

Evaluation of Monitored SO₂ NAAQS Exceedances Due to the Corner Vortex

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ABSTRACT

SO₂ concentrations due to a 63.1 m boiler stack exceed the new 1-hour SO₂ NAAQS at a nearby monitoring station located on elevated terrain. AERMOD is showing compliance at the monitoring station with predicted concentrations a factor of two or more lower than monitored. After investigating the stack and 38.2 m tall upwind building configuration, it was noticed that the upwind building corner is directly in line with the monitoring station and stack. When the wind blows along a building corner, two vortices are generated that tend to suppress plume rise and increase ground-level concentrations. Current AERMOD building downwash equations do not account for corner effects; hence, the observed model under prediction is expected. If the corner vortex could be eliminated or reduced it was suspected that monitored concentrations would decrease and the facility would be closer to showing compliance with the new 1-hr SO₂ NAAQS. This paper will discuss the corner vortex issue, building modifications that have been developed and field tested to eliminate corner vortices and a wind tunnel modeling study of the problem. First, wind tunnel modeling was conducted for the existing building configuration, so the wind tunnel predictions could be compared with field observations. Next, wind tunnel modeling was used to evaluate various modifications to the building to eliminate the corner vortex and associated high concentrations. The building modifications included porous screens on the roof and rounded building corners. These building modifications reduced downwind concentrations by 15 to 20%. Since this concentration reduction was not sufficient to meet the NAAQS, taller stacks were also evaluated. Wind tunnel model predictions showed that a stack height of approximately 100 m is needed to show compliance with the NAAQS.

INTRODUCTION

Air monitoring data for an industrial facility is showing SO₂ concentrations exceeding the 1-hour NAAQS at a nearby elevated water tower monitoring location (denoted as “WTM”). An analysis of emission sources and air quality modeling both now and in the past indicate that the Industrial Facility appears to be the primary contributor to the ambient air impact at this monitor, specifically a stack denoted as “S09”. The WTM is about 600 m (2000 ft) downwind of stack S09. Predicted concentrations using AERMOD^{1,2} cannot reproduce the high measured concentrations at the WTM and are about a factor of two less than the observations.

After investigating the building geometry, it was noticed that the nearby tallest building corner is directly upwind of the stack when the wind blows directly toward the WTM (see Figure 1). When the wind blows along a building corner, corner vortices are generated that enhance building downwash. This enhancement effect is not included in AERMOD. Past wind tunnel modeling studies have shown that these corner vortices can increase concentrations by as much as a factor of two. Hence, one would expect AERMOD to underpredict measured concentrations for this situation. Petersen³ provided comments at the 9th Conference on Air Quality Modeling on behalf of the A&WMA AB-3 committee on this topic. At this point, EPA has not developed an algorithm to deal with this problem.

Figure 1. Depiction of Industrial Facility and Flow Toward Water Tower Monitor



There are several optional methods whereby the concentration levels at the water tower monitor can be reduced, as follows: 1) eliminate the corner vortices; 2) increase the stack height; and/or 3) install additional emission control. This purpose of this study was to evaluate options 1 and 2 using wind tunnel modeling.

In the past, wind tunnel modeling has not been used directly for air quality permitting type applications. It has been used indirectly by determining “Equivalent Building Dimensions” to replace BPIP building dimension inputs in AERMOD/PRIME^{4,5} or for model validation and development purposes^{6,7}. The primary reasons for this were: 1) the time and expense to evaluate all meteorological conditions in the wind tunnel; 2) the wind tunnel can not accurately simulate buoyant plume rise at a reasonable model scale and hence will significantly overestimate maximum ground-level concentrations; 3) the wind tunnel has not been shown to adequately simulate the stable or convective boundary layer; and 4) the wind tunnel has not been evaluated against EPA field data bases. These problems were overcome by Petersen and Beyer-Lout⁸ where a hybrid wind tunnel modeling approach (HYWINMOD) was developed and validated against a field data base (i.e., Bowline Point).

Based on the above, a wind tunnel modeling study was conducted with the ultimate goal of helping develop a strategy for showing compliance with the 1-hr SO₂ NAAQS at the WTM. To meet this goal the following project plan was developed:

- Compare wind tunnel predictions (HYWINMOD) with field observations at the WTM. The wind tunnel modeling method utilized in the study (HYWINMOD) allowed for a direct hour-by-hour comparison with field observations. This phase was used to support the use of wind tunnel modeling (HYWINMOD) for developing the strategy for showing compliance with the 1-hr SO₂ NAAQS. It should be noted that wind tunnel modeling includes the effect of corner vortices and was expected to show better agreement with field observations than AERMOD.
- Verify that the worst-case concentrations were likely to occur at the location of the WTM due to its elevated position. This conclusion was reached after conducting wind tunnel testing in several directions.
- Evaluate the feasibility of decreasing concentrations at the WTM by eliminating the corner vortex. This phase evaluated various vortex mitigation devices to assess the percent measured SO₂ reduction that could be expected at the WTM.
- Based on HYWINMOD, determine the stack height required to show compliance with the 1-hr SO₂ NAAQS at the WTM. If the vortex mitigation was not sufficient to show compliance, then this phase was designed to determine the stack height where concentration levels at the WTM are expected to meet the SO₂ NAAQS. This evaluation also included the impact of a 2nd stack (S11, which is used intermittently) that could contribute to monitored concentrations when it operates.

