Justifying a GEP Stack Height Taller than the EPA Formula Height

A&WMA's 108th Annual Conference & Exhibition, Raleigh, NC, 2015

Paper # 415

Ronald L. Petersen, Ph.D., CCM, Anke Beyer-Lout
CPP, Inc., 2400 Midpoint Drive, Suite 190, Fort Collins, CO 80525, rpetersen@cppwind.com
Tom Emond
Expera Specialty Solutions, 515 West Davenport Street, Rhinelander, WI

ABSTRACT

Air monitoring data for the City of Rhinelander, WI shows SO_2 concentrations exceeding the 1-hour standard at the water tower monitoring location (WTM) and, as a result, this area has been designated a SO_2 non-attainment area. An analysis of emission sources and air quality modeling indicates that the Expera Rhinelander Mill 63 m tall cyclone boiler stack (S09) appears to be the primary contributor to the ambient air impact at this monitor. One solution being evaluated for showing compliance with the 1-hr SO_2 NAAQS is raising the 63 m tall S09 stack to the GEP stack height. Based on the Boiler 7 building dimensions the formula GEP stack height is 75 m.

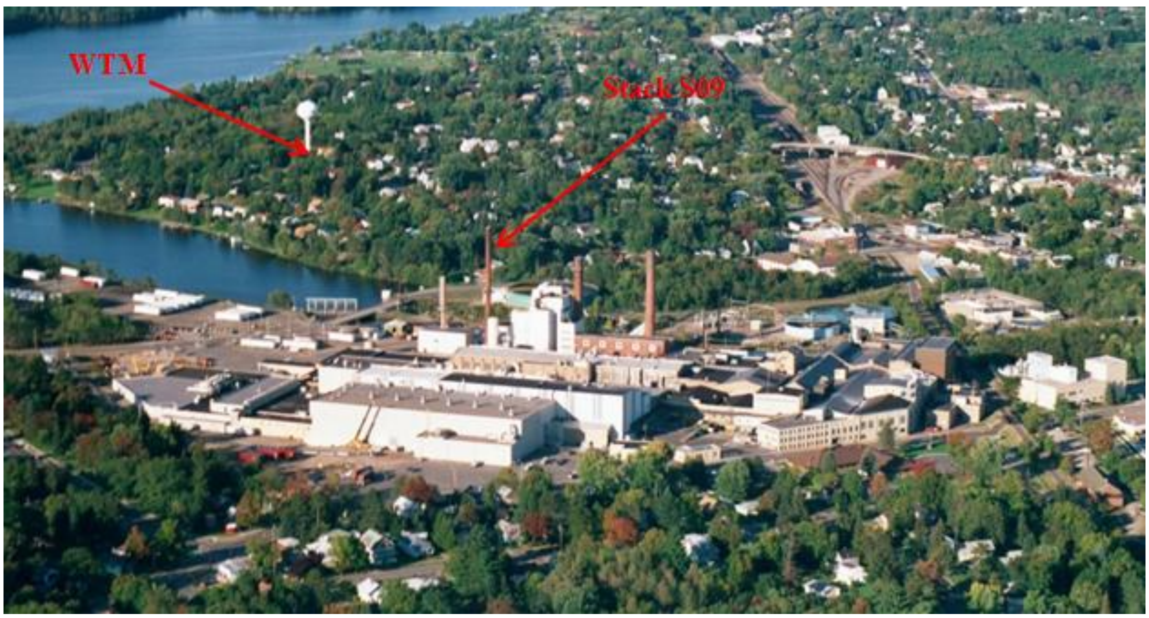
After investigating the Expera Rhinelander Mill building geometry, it was noticed that the Boiler 7 building corner is directly upwind of the stack when the wind blows directly toward the WTM. When the wind blows along a building corner, building corner vortices are generated that enhance building downwash by as much as a factor of two over that observed for wind directions normal to a building face. Past wind tunnel results suggest that the actual GEP stack height could be up to 95 m for this corner vortex situation. Hence, the purpose of this study was to determine the actual GEP stack height for the Expera Rhinelander Mill cyclone boiler stack (S09) using wind tunnel modeling.

This paper provides detailed information on determining GEP stack height, outlines the wind tunnel modeling method required to demonstrate a GEP stack height taller than the EPA formula height and provides detailed results documenting that a 90 m stack height is creditable as GEP which is well above the 75 m EPA formula height. As part of the GEP stack height demonstration, results are provided that document that the wind tunnel simulation provides similar turbulence and dispersion characteristics as the atmosphere.

INTRODUCTION

This paper documents a wind-tunnel study conducted to determine the "Good Engineering Practice" stack height for the Expera Rhinelander Mill cyclone boiler stack (S09) in Rhinelander, WI as shown in Figure 1. Air monitoring data for the City of Rhinelander, WI 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 appears to be the primary contributor to the ambient air impact at this monitor, specifically the 63 m cyclone boiler stack (S09). The air quality monitor is about 600 m (2000 ft) NNE of the cyclone boiler stack (S09) as shown in Figure 1.

Figure 1. View of Rhinelander Mill, Stack S09 and the Water Tower Monitor Looking Toward the Northeast.



After investigating the Expera Rhinelander Mill 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. When the wind blows along a building corner, building corner vortices are generated that enhance building downwash. Past wind tunnel modeling studies[1] 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 the Boiler 7 building dimensions (38.4 m height and 24.4 m projected width) the formula GEP stack height for S09 is 75 m. The wind tunnel results presented by EPA[1]suggest that the actual GEP stack height could be up 95 m for this corner vortex situation.

Therefore, the purpose of this study was to determine the actual GEP stack height for the Expera Rhinelander Mill cyclone boiler stack (S09) 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.

To meet the objectives of the study, a 1:240 scale model of the Rhinelander Mill and nearby surroundings within a 450m (1360 ft) radius was constructed and placed in a boundary-layer wind tunnel. Terrain and roughness elements were added downwind of the turntable so downwind distances out to 1,400 m could be evaluated. Model operating conditions were 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 were measured with and without the nearby buildings present for various meteorological conditions. The results were then analyzed to determine the GEP stack height.

