CERMAK
PETERKA
PETERSEN

WIND ENGINEERING AND AIR QUALITY CONSULTANTS

Protocol

Fluid Modeling Good Engineering Practice Stack Height Determination for Rhinelander Mill Stack S09

Expera Specialty Solutions
515 West Davenport Street
Rhinelander, WI

CPP Project: 7835

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

Fluid Modeling Good Engineering Practice

Stack Height Determination for

Rhinelander Mill

Stack S09

CPP Project 7835

June 13, 2014

Prepared by:

Ronald L. Petersen, Ph.D., CCM, Principal

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

Prepared for:

Expera Specialty Solutions
515 West Davenport Street
Rhinelander, WI

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

AGL	Above Ground Level	(m)
A	Calibration Constant	(-)
B	Calibration Constant	(-)
B_o	Buoyancy Ratio	(-)
C	Concentration	(ppm or $\mu g/m^3$)
C_o	Tracer Gas Source Strength	(ppm or $\mu g/m^3$)
C_{max}	Maximum Measured Concentration	(ppm or $\mu g/m^3$)
C_s	Concentration of Calibration Gas	(ppm or $\mu g/m^3$)
	Concentration Estimate for Full-scale Sampling Time, t_s	($\mu g/m^3$)
C_k	Concentration Estimate for Wind-tunnel Sampling Time, t_k	($\mu g/m^3$)
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

1. INTRODUCTION

This protocol describes the wind-tunnel study that will be conducted by CPP, Inc (CPP) on behalf of Expera Specialty Solutions (Expera) to determine the "Good Engineering Practice" stack height for Rhinelander Mill Stack S09. The Rhinelander Mill is located in Rhinelander, WI, as shown in Figure 1. Air monitoring data for the City of Rhinelander, Wisconsin (Oneida County) shows SO_2 concentrations exceeding the 1-hour standard at the water tower monitoring location (WTM). As a result, this area has been formally designated a SO_2 non-attainment area (August 5, 2013 Federal Register). An analysis of emission sources and air quality modeling indicates that the Expera Rhinelander Mill (WPRM) appears to be the primary contributor to the ambient air impact at this monitor, specifically the cyclone boiler stack (S09). The WTM is about 600 m (2000 ft) NNE of the cyclone boiler stack (S09).

A review of the Rhinelander Water Tower monitoring data for 2007-2009 (Paine and Petersen, 2013) indicates that the "design value" concentration that should be compared to the SO_2 NAAQS of 196.5 $\mu g/m^3$ is 512.7$\mu g/m^3$. The predicted "design value" concentration based on AERMOD at the WTM is more than a factor of two lower than observed. After investigating the building geometry, it was noticed that the Boiler 7 building corner is directly upwind of the stack when the wind blows directly toward the WTM (Paine and Petersen, 2011). When the wind blows along a building corner, building corner vortices are generated that enhance building downwash. This enhancement effect is not included in AERMOD. Past wind tunnel modeling studies (EPA, 1985) have shown that these corner vortices can increase concentrations by as much as a factor of two over that observed for wind directions normal to a building face; even at the formula Good Engineering Practice (GEP) stack height. Based on EPA (1981), the formula GEP stack height is 75 m based on Boiler 7 (38.4 m height and 24.4 m projected width). The wind tunnel results presented in EPA (1985) suggest that the actual GEP stack could be up to 2.5 times the building height, or 95 m, for this corner vortex situation.

There are several optional methods whereby the concentration levels at the Water Tower Monitor and all other locations can be reduced to levels below the 1-hr SO_2 NAAQS, as follows: 1) increase the stack height; 2) install additional emission control; and/or 3) additional controls in conjunction with merged flues. This purpose of this study is to evaluate option 1 using wind tunnel modeling with an ultimate goal of helping develop a strategy for showing compliance with the 1-hr SO_2 NAAQs at the WTM.

As discussed in Section 2.1, a source can increase the height of a stack to any height but must use the GEP stack height for purposes of setting an emission limit. Hence, the purpose of this study is to determine the maximum creditable S09 stack height (i.e., the wind tunnel determined GEP stack height) that can be used for dispersion modeling purposes.

To meet the objectives of the study, a 1:240 scale model of the Rhinelander Mill and nearby surroundings within a 450 m (1360 ft) radius will be constructed and placed in CPP's boundary-layer wind tunnel on a turntable. Terrain and/or roughness elements will be added downwind of the turntable so downwind distances out to 1,500 m can be evaluated. Model operating conditions will be set to simulate actual meteorological and Stack S09 operating conditions. For the GEP stack height determination, ground-level concentrations of hydrocarbon tracer gases released from Stack S09 will be measured with and without the nearby buildings present for various meteorological conditions. The results will then be analyzed to determine the actual GEP stack height.

This protocol describes the technical aspects and project plan for conducting the wind tunnel study designed to meet the stated project objectives. The methods outlined in this protocol have been used on many previous GEP stack height evaluations (see Table 1), many of which have been reviewed and approved by the appropriate State and/or EPA agency.

2. TECHNICAL CONSIDERATIONS

2.1 DEFINITION OF GEP STACK HEIGHT

In the stack height regulation (40 CFR 51.100 (ii)), GEP stack height is defined to be

***the greater* of [emphasis added]**:

DEFAULT MINIMUM GEP STACK HEIGHT

"(1) 65 meters, measured from the ground level elevation at the base of the stack;

FORMULA GEP STACK HEIGHT

(2) (i) for stacks in existence on January 12, 1979, and for which the owner or operator had obtained all applicable permits or approvals required under 40 CFR Parts 51 and 52,

$$H_g = 2.5H \quad (1)$$

provided that the owner or operator produces evidence that this equation was actually relied on in establishing an emission limitation:

(ii) for all other stacks,

$$H_g = H + 1.5L \quad (2)$$

where

H_g = good engineering practice stack height, measured from the ground-level elevation at the base of the stack,

H = height of nearby structure(s) measured from the ground-level elevation at the base of the stack,

L = lesser dimension, height or projected width, of nearby structure(s),

provided that the EPA, State, or local control agency may require the use of a field study or fluid model to verify GEP stack height for the source; or

WIND TUNNEL DETERMINED MAXIMUM GEP STACK HEIGHT

(3) The height demonstrated by a fluid model or a field study approved by the EPA, State, or local control agency, which ensures that the emissions from a stack do not result in excessive concentrations of any air pollutant as a result of atmospheric downwash, wakes, or eddy effects created by the source itself, nearby structures or nearby terrain features."

Equation (1) is essentially the formula specified by Congress in the Clean Air Act. Equation (2) is a more restrictive formula (for tall-thin structures) which simplifies to Equation (1) for structures that are wider than they are tall. EPA (1985, pp 36-37) makes it clear that the highest height resulting from the application of the formula to multiple structures is the formula height. Formula height is GEP unless a verification is required or unless a higher height is demonstrated under 40 CFR 51.100 (ii)(3), a wind tunnel modeling evaluation.

To quantitatively determine the GEP height through wind tunnel modeling, the stack height regulation goes on to define an excessive concentration as (40 CFR 51.100 (kk) (1)):

> "A maximum ground-level concentration due to emissions from a stack due in part or whole to downwash, wakes, or eddy effects produced by nearby structures or terrain features which individually is at least 40% in excess of the maximum concentration experienced in the absence of such downwash, wakes, or eddy effects and which contributes to a total concentration due to emissions from all sources that is greater than an ambient air quality standard."

Based on this definition, wind tunnel testing is conducted for various stack heights until the maximum credible GEP stack height is found. If that height is higher than the formula GEP stack height, the wind tunnel determined height is the actual GEP stack height.

40 CFR Part 51 (pages 27892 and 27899) goes on the say that:

> "Section 123 of the Clean Air Act as amended, requires EPA to promulgate regulations to ensure that the degree of emission limitation required for the control of any air pollutant under an applicable State implementation plan (SIP) is not affected by that portion of any stack height which exceeds good engineering practice (GEP) or by any other dispersion technique."
>
> "No source is precluded from building a stack height greater than formula height if such height is believed to be needed to avoid excessive downwash. However, the design and purpose of section 123 prohibit SIP credit for that effort unless a relatively rigorous showing can be made."

These statements in effect say that a source can build a stack taller than the formula but must set the emission limit (using AERMOD or other approved model) based on the formula height or GEP stack height that is taller than the formula determined from a wind tunnel modeling study.

2.2 Setting Model Operating Conditions and Similarity Requirements

General

For GEP type studies, the criteria that are used for simulating plume trajectories and the ambient air flow are summarized below. These are the criteria that are recommended by EPA (1981) and that have been used on past GEP studies conducted by CPP (Greenway et al., 1981; Halitsky et al., 1986; Petersen and Parce, 1993; Petersen, 1987). Hence, the criteria discussed below will be used for setting modeling operating conditions.

Modeling Plume Trajectories

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

$$R = \frac{V_e}{U_h} \qquad (1)$$

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

(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 was fully turbulent upon exit as it is in the full scale. This criteria is met if the stack Reynolds number ($Re_s = dV_e/v_s$), 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). Even though the stack Reynolds number will be greater than 670, a trip will be installed inside the model stack to ensure fully turbulent flow in the exhaust stream prior to exiting the stack.

It should be noted that Froude number similarity is not used, as recommended by EPA (1981), as it would require extremely low wind tunnel speeds and building wake effects would be incorrectly modeled.

Modeling the Airflow and Dispersion

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

- all significant structures within a 415 m (1360 ft) radius of the stacks will be modeled at a 1:240 scale reduction. Upwind of this area, roughness elements will be installed to represent the upwind roughness within 3.2 km of the stack. Terrain and/or roughness elements will be added downwind of the turntable so downwind distances out to 1,500 m can be evaluated.
- the mean velocity profile through the entire depth of the boundary layer will be represented by a power law $U/U_\infty = (z/z_\infty)^n$ where U is the wind speed at height z, U_∞ is the freestream velocity at z_∞ and the power law exponent, n, is dependent on the surface roughness length, z_o, through the following equation:

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

- Reynolds number independence will be ensured: the building Reynolds number ($Re_b = U_b H_b / \nu_a$; the product of the wind speed, U_b, at the building height, H_b, times the building height divided by the viscosity of air, ν_a) will be greater than 11,000 as recommended by Snyder (1981) for rectangular structures.
- a neutral atmospheric boundary layer will be established (Pasquill–Gifford C/D stability) by setting the bulk Richardson number (R_{ib}) equal to zero in model and full scale.

Summary

Using the above criteria and the source characteristics shown in Table 2, the model test conditions for this site have been computed for the stacks under evaluation. The model test conditions were computed for D stability at the simulated wind speeds (see Section 2.5) and are provided in Appendix A. Appendix A also includes a more detailed discussion on wind tunnel scaling issues.

2.3 EXHAUST SOURCES, SOURCE PARAMETERS AND EMISSION RATES

The cyclone boiler stack location (S09) is shown in Figure 3. The full-scale exhaust parameters simulated in the wind tunnel for the cyclone boiler stack S09 are listed in Table 2.

To determine the maximum creditable GEP stack height, three emission scenarios will be evaluated as follow:

- maximum load: the PTE allowed in the permit at the boiler's rated capacity (3.5 lbs SOx/MMBtu @ 300 MMBtu/hr);
- nominal load: the typical or average loading; and
- minimum load: a theoretical scenario that represents maximum sulfur content (3.5 lbs SOx/MMBtu @ 300 MMBtu/hr) at the minimum thermal input rate (minimum exit velocity and temperature).

The stack and emission parameters for these scenarios are provided in Table 2.

2.4 NEARBY STRUCTURES AND TERRAIN

Figure 2 shows an aerial view of the Rhinelander Mill. In general the terrain rises to a maximum of about 1660 ft, MSL to the NNE of the mill or 30 m (100 ft) above plant grade. The terrain is just sufficiently high in this direction to qualify for a terrain GEP demonstration study (terrain must rise to 0.4 Hg or 30 m). However, since Boiler 7 is closer and taller than the nearby terrain, its effect on the GEP stack height will be more significant and will be the focus of this evaluation.

The adjacent plant structures are nearby and are configured such that excessive concentrations may occur mainly due to the Boiler 7 structure as discussed in Section 1. To evaluate the effects of structures, shown in Figures 3 and 4, tests are first conducted with all structure in place (referred to as the "Building In" tests). All nearby structures are then removed (referred to as the "Building Out" tests) and the resulting concentrations are compared to those measured with the buildings in. Figures 5 and 6 show the wind tunnel configuration with nearby structures removed. If the ratio of maximum concentration with the "Buildings In" to that with "Buildings Out" is equal to 1.4 and if the maximum concentration with "Buildings In" exceeds a NAAQS limit, excessive concentrations will have been demonstrated and that stack height will be the GEP stack height.

When conducting the "Building Out" tests, all structures that are nearby are removed. A structure is defined a nearby if the distance from the stack to the building is less than or equal to five times the lesser of the height of width of the structure. Since most of the Rhinelander Mill structures are connected or touching, most Rhinelander Mill structures will be removed.

2.5 SURFACE ROUGHNESS

To simulate full scale wind profiles in the wind tunnel, it is necessary to match the surface roughness length used in the model to that of the actual site. The surface roughness lengths for the Rhinelander Mill site were specified using AERSURFACE (EPA, 2008). To define surface roughness values for the flow approaching the Rhinelander Mill Stack S09, the AERSURFACE tool with a radius of 3.2 km around the site was used (based on the model scale and length of the wind tunnel). Table 3 shows the AERSURFACE results in 30 degree intervals around the Rhinelander Mill as well as the specified roughness values for the wind tunnel test sectors. It is evident that two approach flows are necessary to accurately represent the full scale wind profiles in the wind tunnel. For wind directions of 300 through 30 degrees, the surface roughness values are small with a mean of 0.062 m representing the water to the north of the site. For wind directions of 30 through 300 degrees, the mean surface roughness is 0.489 m.

The surface roughness length around the Rhinelander-Oneida County Airport was specified using the AERSURFACE tool with a radius of 1 km around the anemometer location. The average surface roughness length was determined to be 0.56 m for the airport (see Table 3).

2.6 TEST WIND SPEEDS

The EPA stack height guideline (EPA, 1981) recommends that the design wind speed for GEP stack height and excessive concentration evaluations be less than the 2 percent wind speed (the wind speed that is exceeded less than 2 percent of the time) unless it can be demonstrated that higher wind speeds cause an exceedance of NAAQS limits. This speed was set as the limiting speed for all wind tunnel tests.

The 2 percent wind speed for the was based on meteorological observations at the Rhinelander-Oneida County Airport 10 m anemometer for the period 1998-2010. The wind rose for that period is shown in Figure 7. Figure 8 shows that the 2 percent wind speed is 7.9 m/s. All concentration tests to determine GEP stack height will be conducted with speeds at or below the 2 percent wind speed.

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

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

where

U_r	=	wind speed at reference height (m/s),
z_r	=	reference height above plant grade (600 m),
U_∞	=	wind speed at freestream height (m/s),
z_∞	=	freestream height (600 m),
U_{anem}	=	wind speed at appropriate anemometer (m/s),
z_{anem}	=	height above grade for Uanem (10 m),
n_a	=	wind power law exponent at the anemometer (0.22 at the Airport),
n_s	=	wind power law exponent at the site (0.21 at the site).

Tables AA-AC in Appendix provide the calculated results using the above equations. It should be noted that the power law exponents were calculated using Equation 4 with z_o equal to 0.56 m at the airport and 0.49 m at the site.

2.7 Data Acquisition

The EPA stack height guideline (EPA, 1981) requires that certain information be collected for GEP stack height demonstrations. The data that are recommended to be collected are summarized below and in Table Table 4.

- Three vertical profiles of mean velocity, and vertical and longitudinal turbulence intensity and shear stress—for Atmospheric Dispersion Comparability (ADC) and excessive concentration tests (see Section 3.3 for a discussion on the ADC tests).
- Lateral profiles of mean velocity and turbulence intensity along the model surface and at a height close to plume altitude near the stack location and near the end of the planned study area (six profiles)—for ADC and GEP stack heights tests.
- Vertical and lateral concentration profiles through the plume centerline—three for ADC tests and four for GEP stack height tests.
- Ground-level longitudinal profiles of concentration along the plume centerline—for ADC, Reynolds number and GEP stack heights tests.
- Two to four lateral ground-level concentration profiles including one at the position of maximum ground-level concentration—GEP stack heights tests.

CPP has collected much of this information on past projects of a similar nature. For this study no ADC tests will be conducted. This study will mainly focus those items outlined in Table 4. Table 5 summarizes the concentration measurements that are planned.

The wind tunnel and instrumentation that will be used to collect the data are described in Appendix B.

