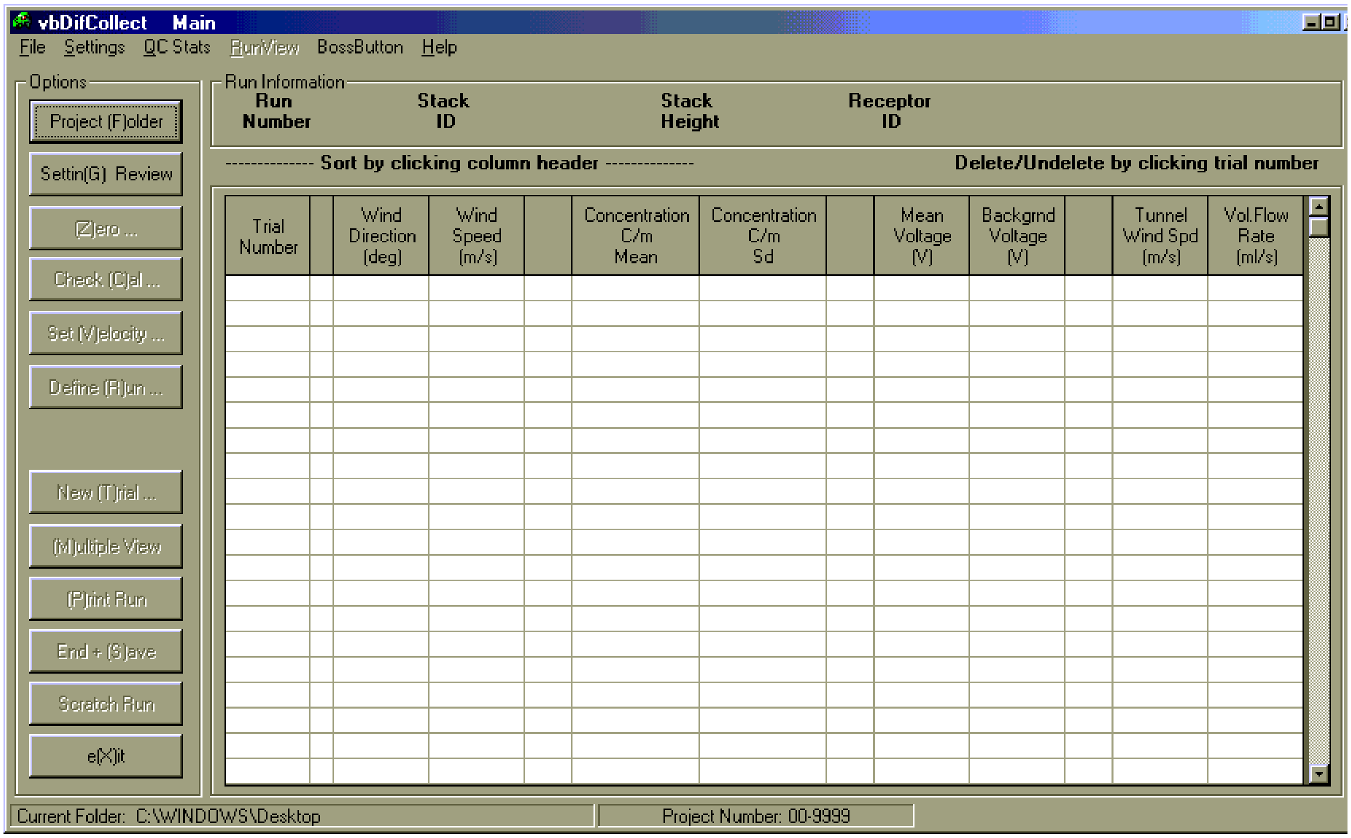


Figure B.3. vbDIFCOLLECT main screen - prior to setup and data collection.

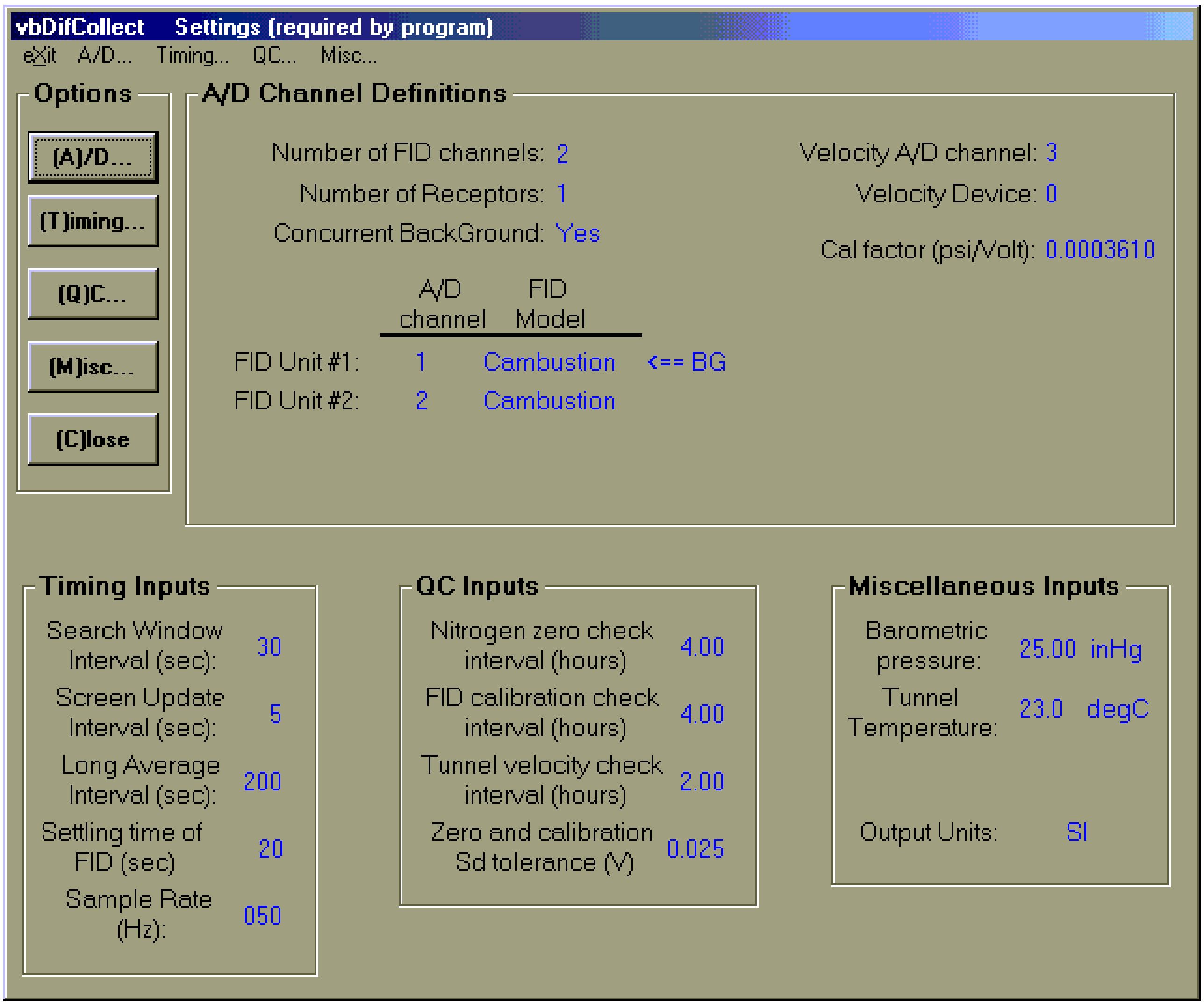


Figure B.4. vbDIFCOLLECT settings screen.

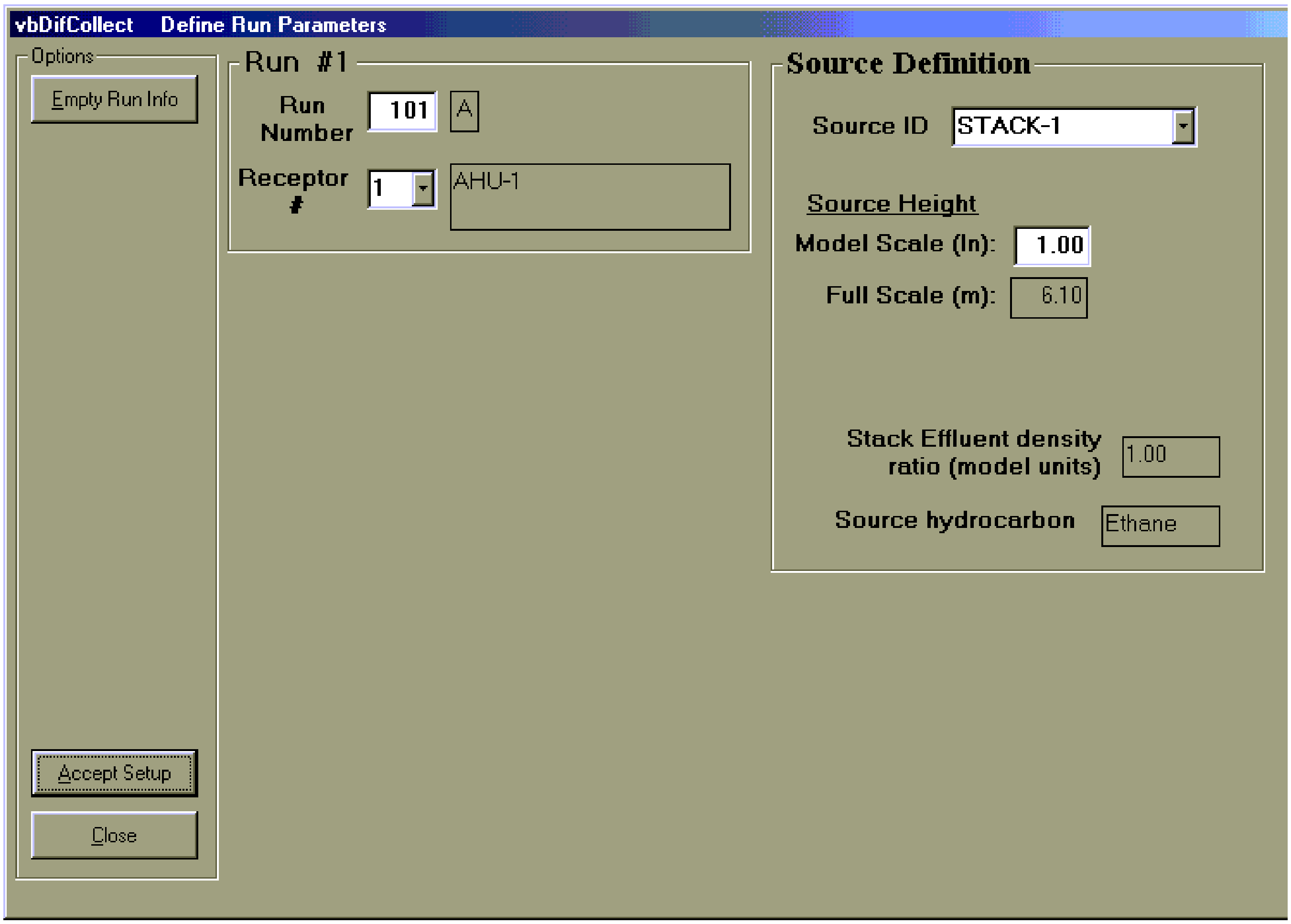


Figure B.5a. vbDIFCOLLECT define run parameters screen.