Regarding the likelihood of being able to solve the vortex problem, Banks^{9,10} has studied roof corner vortices extensively, in order to better understand the wind loads they create on the roof and on items mounted on the roof, such as solar panels. Part of this research involved the development of modifications to the edge of the roof in order to disrupt the formation of the vortices. Two methods - which were quite successful - involved the use of a spoiler or a fence to prevent the vortex from reattaching at the corner. These studies were performed on a small low rise building, but the results are expected to apply to a roof of any size. The size and extent of fencing (or other mitigation) required on a much larger roof could be readily determined through wind tunnel testing.

The following sections of this paper discuss the building corner vortex issue in more detail, the comparison of wind tunnel predictions with field observations and the results of the wind tunnel modeling evaluation of this issue.

BUILDING CORNER VORTEX ISSUE

When the wind blows along a building corner, two vortices are generated that rotate in the manner shown in Figure 2. These vortices rotate such that downward velocity is generated directly downwind of the building. This downward velocity will tend to suppress plume rise for stacks downwind of the building and increase ground-level concentrations. As shown in Figure 1, the southwest corner of the tallest building lines up directly with the Water Tower monitor. Hence, it is suspected that the corner vortex is reducing the plume rise and enhancing the

building downwash over that predicted by AERMOD. This, in turn, is causing the observed concentrations at the Water Tower monitor to be higher than predicted by AERMOD.

Figure 2. Schematic and Photograph of Corner Vortices

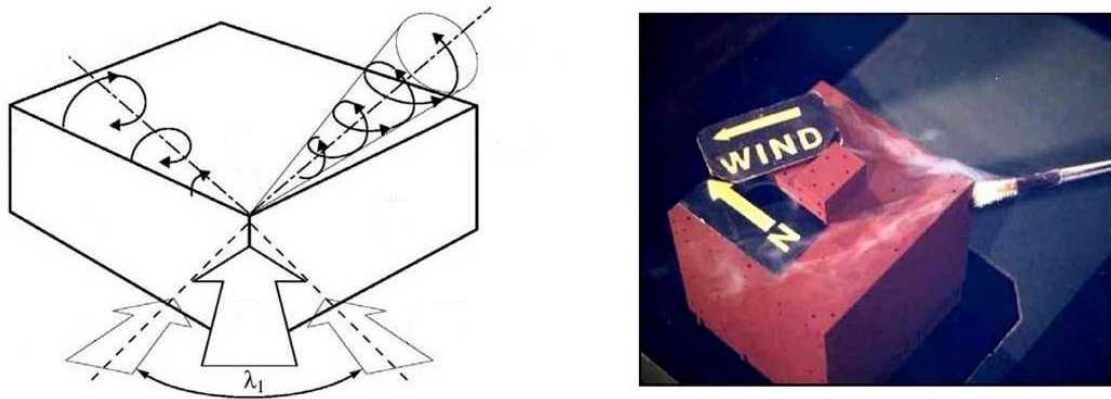
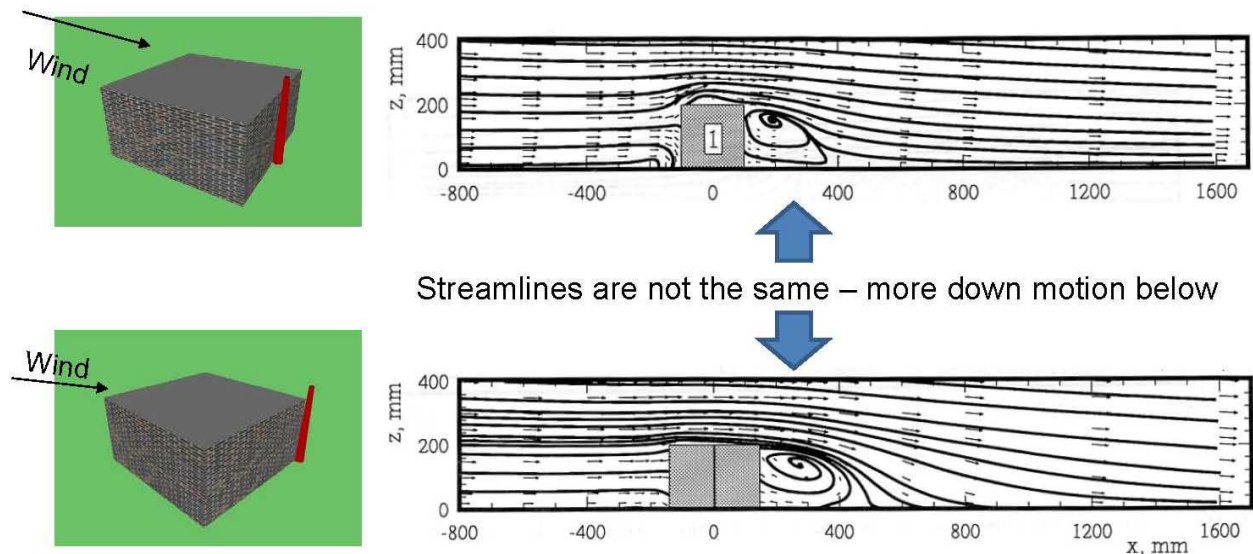


Figure 3 shows streamlines from an EPA wind tunnel study¹¹ for a case with the wind perpendicular to the building face and another case with the wind along a building diagonal. The AERMOD model was designed using only the information from this study with wind blowing perpendicular to the building face. The algorithms in AERMOD (which uses the PRIME downwash model²) do not include the added downward motion for the diagonal wind direction.