2.8 Quality Control

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

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

3. PROJECT PLAN

To meet the project objectives, six tasks are planned. The six tasks, which are discussed in detail below, are: 1) protocol development and approval; 2) model construction and setup; 3) wind tunnel testing - documentation tests; 4) visualization and meeting at CPP; 5) wind tunnel testing – GEP stack tests; and 6) analysis and reporting.

3.1 TASK 1 - TEST PROTOCOL DEVELOPMENT

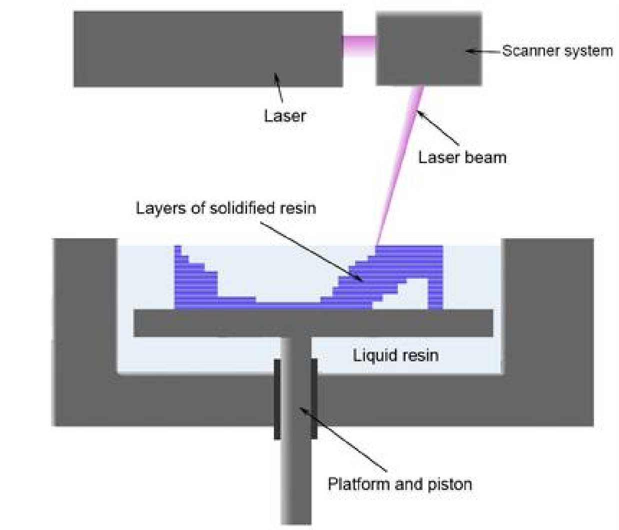
During this phase of the project, this test protocol will be developed and finalized. The protocol defines the methods used to conduct the study, the area and sources to be modeled, the wind directions and wind speeds to be simulated and the results that will be provided.

3.2 TASK 2 - MODEL CONSTRUCTION AND SETUP

A 1:240 scale model of the Stack S09 and nearby surroundings will be constructed and placed on a turntable. The turntable model will include all significant structures within a 415 m (1360 ft) radius of the Stack S09. The 415 m radius includes all significant nearby structures as identified by BPIP. Upwind of that radius, roughness elements will be installed to represent the approach roughness within a 3.2 km radius of stack. Downwind of the turntalbe, terrain and/or roughness elements will be installed so the measurements can be obtained out to 1,500 m. The turntable area modeled is depicted in Figure 3. A close-up plan view of the area that includes detailed structural models is provided in Figure 4.

The Boiler 7 building model will be constructed utilizing the 3D drawing files developed from plan and elevations drawings. These files are used to generate a file that is used directly to construct the scale model of the the Boiler 7 Building using either a Stereolithography (SLA) or 3D printing process. Both Stereolithography and 3D printing processes use the same file output type to create the models. Also, both processes typically build the models in layers of 0.004" per layer. For this project both processes will be used to construct various structural elements depending upon the needed durability.

In the way of background, Stereolithography is a process that uses a vat of liquid resin that is hardened by using a laser to cure the material one layer at a time. The models tend to be more flexible, thus they can withstand impacts better. Below is a simplified image of the process. 3D printing is a process that uses a polymer powder and 2D printing technologies combined to build 3D parts. Once created, the parts go through post-processing to strengthen them.



The process creates rigid parts that are more stable over time than SLA but are also more brittle. Similar to the SLA process, 3D printing involves building the model one layer at a time. Above is a simple schematic that illustrate the SLA process. The 3D printing process is very similar. Figure 9 shows 3D drawings of the model that will be used as the basis for model construction. It should be noted that simple site buildings will be constructed manually out of Styrofoam.

The stack will be constructed of brass tubes and will be supplied with an air–hydrocarbon mixture of the appropriate density. Measures will be taken to ensure that the flow is fully turbulent upon exit. Precision gas flow meters will be used to monitor and regulate the discharge velocity.

All testing will be carried out in CPP's closed-circuit wind tunnel shown in Figure 10. Turning vanes at the tunnel elbows were used to maintain a homogeneous flow at the test-section entrance. Spires and a trip at the leading edge of the test section begin the development of the atmospheric boundary layer. The long boundary layer development region between the spires and the site model was filled with roughness elements, as indicated in the wind-tunnel schematic presented in Figures 11 and 12. Figure 11 shows an example wind tunnel setup that will be used when testing with all site structures present and Figure 12 shows an example wind tunnel setup that will is used for testing with nearby structure removed. These roughness patterns are experimentally set to develop the appropriate approach boundary layer wind profile and approach surface roughness length. Testing will be conducted with the target approach surface roughness length specified in Table 3.

For all testing, concentration measurements will be obtained at various locations on the surface of the wind tunnel so that at approximately 45 locations will be sampled for each simulation. A typical sampling grid consists of 5 to 9 measurement points located in each of 5 or 6 rows that are spaced perpendicular to the wind direction. The lateral and longitudinal spacing of measurement points is designed so that the maximum concentrations are defined in the lateral and longitudinal directions. Initial testing is conducted to confirm the sampling grid design and to alter the design if necessary. A schematic of a typical sampling grid is shown in Figure 13. It should be noted that one background sample is taken upwind of the stack so that the background can be subtracted from the all other measurements.

3.3 TASK 3 - WIND TUNNEL TESTING – DOCUMENTATION TESTS

Before conducting the detailed wind tunnel testing, a series of wind tunnel documentation tests are typically conducted as recommended by EPA. The tests include: 1) atmospheric dispersion comparability (ADC) tests, and 2) Reynolds number tests.

The atmospheric dispersion comparability (ADC) tests are conducted in the absence of buildings, other surface structures, large roughness and/or elevated terrain to show that dispersion in the wind tunnel is comparable to that described for the atmosphere by the basic Gaussian plume distribution. The stack height used for the tests is 50 or 100 m based on CPP's past experience conducting such studies. Concentration measurements for these tests must show comparability to the equations developed for predicting dispersion in flat terrain (i.e., Pasquill–Gifford stability class C or D; Turner, 1994). CPP conducted such tests on a past project with the same 1:240 scale reduction and these tests will not be repeated.

For the Reynolds number tests, a scale model of the Rhinelander Mill and vicinity will be installed in the wind tunnel. A tracer gas will be emitted from the new stack with the stack height set equal to the GEP stack height. Ground-level concentration measurements will then be taken downwind of the power station for three different Reynolds numbers. If Reynolds number effects are negligible, the normalized concentration results should be equivalent (within 10 percent). The minimum test speed for the remaining tests will be chosen such that Reynolds number effects are negligible. Table 5 lists the tests that will be conducted.

3.4 TASK 4 - MEETING AT CPP

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

3.5 TASK 5 - WIND TUNNEL TESTING – GEP STACK HEIGHT TESTING

The actual GEP stack height will be determined for Stack S09. To determine the GEP stack height, the tests summarized in Table 5 will be conducted. The first series of tests will be conducted with the stack height set equal to 75 m, the formula GEP stack height. A series of five wind directions, with the building corner upwind, will then be evaluated to determine the wind direction giving the highest ground level concentration and highest concentration ratio with and without the upwind building present (i.e., greatest downwash effect). Other wind directions may be added if deemed appropriate. At the critical wind direction, a series of tests will then be conducted to define the wind speed that results in the highest ground level concentration and greatest downwash effect. Next, a series of tests will be conducted at various stack heights at the critical wind direction and wind speed. Once these tests are completed, testing at additional wind speeds, wind directions, and load conditions will be conducted at the preliminary GEP stack height to zero-in on the final GEP stack height. Once the GEP stack height is found, selected documentation tests and analyses as recommended by EPA (1981) will be conducted. These tests/analyses include:

- Repetitive tests with and without nearby structures present to demonstrate the tests were repeatable and that the maximum ground-level concentration was measured;

The following other documenation tests recommended by EPA (1981), will not conducted as they have beend carried out on past similar projects and offer no additional information regarding the GEP stack height.

- Elevated measurements of horizontal and vertical concentration distributions at several locations downwind of the stack under evaluation; and
- Calculations of horizontal and vertical dispersion coefficients, and their variation with downwind distance.
- Vertical and horizontal measurements of air flow characteristics within the region over which concentration measurements were obtained.

3.6 ANALYSIS AND REPORTING

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

- conversion of wind tunnel concentrations to full-scale hourly average normalized concentrations using the equation recommended by Snyder (1981); and
- specification of GEP stack height for Stack S09.

Upon completion of all analyses, a concise, comprehensive report will be prepared and submitted to the client for review and comment. After comments on the report are received, final bound copies will be provided.

4. REFERENCES

Arya, S.P.S., and J.F. Lape, Jr., "A Comparative Study of the Different Criteria for the Physical Modeling of Buoyant Plume Rise in a Neutral Atmosphere," *Atmospheric Environment*, Vol. 24A, No. 2, pp. 289–295, 1990.

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

EPA, "Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulation) Revised," USEPA Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA–45014–80–023R, 1985.

EPA, "Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height," USEPA Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA–450/4–81–003, July 1981.

Huber, A. H, and W. H. Snyder, "Building Wake Effects on Short Stack Effluents," *Preprint Volume for the Third Symposium on Atmospheric Diffusion and Air Quality*, American Meteorological Society, Massachusetts, 1976.

Huber, A. H., and W. H. Snyder, "Wind Tunnel Investigation of the Effects of a Rectangular-Shaped Building on Dispersion of Effluents from Short Adjacent Stacks," *Atmospheric Environment*, Vol. 16, No. 12, pp. 2837–2848, 1982.

Greenway, A.R., J.E. Cermak, R. L. Petersen, and H.C. McCullough, "Physical Modeling Studies for GEP Stack Height Determinations," 74th Annual Meeting of the APCA, Paper No. 81–20.3, CEP80–81 JAP–JEC33, Philadelphia, Pennsylvania, June 21–26, 1981.

Halitsky, J. A., R. L. Petersen, S.D. Taylor, and R. B. Lantz, "Nearby Terrain Effects on a Good Engineering Practice Stack Height," paper to be presented at 79th Annual APCA Meeting in Minneapolis, Minnesota, 1986.

Huber, A. H, and W. H. Snyder, "Building Wake Effects on Short Stack Effluents," Preprint Volume for the Third Symposium on Atmospheric Diffusion and Air Quality, American Meteorological Society, Massachusetts, 1976.

Huber, A. H., and W. H. Snyder, "Wind Tunnel Investigation of the Effects of a Rectangular-Shaped Building on Dispersion of Effluents from Short Adjacent Stacks," Atmospheric Environment, Vol. 16, No. 12, pp. 2837–2848, 1982.

Paine, R., and R. Petersen, "Analysis and Resolution of Rhinelander's Monitored SO_2 Concentrations Above the One-Hour Standard, Joint AECOM and CPP White Paper, April 28, 2011.

Petersen, R.L., D.K. Parce, J.L. West, R.J. Londergan, "Effect of a Neary Hill on Good Engineering Practice Stack Height," 86th Annual AWMA Conference, Denver, CO, June 14-18, 1993.

Petersen, R.L., "Fluid Modeling for Good Engineering Practice Stack Height at Homer City Generating Station," prepared for TRC Environmental Consultants, Inc., East Hartford, CT, by Cermak Peterka Petersen, Inc., Report No. 86-0338, October, 1987.

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

FIGURES

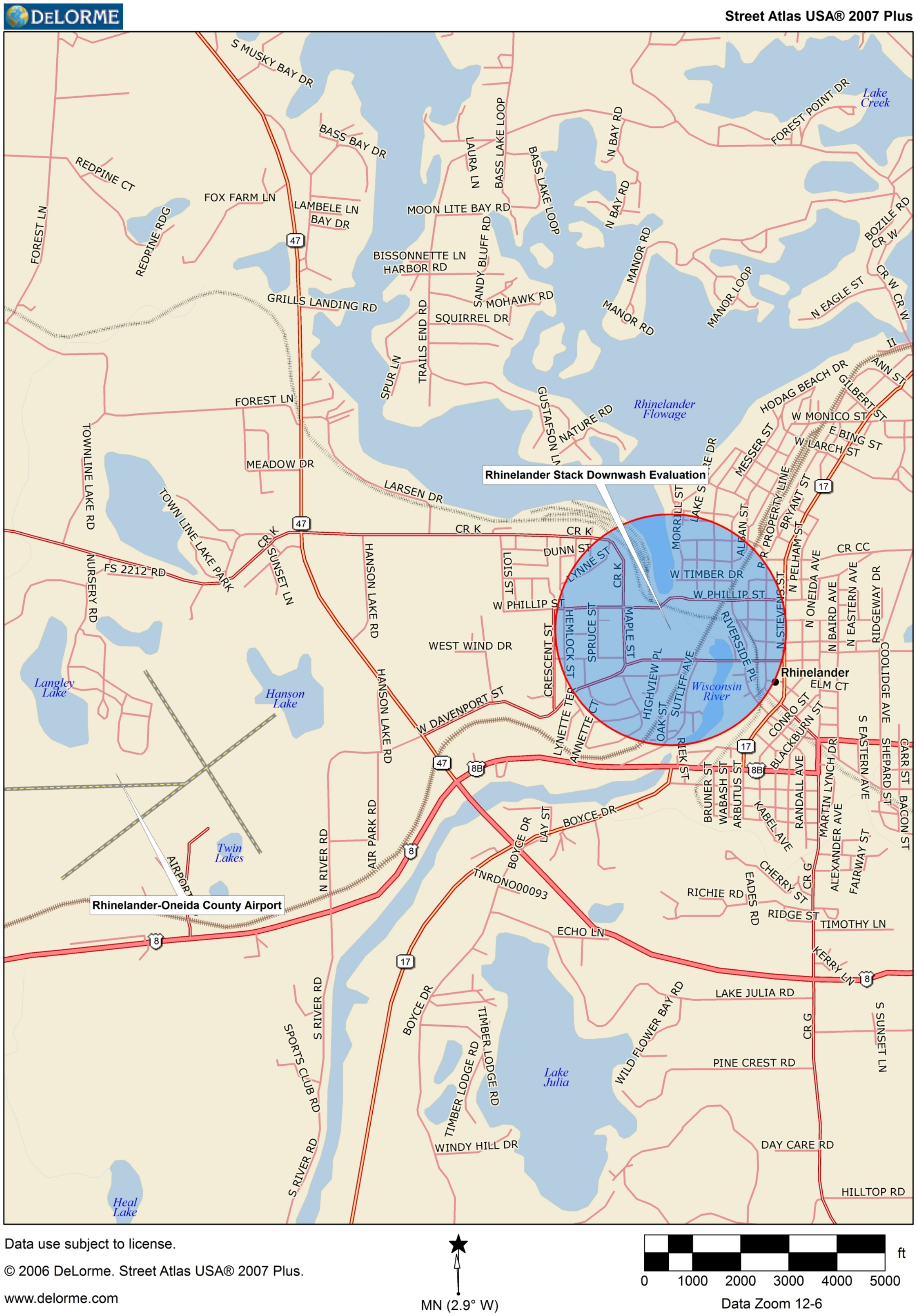


Figure 1. Site location and project anemometer.

Figure 2. Aerial view of Rhinelander Mill.