Included in this paper are a description of various technical considerations, a discussion of the experimental methods, the results and conclusions of the study.

TECHNICAL CONSIDERATIONS

Definition of Good Engineering Practice Stack Height

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

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,

Equation 1:

$$H_g = 2.5H$$

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,

Equation 2:

$$H_g = H + 1.5L$$

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[1] 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.

Equation (2) is appropriate for calculating the GEP stack height for S09. Using a building height, H, of 38.4 m and a projected building width, L, of 24.4 m, results in formula height of 75 m.

To determine the actual GEP height wind tunnel modeling is required and the stack height regulation goes on to define an excessive concentration as (40 CFR 51.100 (kk) (1)) as:

> "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 height 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.

SETTING MODEL OPERATING CONDITIONS AND SIMILARITY REQUIREMENTS

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[2] and that have been used on past GEP studies.[3,4,5,6] To model plume trajectories, EPA[2] states that the following ratios must be matched in model and full scale:

Equation 3:

$$\frac{V_e}{U_h},\ \frac{\rho_s}{\rho_a},\ \frac{d}{H_s}$$

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)
d = stack diameter (m), and
H_s = stack height (m).
which is the same as matching momentum length scale, M_o, or

Equation 4:

$$M_o = \frac{\rho_s}{\rho_a}\left(\frac{d\,V_e}{H_s U_h}\right)^2$$

For this study, density ratio in the wind tunnel was not equivalent to full scale, but the momentum ratio was matched in model and in full scale. This ensures that model and full scale momentum plume rise are equal. In addition, the stack gas flow in the model was fully turbulent upon exit as it is in the full scale.

It should be noted that Froude number similarity is not used, as recommended by EPA[1], as it would require extremely low wind tunnel speeds and building wake effects would be incorrectly modeled. This, in effect, means that the wind tunnel simulated plume rise will not include buoyancy effects and full scale plume rise will be underestimated.

To simulate the airflow and dispersion around the buildings, the following criteria were met[7]:

- all significant structures within a 415 m (1360 ft) radius of the stacks were modeled at a 1:240 scale reduction. Upwind of this area, roughness elements were installed to represent the upwind roughness within 3.2 km of the stack. Terrain and roughness elements were added downwind of the turntable so downwind distances out to 1,400 m could be evaluated.

- the mean velocity profile through the entire depth of the boundary layer is 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:

Equation 5:

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

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

Table 1. Full-scale Source Parameters and Emission Scenarios

Source Description	Source ID	Stack Height Above Base (m)	Exit Diameter (m)	Exit Temp. (K)	Volume Flow Rate (m^3/s)	Exit Velocity (m/s)
Rhinelander S09 - maximum load	S09 max	63	2.13	430.4	47.23	13.25
Rhinelander S09 - nominal load	S09 nom	63	2.13	422.0	34.21	9.60
Rhinelander S09 - minimum load	S09 min	63	2.13	422.0	26.50	7.44

EXHAUST SOURCES, SOURCE PARAMETERS AND EMISSION RATES

The cyclone boiler stack location (S09) is shown in Figure 1. The full-scale exhaust parameters simulated in the wind tunnel for the cyclone boiler stack S09 are listed in Table 1.

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

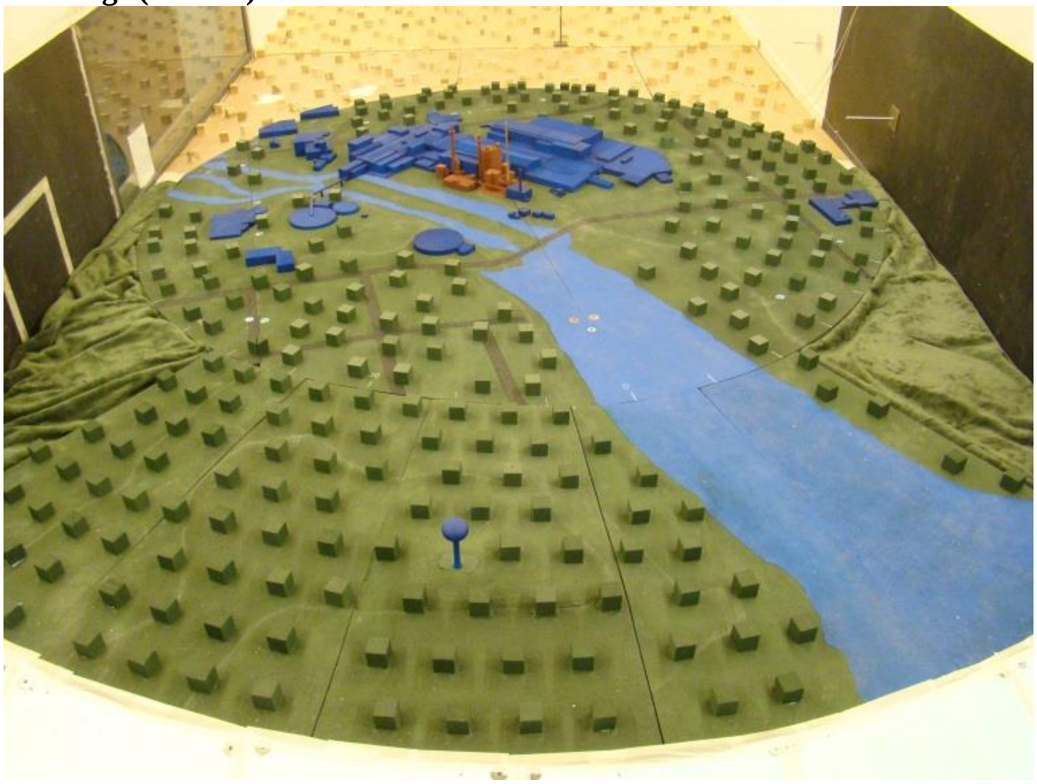
- maximum load: the PTE allowed in the permit at the boiler's rated capacity (3.5 lbs SOx/MMBtu @ 300 MMBtu/hr);
- nominal load: the average thermal loading (gas exit velocity and temperature) and average sulfur content (SOx emission rate); and
- minimum load: a theoretical scenario that represents maximum sulfur content (3.5 lbs SOx/MMBtu) at the minimum thermal input rate of approximately 215 MMBtu/hr, as limited by the boiler's turndown ratio (minimum exit velocity and temperature).