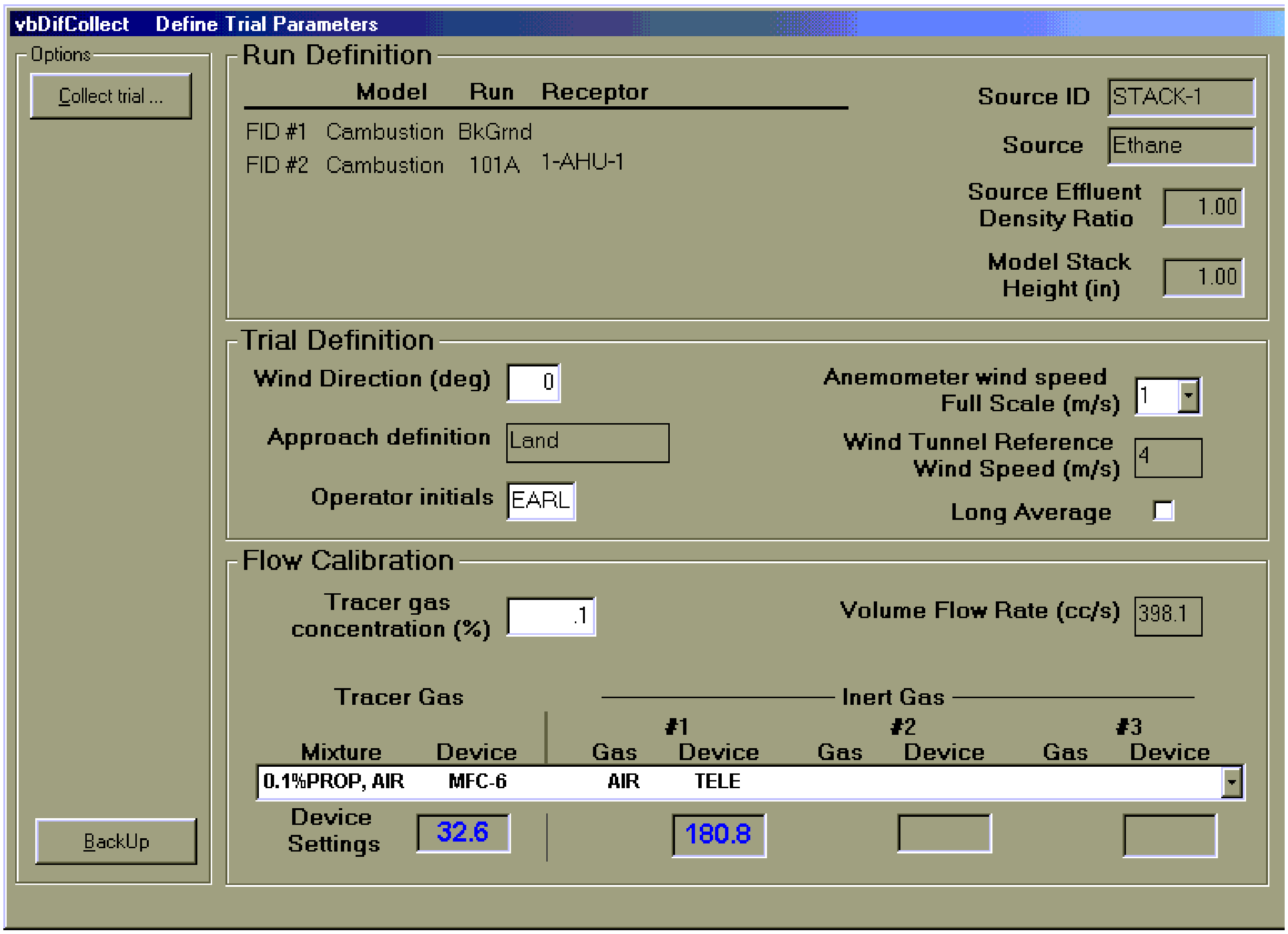


Figure B.5b. vbDIFCOLLECT define trial parameters screen.

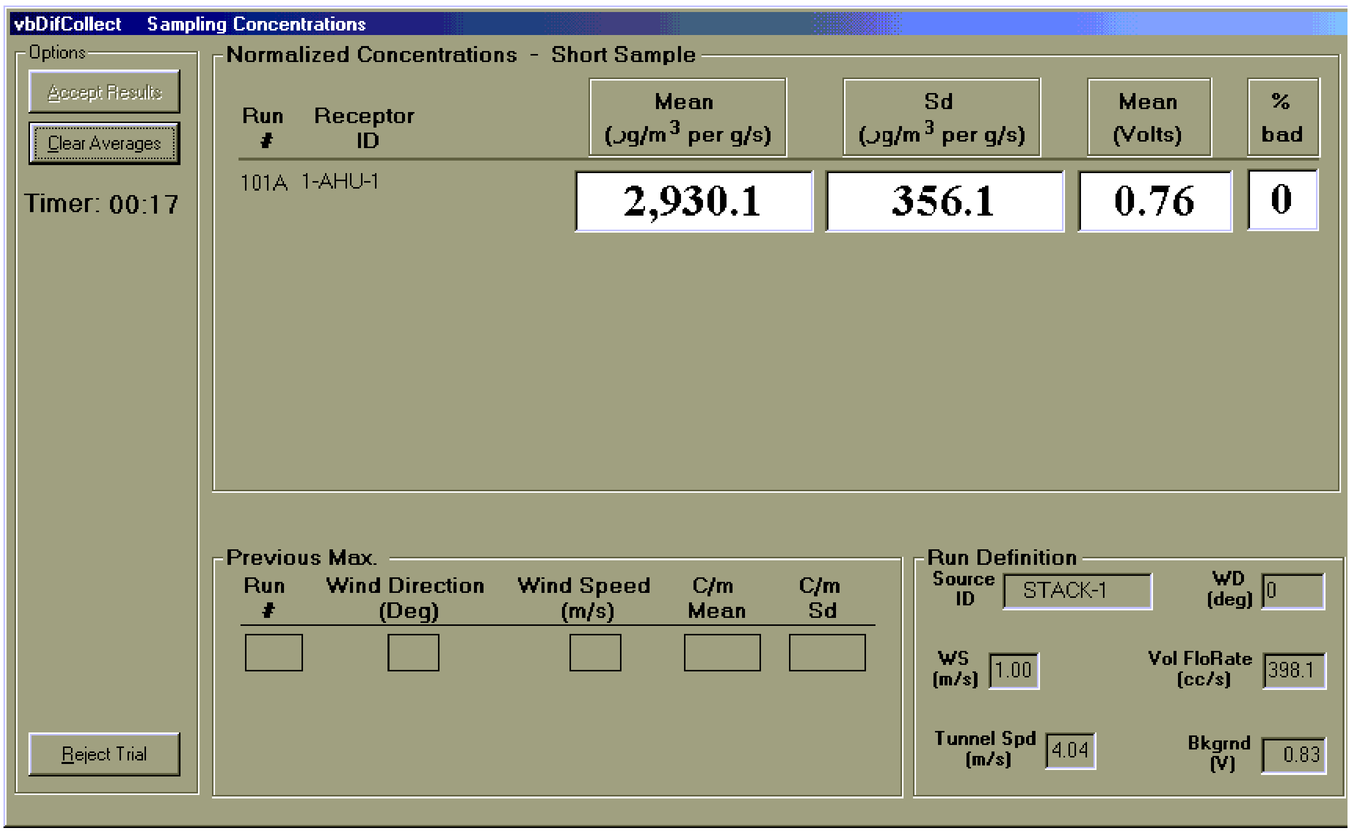
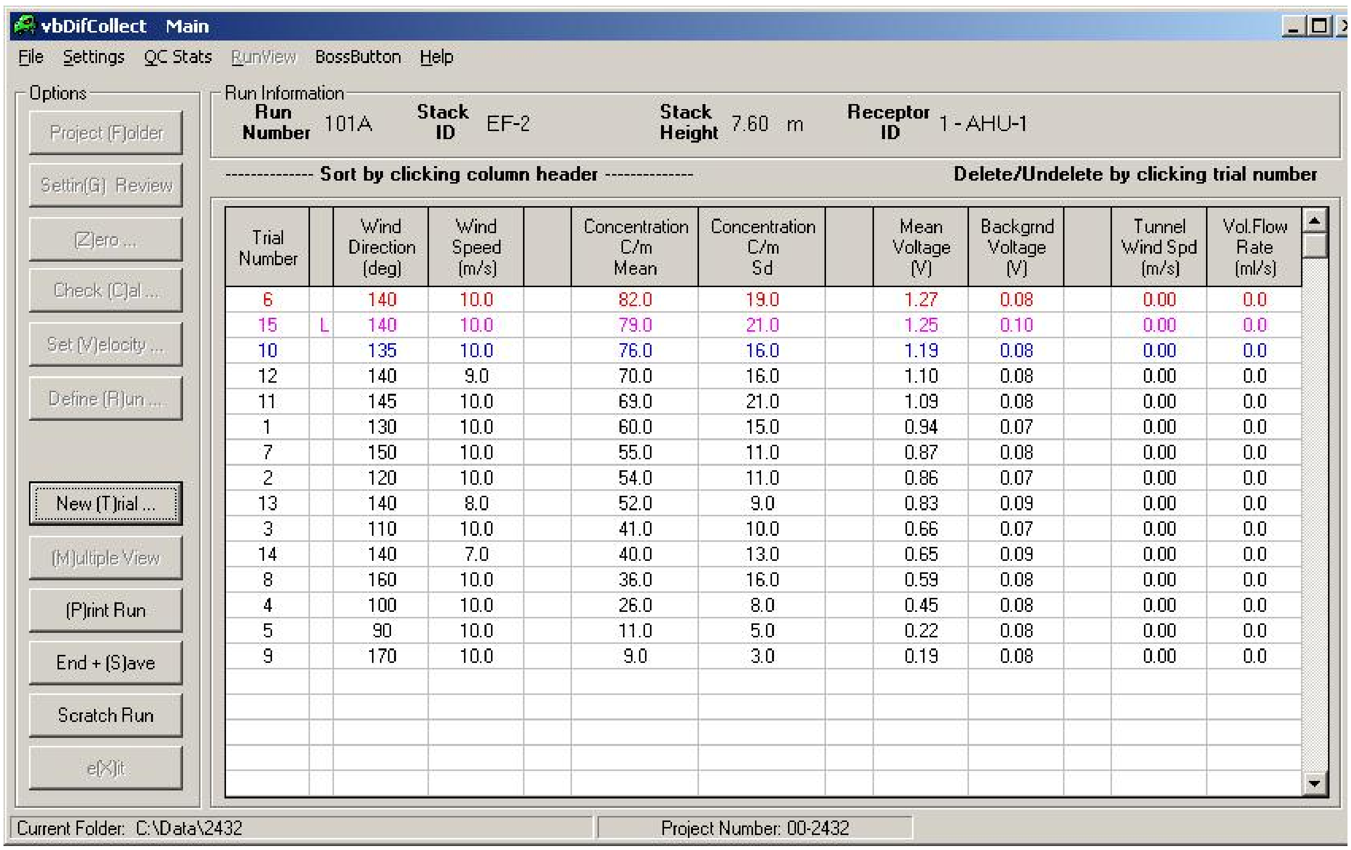


Figure B.6. vbDIFCOLLECT concentration sampling screen.