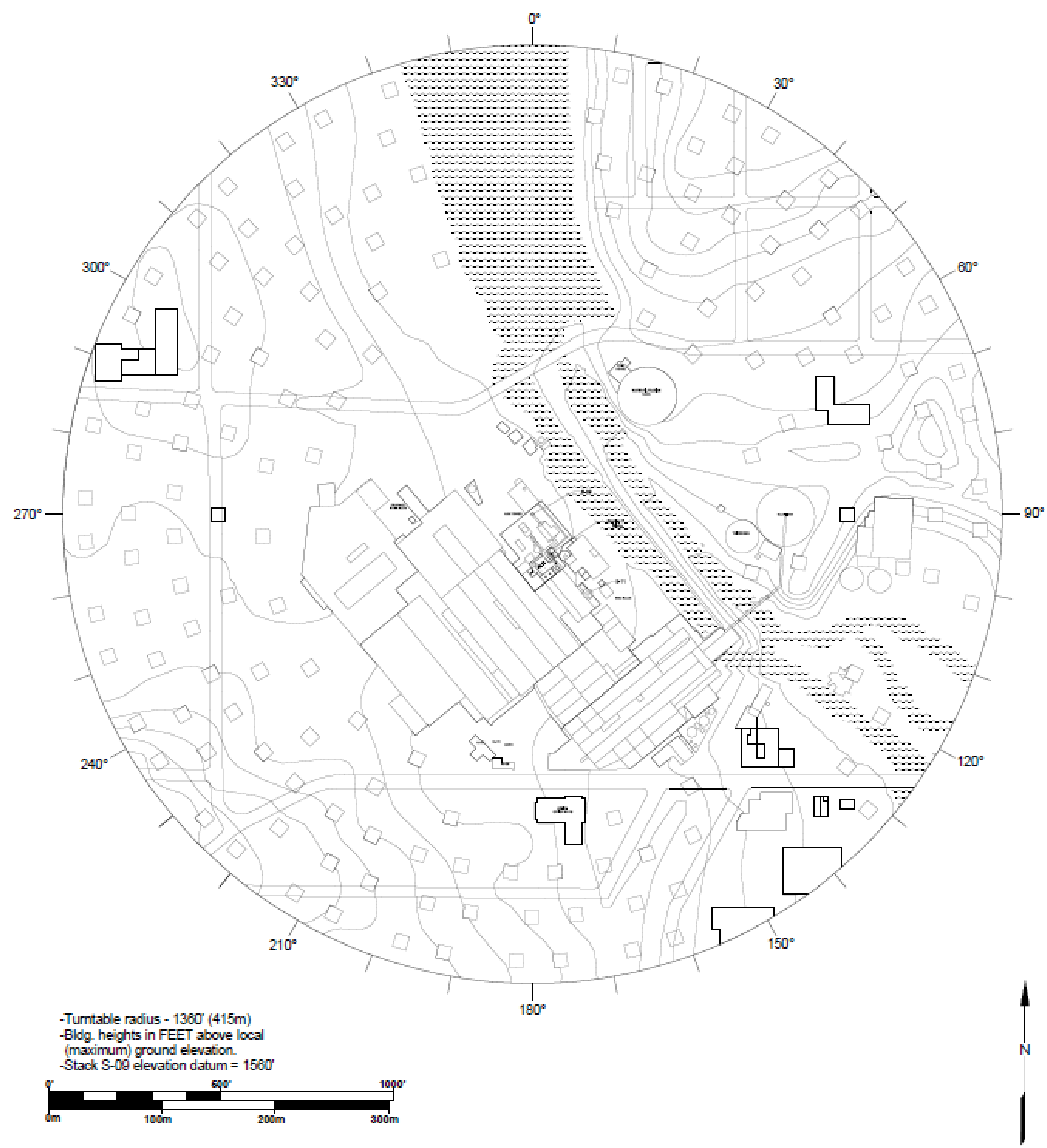


Figure 3. Model turntable drawing showing the test configuration with all building present.

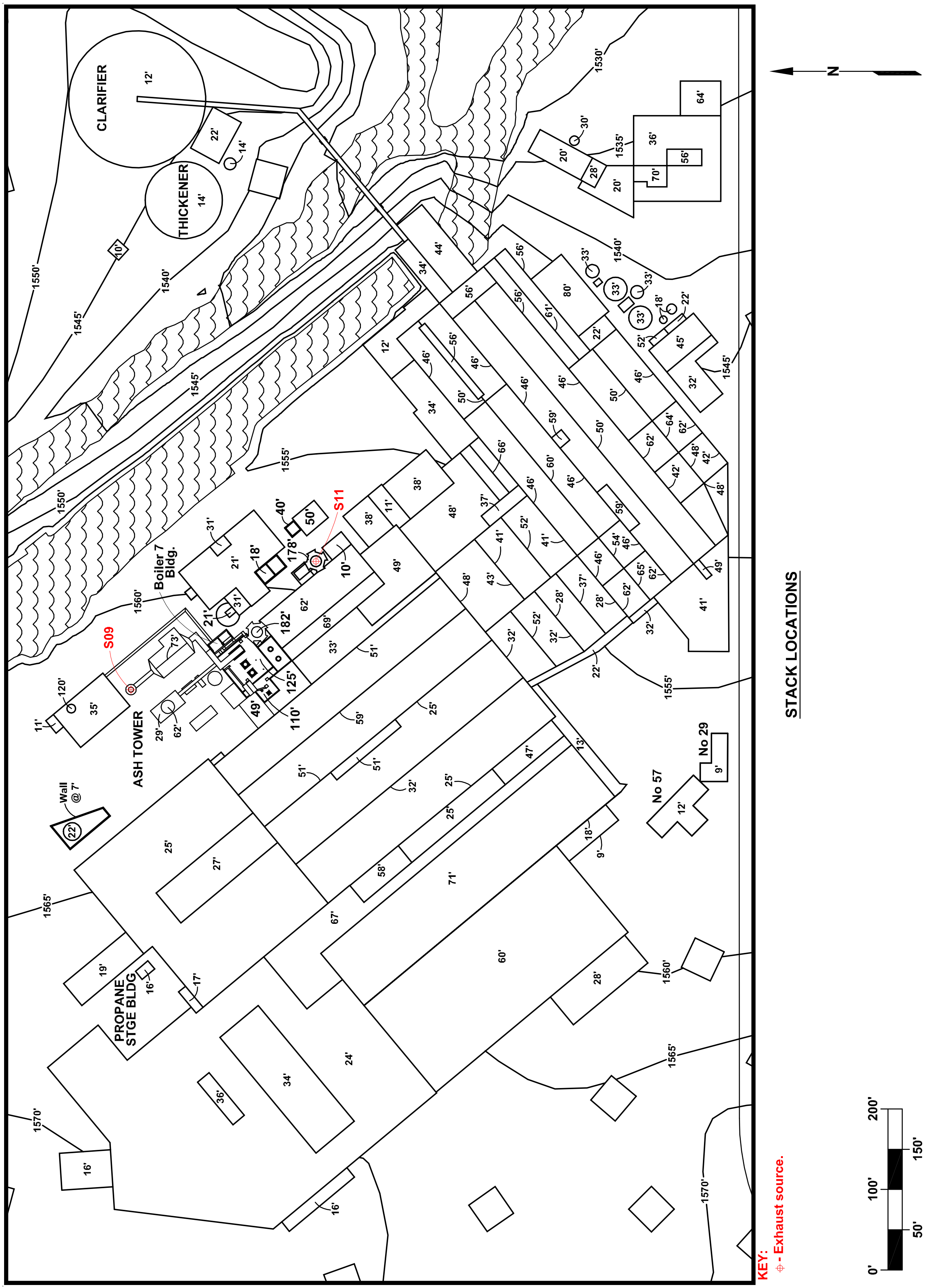


Figure 4. Close-up plan view of buildings and stacks, all building in configuration.

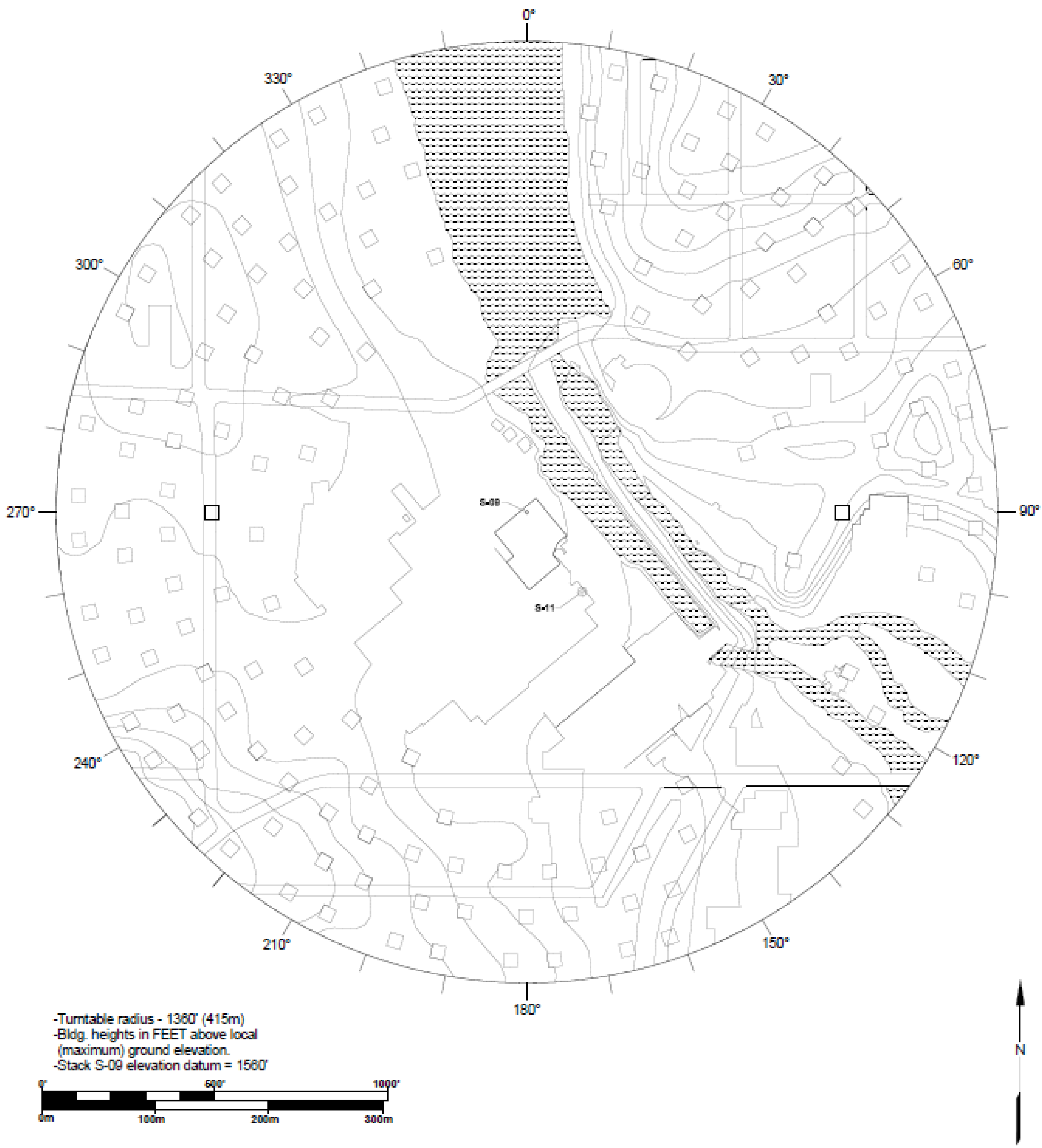


Figure 5. Model turntable drawing showing the test configuration with nearby building removed.

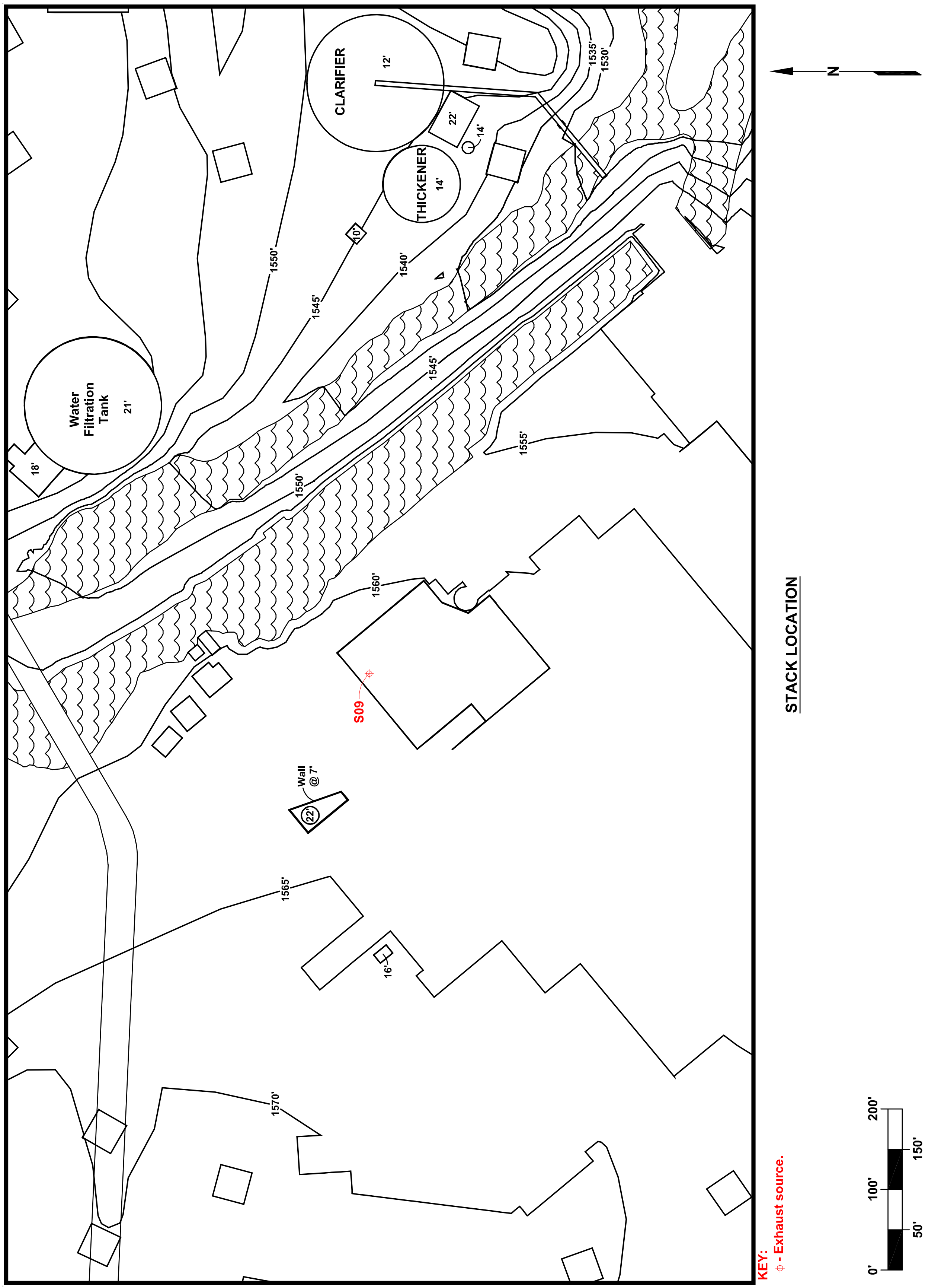


Figure 6. Close-up plan view of buildings and the stack, nearby buildings out configuration.