NEARBY STRUCTURES AND TERRAIN

Figure 1 shows an aerial view of the Rhinelander Mill. In general the terrain rises to a maximum of about 506 m (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 the Boiler 7 Building is closer and taller than the nearby terrain, its effect on the GEP stack height was determined to be more significant and was 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 previously. To evaluate the effects of structures, shown in Figures 2 and 3, tests are first conducted with all structures in place (referred to as the "Building In" tests). All 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 2 and 3 show the wind tunnel configuration with the 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 is the GEP stack height.

Figure 2: View of the turntable with buildings in place (top); View of the turntable without buildings (bottom).



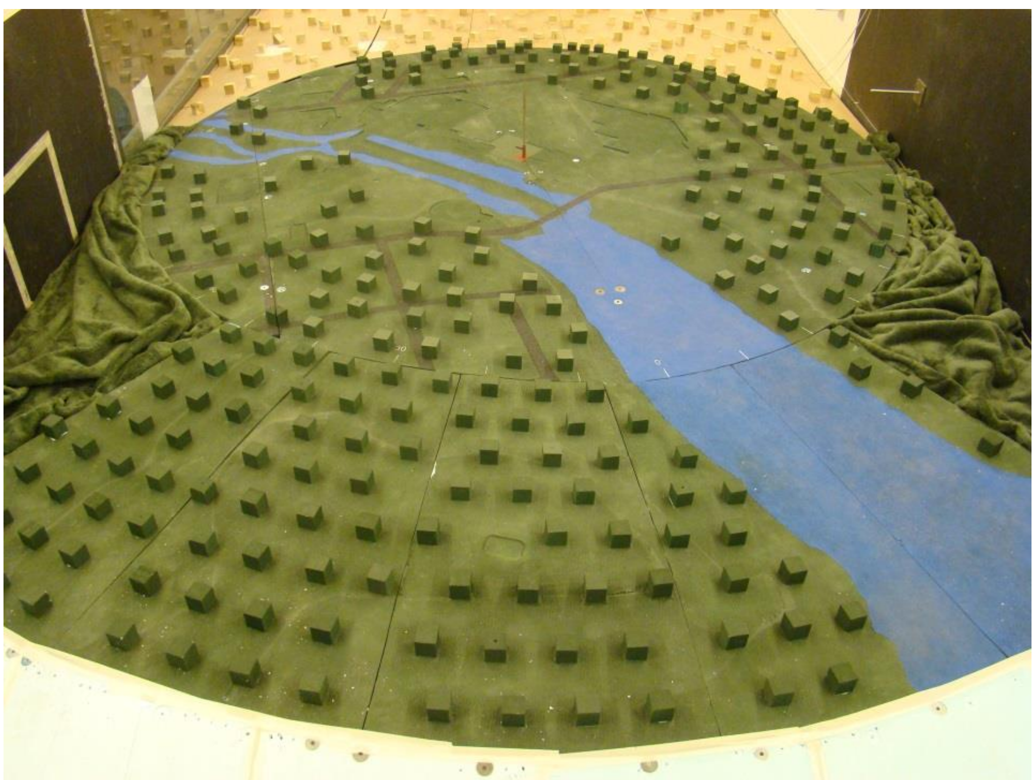
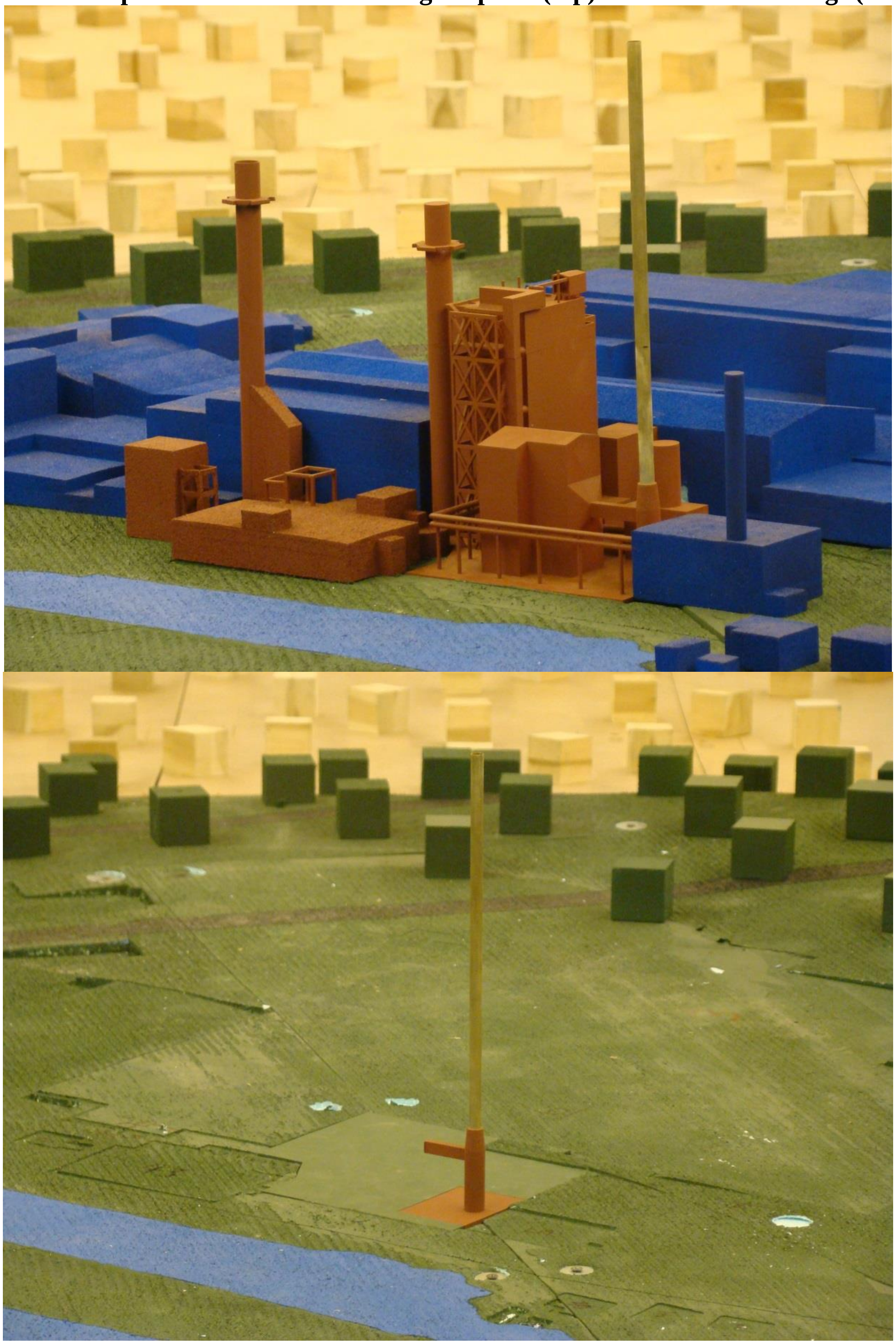