Figure 3. Streamlines for Winds Perpendicular to Building Face and Along Building Diagonal



Streamline figures from: Snyder, W.H. and R.E. Lawson, Jr.: Wind Tunnel Measurements of Flow Fields in the Vicinity of Buildings; 8th Joint Conference on Appl. of Air Poll. Met. With A&WMA; AMS, Boston, MA, 1994; pp. 244-250

The effect of corner vortices on ground-level concentrations can be seen in Figures 4 and 5. Figure 4 was developed using an EPA document.¹² This figure, which is for a similarly shaped building, shows concentrations may increase by about a factor of two for a diagonal wind

direction. Figure 5 shows results from tests conducted by the author which shows similar results as those presented by EPA in Figure 4 (i.e., a factor of two concentration increase for the diagonal wind direction).

Figure 4. Maximum Concentrations versus Downwind Distance for Winds Perpendicular (0-Degree Wind Direction) to Building Face and Winds Along Building Diagonal (45-Degree Wind Direction) – EPA Report

EPA Guideline for Determining GEP Stack Height – Technical Support
Document, EPA-450/4-80-023, July 1981
Comparison for Building with $W/H = 1$

Boiler 7

$H_s/H_b = 1.65$

$W/H = 0.6$

Concentration Ratio ~ 2.0

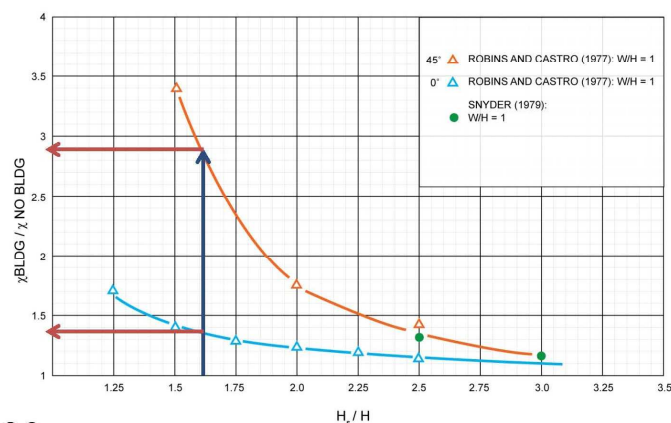
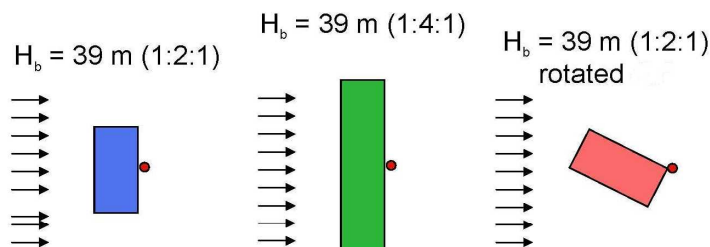
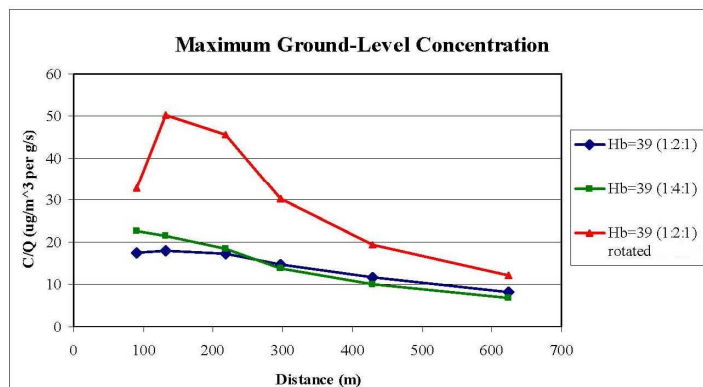


Figure 5. Maximum concentrations versus downwind distance for winds perpendicular (0 degree wind direction) to building face and winds along building diagonal (45 degree wind direction) – CPP Wind Tunnel Testing