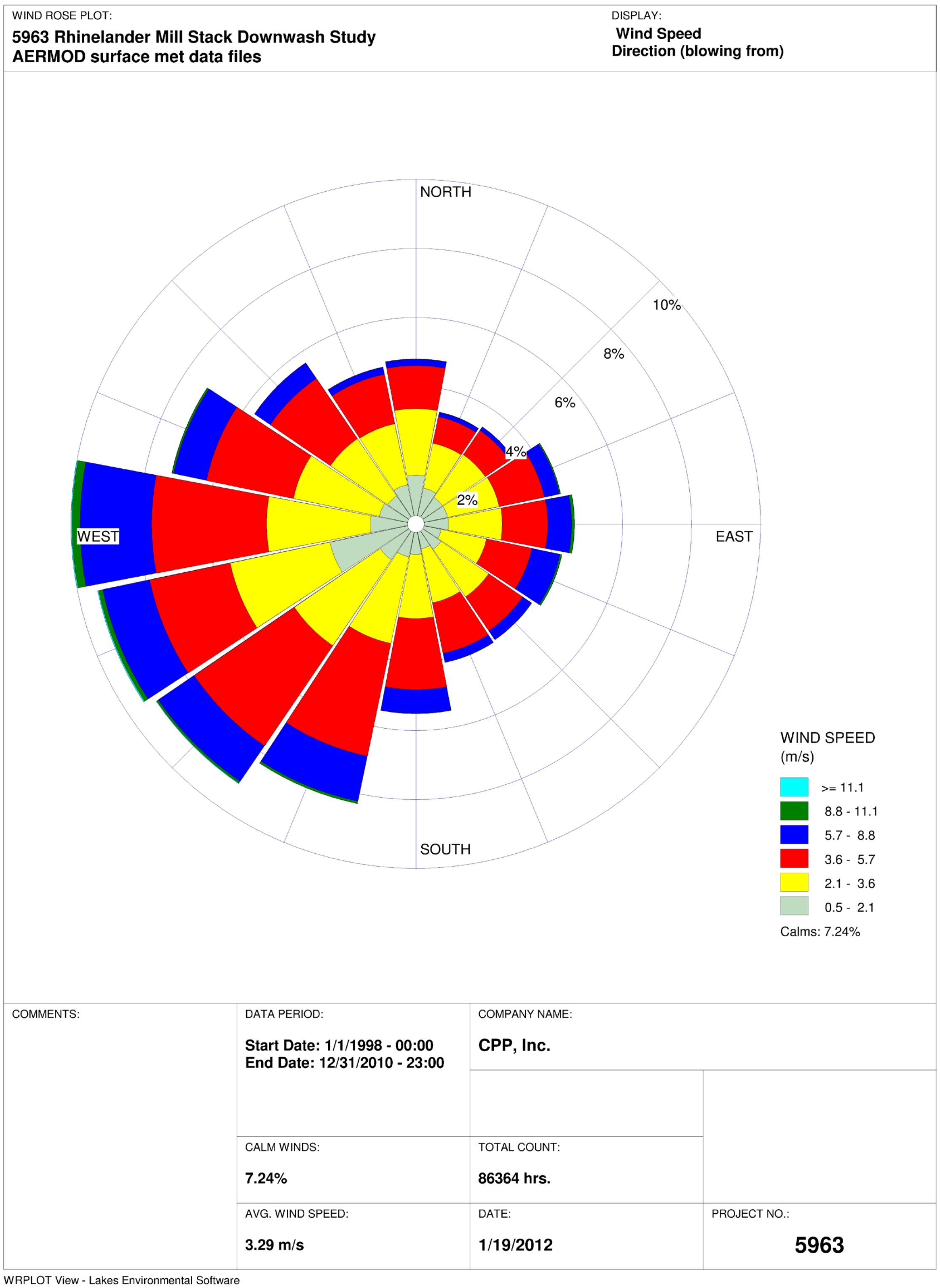
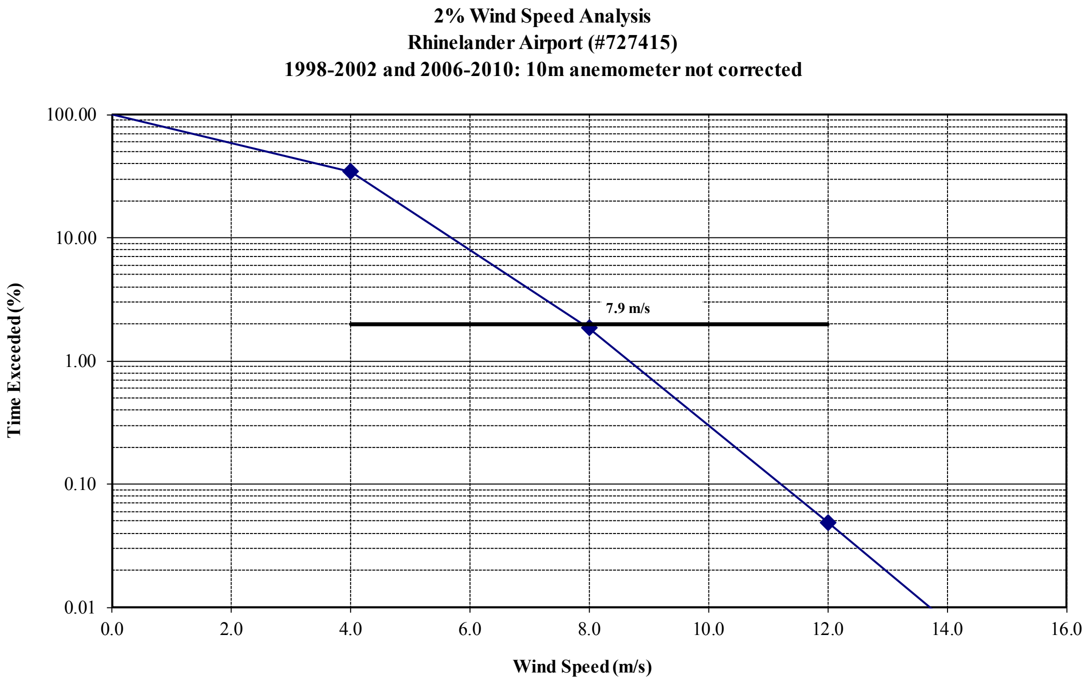


Figure 7. Wind rose for the Rhinelander-Oneida County Airport anemometer.



Joint Probability Distribution of Wind Speed and Wind Direction at the Rhinelander Airport (#727415) Anemometer

Category: Maximum Wind Speed (m/s):	1 4.0	2 8.0	3 12.0	4 16.0	5 >16	Totals by Direction (%)
N	3.701	1.011	0.014	0.002	0.000	**4.728**
NNE	2.811	0.655	0.010	0.001	0.000	**3.477**
NE	2.723	0.651	0.008	0.000	0.000	**3.383**
ENE	2.983	1.334	0.066	0.005	0.000	**4.387**
E	2.876	1.564	0.145	0.004	0.000	**4.588**
ESE	2.511	1.781	0.143	0.002	0.000	**4.437**
SE	2.875	1.119	0.025	0.000	0.000	**4.019**
SSE	2.812	1.350	0.006	0.000	0.000	**4.169**
S	3.226	2.137	0.054	0.000	0.000	**5.417**
SSW	4.470	3.805	0.139	0.001	0.000	**8.415**
SW	5.092	3.703	0.173	0.011	0.000	**8.979**
WSW	6.181	3.029	0.341	0.010	0.000	**9.561**
W	5.192	4.125	0.506	0.011	0.001	**9.835**
WNW	4.458	2.974	0.144	0.001	0.000	**7.576**
NW	3.521	2.003	0.023	0.000	0.000	**5.547**
NNW	3.539	1.291	0.008	0.000	0.000	**4.837**
Calm	6.650					
Totals by Category (%):	**65.620**	**32.530**	**1.805**	**0.048**	**0.001**	**100**
Time Exceeded (%):	**34.384**	**1.854**	**0.049**	**0.001**	**0.000**	

Figure 8. Wind speed and direction distribution for the Rhinelander-Oneida County Airport anemometer.

3D Drawings of Boiler 7 Building and S09 Stack

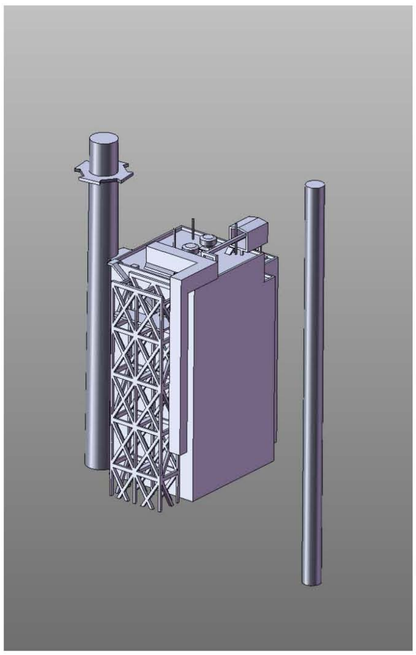
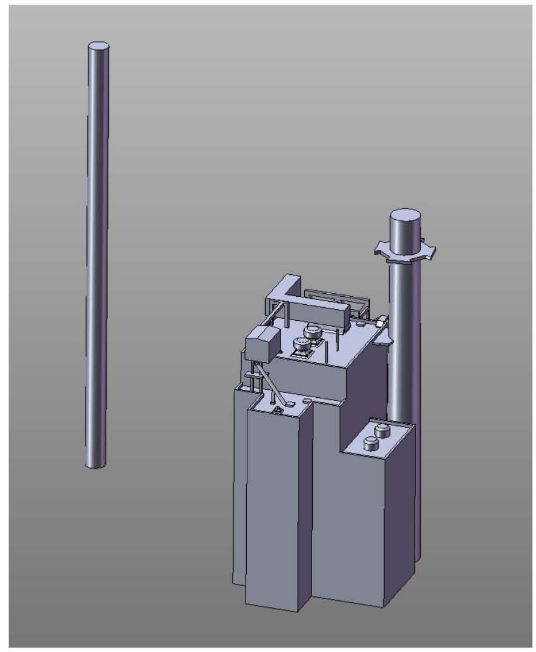



Figure 9. 3D views of the Boiler 7 model.

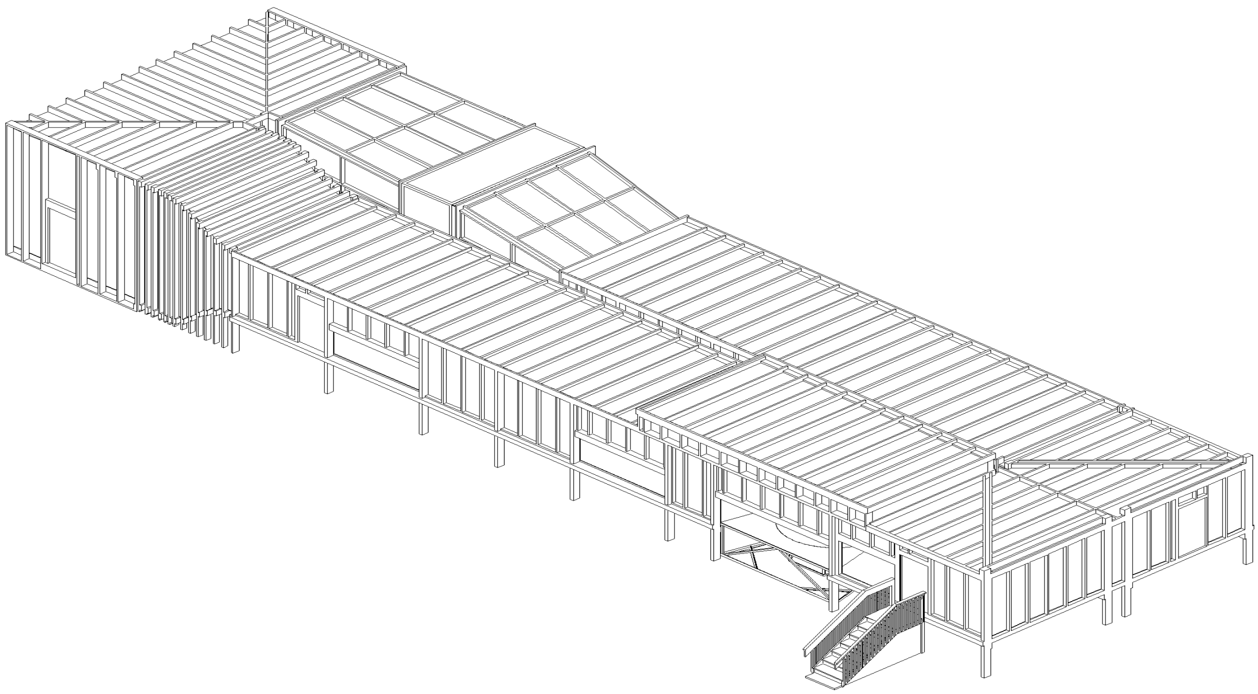


Figure 10. CPP's closed-circuit wind tunnel & performance specifications used for testing

1.	**Dimensions**	
	Test Section Length	*68.0 ft (20.7 m)*
	Test Section Width	*12.0 ft (3.66 m)*
	Ceiling Height	*7.0 ft (2.1 m)*
2.	**Wind-Tunnel Fan**	
	Horse Power	*4 X 15 hp (4 X 11.2 kW)*
	Drive Type	*6 blade axial fan, variable speed motor*
	Speed Control	*Fine: blade pitch control*
3.	**Boundary-Layer**	
	Free Stream Velocities	*0.0 fps to 45.0 fps (0.0 to 13.7 m/s)*
	Boundary-Layer Thickness	*Up to 5.0 ft (1.5 m)*
4.	**Stream wise Pressure Gradient**	*Zeroed by slotted roof over test section*

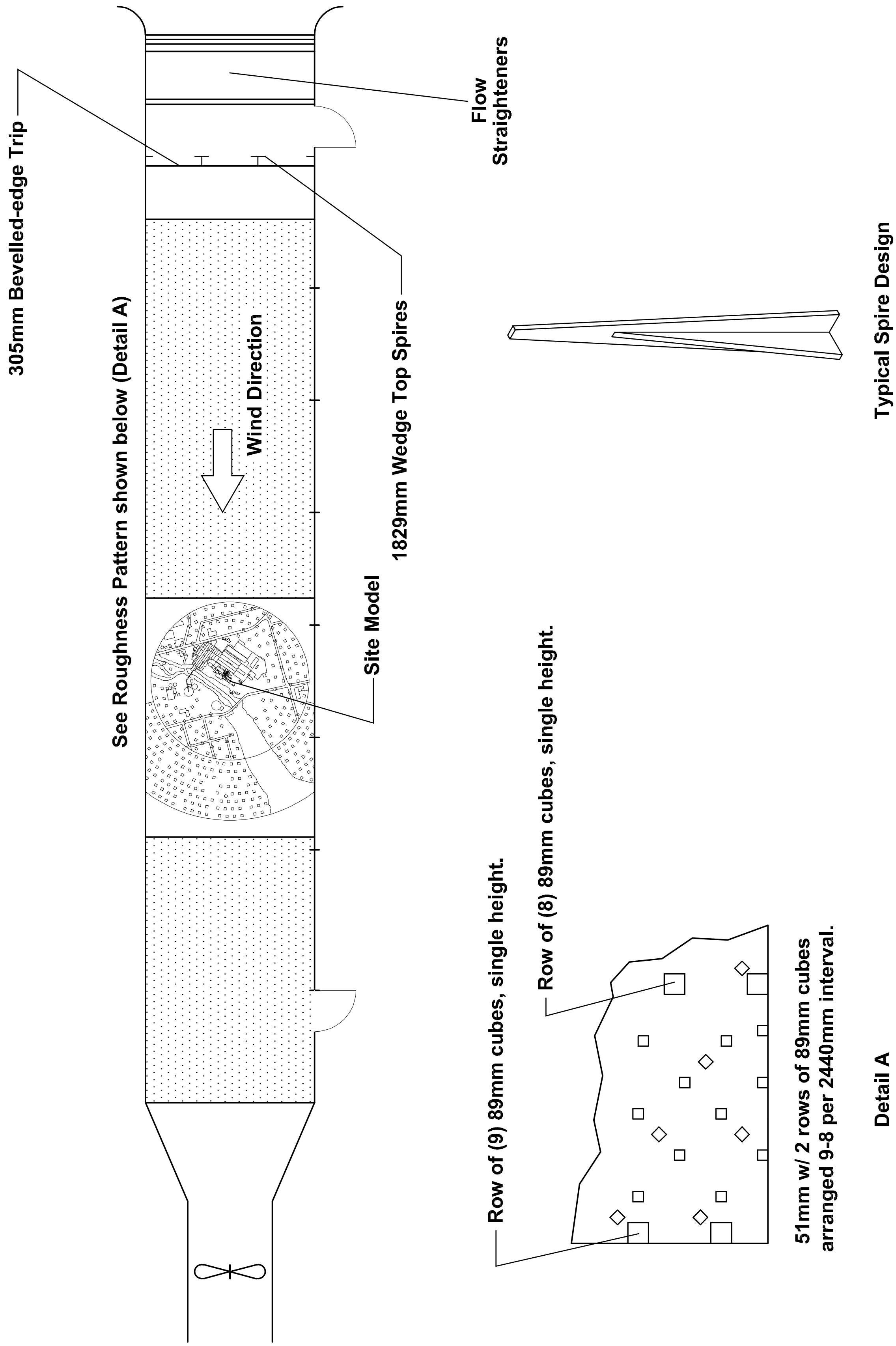


Figure 11. Schematic of example wind tunnel setup for GEP test with all site structures present.