Figure 3: Close-up of stack S09 with buildings in place (top) and without buildings (bottom).



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

SURFACE ROUGHNESS

Rhinelander Site[9]

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 site were specified using AERSURFACE[8]. For the wind directions evaluated in this study, the mean surface roughness is 0.49 m.

Rhinelander Airport[9]

The surface roughness length around the Rhinelander-Oneida County Airport is used to scale the wind speeds at the airport to the site and was initially specified using the AERSURFACE[8] tool with a radius of 1 km around the anemometer location using 1992 National Land Cover Data (NLCD). The average surface roughness length was determined to be 0.56 m for the airport. Analysis indicated that the 1992 NLCD information for the Rhinelander airport is not representative of current conditions. The 1992 NLCD has more forest (high surface roughness) around the anemometer than current conditions. Based on a refined analysis, the average surface roughness at the airport was determined to 0.25 m which was used for this evaluation.

TEST WIND SPEEDS

The EPA[1] stack height guideline recommends that the design wind speed for GEP stack height evaluations be less than or equal to the 2 percent wind speed unless it can be demonstrated that higher wind speeds cause an exceedance of NAAQS limits. The 2 percent wind speed was calculated based on meteorological observations at the Rhinelander-Oneida County Airport 7.9 m anemometer for the periods 1998-2002 and 2006-2010 (i.e., these two periods were used for model evaluation purposes and were deemed sufficient for obtaining a representative 2% wind speed). This is equivalent to a 8.25 m/s wind speed at 10m. All wind tunnel tests were conducted with simulated airport wind speeds at or below the 2 percent wind speed.

WIND TUNNEL MODELING METHODOLOGY

Scale Model

A 1:240 scale model of the Rhinelander Mill Stack S09 and nearby surroundings was constructed and placed on a 3.45 m diameter turntable. The area modeled is depicted in

Figure 2 for the ‘Building In’ and ‘Building Out’ configurations, respectively. The model included all significant structures and terrain within a 450m (1360 ft) radius of the Rhinelander Mill Stack S09.
Residential areas were represented by roughness elements design to simulate the roughness lengths. The 415 m radius includes all significant nearby structures as identified by BPIP. Upwind of the turntable, roughness elements were installed to represent the approach roughness within a 3.2 km radius of stack. Downwind of the turntable, terrain and/or roughness elements was installed so the measurements could be obtained out to 1.4 km. Close-up photographs of the model with and without buildings are shown in Figure 3.

The Boiler 7 building model was constructed utilizing the 3D drawing files developed from plan and elevations drawings. These files were used to generate a file that is used directly to construct the scale model of 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 were used to construct various structural elements depending upon the needed durability.

Stack S09 was constructed of a brass tube. A trip was installed within the stack to ensure that the stack flow was fully turbulent upon exit. The stack was supplied with a tracer gas (ethane) and nitrogen mixture with a density similar to room temperature air. Precision mass flow controllers were used to monitor and regulate the discharge momentum.

Wind Tunnel Setup

All testing was carried out in a closed-circuit wind tunnel. 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 boundary layer development region between the spires and the site model was filled with roughness elements in a pattern experimentally set to develop the appropriate approach boundary layer wind profile and approach surface roughness length.

Test Methodology

Table 2 lists the concentration tests that were conducted for this study. In all, three series of tests were conducted. Runs 101 through 133 and 201 through 233 were conducted to determine what wind direction, wind speed, operating conditions and stack height results in the highest concentration ratio. The concentration ratio is defined to be the ratio of the maximum ground-level concentration with buildings present and the maximum ground-level concentration without buildings. Once the GEP stack height was estimated based on the initial testing, GEP stack height confirmation tests were conducted (Runs 141-143 and 241-243).