Trial Number		Wind Direction (deg)	Wind Speed (m/s)		Concentration C/m Mean	Concentration C/m Sd		Mean Voltage (V)	Backgrnd Voltage (V)		Tunnel Wind Spd (m/s)	Vol.Flow Rate (ml/s)
6		140	10.0		82.0	19.0		1.27	0.08		0.00	0.0
15	L	140	10.0		79.0	21.0		1.25	0.10		0.00	0.0
10		135	10.0		76.0	16.0		1.19	0.08		0.00	0.0
12		140	9.0		70.0	16.0		1.10	0.08		0.00	0.0
11		145	10.0		69.0	21.0		1.09	0.08		0.00	0.0
1		130	10.0		60.0	15.0		0.94	0.07		0.00	0.0
7		150	10.0		55.0	11.0		0.87	0.08		0.00	0.0
2		120	10.0		54.0	11.0		0.86	0.07		0.00	0.0
13		140	8.0		52.0	9.0		0.83	0.09		0.00	0.0
3		110	10.0		41.0	10.0		0.66	0.07		0.00	0.0
14		140	7.0		40.0	13.0		0.65	0.09		0.00	0.0
8		160	10.0		36.0	16.0		0.59	0.08		0.00	0.0
4		100	10.0		26.0	8.0		0.45	0.08		0.00	0.0
5		90	10.0		11.0	5.0		0.22	0.08		0.00	0.0
9		170	10.0		9.0	3.0		0.19	0.08		0.00	0.0

Figure B.7. vbDIFCOLLECT main screen - after data collection.

```
* Vent program project information file: 9999PROJ.INP                    *
*
*
*   Project     Project Title
*   Year  ####   (as desired to appear on outputs, in ", 65 char max)
*              ----+----1----+----2----+----3----+----4----+----5----+----6----+
   03   9999  "vbDIFCOLLECT Bench Test"
*
* Approach Info:
*                              WD
*         Number                    Range
*         of       Label Id         (deg)
*  Scale   Apprch   (9 char max)      Start     End
*--------------------   ----+----          -----------------------
   240      1       "Land   "          0        359
*
* Measurement Location Descriptions
*
*              Recep.
*   Recep.       Loc.
*   Loc.         Description
*   Number       (30 char max; in double quotes)
*   -----------   "----+----1----+----2----+----3"
    1           "AHU-1                         "
    2           "AHU-2                         "
    3           "AHU-3                         "
    4           "AHU-4                         "
    5           "AHU-5                         "
    6           "North Courtyard               "
    7           "North Entrance                "
    8           "South Courtyard               "
    9           "South Entrance                "
   -1
*
```

Figure B.8.   Sample vbDIFCOLLECT project input file.

```
*     Stack Flow Rate vs. Wind Speed Input file: 9999FLOW.INP
*     Used with Ventilation Projects using High-frequency FID
*
*     Number of stack/flow rate setups
*     (one for each stack design with differing flow rates and
*     for each approach flow)
*     -------------------------------------------------------------
      2
*
*     Number of Wind Speeds (max 15):
*     -------------------------------------------------------------
      7
*
*     Flow Rates/Tunnel Speed vs. Anemometer & Reference Wind Speeds:
*
*     Full Scale (m/s)
*     ---------------------------------------------------------------------------------
      Anemometer Wind Speeds (m/s)            1.00  2.00  3.00  4.00  5.00  7.00  10.00
      Reference Wind Speeds (m/s)             1.58  3.17  4.75  6.34  7.92  11.09  15.85
*     ---------------------------------------------------------------------------------
*                                  Dens.  FR - Flow Rates (ml/s)
*     Stack Label    Approach Label Ratio  TV - Tunnel Speeds (m/s)
*     "----+----1--" "----+----"    ---      +-----------------------------------------------
      "STACK-1     " "Land     "    1.00   FR 979.68 489.84 326.56 244.92 195.94 139.95 97.97
                                           TV 4.00   4.00   4.00   4.00   4.00   4.00   4.00
*
      "STACK-2     " "Land     "    1.00   FR 90.56  45.28  30.19  22.64  18.11  12.94  9.06
                                           TV 4.00   4.00   4.00   4.00   4.00   4.00   4.00
*
```

Figure B.9. Sample vbDIFCOLLECT project flow rate input file.

```
* Flow Meter Calibration Data for project, 9999FCAL.INP
* ================================================================================
* Calibration Number 4 and 2
*
*  # of        Tracer gas  Tracer conc  Specific wt.
*  components  "----+--"   (%)          (1 = neutral)
   2           "Ethane "   10.0         1.00
*
* Component 1 Calibration Information
* --------------------------------------------------------------------------------
*  Gas          Calibration
* Label         Volume Device    Date       Operator  Standard
* "----+-----"  (%)   "----+-"  "----+---"  "---"     "-----+----"
 "Ethane     "  10. 0 "MFC-2 "  "04-16-02"  "JTG"     "Gilibrator"
*
* Power law fit                         Applicable range of settings
* Setting = A * (Flow rate (cc/s))**B    Lower      Upper
*   A       B                           Setting    Setting
   2.28020  1.00752                       3          117
*
* Component 2 Calibration Information
* --------------------------------------------------------------------------------
*  Gas          Calibration
* Label       Volume Device    Date       Operator  Standard
* "----+-"    (%)   "----+-"  "----+---"  "---"     "----+-----"
  "N2    "    90.0  "MFC-1 "  "08-28-01"  "JWL"     "Gilibrator"
*
* Power law fit                         Applicable range of settings
* Setting = A * (Flow rate (cc/s))**B    Lower      Upper
*   A       B                           Setting    Setting
  0.15771   0.99440                       3          117
*
* ================================================================================
```

Figure B.10. Sample vbDIFCOLLECT flow calibration input file.

```
* vbDIFCOLLECT, Setup file: 9999VSET.INP
*
*  Search   Screen   Final    FID
*  Window   Update   Average  Settling
*  Interval Interval Interval time
*  (sec)    (sec)    (sec)    (sec)
*  -------  -------- -------- --------
    30.0     5.0     220.0    20.0
*
* Velocity
* Measurement   Calibration
* Equipment     Factors
* -----------   -----------
  0   'Pitot'   0.0003762   <--   psi/V
*
*  Input
*  Temperature                     Barometric   Sample
*  flag             Tunnel         Pressure     Rate
* (0-degC, 1-degF)  Temperature    (inHg)       (Hz)
* ----------------  -----------    ----------   ------
   0        'degC'  21.20          25.21        50.00
*
*  Pitot    Number   Continuous   FID
*  A/D      of FID   Background   A/D
*  channel  channels 0-No         channels
*  (0-15)   (1-4)    1-Yes        (0-15)
*  -------  -------- ----------   --------------
   1        2        1            2 3
*
*   Nitrogen                  Tunnel     Zero /      English
*   Zero      Calibration     Velocity   Cal.        Output
*   Check     Check           Check      Sd          Units
*   Interval  Interval        Interval   Tolerance   0-No
*   (hr)      (hr)            (hr)       (V)         1-Yes
*   --------  -----------     --------   ---------   -------
      3.0     3.0             1.0        0.085       0
*
* Nitrogen Zero Time Stamp   FID       FID
* --Time-- ---Date---      --Model-- --Range--
 '09:33 PM 01-01-2003'
  01  0.024                  1         100
  02  0.064                  0         500
  03  0.000                  0         500
  00  0.000                  0         500
*
* Tracer Calibration Time Stamp      Cal Gas
* --Time-- ---Date---  -Tracer--  Conc.  Bot ID
 '09:33 PM 01-01-2003' 'Ethane'   500    'c3367ax'
  01  5.096
  02  4.173
  03  3.196
  00  0.000
*
```

Figure B.11. Sample vbDIFCOLLECT variable setting input file.

cpp

APPENDIX

C

CONCENTRATION DATA FIT AND ANALYSIS

TABLE OF CONTENTS

C.1. CONCENTRATION DISTRUBUTION CURVE FIT

It is often advantageous to evaluate the distribution of concentrations from a single source or multiple sources at a receptor location as a continuous function of wind speed and wind direction rather than at discrete wind speeds and wind directions as measured in the wind tunnel. The continuous function (i.e., curve fit) is derived for the distribution of concentration versus approach wind speed and wind direction by assuming that the plume spread follows a Gaussian distribution:

$$\frac{C}{m} = \frac{1}{\pi\sigma_y\sigma_z U} \cdot \exp\left[-\frac{1}{2}\left(\frac{y-\bar{y}}{\sigma_y}\right)^2\right] \cdot \exp\left[-\frac{1}{2}\left(\frac{h_s+h_r}{\sigma_z}\right)^2\right] \cdot 10^6 \qquad \text{(C.1)}$$

The concentration C [µg/m^3], normalized by the emission rate m [g/s], at ground level $(z=0)$, is a function of the distance from the plume center line $(y-\bar{y})$, the effective stack height (h_s+h_r), and the wind speed U (at 600m). The dispersion coefficients σ_y and σ_z are functions of the downwind distance x.

Starting from equation (C.1) a fit equation was developed to fit the wind tunnel data:

$$\frac{C}{m} = \frac{A}{\pi\sigma_{y,WT}\sigma_{z,WT} U} \cdot \exp\left[-\frac{1}{2}\left(\frac{x \cdot \tan(WD - WDc)}{\sigma_{y,WT}}\right)^2\right] \cdot \exp\left[-\frac{1}{2}\left(\frac{h_s}{\sigma_{z,WT}} + \frac{K}{\sigma_{z,WT}U^2}\right)^2\right] \cdot 10^6 \quad \text{(C.2)}$$

where A is a curve fit constant, h_s is the stack height, WD is the wind direction (in degrees), WDc is the critical wind direction (in degrees) where the peak concentration occurs. The curve fit parameters (A, WDc, K, $\sigma_{y,WT}$ and $\sigma_{z,WT}$) are determined using a step-wise iteration to minimize the mean-square-error (*MSE*) between the predicted normalized concentration and the measured value. Only data collected at the critical wind direction (i.e., the wind direction where the maximum normalized concentration was measured) and data collected at the critical wind speed (i.e., the wind speed where the maximum normalized concentration was measured) are used for this analysis. The normalized concentrations measured in the wind tunnel used for the fit, as well as the curve fit parameters are provided in Appendix D.

Using equation (C.2) hourly normalized concentrations are computed for every hour of the year. Maximum 1-hour, 8-hour, 3-month and annual normalized concentrations are obtained by calculating the running average for every averaging time. For the 24-hour averaging time a daily average was computed. The maximum normalized concentration for each averaging time was then saved to be displayed in tables in the final report.