Stack Height:
 $H_s = 48$ m

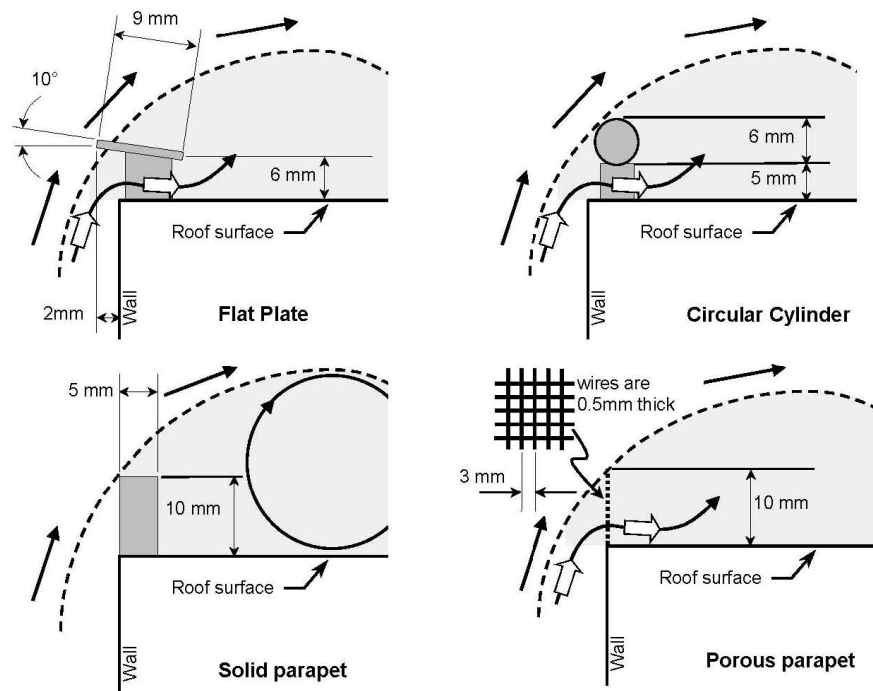


Wind Tunnel
Measurements



Based on the above, if the corner vortex could be mitigated, concentrations at the Water Tower monitor could be reduced by at least a factor of two. Banks^{9,10} has conducted extensive research regarding mitigation of the corner vortex. Some mitigation devices that he evaluated are shown schematically in Figure 6. Wind tunnel and field testing was conducted to confirm the effectiveness of these vortex mitigation methods. Based on the wind tunnel testing, the most effective device was the horizontal flat plate installed some distance above and overhanging the roof. The second most effective device was a vertical porous screen wall running along the edge of the building. Banks also found that a solid parapet, which Boiler 7 has, increased the vortex intensity.

Figure 6. Schematic Showing Various Vortex Mitigation Devices (Model Scale is 1:25)



APPROACH FOR RESOLVING BUILDING DOWNWASH PROBLEM - USE HYWINMOD

HYWINMOD

The HYWINMOD (**H**ybrid **W**ind Tunnel/**N**umerical **M**ODEl) approach is described in detail in Petersen and Beyer-Lout⁸ and is shown schematically in Figure 7. Each element of the approach is listed below.

Figure 7. Schematic Illustrating the HYWINMOD approach



The new HYWINMOD method consisted of the following steps:

- Construct a scale model of facility.
- Define the approach surface roughness using AERSURFACE¹⁴.
- Specify model operating conditions assuming a neutral atmosphere and neutrally buoyant plume.
- Install model in the wind tunnel and establish the appropriate approach mean wind speed and turbulence profiles.
- Define the concentration as function of wind speed and wind direction at each receptor location of interest (i.e., the WTM).
- Using the concentration data, define a fit function at each receptor location.
- Obtain hourly meteorological data that is appropriate for the site (hourly wind speed, wind direction, temperature, etc.).
- Obtain hourly source data (emission rate, temperature, volume flow rate, exit velocity).
- Process hourly meteorological data to obtain hourly wind speed, wind direction and temperature close to or at stack height, as well as Monin-Obukhov length.
- At each receptor predict the hourly concentration using the fit function with stability and plume rise adjustments, the hourly meteorological data and the hourly source data.
- Post-process the hourly concentration predictions to obtain maximum concentration at each receptor for the averaging times of interest.