Table 2. Test Plan and Predicted Concentrations and Concentration Ratios

Run #	Source ID	Stack Height Above Base (m)	Anemometer Wind Speed (m/s)	Wind Direction (Deg.)	Maximum Normalized Concentrations* Buildings In (μg/m³ per g/s)	Buildings Out (μg/m³ per g/s)	Concentration Ratio $(C_{max})_{in}/(C_{max})_{out}$
Preliminary GEP Stack Height Tests							
worst wind direction tests							
101, 201	S09 max	85.0	7.9	185	3.92	2.55	1.54
102, 202	S09 max	85.0	7.9	190	3.95	2.43	1.63
103, 203	S09 max	85.0	7.9	195	3.81	3.12	1.22
104, 204	S09 max	85.0	7.9	200	3.91	2.52	1.55
105, 205	S09 max	85.0	7.9	205	3.70	2.54	1.45
worst wind speed tests							
111, 211	S09 max	85.0	6	190	4.58	2.94	1.56
112, 212	S09 max	85.0	5	190	4.61	3.24	1.42
worst load tests							
121, 221	S09 nom	85.0	7.9	190	2.54	1.77	1.43
122, 222	S09 min	85.0	7.9	190	2.44	1.52	1.61
stack height tests							
131, 231	S09 max	87.5	7.9	190	3.25	2.10	1.55
132, 232	S09 max	90.0	7.9	190	3.42	2.23	1.53
133, 233	S09 max	95.0	7.9	190	2.79	2.28	1.22
Final GEP Stack Height Tests							
documentation tests							
141, 241	S09 max	90.0	7.9	190	3.13	2.31	1.36
142, 242	S09 max	90.0	7.9	190	3.29	2.24	1.47
143, 243	S09 max	90.0	7.9	190	3.35	2.26	1.48
Average	**S09 max**	**90.0**	**7.9**	**190**	**3.31**	**2.27**	**1.46**

Data Acquisition

After the desired atmospheric conditions were established in the wind tunnel, a mixture of inert gas (nitrogen) and a tracer (ethane) of predetermined concentration was released from the stack at the required rate. The concentration of the tracer gas was measured at specified grid points downwind of the stack using a high frequency flame ionization detector (HFFID) mounted on a computer controlled movable traverse.

The lateral concentration results at each distance downwind of the stack were plotted and a function based on the Gaussian plume equation was fit to the data using a weighted least squares approach. The highest concentrations were weighted more than lower concentrations, to ensure that peak concentrations are captured in the data fit. The resulting maximum concentrations for each distance downwind of the stack were then used to determine the overall maximum concentration versus downwind distance.

Atmospheric Dispersion Comparability Tests

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 these tests is typically 50 or 100 m. 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). Since these tests have been previously conducted[12] for model scales ranging from 1:250 to 1:3000 they were not repeated as part of this study.

RESULTS OF CONCENTRATION TEST

Flow Structure Over Model

Flow measurements were made approaching the turntable to ensure that the approach boundary layer wind profile and turbulence characteristics in the wind tunnel match the target full scale conditions. These measurements demonstrated that the all boundary characteristic were representative for an approach surface roughness length of 0.49 m.

Measured turbulence components (u', v' and w') normalized by the best fit friction velocity (u*) also matched what is expected in the atmosphere[10]:

- u'/u* ~ 2.4
- v'/u* ~ 1.9
- w'/u* ~ 1.25

Reynolds Number Independence Tests

Tests were conducted to confirm Reynolds number independence. Three different wind-tunnel speeds were set at the reference height (4, 6 and 8 m/s) and ground-level concentrations were measured with and without buildings present. The results indicated that Reynolds number effects can be neglected at wind-tunnel speeds of 6 m/s or greater and all tests conducted to determine the GEP stack height were conducted at a wind-tunnel speed of 6 m/s.

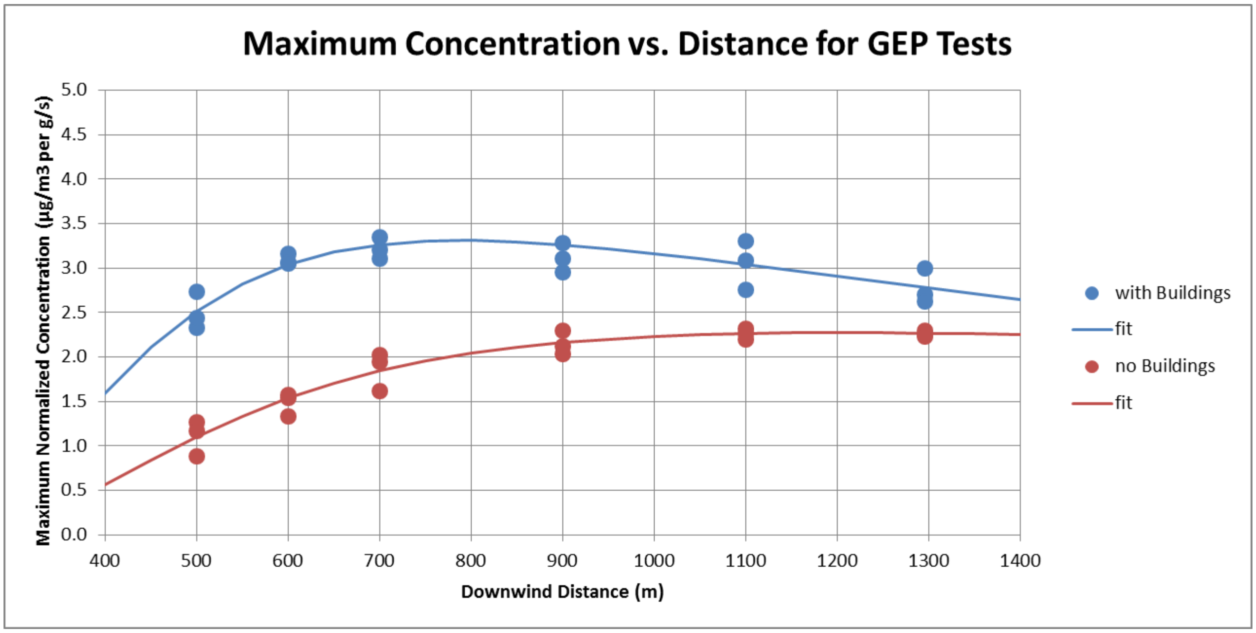
Detailed Plume Behavior

For a GEP stack height demonstration study, the following measurements were obtained as recommended by EPA[2]:

- longitudinal profiles of maximum ground-level concentration
- lateral profiles of ground-level concentration at the downwind distance of maximum concentration
- horizontal and vertical concentration distributions at four locations downwind of the stack; and
- calculations of horizontal and vertical dispersion coefficients and the variation of these coefficients versus downwind distance.

shows the ground-level longitudinal profiles of maximum concentration due to stack S09 taken with and without buildings present at the 190 degree wind direction. In the figure three repeated tests are reported for the cases with and without buildings present. The figure demonstrates that the wind-tunnel experiments were repeatable and the maximum concentration in the longitudinal direction was measured. With buildings present, the maximum concentration occurs at a downwind distance of 700 m. Without buildings, the maximum occurs at 1100 m.