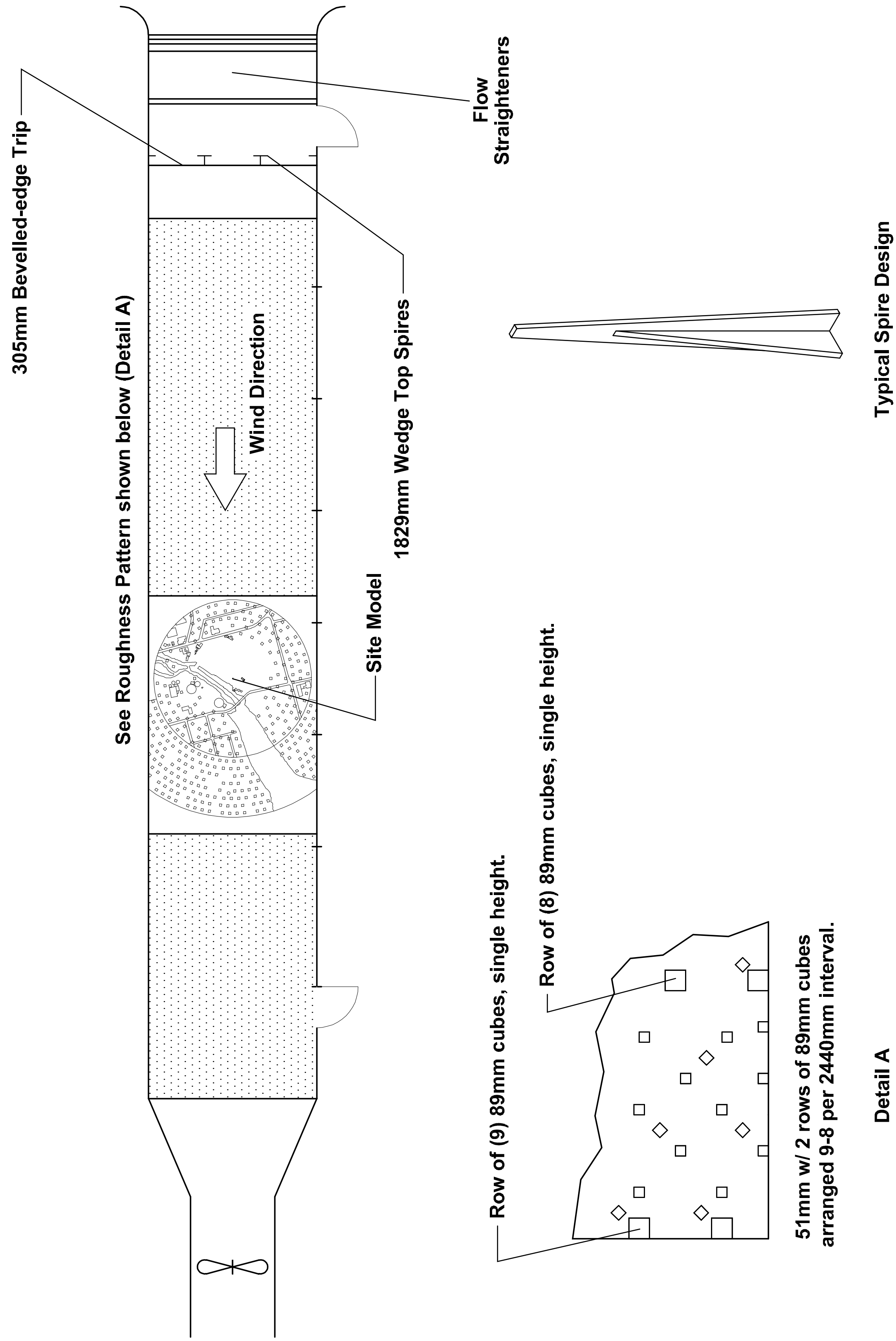


Figure 12. Schematic of example wind tunnel setup for GEP test with nearby structures removed.

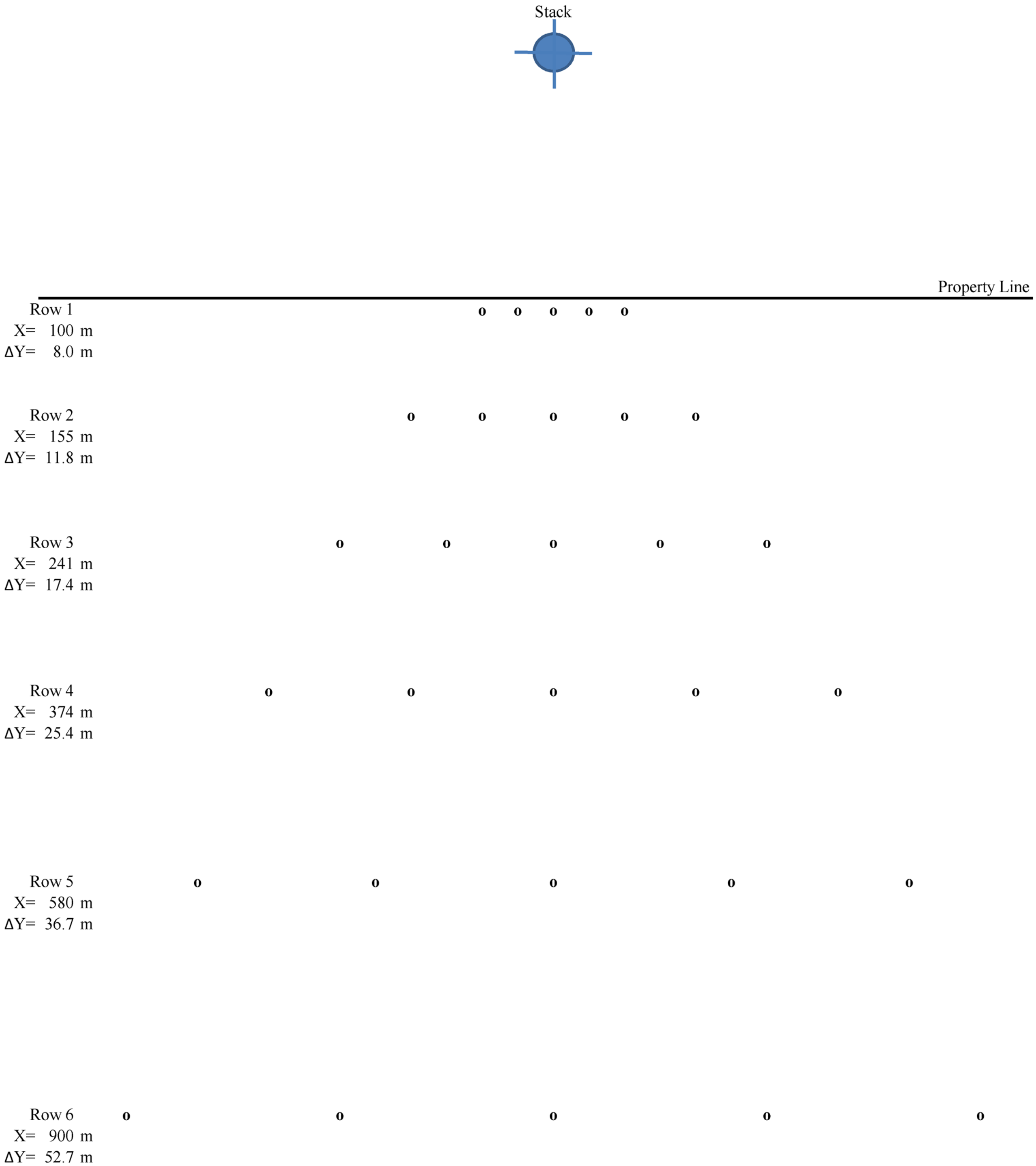


Figure 13. Schematic of typical ground-level concentration sampling grid. Note: X denotes the distance to the stack and ΔY is the distance between sampling points for a specific row.

TABLES

Table 1. Summary of GEP Stack Height Studies Carried out by CPP Principals

1979	ASARCO, Inc.	Arizona Smelter	GEP
	Toledo Edison	Bayshore Power Plant	GEP
1980	Allegheny Power Service Corporation	Armstrong Power Plant	GEP
	Monongahela Power Company	Albright Power Plant	GEP
	The Bunker Hill Company	Idaho Smelter	GEP
1981	Grain Processing Corporation	Iowa Grain Processing Plant	GEP
	Cleveland Electric Illuminating	East Lake Power Plant, OH	GEP
	Muscatine Power and Water	Muscatine Power Plant, IA	GEP
	Cleveland Electric Illuminating	Avon Power Plant, OH	GEP
1982	City Water Light and Power	Dallman Power Plant, IL	GEP
1985	Kennecott	Utah Smelter	GEP
1986	Dairyland Power Cooperative	Alma Power Plant, WI	GEP
	Thilmany Pulp and Paper	Kaukauna Mill, WI	GEP
	Westvaco	Covington Mill, WV	GEP
	Pennsylvania Electric Co.	Homer City Station, PA	GEP
	Pennsylvania Electric Co.	Seward Power Station, PA	GEP
	Pennsylvania Electric Co.	Shawville Power Station, PA	GEP
	Penn Power Company	Bruce Mansfield Station, PA	GEP
	Cincinnati Gas & Electric	Miami Fort Power Station, OH	GEP
1987	Jefferson Smurfit Corporation	Alton Paper Mill, IL	GEP
	Penn Power	Stack Height Evaluation, PA	GEP
	Hawaiian Electric Co.	Kahe Generating Station, HI	GEP
	Public Service of Indiana	Gibson Station, IN	GEP
	Indianapolis Power & Light	Pritchard Station, IN	GEP
1988	No. Indiana Public Service Company	Mitchell Station, IN	GEP
1989	Stanley Consultants	Archer Daniels Midland, IA	GEP
1990	Kodak	Kodak Park, NY	GEP
	Cincinnati Gas & Electric	Miami Fort Station, OH	GEP
	Amoco Corporation	Whiting Refinery, IN	GEP
1991	Wisconsin Power & Light	Rock River Station, WS	GEP
	ENSR	West Point Mill, VA	GEP
	Dayton Power & Light	Power Plant Evaluation, OH	GEP
1992	Metropolitan Edison	Titus Station, PA	GEP
	HMM Associates	Taunton Lighting Plant, MA	GEP
	Louisville Gas & Electric	LG&E, KY	GEP
1993	Penelec	Homer City Unit #3	GEP
1994	Montana Sulphur SRU Stack	Montana Sulphur & Chemical Co.	GEP
1998	EarthTech	Mystic Power Station	GEP
1999	Black & Veatch	Sempra Energy Resources Power Plant	GEP
2001	Duke Power	Duke Power	GEP
	Washington Group	Allegheny Energy Systems	GEP
	Duke Power	Duke Power Allen Plant	GEP
2006	Reliant Energy and ENSR	Cheswick Generating Station	GEP

Table 2. Source Parameters and Emission Scenarios

Source Parameters and Emission Scenarios

Source Description	Source ID	Height Above Base	Exit Diameter	Exit Temp. (^oF)	Volume Flow Rate (cfm)	Exit Velocity (fpm)	SO_2 Emission Rate (lbs/hr)
Rhinelander S09 - maximum load	S09 max	206.9	83.8	315.0	100,000	2,608.6	1,050
Rhinelander S09 - nominal	S09 nom	206.9	83.8	300.0	72,426	1,889.3	690
Rhinelander S09 - minimum load	S09 min	206.9	83.8	300.0	56,100	1,463.4	760

Site Parameters:

Scale Reduction:	240	
Grade Elevation (m):	475.5	1560 ft msl
Typical Building Height (m):	38.1	
Ambient Temperature (^oK):	279.1	Annual Average Temperature
Anemometer Height (m):	10.00	Rhinelander-Oneida County Airport
Anemometer Surface Roughness (m):	0.56	Rhinelander-Oneida County Airport
Site Anemometer Height (m):	10.00	
Site Surface Roughness (m):	0.49	
2 Percent Wind Speed (m/s):	7.9	Rhinelander-Oneida County Airport (Period of Record: 1998 - 2010)

Metric Units

Source Description	Source ID	Height Above Base	Exit Diameter	Exit Temp. (K)	Volume Flow Rate (m^3/s)	Exit Velocity (m/s)	SO_2 Emission Rate (g/s)
Rhinelander S09 - maximum load	S09 max	63.09	2.13	430.4	47.23	13.25	132.30
Rhinelander S09 - nominal	S09 nom	63.09	2.13	422.0	34.21	9.60	86.94
Rhinelander S09 - minimum load	S09 min	63.09	2.13	422.0	26.50	7.44	95.76

Table 3. AERSURFACE Surface Roughness Results

Rhinelander Site

AERSURFACE Sector (degrees)	AERSURFACE Sector (number)	AERSURFACE Calculated surface roughness (m)		Roughness on Turntable (m)	Wind Tunnel Approach Roughness (m)
		415 m radius (68" TT)	3.2 km radius (WT approach)		
0 - 30	1	0.443	0.054	0.676	0.062
30 - 60	2	0.862	0.428	0.676	0.489
60 - 90	3	0.766	0.639	0.676	0.489
90 - 120	4	0.623	0.635	0.676	0.489
120 - 150	5	0.785	0.556	0.676	0.489
150 - 180	6	0.459	0.570	0.676	0.489
180 - 210	7	0.599	0.200	0.676	0.489
210 - 240	8	0.406	0.411	0.676	0.489
240 - 270	9	0.695	0.415	0.676	0.489
270 - 300	10	0.851	0.549	0.676	0.489
300 - 330	11	0.945	0.114	0.676	0.062
330 - 360	12	0.075	0.018	0.075	0.062

Rhinelander Airport

AERSURFACE Sector (degrees)	AERSURFACE Sector (number)	AERSURFACE Calculated surface roughness (m) 1 km radius
0 - 30	1	0.487
30 - 60	2	0.698
60 - 90	3	0.594
90 - 120	4	0.183
120 - 150	5	0.463
150 - 180	6	0.577
180 - 210	7	0.419
210 - 240	8	0.429
240 - 270	9	0.398
270 - 300	10	0.746
300 - 330	11	0.755
330 - 360	12	0.915
	Average	0.555

Table 4. Summary of Test Measurements as recommended by EPA (1981)

Test Type	Measured Quantity	Measurement Locations x	y	z	Traverse Direction	No. of Tests	
Documentation	$U, U'/U, W'/U, U_*/U$	$0, L/2, L$	0	v	z	3	
With	$U, U'/U$	$0, L$	v	$h/2, h, 1.5h$	y	6	
Buildings	C	1,2,3,4	v	v	y,z	4	
Present	C	v	v	0	x,y	3	repeats
Documentation	$U, U'/U, W'/U, U_*/U$	$0, L/2, L$	0	v	z	3	
With	$U, U'/U$	$0, L$	v	$h/2, h, 1.5h$	y	6	
Buildings	C	1,2,3,4	v	v	y,z	4	
Removed	C	v	v	0	x,y	3	repeats

Notation:

T — Ambient Temperature

U — Mean Velocity

U'/U — Longitudinal Turbulence Intensity

W'/U — Vertical Turbulence Intensity

U_*/U — Normalized Friction Velocity

C — Concentration

h — Stack Height

L — Length of Test Area from Stack

v — Variable

1,2,3,4 — Locations to be Determined

x — Longitudinal

y — Lateral

z — Vertical

Table 5. GEP Stack Height Determination Test Plan

Run No.	Source ID	Stack Height Above Base (ft)	Stack Height Above Base (m)	Anemometer Wind Speed (m/s)	Wind Direction (Deg.)	Surface Roughness Length (m)
Reynolds Number Tests - Three Tunnel Speeds or 2, 4 and 8 m/s						
Buildings in place						
1	S09 max	246.0	75.0	7.9	195	0.489
2	S09 max	246.0	75.0	7.9	195	0.489
3	S09 max	246.0	75.0	7.9	195	0.489
Buildings removed						
6	S09 max	246.0	75.0	7.9	195	0.489
7	S09 max	246.0	75.0	7.9	195	0.489
8	S09 max	246.0	75.0	7.9	195	0.489
Preliminary GEP Stack Height Tests						
Buildings in place						
Worst wind direction tests						
101	S09 max	246.0	75.0	7.9	185	0.489
102	S09 max	246.0	75.0	7.9	190	0.489
103	S09 max	246.0	75.0	7.9	195	0.489
104	S09 max	246.0	75.0	7.9	200	0.489
105	S09 max	246.0	75.0	7.9	205	0.489
Worst Wind Speed Tests						
111	S09 max	246.0	75.0	6	WWD	0.489
112	S09 max	246.0	75.0	5	WWD	0.489
Worst Load Tests						
121	S09 nom	246.0	75.0	WWS	WWD	0.489
122	S09 min	246.0	75.0	WWS	WWD	0.489
Stack Height Tests						
131	WL	SH1	SH1	WWS	WWD	0.489
132	WL	SH2	SH2	WWS	WWD	0.489
133	WL	SH3	SH3	WWS	WWD	0.489
Buildings removed						
Worst wind direction tests						
201	S09 max	246.0	75.0	7.9	185	0.489
202	S09 max	246.0	75.0	7.9	190	0.489
203	S09 max	246.0	75.0	7.9	195	0.489
204	S09 max	246.0	75.0	7.9	200	0.489
205	S09 max	246.0	75.0	7.9	205	0.489
Worst Wind Speed Tests						
211	S09 max	246.0	75.0	6	WWD	0.489
212	S09 max	246.0	75.0	5	WWD	0.489
Worst Load Tests						
221	S09 nom	246.0	75.0	WWS	WWD	0.489
222	S09 min	246.0	75.0	WWS	WWD	0.489
Stack Height Tests						
231	WL	SH1	SH1	WWS	WWD	0.489
232	WL	SH2	SH2	WWS	WWD	0.489
233	WL	SH3	SH3	WWS	WWD	0.489
Final GEP Stack Height Tests						
Buildings in place						
Documentation Tests						
141	WL	GEP	GEP	WWS	WWD	0.489
142	WL	GEP	GEP	WWS	WWD	0.489
143	WL	GEP	GEP	WWS	WWD	0.489
Buildings removed						
Documentation Tests						
141	WL	GEP	GEP	WWS	195	0.489
142	WL	GEP	GEP	WWS	195	0.489
143	WL	GEP	GEP	WWS	195	0.489

Notes: WWD: Worst Wind Direction; WWS: Worst Wind Speed; SH1: Stack Height 1; WL: Worst Load

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):

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

$$\frac{\partial U_i^*}{\partial t^*} + U_j^* \frac{\partial U_i^*}{\partial x_j^*} - \left[\frac{L_o \Omega_o}{U_o}\right] 2 \in_{ijk} \Omega_j^* U_k^* =$$

$$- \frac{\partial \rho^*}{\partial x_i^*} + \left[\frac{\Delta T_o L_o g_o}{T_o U_o^2}\right] \Delta T^* g^* \delta_{i3} + \left[\frac{\nu_o}{U_o L_o}\right] \frac{\partial^2 U_i^*}{\partial x_k^* \partial x_k^*} + \frac{\partial}{\partial x_k^*} - \overline{(U'^*_i U'^*_j)} \tag{A.2}$$

and

$$\frac{\partial T^*}{\partial t^*} + \frac{U_i^* \partial T^*}{\partial x_i^*} =$$

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

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:

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

- equal Prandtl number:

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

- equal Eckert number:

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

- 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

$$\mathrm{Re}_s = \frac{V_e d}{v_s} \qquad \text{(A.13)}$$

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:

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

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

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

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

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

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

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

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

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

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

A.3. 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:

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

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 the 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 criteria 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, spires, 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 spires 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. The tunnel setup drawings in the main report show 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.