C.2. CONCENTRATION DATA CORRECTION

C.2.1 PLUME RISE AND BUOYANCY CORRECTION

Buoyancy and atmospheric stability effects were neglected during the wind-tunnel study. To account for increased plume rise due to buoyancy and decreased plumed rise due to stable stratification a correction factor R is introduced:

$$\frac{C}{m} = \frac{1}{\pi \sigma_{y,WT} \sigma_{z,WT} U} \cdot \exp\left[-\frac{1}{2}\left(\frac{x \cdot \tan(WD - WDc)}{\sigma_{y,WT}} \right)^2 \right] \cdot \exp\left[-\frac{1}{2}\left(\left(\frac{h_s}{\sigma_{z,WT}} + \frac{K}{\sigma_{z,WT} U^2} \right) R \right)^2 \right] \cdot 10^6 \quad \text{(C.3)}$$

This correction factor is the ratio of the actual plume height due to momentum, buoyancy and stability at the site (with the site specific ambient temperature) and the plume height simulated in the wind tunnel (neutral conditions):

$$R_{st} = \frac{[h_s + h_r]_S}{[h_s + h_r]_{WT}} \quad \text{(C.4)}$$

For convective and neutral conditions, the total plume rise at the site $[h_r]_s$ is the sum of momentum plume rise $h_{r,m}$ and buoyant plume rise $h_{r,b}$.

$$h_r = \left(h_{r,m}{}^3 + h_{r,b}{}^3 \right)^{1/3} \quad \text{(C.5)}$$

For stable conditions, the total plume rise at the site is the sum of momentum plume rise $h_{r,m}$ and buoyant plume rise $h_{r,b}$, limited by the stable plume rise limit $h_{r,st}$.

$$h_r = \min\left\{ \left(h_{r,m}{}^3 + h_{r,b}{}^3 \right)^{1/3}, h_{r,st} \right\} \quad \text{(C.6)}$$

In the wind tunnel the total plume rise at the site $[h_r]_{WT}$ is only due to momentum $h_{r,m}$.

The momentum plume rise above stack height is calculated as follows (EPA, 2004):

$$h_{r,m} = \left(\frac{3 F_m x}{\beta^2 U_h{}^2} \right)^{1/3} \quad \text{(C.7)}$$

with the momentum flux F_m:

$$F_m = \left(\frac{T_a}{T_s}\right) V_e^{\,2} \left(\frac{d^2}{4}\right) \tag{C.8}$$

and $\beta = 0.6$. x is the downwind distance from the stack, U_h is the wind speed at stack top, T_a is the ambient temperature, T_s is the stack exit temperature and V_e is the stack gas exit velocity.

The buoyant plume rise above stack height is calculated as follows (EPA, 2004):

$$h_{r,b} = \min\left[\left(\frac{3}{2\beta^2}\frac{F_b}{U_h^{\,3}}x^2\right)^{1/3}, h_{f,b}\right] \tag{C.9}$$

with the buoyancy flux F_b:

$$F_b = \frac{gV_e d^2 (T_s - T_a)}{4T_s} \tag{C.10}$$

The final buoyancy rise depends on the magnitude of the buoyancy flux:

$$h_{f,b} = 21.425\frac{F_b^{\,3/4}}{U_h} \quad \text{for } F_b < 55$$

$$h_{f,b} = 38.71\frac{F_b^{\,3/5}}{U_h} \quad \text{for } F_b > 55 \tag{C.11}$$

For stable conditions the total plume rise above stack height is limited by the maximum stable rise and the calm rise limit:

$$h_{r,st} = \min\left[2.66\left(\frac{F_b}{U_h N^2}\right)^{1/3}, 4\frac{F_b^{\,1/4}}{N^{3/4}}\right] \tag{C.12}$$

N is the Brunt-Vaisala frequency $N = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}$ where θ is the potential temperature and z is the height. The potential temperature is taken to be equal to the ambient temperature at stack height T_a. For stability class E, $\frac{\partial\theta}{\partial z}$ is taken as 0.02 K/m and for stability class F, $\frac{\partial\theta}{\partial z}$ is taken as 0.035 K/m (EPA, 1995).

Plume buoyancy also influences the spread of the plume. Therefore, the dispersion coefficients are taken as a combination of dispersion due to ambient turbulence (as measured in the wind tunnel) and dispersion from turbulence due to plume buoyancy (EPA, 2004).

$$\frac{C}{m}=\frac{1}{\pi(\sigma_{y,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}U}\cdot\exp\left[-\frac{1}{2}\left(\frac{x\cdot\tan(WD-WDc)}{(\sigma_{y,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}}\right)^{2}\right]$$
$$\cdot\exp\left[-\frac{1}{2}\left(\left(\frac{h_s}{(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}}+\frac{K}{(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}U^{2}}\right)R\right)^{2}\right]\cdot 10^{6} \quad \text{(C.13)}$$

The buoyancy induced dispersion coefficient is defined as follows:

$$\sigma_b=\frac{0.4h_r}{\sqrt{2}} \quad \text{(C.14)}$$

where h_r is the total plume rise (see equations C.5 and C.6).

C.2.2 STABILITY CORRECTION

The dispersion coefficients σ_y and σ_z are functions of atmospheric stability. However, atmospheric stability effects were neglected during the wind-tunnel study. The normalized concentrations measured in the wind tunnel are valid for neutral stability. The dispersion coefficients σ_y and σ_z are corrected for stability effects using the ratio of turbulence intensity at the site i and the turbulence intensity in the wind tunnel i_{WT}.

$$\sigma_y=\sigma_{yWT}\frac{i_y}{i_{yWT}}=\sigma_{yWT}S_y \text{ and } \sigma_z=\sigma_{zWT}\frac{i_z}{i_{zWT}}=\sigma_{zWT}S_z \quad \text{(C.15)}$$

where σ_{yWT} and σ_{zWT} are the dispersion coefficients determined by fitting the wind tunnel data, i_y and i_z are the lateral and vertical turbulence intensities of the site (calculated using the specific meteorological conditions at the site) and i_{yWT} and i_{zWT} are the lateral and vertical turbulence intensities for neutral stability, as simulated in the wind tunnel.

The correction factors S_y and S_z are included in the concentration prediction equation:

$$\frac{C}{m}=\frac{1}{\pi(\sigma_{y,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}S_y(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}S_zU}\cdot\exp\left[-\frac{1}{2}\left(\frac{x\cdot\tan(WD-WDc)}{(\sigma_{y,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}S_y}\right)^{2}\right]$$
$$\cdot\exp\left[-\frac{1}{2}\left(\left(\frac{h_s}{(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}}+\frac{K}{(\sigma_{z,WT}{}^{2}+\sigma_{b}{}^{2})^{1/2}U^{2}}\right)\frac{R}{S_z}\right)^{2}\right]\cdot 10^{6} \quad \text{(C.16)}$$

The lateral and vertical turbulence intensities are calculated as follows:

$$i_y = \frac{\sigma_{vm}}{u} \text{ and } i_z = \frac{\sigma_{wml}}{u} \quad (C.17)$$

The mechanically generated lateral velocity variance (=turbulence) is $\sigma_{vm} = Cu_*$ where C is set equal 1.9. The mechanically generated vertical velocity variance (=turbulence) is

$$\sigma_{wml} = 1.3u_*\left(1-\frac{z}{z_i}\right)^{1/2},$$

where z is the stack height and zi is the boundary layer height. The boundary layer height is defined as follows:

$z_i = 0.4\left(\frac{u_* absvl(L)}{f}\right)$ where f is the Coriolis parameter and L is the Monin-Obukhov-Length.

(u*/u)actual is dependent on stability and is calculated on an hourly basis for the site using the following equations:

<u>Convective Boundary Layer (L<0)</u>

$$\frac{u}{u_*} = \frac{1}{k}\left[\ln(z/z_o) - \psi_m(z/L) + \psi_o(z_o/L)\right] \quad (C.18)$$

where

$$\psi_m(z/L) = 2\ln\left(\frac{1+\mu}{2}\right) + \ln\left(\frac{1+\mu^2}{2}\right) - 2\arctan(\mu) + \pi/2 \quad (C.19)$$

$$\psi_o(z_o/L) = 2\ln\left(\frac{1+\mu_o}{2}\right) + \ln\left(\frac{1+\mu_o}{2}^2\right) - 2\arctan(\mu_0) + \pi/2 \quad (C.20)$$

$$\mu = (1-16z/L)^{1/4} \text{ and } \mu_o = (1-16z_o/L)^{1/4} \quad (C.21)$$

<u>Stable Boundary Layer (L>0)</u>

$$\frac{u}{u_*} = \frac{1}{k}\left[\ln(z/z_o) - \psi_m(z/L) + \psi_o(z_o/L)\right] \quad (C.22)$$

where $\psi_m(z/L) = -17\left(1-\exp\left(-0.29\frac{z}{L}\right)\right)$ and $\psi_o(z_o/L) = -17\left(1-\exp\left(-0.29\frac{z_o}{L}\right)\right)$

<u>Wind Tunnel - Neutral Boundary Layer</u>

In the wind tunnel neutral conditions were simulated. The Monin-Obukhov-Length is *L* = +/-*Inf*. Therefore, the boundary layer height is z_i = *Inf*. As for the site, *z* is set to stack height.

The mechanically generated lateral velocity variance in the wind tunnel is $\sigma_{vm} = Cu_*$ where C is set equal 1.9 and the vertical velocity variance in the wind tunnel is $\sigma_{wml} = 1.3u_*$.

U* in the wind tunnel is calculated as follows:

$$\frac{u}{u_*} = \frac{1}{k}\left[\ln(z / z_o)\right] \quad \text{(C.23)}$$

C.3. REFERENCES

EPA, *User's Guide for the Industrial Source Complex (ISC) Dispersion Models, Volume II - Description of Model Algorithms*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, EPA-454/B-95-003b, September 1995.

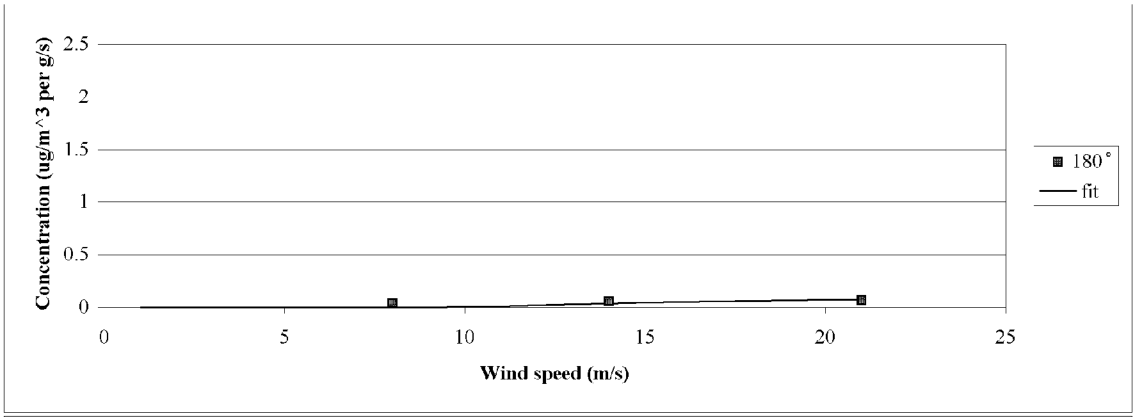
EPA, *AERMOD: Description of Model Formulation*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, EPA-454/R-03-004, September 2004.