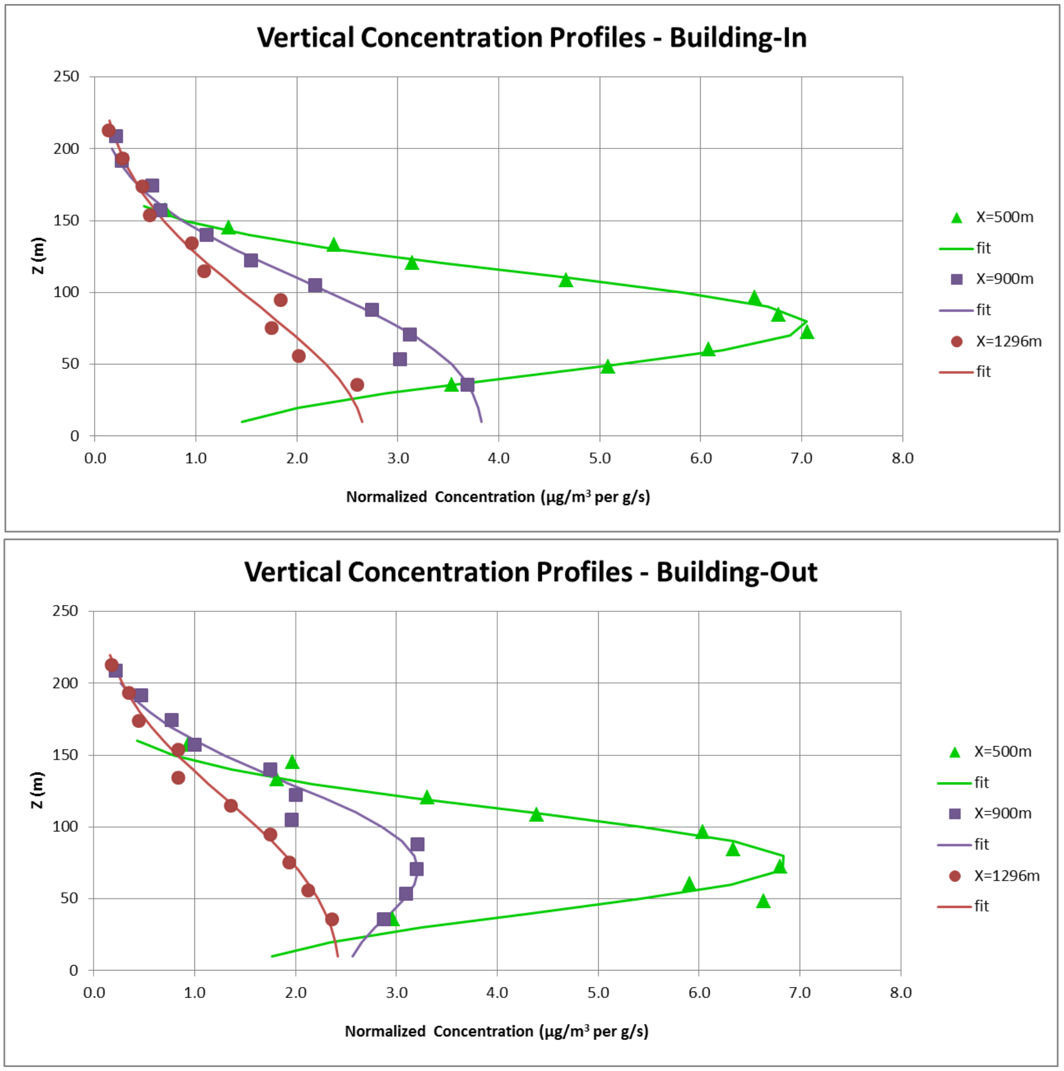
Figure 4. Longitudinal profiles of maximum ground-level concentration for final GEP stack height tests



Ground-level lateral concentration profiles at the downwind distances where maximum concentrations occurred with and without buildings present were also obtained and again demonstrated the consistency of the results. These profiles indicated that the maximum concentrations were measured in the lateral direction.

Vertical concentration distributions due to stack S09 taken with and without buildings present at the 190 degree wind direction for three downwind distances are shown in Figure 5. Lateral profiles were also taken at the 90 m stack height but are not provided herein.

Figure 5. Vertical concentration profiles approximately at plume centerline (Y=0 m) at three downwind distances with and without buildings for final GEP stack height tests



The observed concentration data in the vertical and horizontal directions were fit to the Gaussian Plume equation and the dispersion coefficients (σ_y and σ_z), as well as plume height H were determined.

Equation 6:

$$\frac{C}{m} = \frac{A}{\sigma_y \sigma_z} exp\left(-\frac{1}{2}\frac{(y-\bar{y})}{\sigma_y}\right)\left\{exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z{}^2}\right) + exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z{}^2}\right)\right\}$$

where

A	=	fit constant
$(y-\bar{y})$	=	distance from plume center line (m),
z	=	height above ground (m),

The data fit for each downwind distance is shown in Figure 5. The resulting horizontal and vertical dispersion coefficients with and without buildings versus downwind distance are summarized in Figure 6. The figures show that the horizontal and vertical dispersion coefficients with and without the buildings present are generally equal. Since the vertical dispersion coefficients with and without the buildings present are nearly equal, the increase in maximum ground-level concentrations with the building present is not due to increased vertical dispersion. The difference in ground-level concentrations with and without the buildings present is mainly due to the plume rise difference as shown in Figure 7. The plume rise is significantly reduced with buildings in place. This confirms the corner vortex effect which creates a downward vertical velocity. Note that the plume heights shown in Figure 7 are above local grade.