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:

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

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.

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:

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

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.

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 1/32nd 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):

$$P_a = 1013 \exp\left[\frac{x}{-8350}\right] \tag{A.26}$$

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:

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

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]:

$$\rho_s = \rho_a \lambda \tag{A.28}$$

[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):

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

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, v_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:

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

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:

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

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:

$$\mathrm{Re} = \frac{L\ U}{\nu} \tag{A.39}$$

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

Arya, S.P.S., and J.F. Lape, Jr., "A Comparative Study of the Different Criteria for the Physical Modeling of Buoyant Plume Rise in a Neutral Atmosphere," *Atmospheric Environment*, Vol. 24A, No. 2, pp. 289-295, 1990.

Cermak, J. E., "Applications of Fluid Mechanics to Wind Engineering," *Journal of Fluids Engineering*, Vol. 97, p. 9, 1975.

Counihan, J., "Adiabatic Atmospheric Boundary Layers. A Review and Analysis of Data From the Period 1880–1972," *Atmospheric Environment*, September 1975.

EPA, "Guideline for Fluid Modeling of Atmospheric Diffusion," U.S. EPA, Environmental Sciences Research Laboratory, Office of Research and Development, Research Triangle Park, North Carolina, Report No. EPA–600/8–81–009, 1981.

EPA, "Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulation)," US EPA Office of Air Quality, Planning and Standards, Research Triangle Park, North Carolina, EPA–45014–80–023R, 1985.

Halitsky, J., R.L. Petersen, S.D. Taylor, and R.B. Lantz, "Nearby Terrain Effects in a Good Engineering Practice Stack Height Demonstration," 79th Annual APCA Meeting, Minneapolis, Minnesota, June 22–27, 1986.

Hoult, D.P., and J.C. Weil, "Turbulent Plume in a Laminar Cross Flow," *Atmospheric Environment*, v. 6, pp. 513–531, 1972.

Meroney, R.N., "Guidelines for Fluid Modeling of Dense Gas Cloud Dispersion," *Journal of Hazardous Materials*, Vol 17, pp 23-46, 1987.

Meroney, R.N., "Bluff body Aerodynamics Influence on Transport and Diffusion," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 33, p. 21, 1990.

Petersen, R.L., "Plume Rise and Dispersion for Varying Ambient Turbulence, Thermal Stratification and Stack Exit Conditions," dissertation, CED77-78RLP25, Colorado State University, Fort Collins, CO, 1978.

Petersen, R.L., "Designing Building Exhausts to Achieve Acceptable Concentrations of Toxic Effluent," *ASHRAE Transactions*, Vol. 93, Pt. 2, 1987.

Petersen, R.L., and D.J. Wilson, "Analytical Versus Wind Tunnel Determined Concentrations Due to Laboratory Exhaust," *ASHRAE Transactions*, Vol. 95, Pt. 2, 1989.

Petersen, R.L., and M.A. Ratcliff, "An Objective Approach To Laboratory Stack Design," *ASHRAE Transactions*, Vol. 97, Pt. 2, 1991.

Schlichting, H., *Boundary-Layer Theory*, 7th ed., Translated by Dr. J. Kestin, McGraw–Hill Book Company, New York, 1978.

TABLES

Table A-AA
Full and Model Scale Similarity Parameters
Rhinelander S09 - maximum load (S09 max)
Anemometer Wind Speed =7.9 m/s

Dimensional Parameters	Full Scale	Model Scale
1 . Typical Building Height, Hb (m)	38.11	0.16
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	475.49	1,524.00
3 . Stack Height above grade, h (m)	63.09	0.26
4 . Stack Inside Diameter, d (m)	2.13	8.873E-03
5 . Stack Inside Area, A_e (m^2)	3.56	6.183E-05
6 . Exit Velocity, V_e (m/s)	13.25	3.36
7 . Exit Temperature, T_s (K)	430.37	293.15
8 . Volume Flow Rate, V (m^3/s)	47.23	2.077E-04
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	956.93	844.00
11 . Ambient Temperature, T_a (K)	279.09	293.15
12 . Air Density, ρ_a (kg/m^3)	1.19	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.77	0.65
14 . Air Viscosity, ν_a (m^2/s)	1.46E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	3.11E-05	1.77E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	19.17	4.86
17 . Free Stream Height, z_{inf} (m)	600.00	2.50
18 . Reference Wind Speed, U_{ref} (m/s)	15.79	4.00
19 . Reference Height, z_{ref} (m)	240.00	1.00
20 . Anemometer Wind Speed, U_a (m/s)	7.90	2.00
21 . Anemometer Height, z_a (m)	10.00	0.04
22 . Site Wind Speed, U_s (m/s)	8.06	2.04
23 . Site Anemometer' Height, z_s (m)	10.00	0.04
24 . Stack Height Speed, U_h (m/s)	11.90	3.02
25 . Building Height Speed, Ub (m/s)	10.69	2.71
26 . Anemometer Surface Roughness Length, $z_{o,\,a}$ (m)	0.56	2.31E-03
27 . Site Surface Roughness Length, $z_{o,\,s}$ (m)	0.49	2.04E-03
28 . Site Surface Friction Velocity, U_* (m/s)	0.97	0.25
Dimensionless Parameters		
29 . Length Scale, SF	240.00	1.00
30 . Time Scale, TS	60.82	1.00
31 . Anemometer Power Law Exponent, n_a	0.22	0.22
32 . Site Power Law Exponent, n_s	0.21	0.21
33 . Velocity Ratio, $R = V_e/U_r$	0.84	0.84
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	1.11	1.11
35 . Stack Height to Building Height Ratio, h/Hb	1.66	1.66
36 . Diameter to Stack Height Ratio, d/h	0.03	0.03
37 . Momentum Ratio, M_o	5.21E-04	5.21E-04
38 . Froude Number, Fr_s	3.94	15.47
39 . Buoyancy Ratio, B_o	2.09E-04	1.35E-05
40 . Density Ratio, λ	0.65	0.65
41 . Stack Reynolds Number (Exterior), $d\ U_h / \nu_a$	1.73E+06	1,479.87
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\ V_e / \nu_s$	9.09E+05	1,685.39
43 . Building Reynolds Number, Reb = Hb Ub / Nua	2.79E+07	23,803.57
44 . Surface Reynolds Number, $z_{o,\,s}\ U_* / \nu_a$	3.25E+04	27.72
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.05	0.05

Table A-AB
Full and Model Scale Similarity Parameters
Rhinelander S09 - nominal (S09 nom)
Anemometer Wind Speed =7.9 m/s

Dimensional Parameters	Full Scale	Model Scale
1 . Typical Building Height, Hb (m)	38.11	0.16
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	475.49	1,524.00
3 . Stack Height above grade, h (m)	63.09	0.26
4 . Stack Inside Diameter, d (m)	2.13	8.873E-03
5 . Stack Inside Area, A_e (m^2)	3.56	6.183E-05
6 . Exit Velocity, V_e (m/s)	9.60	2.43
7 . Exit Temperature, T_s (K)	422.04	293.15
8 . Volume Flow Rate, V (m^3/s)	34.21	1.505E-04
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	956.93	844.00
11 . Ambient Temperature, T_a (K)	279.09	293.15
12 . Air Density, ρ_a (kg/m^3)	1.19	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.79	0.66
14 . Air Viscosity, ν_a (m^2/s)	1.46E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	3.01E-05	1.53E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	19.17	4.86
17 . Free Stream Height, z_{inf} (m)	600.00	2.50
18 . Reference Wind Speed, U_{ref} (m/s)	15.79	4.00
19 . Reference Height, z_{ref} (m)	240.00	1.00
20 . Anemometer Wind Speed, U_a (m/s)	7.90	2.00
21 . Anemometer Height, z_a (m)	10.00	0.04
22 . Site Wind Speed, U_s (m/s)	8.06	2.04
23 . Site Anemometer' Height, z_s (m)	10.00	0.04
24 . Stack Height Speed, U_h (m/s)	11.90	3.02
25 . Building Height Speed, Ub (m/s)	10.69	2.71
26 . Anemometer Surface Roughness Length, $z_{o,\,a}$ (m)	0.56	2.31E-03
27 . Site Surface Roughness Length, $z_{o,\,s}$ (m)	0.49	2.04E-03
28 . Site Surface Friction Velocity, U_* (m/s)	0.97	0.25
Dimensionless Parameters		
29 . Length Scale, SF	240.00	1.00
30 . Time Scale, TS	60.82	1.00
31 . Anemometer Power Law Exponent, n_a	0.22	0.22
32 . Site Power Law Exponent, n_s	0.21	0.21
33 . Velocity Ratio, $R = V_e/U_r$	0.61	0.61
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	0.81	0.81
35 . Stack Height to Building Height Ratio, h/Hb	1.66	1.66
36 . Diameter to Stack Height Ratio, d/h	0.03	0.03
37 . Momentum Ratio, M_o	2.79E-04	2.79E-04
38 . Froude Number, Fr_s	2.93	11.53
39 . Buoyancy Ratio, B_o	1.46E-04	9.45E-06
40 . Density Ratio, λ	0.66	0.66
41 . Stack Reynolds Number (Exterior), $d\ U_h / \nu_a$	1.73E+06	1,479.87
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\ V_e / \nu_s$	6.80E+05	1407.377464
43 . Building Reynolds Number, Reb = Hb Ub / Nua	2.79E+07	23,803.57
44 . Surface Reynolds Number, $z_{o,\,s}\ U_* / \nu_a$	3.25E+04	27.72
45 . Site Friction Velocity Ratio, U_*/U_{inf}	0.05	0.05

Table A-AC

Full and Model Scale Similarity Parameters

Rhinelander S09 - minimum load (S09 min)

Anemometer Wind Speed =7.9 m/s

Dimensional Parameters	Full Scale	Model Scale
1 . Typical Building Height, Hb (m)	38.11	0.16
2 . Grade Elevation Above Mean Sea Level, z=0 (m)	475.49	1,524.00
3 . Stack Height above grade, h (m)	63.09	0.26
4 . Stack Inside Diameter, d (m)	2.13	8.873E-03
5 . Stack Inside Area, A_e (m^2)	3.56	6.183E-05
6 . Exit Velocity, V_e (m/s)	7.44	1.88
7 . Exit Temperature, T_s (K)	422.04	293.15
8 . Volume Flow Rate, V (m^3/s)	26.50	1.165E-04
9 . Exhaust rate, Q (kg/s)	#N/A	#N/A
10 . Ambient Pressure, P_a (hPa)	956.93	844.00
11 . Ambient Temperature, T_a (K)	279.09	293.15
12 . Air Density, ρ_a (kg/m^3)	1.19	1.00
13 . Exhaust Density, ρ_s (kg/m^3)	0.79	0.66
14 . Air Viscosity, ν_a (m^2/s)	1.46E-05	1.81E-05
15 . Gas Viscosity, ν_s (m^2/s)	3.01E-05	1.53E-05
16 . Free Stream Wind Speed, U_{inf} (m/s)	19.17	4.86
17 . Free Stream Height, z_{inf} (m)	600.00	2.50
18 . Reference Wind Speed, U_{ref} (m/s)	15.79	4.00
19 . Reference Height, z_{ref} (m)	240.00	1.00
20 . Anemometer Wind Speed, U_a (m/s)	7.90	2.00
21 . Anemometer Height, z_a (m)	10.00	0.04
22 . Site Wind Speed, U_s (m/s)	8.06	2.04
23 . Site Anemometer' Height, z_s (m)	10.00	0.04
24 . Stack Height Speed, U_h (m/s)	11.90	3.02
25 . Building Height Speed, Ub (m/s)	10.69	2.71
26 . Anemometer Surface Roughness Length, $z_{o,\,a}$ (m)	0.56	2.31E-03
27 . Site Surface Roughness Length, $z_{o,\,s}$ (m)	0.49	2.04E-03
28 . Site Surface Friction Velocity, U_* (m/s)	0.97	0.25
Dimensionless Parameters		
29 . Length Scale, SF	240.00	1.00
30 . Time Scale, TS	60.82	1.00
31 . Anemometer Power Law Exponent, n_a	0.22	0.22
32 . Site Power Law Exponent, n_s	0.21	0.21
33 . Velocity Ratio, $R = V_e/U_r$	0.47	0.47
34 . Stack Velocity Ratio, $R_s = V_e/U_h$	0.62	0.63
35 . Stack Height to Building Height Ratio, h/Hb	1.66	1.66
36 . Diameter to Stack Height Ratio, d/h	0.03	0.03
37 . Momentum Ratio, M_o	1.67E-04	1.67E-04
38 . Froude Number, Fr_s	2.27	8.93
39 . Buoyancy Ratio, B_o	1.13E-04	7.32E-06
40 . Density Ratio, λ	0.66	0.66
41 . Stack Reynolds Number (Exterior), $d\ U_h / \nu_a$	1.73E+06	1,479.87
42 . Stack Flow Reynolds Number (Interior), $Re_s = d\ V_e / \nu_s$	5.27E+05	1,090.14
43 . Building Reynolds Number, Reb = Hb Ub / Nua	2.79E+07	23,803.57
44 . Surface Reynolds Number, $z_{o,\,s}\ U_* / \nu_a$	3.25E+04	27.72
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. This allows the operator to get immediate feed-back on the concentration levels at the receptor. With this information the operator can search for the meteorological condition (wind speed and wind direction) which results in the highest concentration from a single source at a single receptor. To conduct the search for the worse case meteorological condition, the operator collects 30 second samples at various wind directions for a single wind speed to determine the worse case wind direction. For each 30 second sample, the full scale concentration at the sampling point is calculated from the average voltage output from the HFFID using the procedure described below. Once the wind direction has been identified, the operator collects 30 second samples at various simulated wind speeds to determine the worse case wind speed. If the resulting worse case wind speed differs from the wind speed used to define the worst case wind direction, an additional search is conducted at the worse case wind speed to confirm the worst case wind direction. Once the worst case meteorological condition has been identified, an additional 220 second sample is collected for this simulated condition.

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):

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

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

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

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

where:

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

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

p = power law exponent between 0.17 and 0.20.

B.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:

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

where

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

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

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

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

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

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

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

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

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

B.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:

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

and for the split-film sensor:

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

and

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

where

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

R_{Hot} = resistance across hot film with overheat ratio applied $\left(\frac{R_{Hot}}{R_{Cold}} = 1.5 \right)$.

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

$$C_{sd} = C_{cal} \frac{V_{sd}}{V_{cal}} \tag{B.8}$$

where

$$V_{sd} = \sqrt{\frac{\sum_{i=1}^{N} \left(V_i - V_{mean}\right)^2}{N}} \tag{B.9}$$

[Note that this equation is the longer but computationally more accurate form of the standard deviation calculation which requires a separate pass through the data after the mean is computed. This is the prescribed manner standard deviations are computed at CPP.]

The full scale value for the concentration standard deviation is calculated by substituting the value for C_{sd} for C_m in Equation B.1. The standard deviation calculation assumes that the background concentration has a zero standard deviation value.