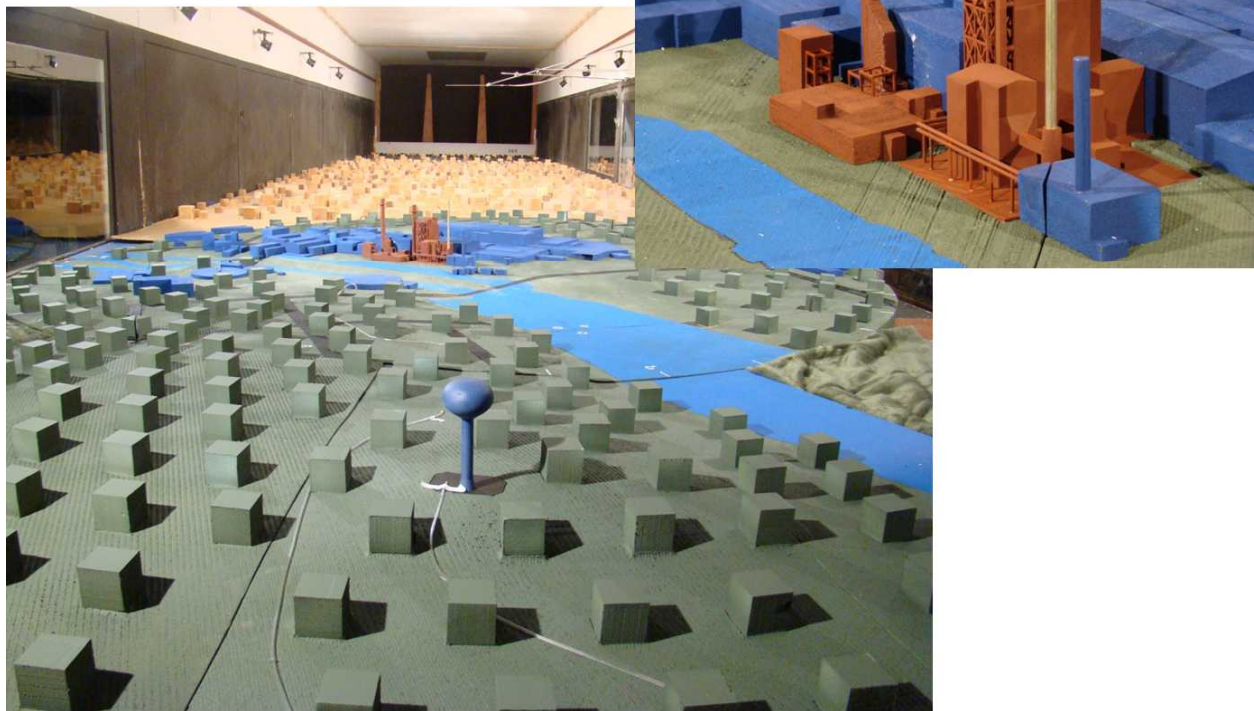
Wind Tunnel Modeling

A 1:240 scale model of the Industrial Facility and surrounding terrain out to a distance of 700 m from the S09 stack was constructed and installed in the wind tunnel. The full scale plume rise and dispersion for the S09 and S11 stacks were simulated using the method outlined in EPA's Fluid Modeling Guideline¹³. It should be noted that the standard method for setting up wind tunnel simulations does not accurately simulate the plume rise due to plume buoyancy.

The S09 and S11 stack locations are shown in Figure 1. Figure 8 shows photographs of the scale model installed in the wind tunnel.

Figure 8. Photographs of the Scale Model of Industrial Facility Installed in Wind Tunnel

1:240 Scale Model



HOURLY CONCENTRATION ESTIMATES

Exhaust Source Parameters.

To post process the wind tunnel data and predict hourly concentrations, hourly stack flows, temperatures and emission rates are preferred. However, for the period 1998-2002, the stack flows and emissions were not available on an hourly basis. Hence, three emission scenarios were considered as follows: 1) maximum load; 2) nominal load; and 3) minimum load. The stack flow and emission parameters for these scenarios are provided in Table 1.

Table 1. Source Parameters and Modeling Scenarios

Source ID	Source Height AGL (m)	Exit Temp. (K)	Volume Flow Rate (m ³ /s)	Exit Velocity (m/s)	SO ₂ Emission Rate (g/s)
S09 max	63.09	430.4	47.23	13.25	132.30
S11 max	60.96	438.7	80.77	8.37	37.80
S09 nom	63.09	427.6	34.21	9.60	86.94
S11 nom	60.96	433.2	56.53	5.86	25.20
S09 min	63.09	422.0	26.50	7.44	95.76
S11 min	60.96	427.6	28.34	2.94	12.60

For the year 2009, detailed flow and emissions data were available for both stacks. The following information was available on a daily basis: steam load, loaded coal, and normalized flow. For 51 days of the year, the percent sulfur content in the coal and SO₂ emission rate were available. This data subset was used to develop a relation between the daily SO₂ emission rate and tons of coal as described in the following equation:

$$\text{Emission Rate (lb/hr)} = 0.1617 \cdot \text{Loaded Coal (tons)} \cdot \text{Sulfur Content (\%)}^{3.4} + 493$$

Hourly emission rates were then estimated using this equation, the daily tons of coal and average or maximum % sulfur in the coal. For model input purposes, it was assumed that flows and emissions were constant throughout each day.

Meteorological Data

The meteorological information of primary interest for this evaluation is the hourly wind speed, wind direction, stability and temperature. The AERMET surface data files for the nearby airport for the years 1998 through 2002 and 2006 through 2010 were utilized. This information was used to correct the wind tunnel predictions for plume buoyancy and atmospheric stability effects. In addition, the information was used to specify the maximum wind speed to test in the wind tunnel, which was set at 15 m/s.