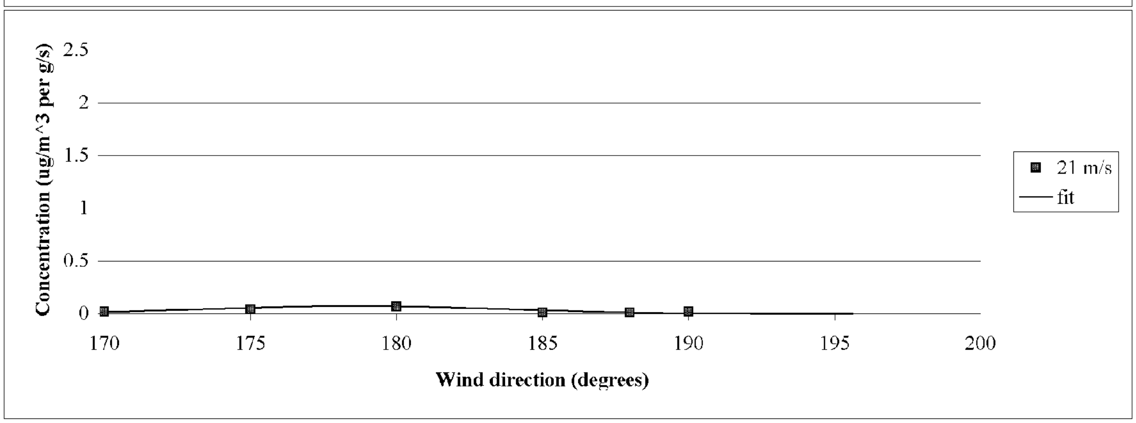
APPENDIX

D

CONCENTRATION DATA TABULATIONS AND DATA FITS

SKC - ASR A_S1



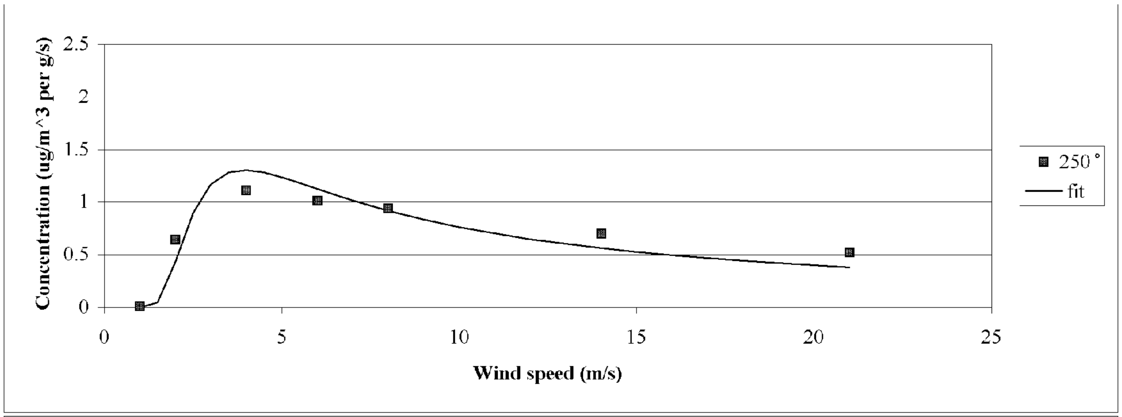


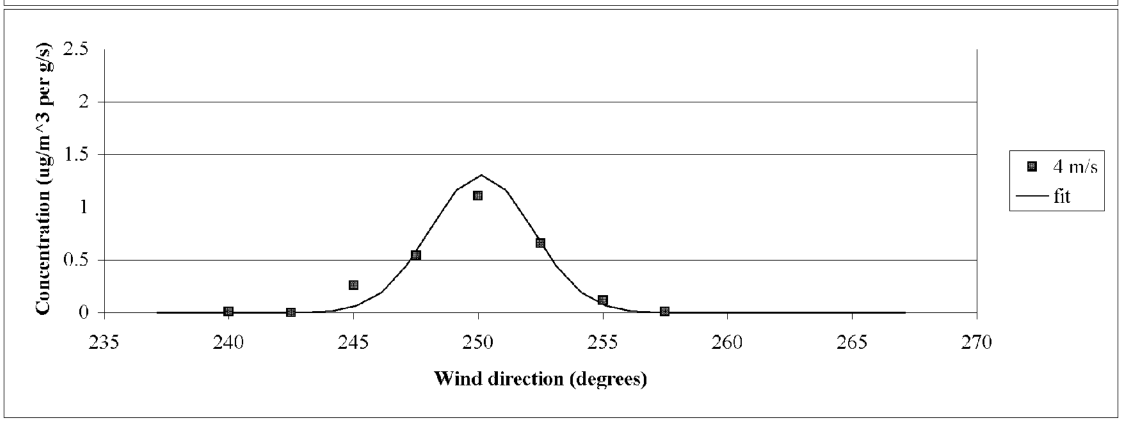
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
180.0	21.0	0.07
180.0	14.0	0.06
180.0	8.0	0.04
170.0	21.0	0.02
175.0	21.0	0.04
180.0	21.0	0.07
185.0	21.0	0.01
188.0	21.0	0.01
190.0	21.0	0.02

fit parameters:

A	1.0
sigma z	56.2
K	6752.4
sigma y	48.3
WDc	178.6
hs	150

SKC - ASR A_S2



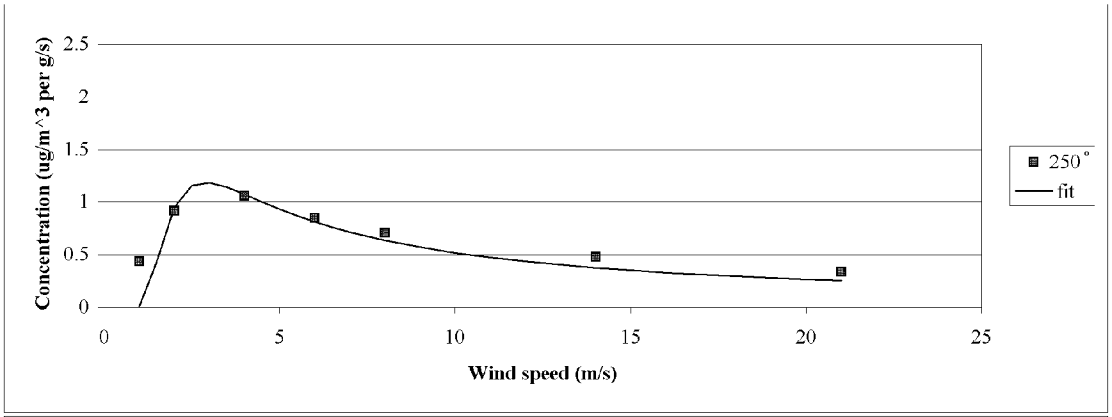


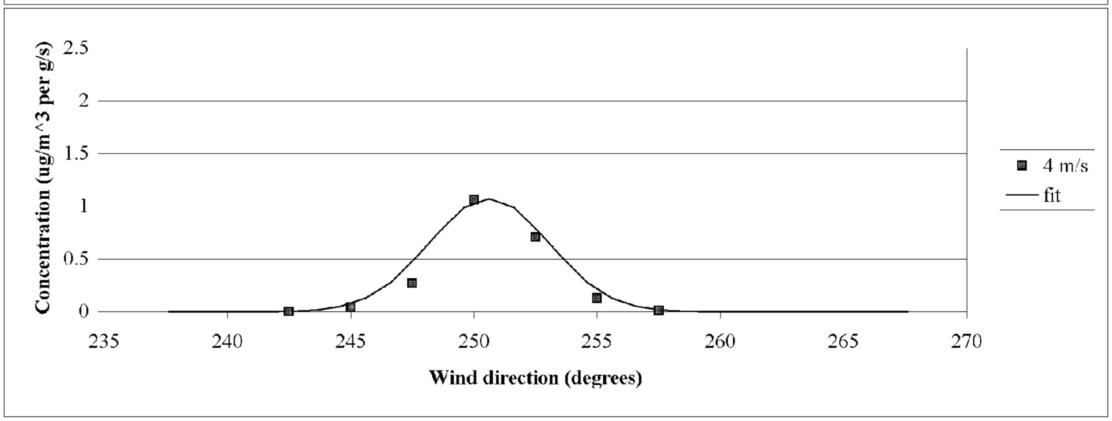
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
250.0	21.0	0.52
250.0	14.0	0.70
250.0	8.0	0.94
250.0	6.0	1.01
250.0	4.0	1.11
250.0	2.0	0.64
250.0	1.0	0.01
240.0	4.0	0.01
245.0	4.0	0.26
250.0	4.0	1.11
247.5	4.0	0.54
255.0	4.0	0.12
252.5	4.0	0.66

fit parameters:

A	1.0
sigma z	100.0
K	436.4
sigma y	126.7
WDc	250.1
hs	150

SKC - ASR A_S3



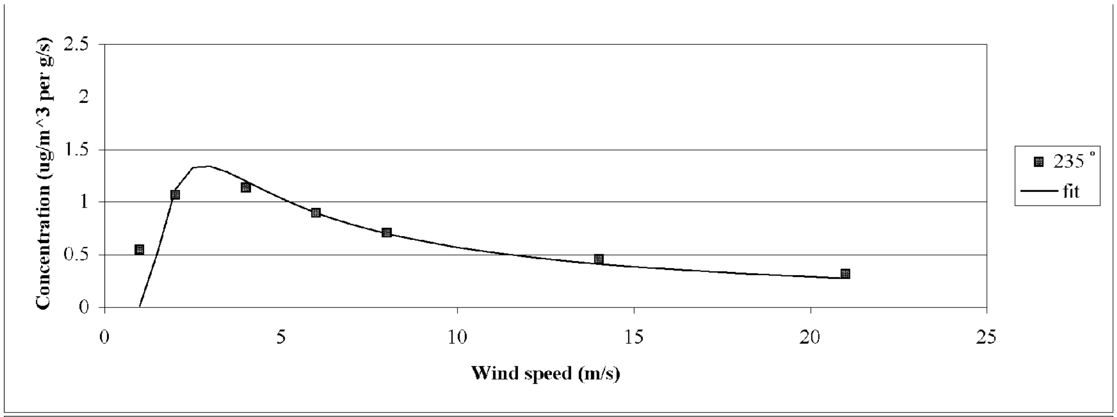


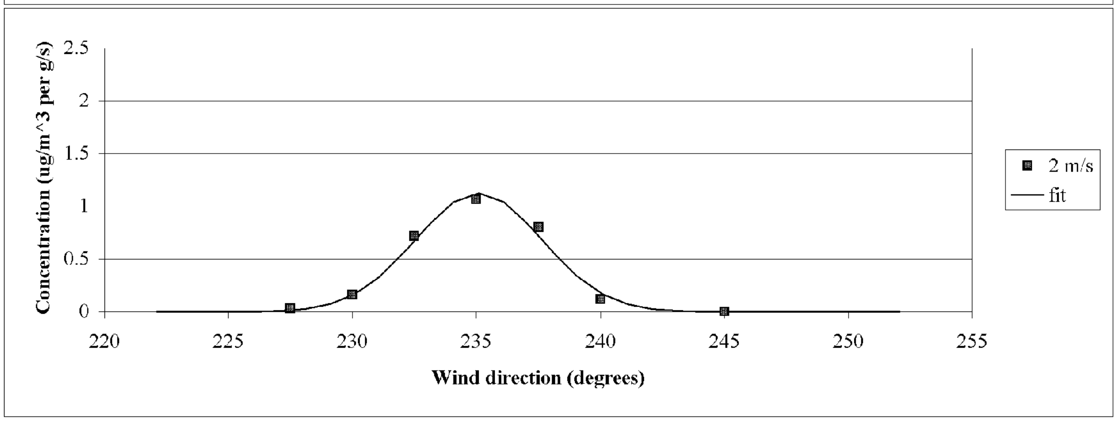
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
250.0	21.0	0.34
250.0	14.0	0.48
250.0	8.0	0.71
250.0	6.0	0.85
250.0	4.0	1.06
250.0	2.0	0.92
250.0	1.0	0.44
242.5	4.0	0.00
245.0	4.0	0.04
247.5	4.0	0.27
250.0	4.0	1.06
252.5	4.0	0.71
255.0	4.0	0.13

fit parameters:

A	1.0
sigma z	111.6
K	278.2
sigma y	215.3
WDc	250.6
hs	150

SKC - ASR A_S4



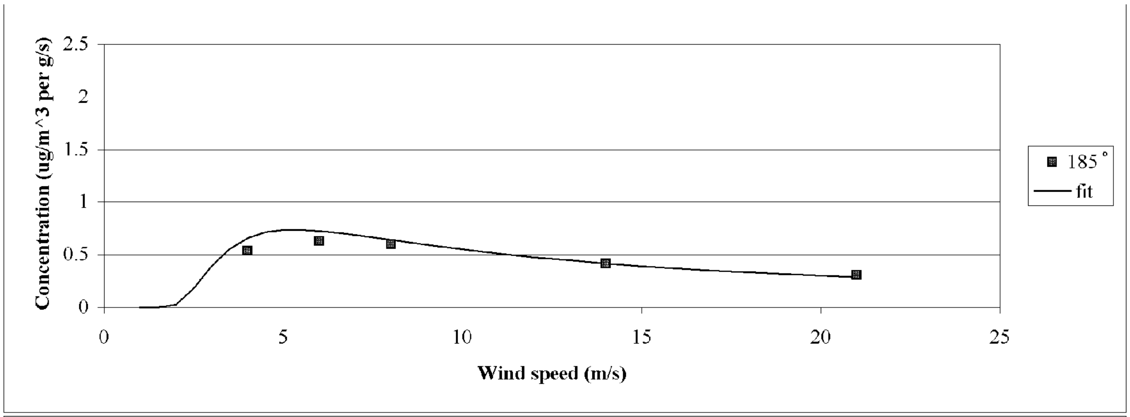


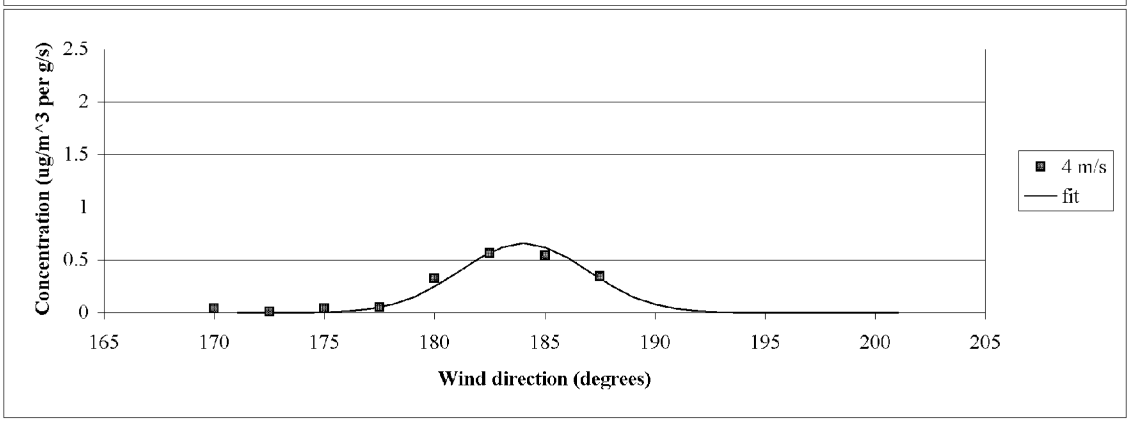
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
235.0	21.0	0.32
235.0	14.0	0.46
235.0	8.0	0.71
235.0	6.0	0.90
235.0	4.0	1.14
235.0	2.0	1.07
235.0	1.0	0.55
227.5	2.0	0.03
230.0	2.0	0.16
232.5	2.0	0.72
235.0	2.0	1.07
237.5	2.0	0.80
240.0	2.0	0.12

fit parameters:

A	1.0
sigma z	125.0
K	317.6
sigma y	210.5
WDc	235.1
hs	150

SKC - ASR A_S5



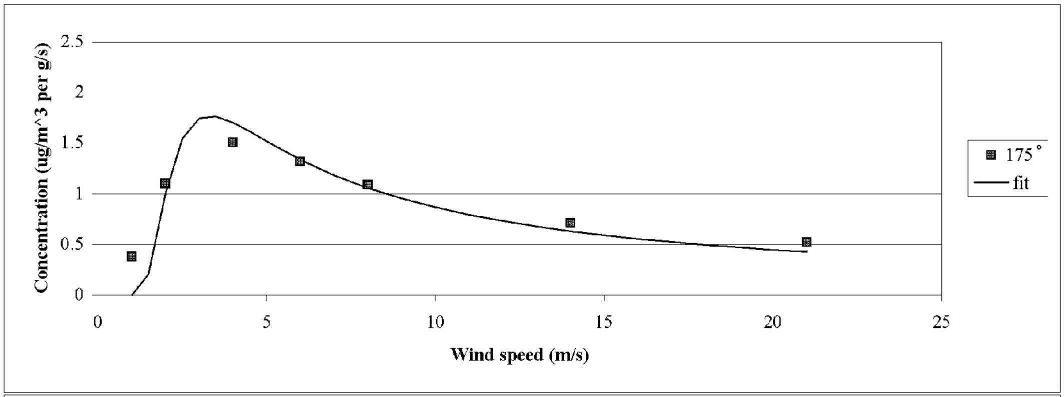


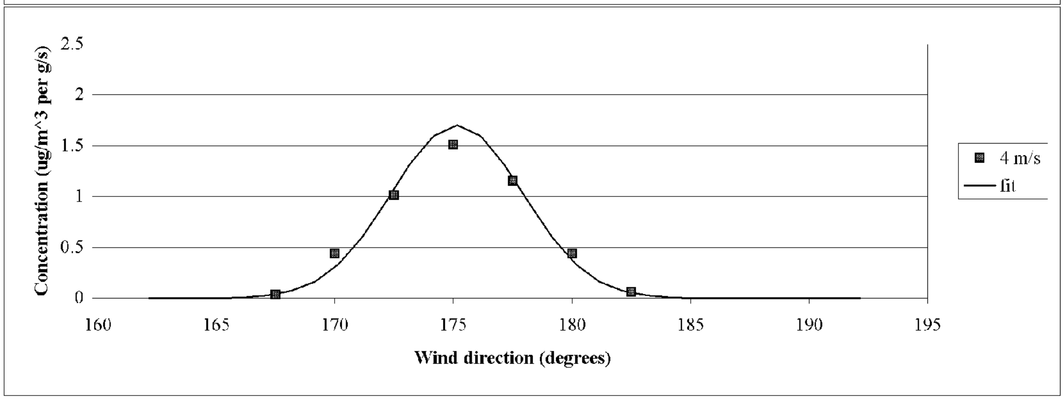
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
185.0	21.0	0.31
185.0	14.0	0.42
185.0	8.0	0.6
185.0	6.0	0.63
185.0	4.0	0.54
170.0	4.0	0.04
175.0	4.0	0.04
177.5	4.0	0.05
180.0	4.0	0.33
182.5	4.0	0.57
185.0	4.0	0.54
187.5	4.0	0.35
172.5	4.0	0.01

fit parameters:

A	1.0
sigma z	90.5
K	661.4
sigma y	142.9
WDc	184.0
hs	150

SKC - ASR A_S6



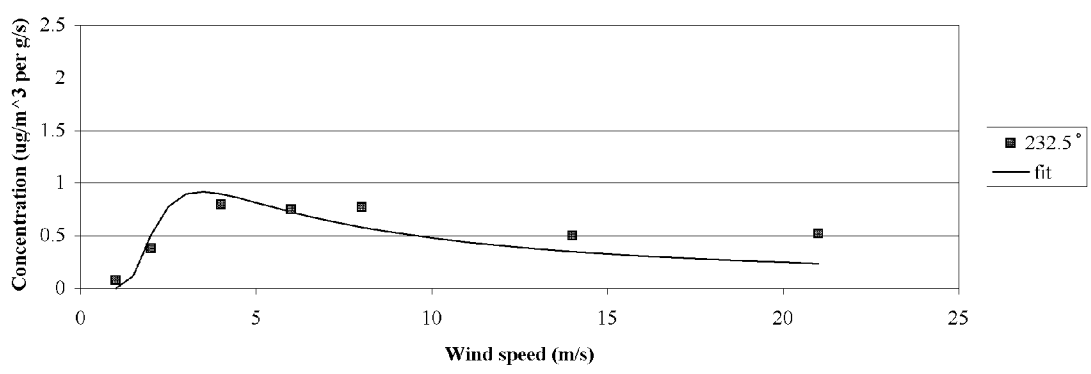


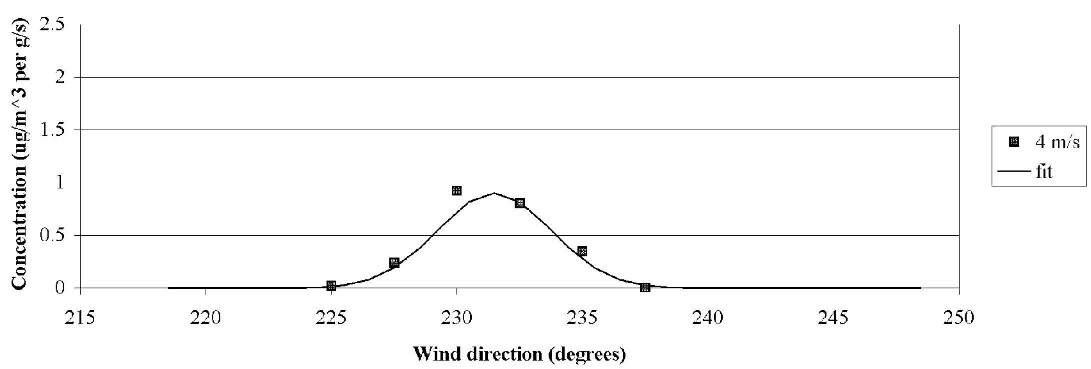
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
175.0	21.0	0.52
175.0	14.0	0.71
175.0	8.0	1.09
175.0	6.0	1.32
175.0	4.0	1.51
175.0	2.0	1.10
175.0	1.0	0.38
182.5	4.0	0.06
170.0	4.0	0.44
172.5	4.0	1.01
175.0	4.0	1.51
177.5	4.0	1.15
180.0	4.0	0.44

fit parameters:

A	1.0
sigma z	151.6
K	611.8
sigma y	196.4
WDc	175.1
hs	150

TTAL - ASR A_T1



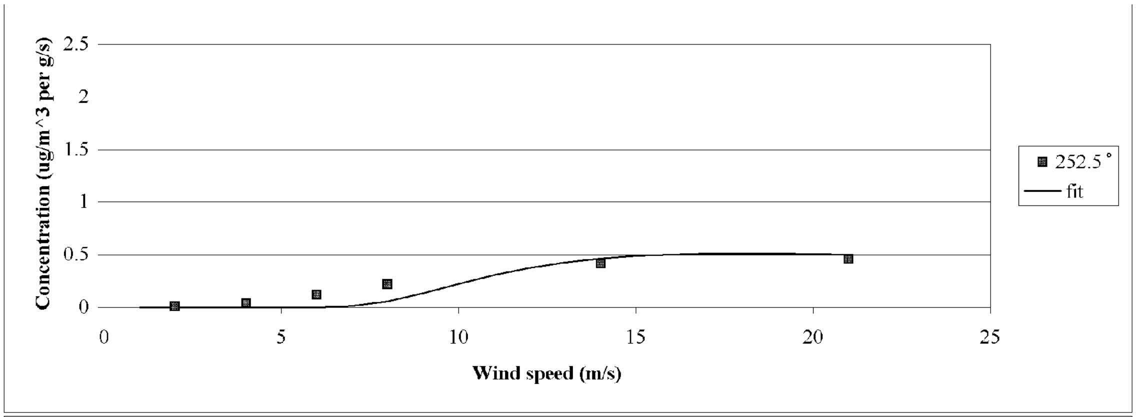


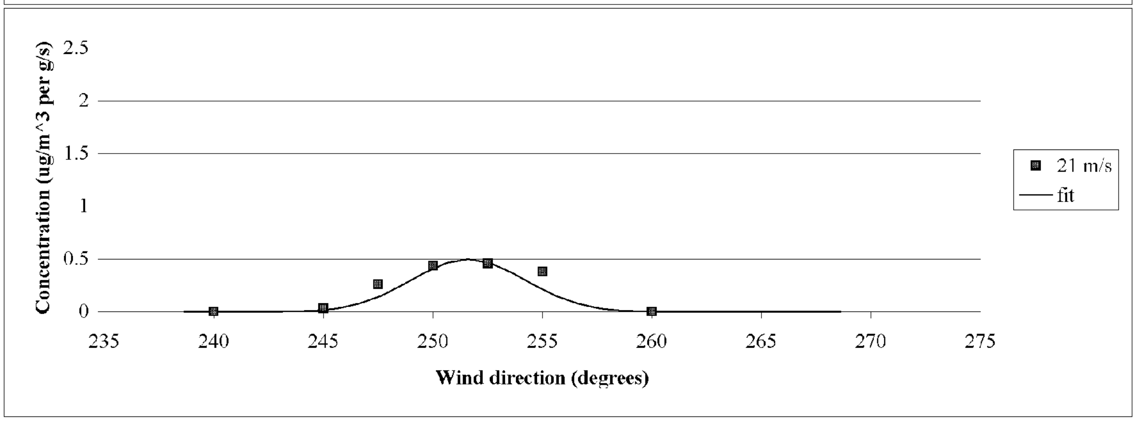
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
232.5	21.0	0.52
232.5	14.0	0.50
232.5	8.0	0.77
232.5	6.0	0.75
232.5	4.0	0.80
232.5	2.0	0.38
232.5	1.0	0.08
225.0	4.0	0.02
227.5	4.0	0.24
235.0	4.0	0.35
232.5	4.0	0.80
230.0	4.0	0.92
237.5	4.0	0.00

fit parameters:

A	1.0
sigma z	97.9
K	323.2
sigma y	199.4
WDc	231.5
hs	150

TTAL - ASR A_T2



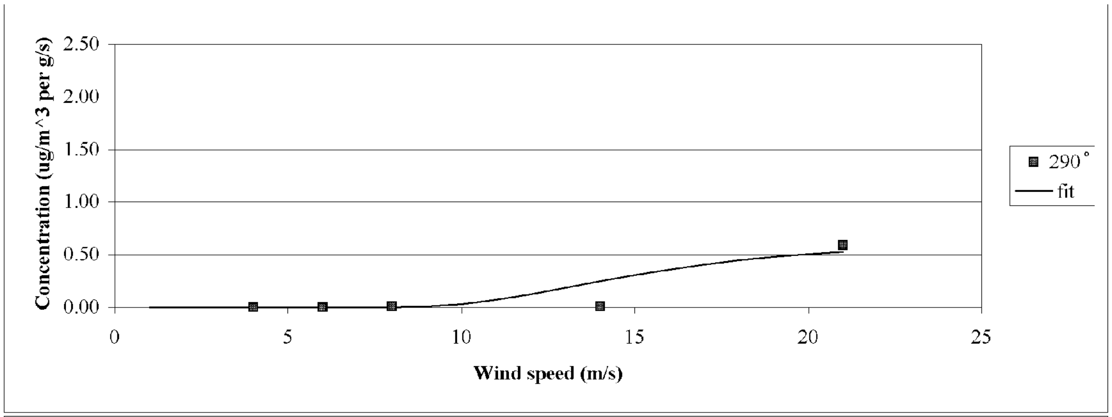


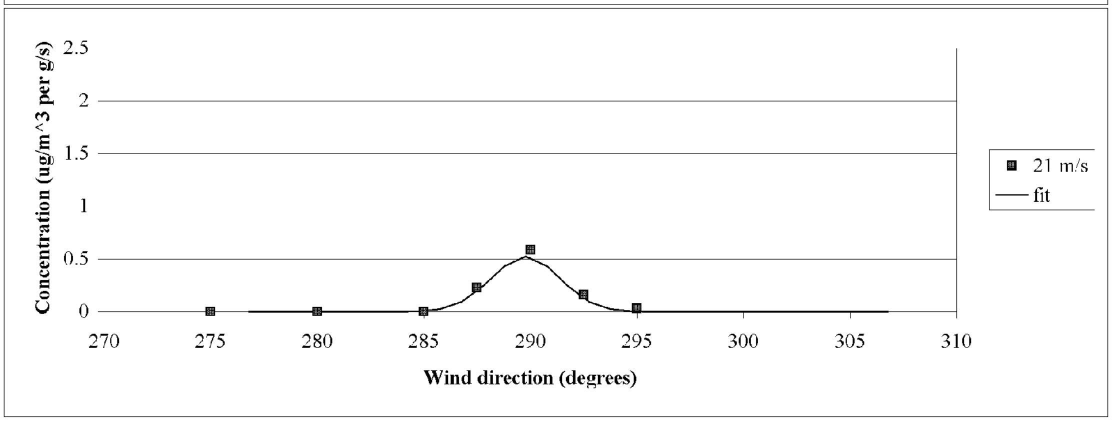
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
252.5	21.0	0.46
252.5	14.0	0.42
252.5	8.0	0.22
252.5	6.0	0.12
252.5	4.0	0.04
252.5	2.0	0.01
240.0	21.0	0.00
245.0	21.0	0.03
247.5	21.0	0.26
250.0	21.0	0.44
252.5	21.0	0.46
255.0	21.0	0.38
260.0	21.0	0.00

fit parameters:

A	1.0
sigma z	129.0
K	13995.4
sigma y	87.0
WDc	251.6
hs	150

TTAL - ASR A_T3



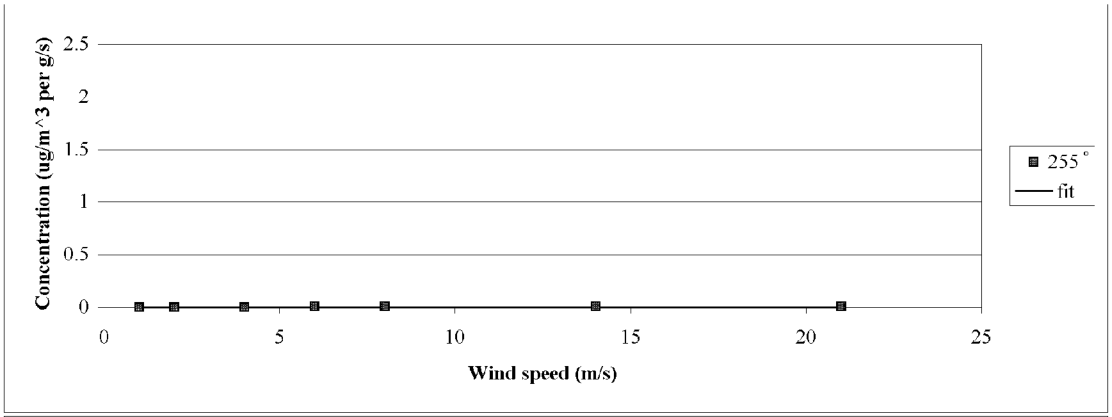


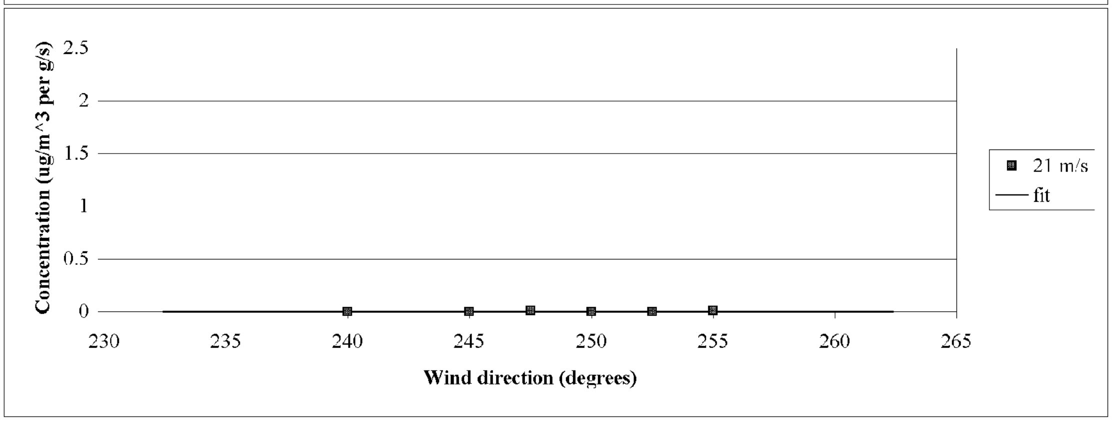
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
290.0	21.0	0.59
290.0	14.0	0.01
290.0	8.0	0.01
290.0	6.0	0.00
290.0	4.0	0.00
275.0	21.0	0.00
280.0	21.0	0.00
285.0	21.0	0.00
290.0	21.0	0.59
287.5	21.0	0.23
295.0	21.0	0.03

fit parameters:

A	1.0
sigma z	69.8
K	10496.7
sigma y	18.7
WDc	289.8
hs	150

TTAL - ASR A_T4



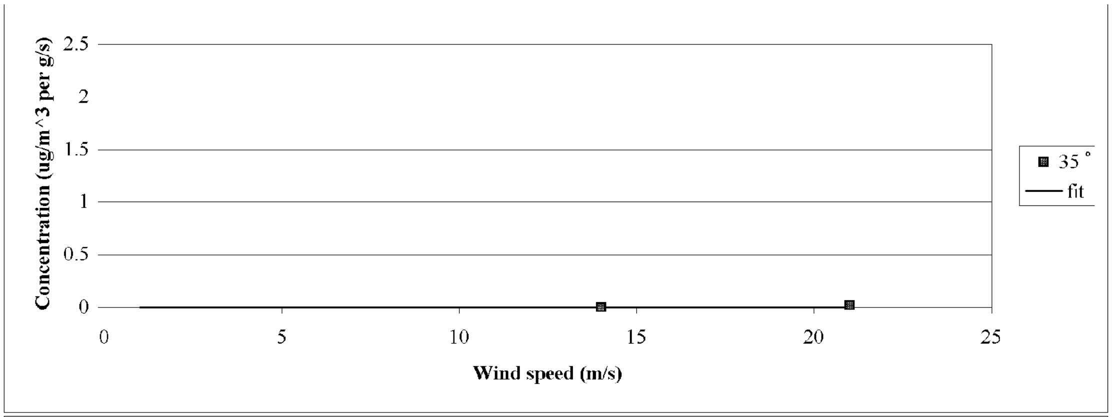


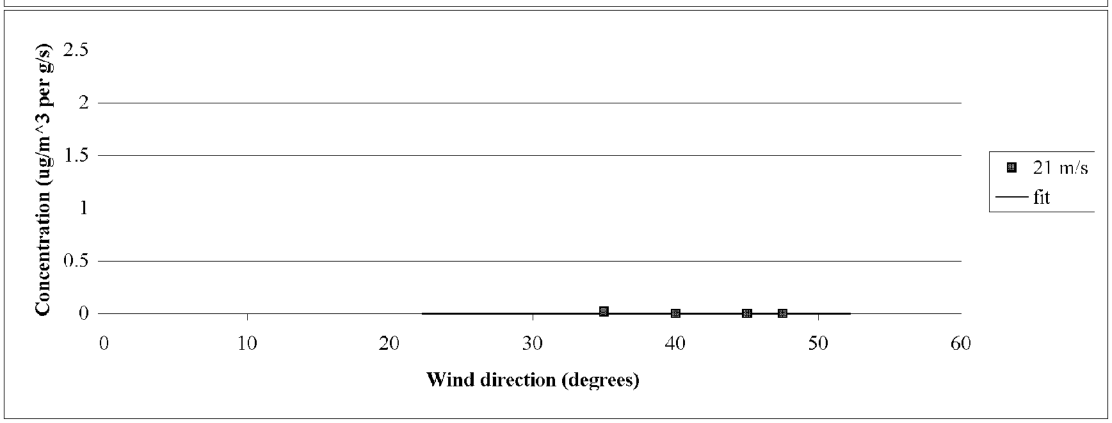
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
255.0	21.0	0.01
255.0	14.0	0.01
255.0	8.0	0.01
255.0	6.0	0.01
255.0	4.0	0.00
255.0	2.0	0.00
255.0	1.0	0.00
240.0	21.0	0.00
245.0	21.0	0.00
247.5	21.0	0.01
250.0	21.0	0.00
252.5	21.0	0.00
255.0	21.0	0.01

fit parameters:

A	1.0
sigma z	43.9
K	32635.9
sigma y	56.8
WDc	245.4
hs	150

TTAL - ASR A_T5



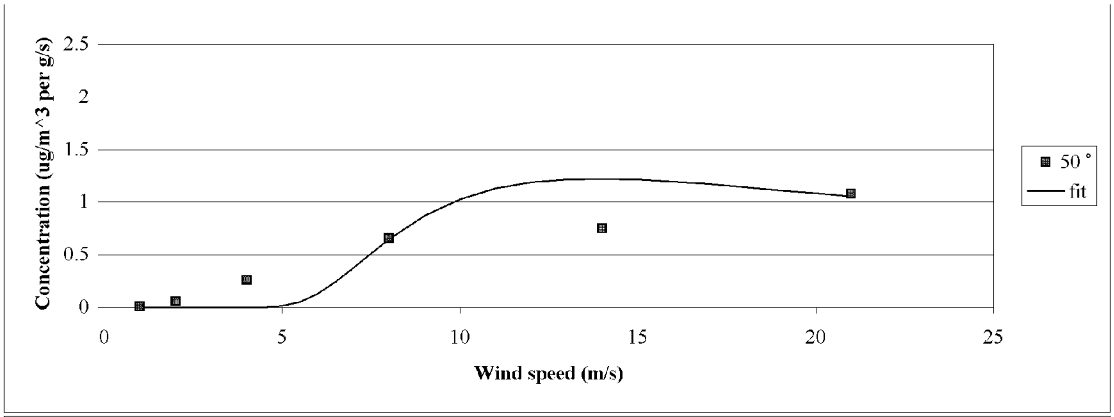


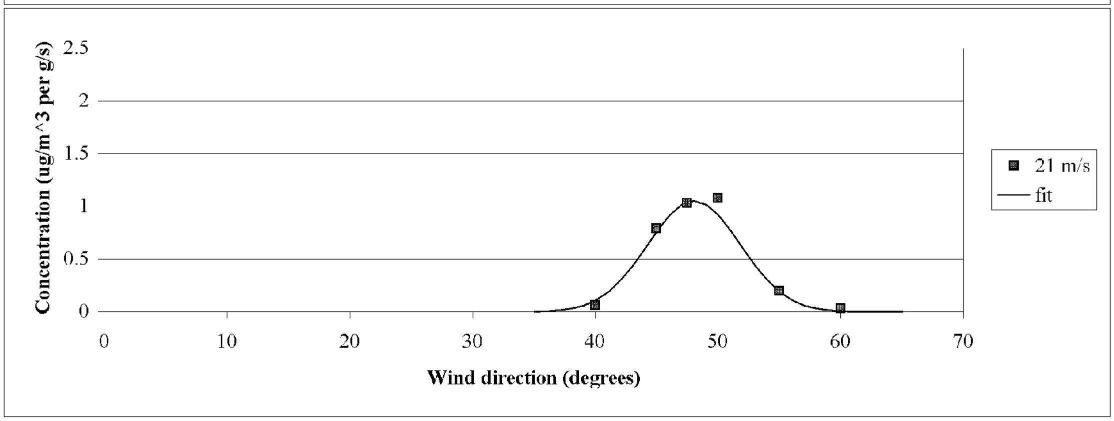
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
35.0	21.0	0.02
35.0	14.0	0.00
35.0	21.0	0.02
40.0	21.0	0.00
45.0	21.0	0.00
47.5	21.0	0.00
40.0	21.0	0.00

fit parameters:

A	1.0
sigma z	39.9
K	14764.4
sigma y	15.1
WDc	35.2
hs	150

TTAL - ASR A_T6



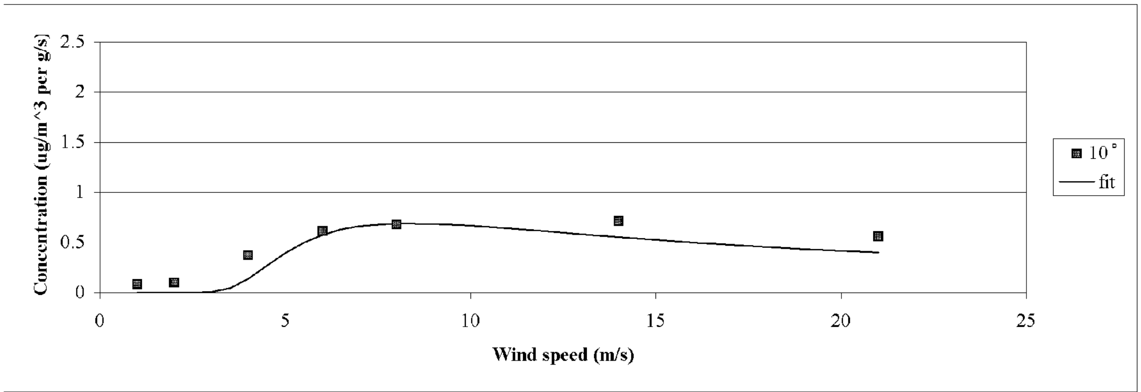


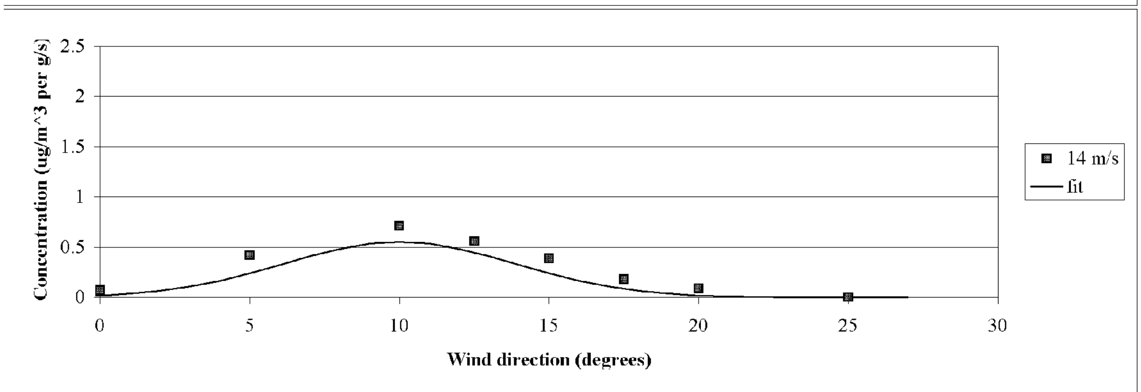
WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
50.0	21.0	1.08
50.0	14.0	0.75
50.0	8.0	0.66
50.0	4.0	0.26
50.0	2.0	0.06
50.0	1.0	0.01
45.0	21.0	0.79
47.5	21.0	1.03
60.0	21.0	0.03
55.0	21.0	0.20
50.0	21.0	1.08
40.0	21.0	0.06

fit parameters:

A	2.5
sigma z	116.3
K	6928.1
sigma y	110.6
WDc	48.0
hs	150.0

TTAL - ASR A_T7





WD [degrees]	WS [m/s]	C/m [ug/m^3 per g/s]
10.0	21.0	0.56
10.0	14.0	0.71
10.0	8.0	0.68
10.0	6.0	0.61
10.0	4.0	0.37
10.0	2.0	0.10
10.0	1.0	0.08
5.0	14.0	0.42
12.5	14.0	0.56
15.0	14.0	0.39
17.5	14.0	0.18
10.0	14.0	0.71
20.0	14.0	0.09

fit parameters:

A	1.0
sigma z	143.0
K	3509.5
sigma y	144.5
WDc	10.0
hs	150