B.1.4.4 Calculations for Averaging and Windowing

Averages for the HFFID readings during an actual run are typically 30 seconds while searching for the worst wind condition, and 220 seconds for the final average. 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 30 or 220 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:

$$V_{\text{mean},window} = \frac{1}{\#blocks} \times \left(V_{\text{mean},1} + V_{\text{mean},2} + \cdots\right) \quad \text{(B.10)}$$

where the individual block means are means of voltages with the zeros subtracted. The standard deviation of the window is:

$$V_{\text{sd},window} = \sqrt{\frac{1}{\#blocks \times N} \times \left(\sum_{block1}^{N} V_i^2 + \sum_{block2}^{N} V_i^2 + \cdots\right) - \left(V_{\text{mean},window}\right)^2} \quad \text{(B.11)}$$

where $\sum_{block}^{N} V_i^2$ is the sum of squares for each 3 second block, and N is the number of readings in a 3-second block. The sum of squares for each block can be computed from the standard deviation of each block from:

$$\sum_{block}^{N} V_i^2 = N\left(V_{\text{sd}}^2 + V_{\text{mean}}^2\right) \quad \text{(B.12)}$$

where V_{mean} is the mean of each block with the zero removed. This method is based on the "short form" of computing standard deviation, which is mathematically similar to but computationally different from the standard deviation calculation for the calibration voltage. [Note that the standard deviation for a window is not the simple mean of standard deviations of the blocks.]

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:

$$\Delta p = \frac{1}{2}\rho_{atmos} U_{m_{ref}}^{z} \quad \text{(B.13)}$$

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:

$$\Delta p\left[V_{pitot} - V_{pitot,zero}\right] \times Calfactor \times 6897.4 \qquad (B.14)$$

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:

$$\rho_{atmos}\ (kg/m^3) = \frac{\rho_{atmos}(in.Hg)\ x\ 3377}{RT} \qquad (B.15)$$

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:

$$Setting = A \times V^B \qquad (B.16)$$

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 file suitable for reports.

The report-quality output file can either be an SI version or an English version. For the English version, anemometer information and stack heights are converted to English units. The concentrations will remain as *C/m* in $\mu g/m^3$ per g/s. The version selection is made in the initial setup menu. An output file with SI (metric) outputs is shown in Figure B.12.

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

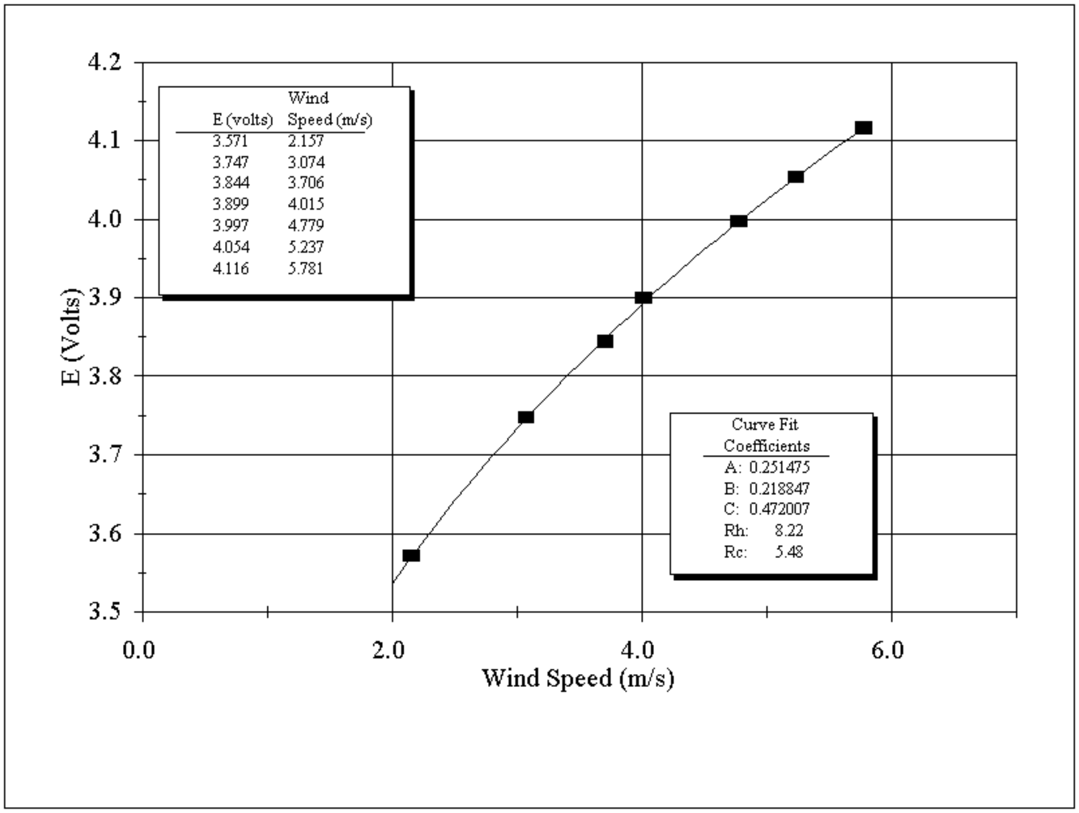


Figure B.1. Sample hot-film calibration curve.

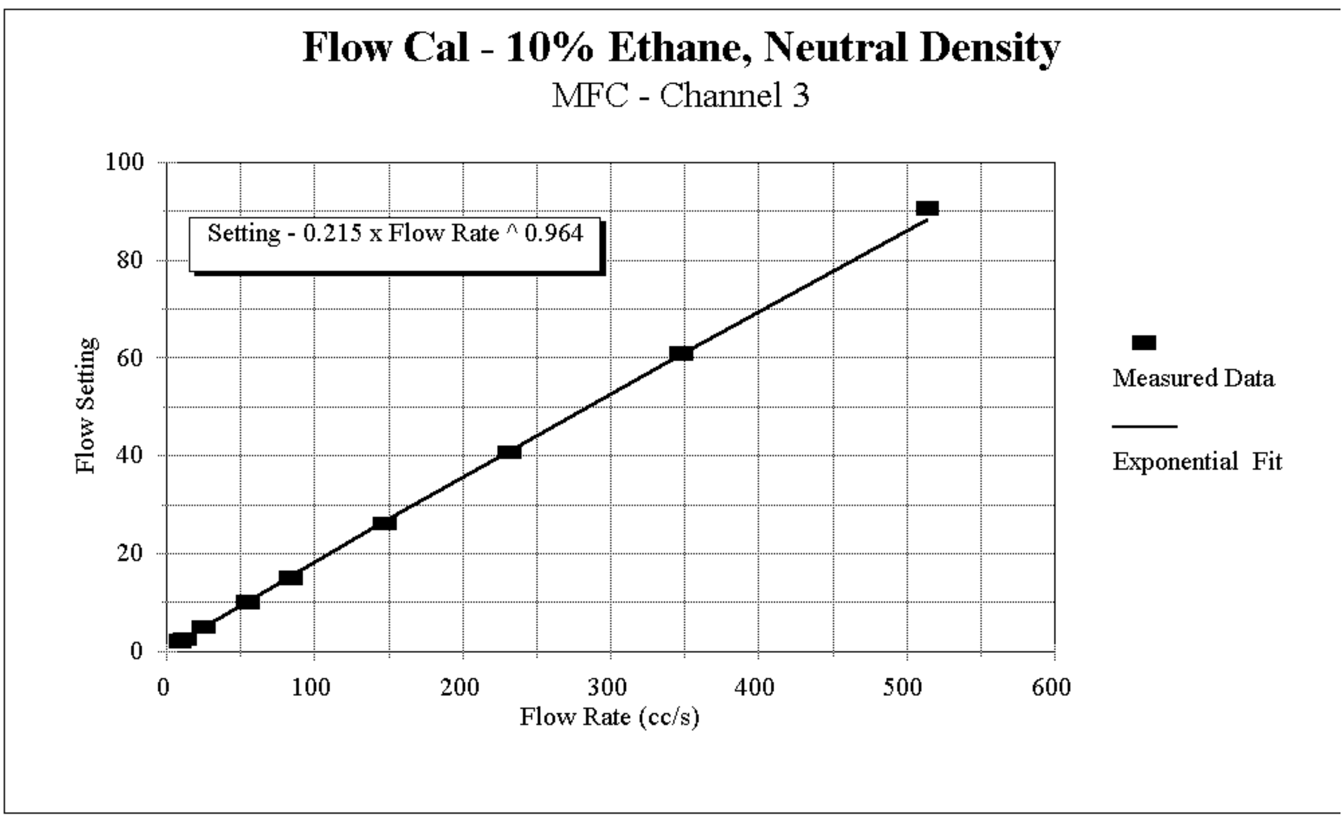


Figure B.2. Sample mass flow controller calibration curve.

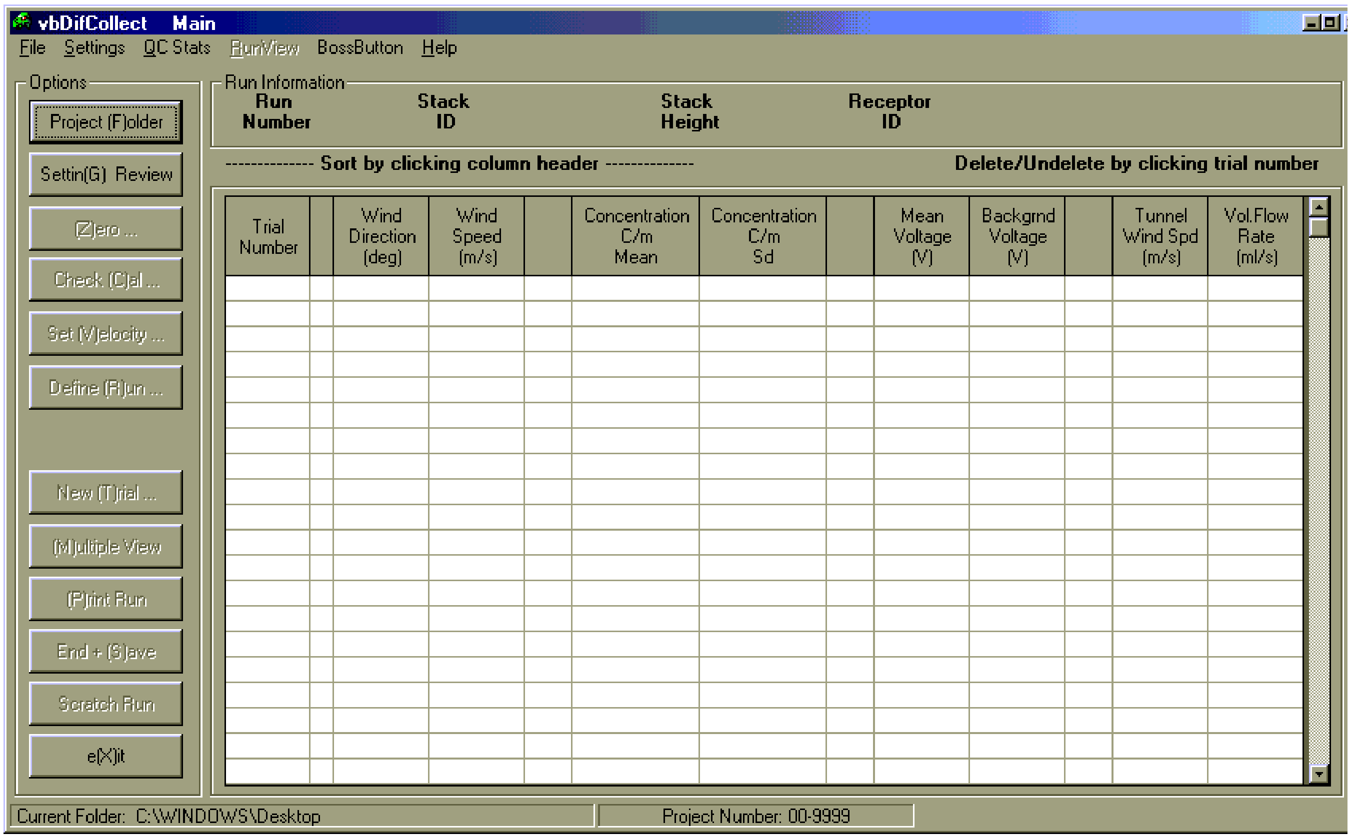


Figure B.3. vbDIFCOLLECT main screen - prior to setup and data collection.

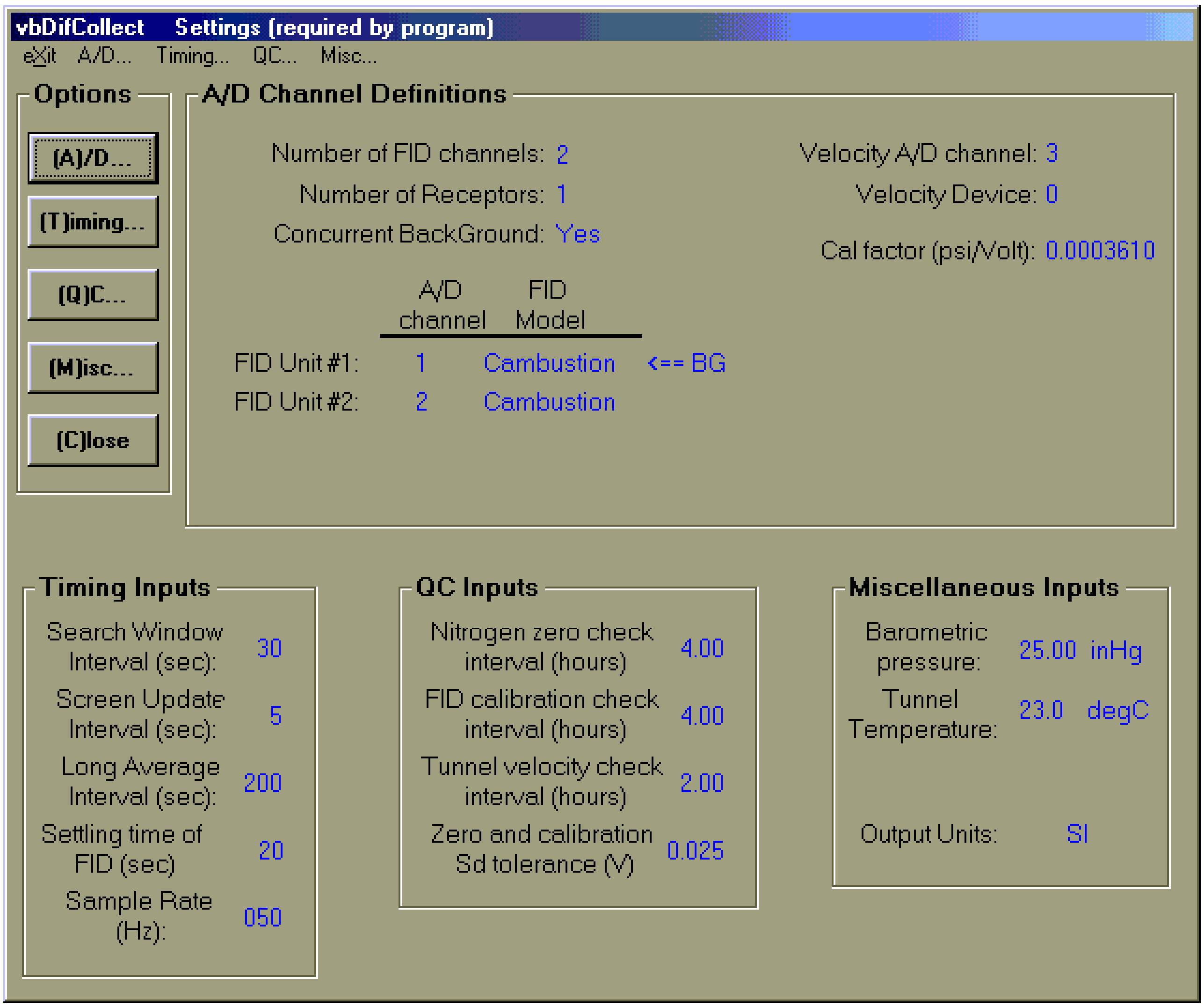


Figure B.4. vbDIFCOLLECT settings screen.