Data Post Processing

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

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

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

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

where WD is the wind direction (in degrees), WD_c is the critical wind direction (in degrees) where the peak concentration occurs. The values for A , $\sigma_{y,WT}$, $\sigma_{z,WT}$, WD_c , and K were found by minimizing the error of the fit to the observed concentrations. To account for increased plume rise due to buoyancy, a correction factor R is introduced. The dispersion coefficients $\sigma_{y,WT}$ and $\sigma_{z,WT}$ were corrected for buoyancy induced dispersion (σ_b):

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

The dispersion coefficients σ_y and σ_z are corrected for stability effects using the correction factors S_y and S_z :

$$\frac{C}{m} = \frac{A \cdot 10^6}{\pi(\sigma_{y,WT}^2 + \sigma_b^2)^{1/2} S_y (\sigma_{z,WT}^2 + \sigma_b^2)^{1/2} S_z U} \cdot \exp \left[-\frac{1}{2} \left(\frac{x \cdot \tan(WD - WDC)}{(\sigma_{y,WT}^2 + \sigma_b^2)^{1/2} S_y} \right)^2 \right] \cdot \left\{ \exp \left[-\frac{1}{2} \left(\frac{z - \left(h_s + \frac{K}{U^2} \right) \frac{R}{S_z}}{(\sigma_{z,WT}^2 + \sigma_b^2)^{1/2}} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{z + \left(h_s + \frac{K}{U^2} \right) \frac{R}{S_z}}{(\sigma_{z,WT}^2 + \sigma_b^2)^{1/2}} \right)^2 \right] \right\} \quad (4)$$

Once the fit function and correction factors were determined, total concentrations were predicted for every hour using the appropriate stack parameters and emission rates.

RESULTS

Concentration Measurements

Normalized concentrations (C/m) due to S09 and S11 were measured at the water tower monitor location for five different wind directions and up to eleven different wind speeds in the wind tunnel. The concentration measurements were utilized for the following purposes:

- Compare wind predictions with field observations at the WTM.
- Evaluate the feasibility of decreasing concentrations at the WTM by eliminating the corner vortex.
- Determine the stack required to show compliance with the 1-hour SO₂ NAAQS at the WTM.

For comparison with field observations and to assess compliance with NAAQS, the normalized concentrations (C/m) measured in the wind tunnel were fit to the function discussed previously. Using the fit function, hourly source parameters and meteorological data, maximum concentrations were predicted at the WTM and were corrected for plume buoyancy. No correction for buoyancy effects was utilized when evaluating the corner vortex. The following paragraphs discuss the results for each of the different areas of evaluation.

Comparison with Field Observations

For the year 2009, daily stack parameters for S09 and S11 were available. Hourly meteorological data and the daily stack parameters were used to calculate total 1-hour concentrations at the Water Tower monitor location. Two different emission scenarios were used for stack S09, as follows: 1) hourly SO₂ emission rates calculated using average coal sulfur content; and 2) hourly SO₂ emission rates calculated using high coal sulfur content. S11 was seldom operating, resulting in no contribution to the total concentration at the WTM location.

Table 2 compares the observed and predicted 4th highest maximum daily 1-hr SO₂ concentrations for 2009. The AERMOD concentration predictions are also displayed in the table, which shows the following:

- Wind tunnel predictions (HYWINMOD) for the average % sulfur case are within 22% of observations (predicted/observed ratio is 0.78) due to S09 and S11 (impact was zero) including background.
- Wind tunnel predictions (HYWINMOD) for the high % sulfur case are within 8% of observations (predicted/observed ratio is 0.92) due to S09 and S11 (impact was zero) including background.

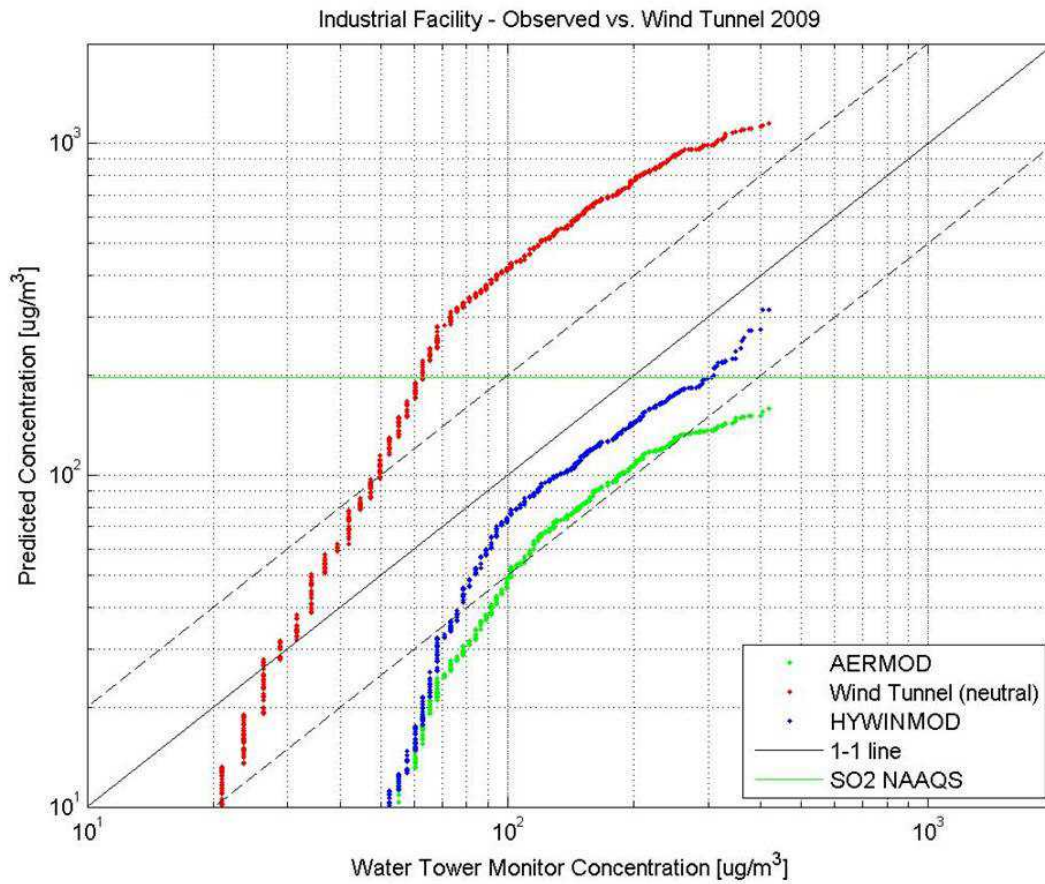
TABLE 2. Wind-tunnel (HYWINMOD) predicted concentrations at WTM