Figure 6. Horizontal and vertical dispersion coefficients for three downwind distances with and without buildings for final GEP stack height tests

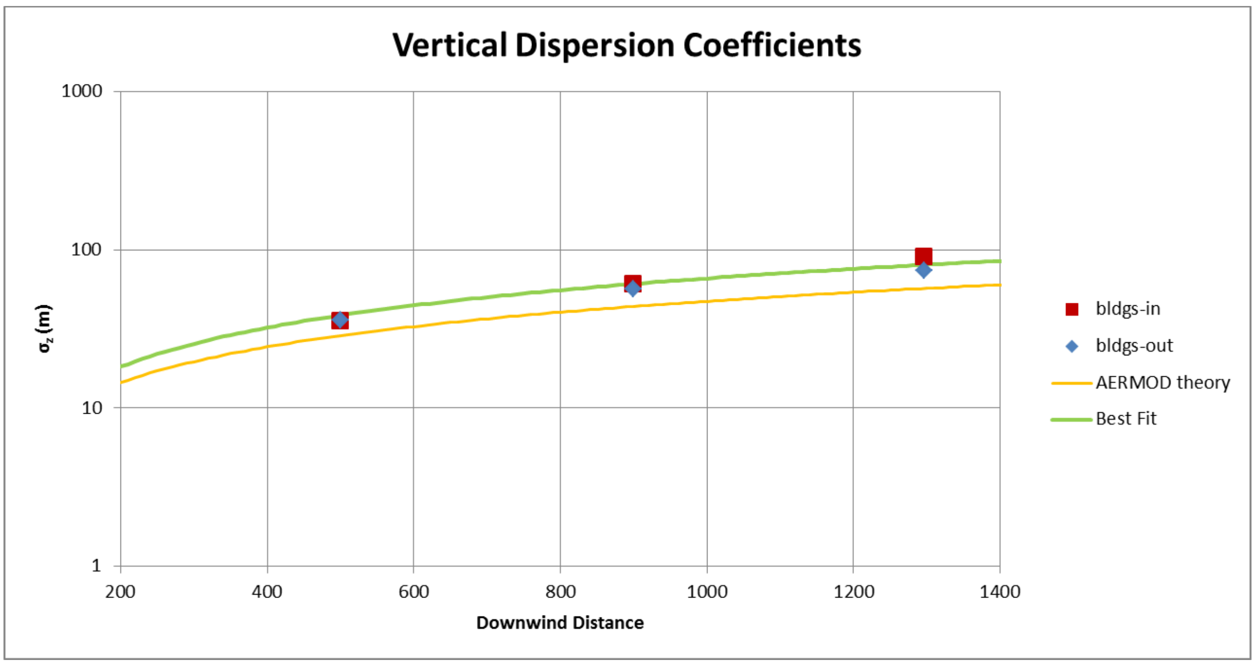
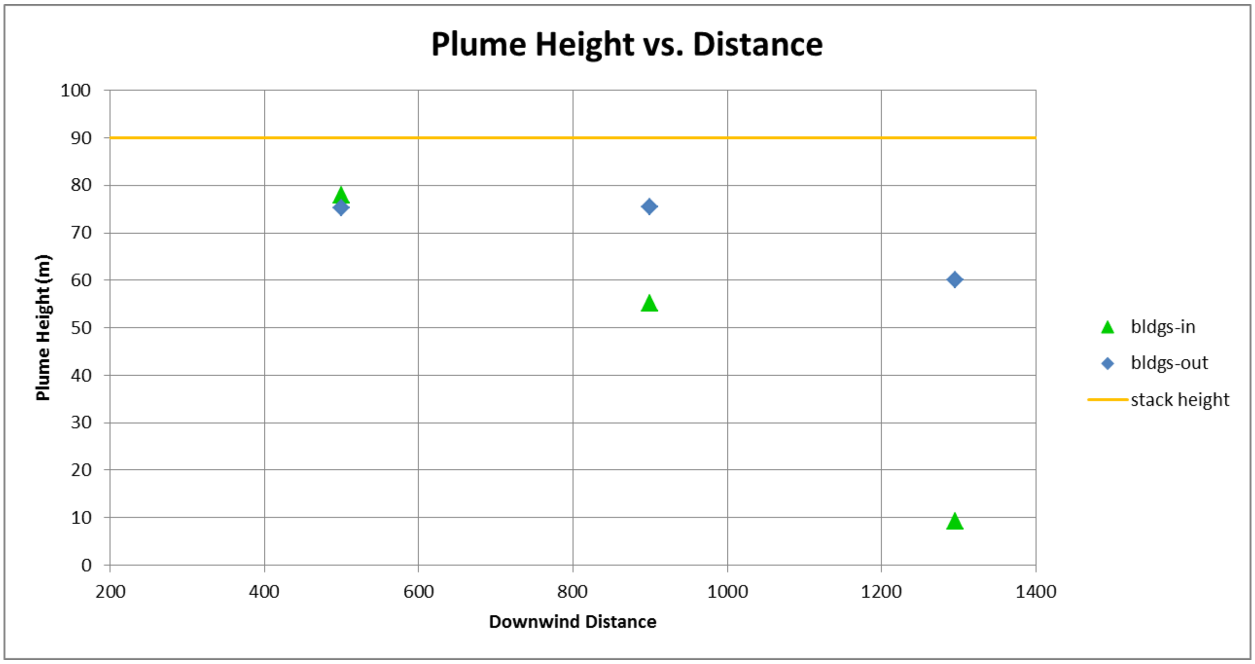


Figure 7. Predicted plume heights for three different downwind distances with and without buildings present



The resulting horizontal and vertical dispersion coefficients are compared to theoretical values in Figure 7 based on the following AERMOD equations[11]:

Equation 7:

$$\sigma_{ya} = \frac{i_y x}{(1+\alpha X)^p} \quad \text{with} \quad X = \frac{i_y x}{z_i}$$

where

i_y	=	lateral turbulence intensity measured in the wind tunnel at stack height
α	=	non-dimensional height scale (α =78),
p	=	exponent (p=0.3),
z_i	=	height of mixed layer – height of wind tunnel roof (504 m)

The same equation is used for the vertical dispersion coefficient σ_z, using the vertical turbulence intensity i_z.