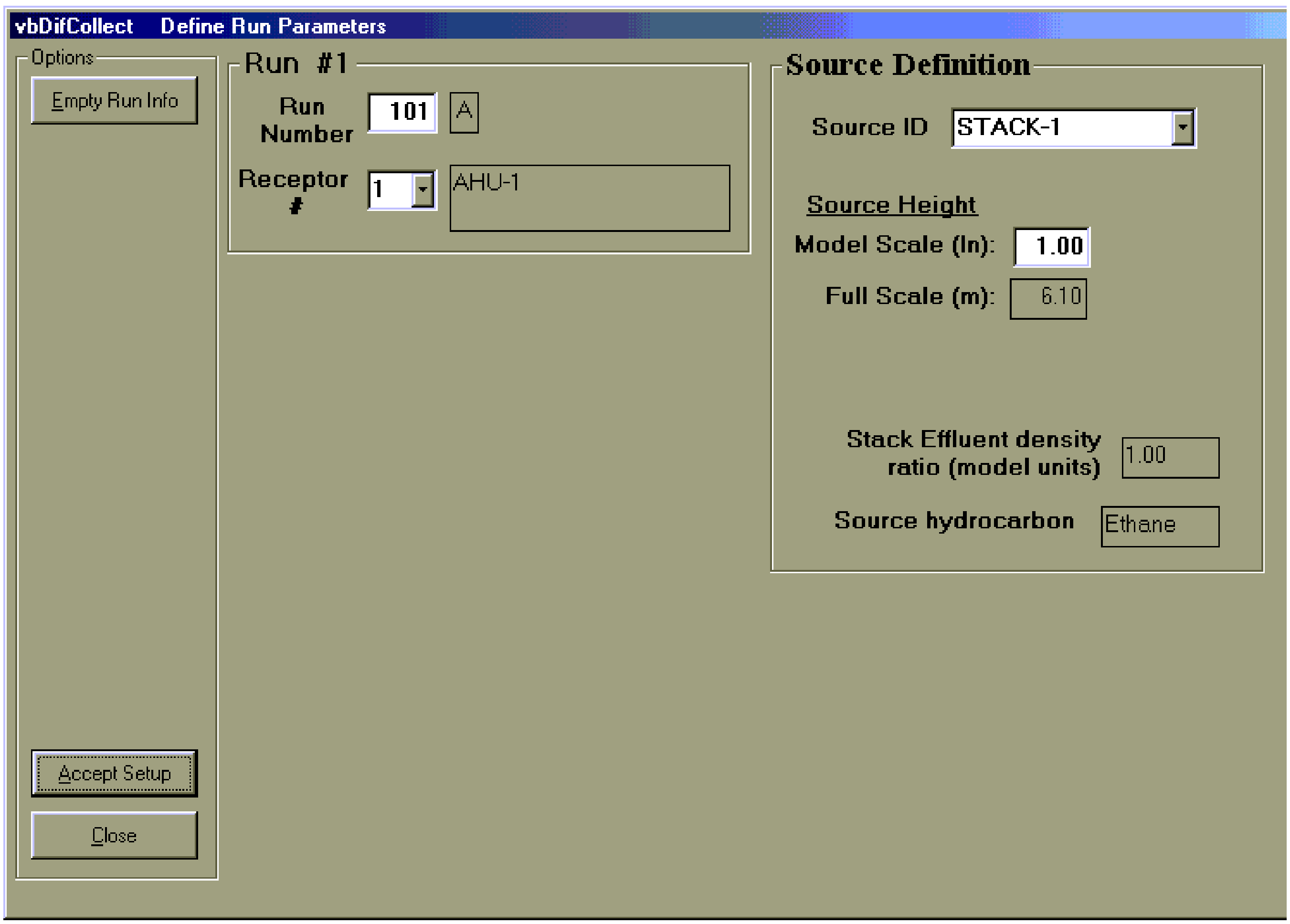


Figure B.5a. vbDIFCOLLECT define run parameters screen.

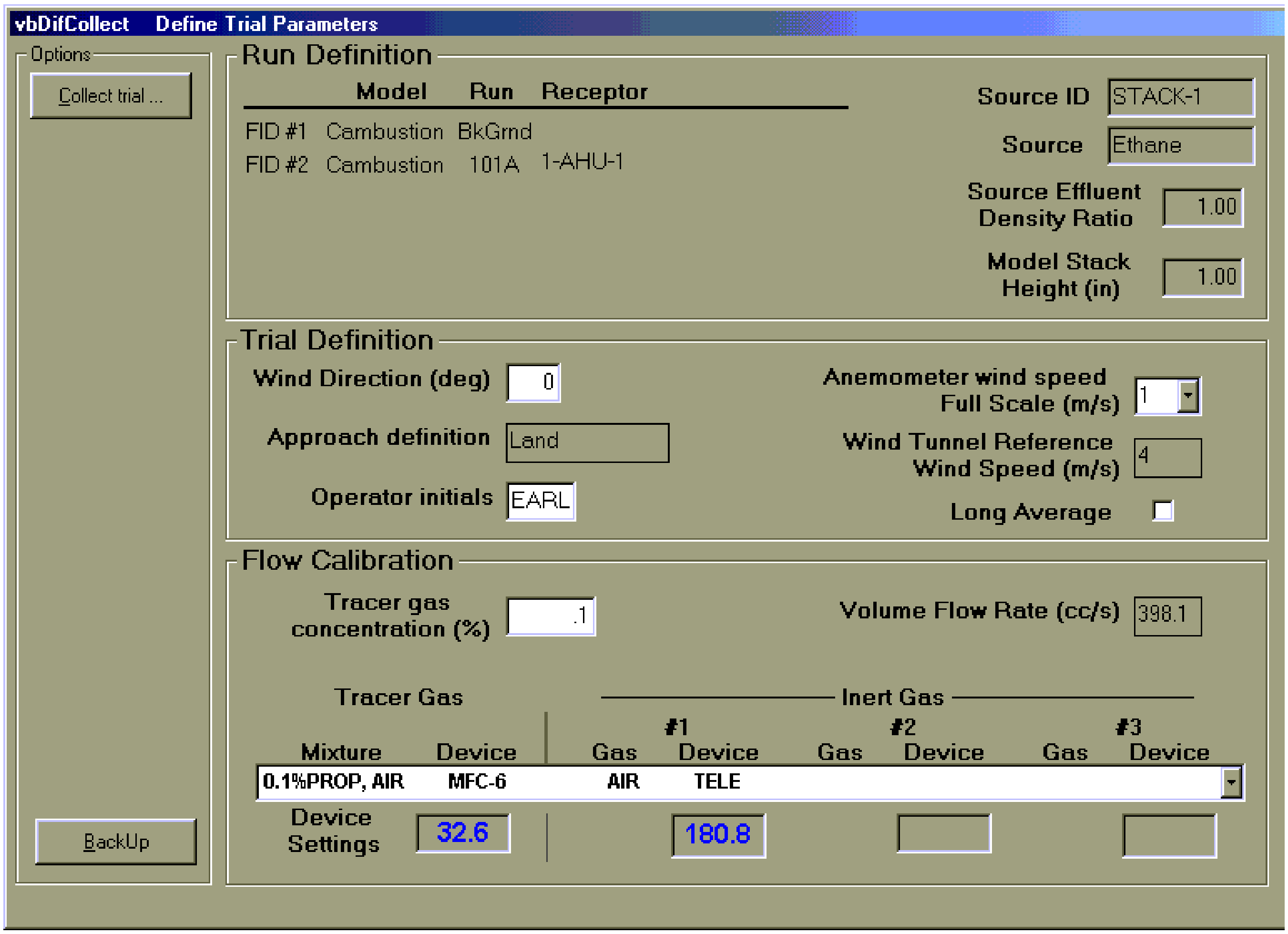


Figure B.5b. vbDIFCOLLECT define trial parameters screen.

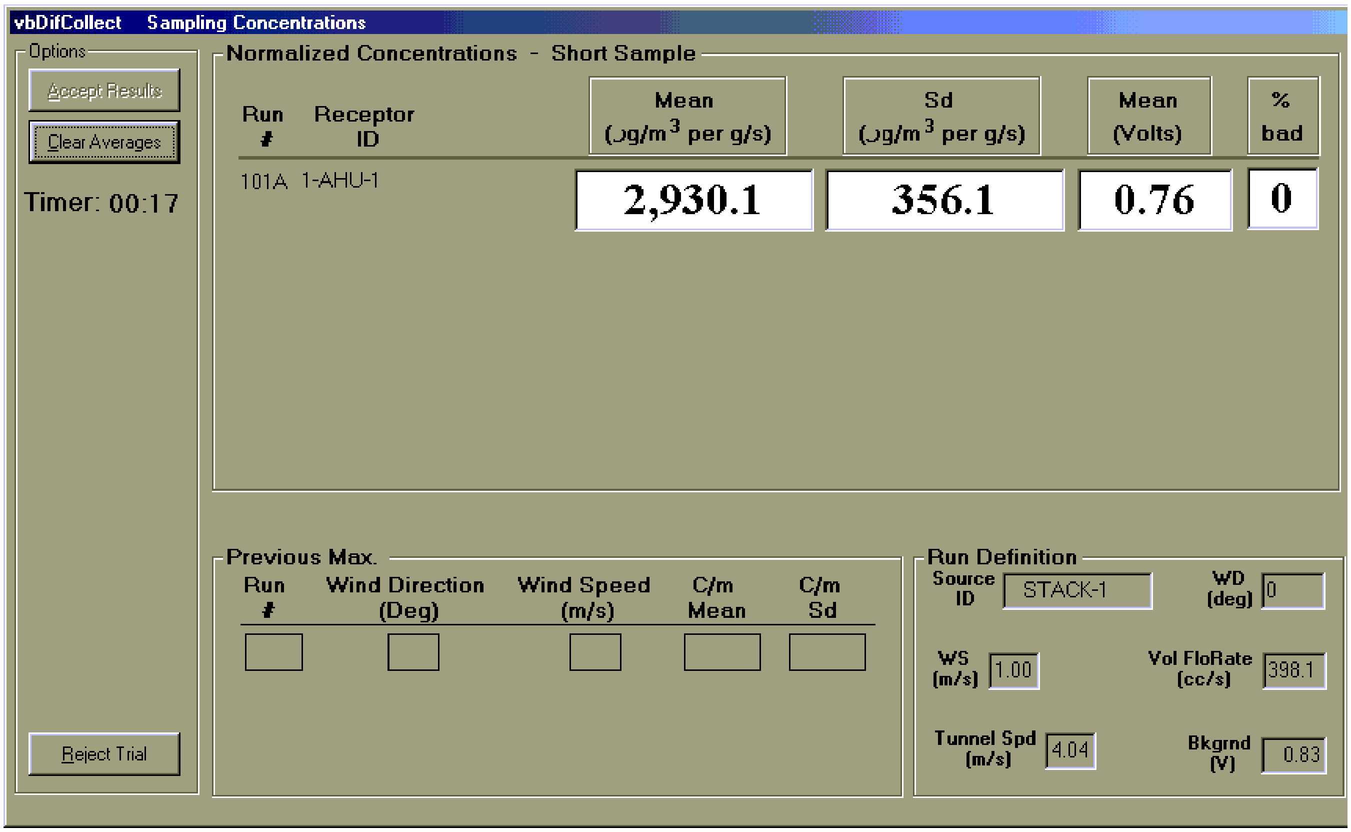
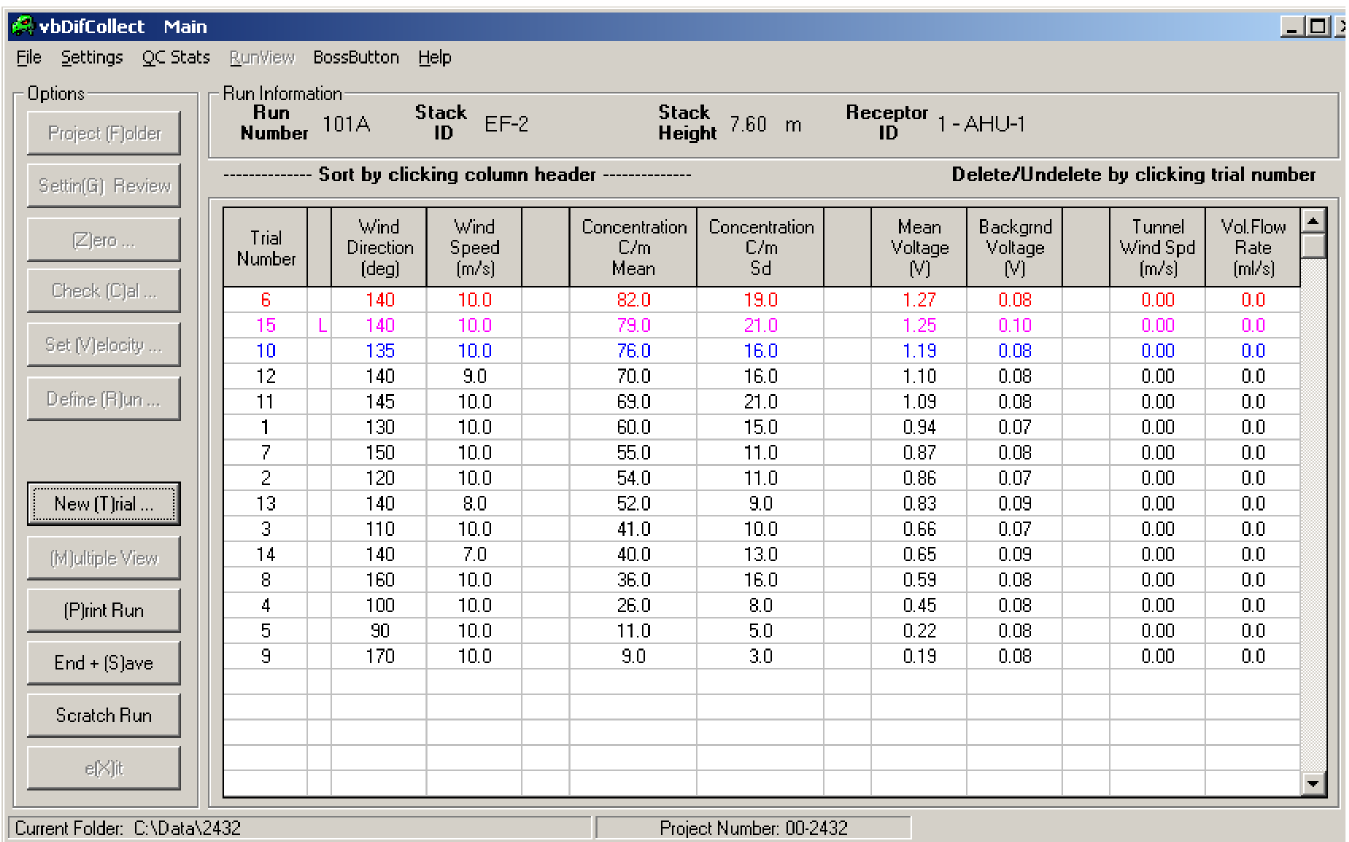


Figure B.6. vbDIFCOLLECT concentration sampling screen.



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 project: 03-9999   vbDIFCOLLECT Bench Test
                                     Date: 01-01-2003
       Run: 901A                       Maximum C/m
      Stack: STACK-1
Stack Height (m):  3.0               (C/m) max    1080  µg/m3 per g/s
    Receptor:  1 AHU-1               Wind Speed   2.0   m/s
      Scale: 240                   Wind Direction 325.0 deg

Trial Results:
                  Range
    Wind  Wind  Mean  FID  100                C/m      Sd
 Trial Dir. Speed  FID Range Bkgd              (µg/m3
 No. (deg) (m/s)  (V)  (-)  (V)                per g/s)

  1   310.0  1.0   .34  500  .07                536   95
  2   310.0  1.0  3.38  500  .08                628   95
  3   320.0  1.0  6.34  500  .09               1186  135
  4   330.0  1.0  5.09  500  .10                949  133
  5   340.0  1.0  2.18  500  .11                397   56
  6   350.0  1.0  1.81  500  .12                325   52
  7      .0  1.0  1.85  500  .13                331   52
  8    10.0  1.0  1.66  500  .14                295   52
  9    20.0  1.0  1.60  500  .15                281   36
 10   325.0  1.0  6.69  500  .16               1243  163
 11   315.0  1.0  5.28  500  .17                974  127
 12   300.0  1.0  1.00  500  .18                163   41
 13   325.0   .7  4.49  500  .20                823  139
 14   325.0   .5  2.40  500  .23                420   67
 15   325.0  2.0  6.89  500  .25               1264  107
 16   325.0  3.0  4.57  500  .25                827   87
 17   325.0  4.0  3.93  500  .25                706   76
 18   325.0  5.0  3.04  500  .25                538   52
 19   320.0  2.0  5.75  500  .24               1049   91
 20   330.0  2.0  4.52  500  .24                818   92
 21 L 325.0  2.0  5.91  500  .24               1080   82

Confirmation reading:
 21   325.0  2.0  5.91  500  .24               1080   82
```

Figure B.12. Sample vbDIFCOLLECT run output file.