Year				2009
Concentration ($\mu\text{g}/\text{m}^3$)	Monitor	4th highest max daily observed, all sources contribute		379.9
	Back-ground	background		21.8
	AERMOD	63.09 m stack height 4th highest max daily predicted concentration - S09 only daily values for exit velocity, temperature and emission rate used	daily emission rates calculated with average SO ₂ emissions	151.1 (172.9 w BG)
	Wind Tunnel	63.09 m stack height 4th highest max daily predicted concentration - corrected, S09 only daily values for exit velocity, temperature and emission rate used	daily emission rates calculated with average SO ₂ emissions	274.0
			daily emission rates calculated with peak SO ₂ emissions	329.2
	WT+BG	63.09 m stack height 4th highest max daily predicted concentration - corrected, S09 only daily values for exit velocity, temperature and emission rate used	daily emission rates calculated with average SO ₂ emissions	295.8
			daily emission rates calculated with peak SO ₂ emissions	351.0
	Ratios (WT+BG)/Obs	63.09 m stack height 4th highest max daily predicted concentration - corrected, S09 only daily values for exit velocity, temperature and emission rate used S11 Impact is zero	daily emission rates calculated with average SO ₂ emissions	0.78
			daily emission rates calculated with peak SO ₂ emissions	0.92

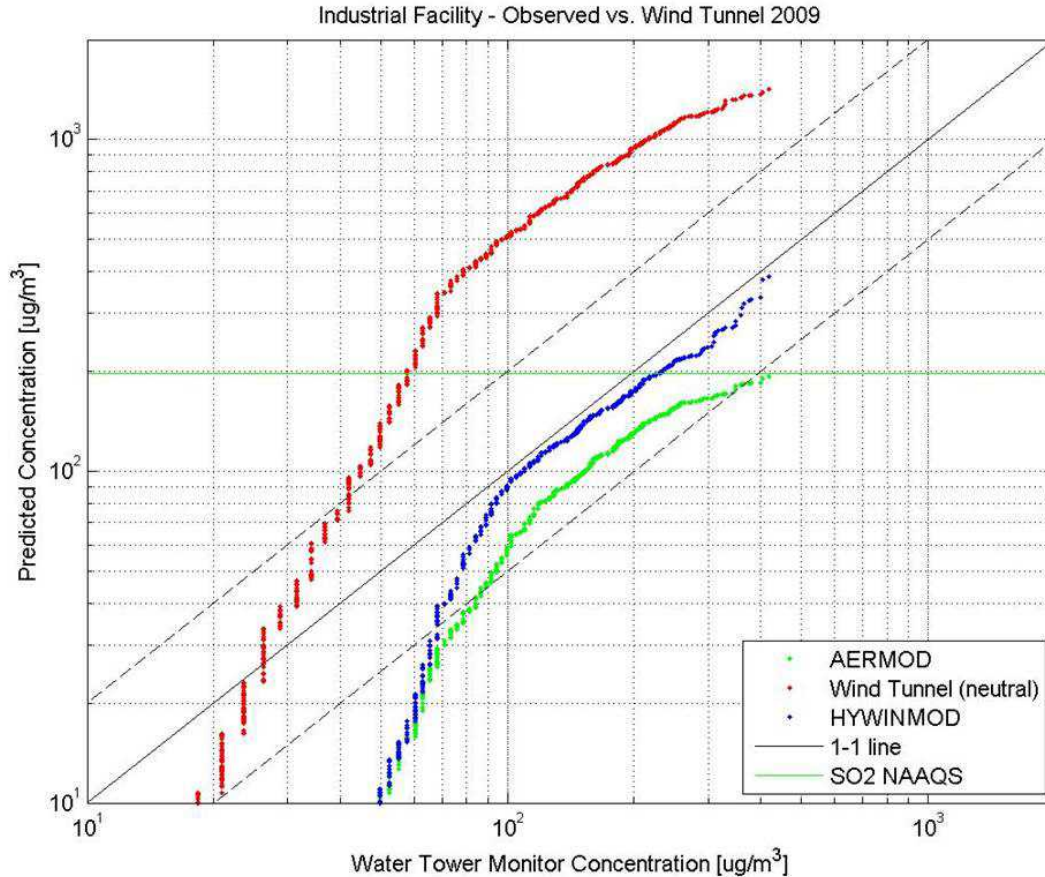
Figure 9 shows the quantile-quantile (Q-Q) plots for the two emission rate scenarios for 2009. In the year 2009 the stoker boiler stack S11 was seldom operating, resulting in no contribution to the total concentration at the WTM.