The AERMOD model formulation document describes the values for α and p as preliminary and points out that the lateral dispersion coefficient estimates obtained using the above equation underestimate the full Prairie Grass data set. The same trend can be seen in Figure 6. Best fit values of α and p were therefore calculated using the wind tunnel determined dispersion coefficients. The best fit results with $\alpha=28$ and $p=0.28$. The best fit graph is also shown in Figure 6. The good agreement between the dispersion theory and the wind tunnel results further supports the validity of this study.

EVALUATION OF GEP STACK HEIGHT

The EPA stack height regulation defines the GEP stack height as one that avoids excessive concentrations due to wakes and eddies created by nearby structures. The regulation further defines excessive concentration to be a concentration that is 40% in excess of the concentration without the nearby buildings present and one that exceeds the appropriate NAAQS (SO_2 for this evaluation). No background concentration was added to the SO_2 concentration results obtained in this study.

Table 2 summarized the results of the tests. The results from the preliminary tests (shown at the top of Table 2) indicated that the highest concentration ratio occurs for a wind direction of 190 degrees (i.e., “worst wind direction tests” in Table 2). Tests were then conducted simulating different anemometer wind speeds that confirmed that a 10 m wind speed of 7.9 m/s results in the highest concentration ratio (i.e., “worst wind speed tests” in Table 2). Additional preliminary tests were then conducted to determine the worst operating conditions (i.e., “worst load tests” in Table 2) to evaluate the GEP stack height. The maximum load case (PTE allowed in the permit at the boiler’s rated capacity - 3.5 lbs SOx/MMBtu @ 300 MMBtu/hr) resulted in the 2nd highest concentration ratio but the highest normalized concentration. Finally, several stack heights were evaluated at the worst case wind direction, wind speed and load case to determine the GEP stack height initially based on the 40% excessive concentration criterion. The “stack height test” results in Table 2 indicated that a 90 m stack was likely at or below the GEP stack height with concentration ratio of 1.53. Hence, the 90 m height was selected as the GEP stack height for documentation purposes.

Documentation tests were then conducted to confirm the GEP stack height for the Rhinelander Mill Stack S09 (shown at the bottom of Table 2). The normalized concentrations for all documentation test runs with and without buildings (runs 141-143 and 241-243 in Table 2) were then averaged (see Figure 4) and the resulting best fit maximum normalized concentrations were multiplied by the emission rate for the maximum load case (see Table 1). The resulting 1-hour SO_2 concentration with buildings in place is shown in Table 3. For example, the average normalized concentration with buildings in place of 3.31 $\mu g/m^3$ per g/s (see bottom row of Table 2) was multiplied by 132.3 g/s (see Table 1) to get the full scale SO_2 concentration of 437.9 $\mu g/m^3$ shown in Table 3.

Table 3 shows that the 1-hour SO_2 concentration for the 90 m stack height exceeds the 1-hour SO_2 NAAQS. The 90 m S09 stack also exhibits a maximum ground-level concentration that is 40% in excess of the concentration without the nearby buildings present. Both GEP stack height criteria are therefore met for the 90 m stack height.

SUMMARY AND CONCLUSIONS

The results of the wind tunnel testing are summarized in Table 3.The table shows that excessive concentrations do occur with a 90 m stack height for S09 and therefore the 90 m stack is creditable as GEP which is significantly higher than the formula GEP height of 75. The results also suggest that a slightly taller stack would also be creditable as GEP since both criteria for GEP stack height are exceeded.

Table 3. Summary of Results

Description	**Maximum SO_2 Concentration ($\mu g/m^3$) 1-hour Average**	**Concentration Ratio with and without Buildings**
Excessive Concentration Limit	196.5	1.40
Stack S09 – 90m stack height at maximum load	437.9	1.46

[1] Results for worst wind direction and wind speed.

The study also showed the following:

- the boundary layer characteristics simulated in the wind tunnel match those expected in the atmosphere for the same surface roughness and neutral stratification.
- the horizontal and vertical dispersion coefficients observed in the wind tunnel also matched what is expected for the atmosphere.
- the main effect of the corner vortex was to decrease plume rise and hence increase ground-level concentrations. The horizontal and vertical dispersion coefficients were nearly identical with and without the building present.

REFERENCES

1. 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.
2. 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.
3. 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.
4. 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.
5. Petersen, R.L., D.K. Parce, J.L. West, R.J. Londergan, "Effect of a Nearby Hill on Good Engineering Practice Stack Height," 86th Annual AWMA Conference, Denver, CO, June 14-18, 1993.
6. 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.
7. 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.
8. EPA, *AERSURFACE User's Guide*, EPA–454/B–08–001, USEPA Office of Air Quality Planning and Standards, Air Quality Assessment Division, Air Quality Modeling Group, Research Triangle Park, North Carolina, 2008.
9. Petersen, R.L. and A. Beyer-Lout. Fluid Modeling Good Engineering Practice Stack Height Determination for the Rhinelander Mill Stack S09, CPP Report 7835, October 2014.
10. Panofsky and Dutton, "Atmospheric Turbulence," John Wiley & Sons, Inc., 1984.
11. Cimorelli, A.J., S.G. Perry, A. Venkatram, J.C. Weil, R.J. Paine, R.B. Wilson, R.F. Lee, W.D. Peters, R.W. Brode, and J.O. Paumier: "AERMOD: Description of Model Formulation," EPA-454/R-03-004, September 2004.
12. Petersen, R.L., "Dispersion Comparability of the Wind Tunnel and Atmosphere for Adiabatic Boundary Layers with Uniform Roughness," Seventh Symposium on Turbulence and Diffusion, American Meteorological Society, Boulder, CO, November 12-15, 1985.