Figure 9. Q-Q plot comparing observed WTM concentration with AERMOD and the wind tunnel (uncorrected for buoyancy and HYWINMOD)

a. average SO₂ emissions



b. peak SO₂ emissions



While the 2009 wind tunnel/field comparison does have more accurate emissions information, the main limitation of this comparison is that the actual hourly emission rates, flows and exit temperatures are unknown. The above comparison assumed that the daily emissions are evenly distributed throughout the day. In addition, the percent sulfur in the coal is unknown on a daily basis and was found to vary considerably for the 51 days that it was measured. The results do show very good agreement when higher emission rates are assumed. The agreement is still very good with average emissions assumed. Due to the apparent random nature of the SO₂ emissions on a daily basis, it is possible that the worst-case wind condition and high SO₂ emissions occurred at the same time. When this happens, good agreement with the monitor is observed (i.e., within 8%).

On the basis of the above comparison, it is evident that the wind tunnel results compare much better with the field observations than AERMOD. The results indicate that the wind tunnel predictions are potentially within 8 to 22% of the field observations, assuming all the impact at the monitor is due to S09 with the assumed background value. Based on this result, use of the wind tunnel (HYWINMOD) to specify a taller stack should have a high degree of confidence, especially if a safety (or calibration) factor is applied to the results.

Vortex Mitigation Evaluation

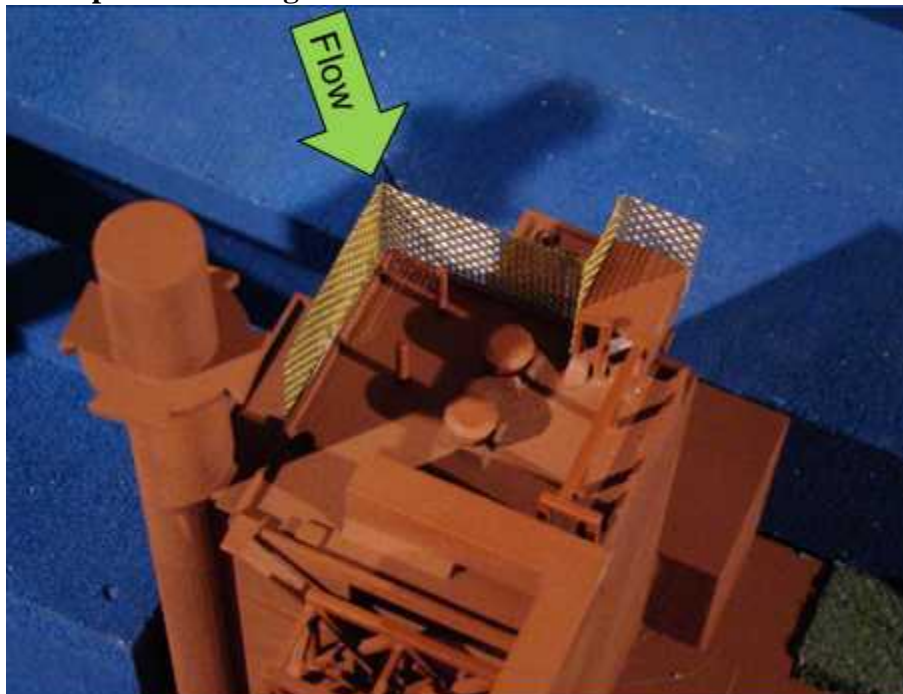
As previously discussed, it was hypothesized that the corner vortex may be contributing to the high concentrations at the monitoring station. Hence, wind tunnel testing was conducted to evaluate the concentration reduction that could be expected by applying vortex mitigation devices to the building. The mitigation measures that were evaluated are summarized below.

- 50% porous screen at all upwind tall boiler and other lower building corners. The screens were all 15 ft high and placed like an additional parapet around each corner.
- 64% porous screen at all upwind corners of tall boiler building. The screens were 10 ft high and placed like an additional parapet around all the stoker boiler upwind building corners.
- The upwind portion of the tall boiler building was streamlined (rounded) using Styrofoam inserts.
- All equipment was removed from the boiler building roof, effectively shortening the building.
- The tall boiler building was removed.

Figure 10 shows 3D views and photographs of select vortex mitigation schemes. Table 3 provides a listing of the concentration reductions at the WTM. The case without the tall boiler building was carried out to determine the maximum reduction that would be possible. For that case, the concentrations were reduced by 0.67 (a factor of 1.48). The next largest reduction of 0.81 (a factor of 1.23) was observed with modified building roof following by the 64% porous screens, a factor of 0.83.

Figure 10. Photographs and 3D Views of Vortex Mitigation Schemes.

a. screens at upwind building corners



b. upwind building corners rounded

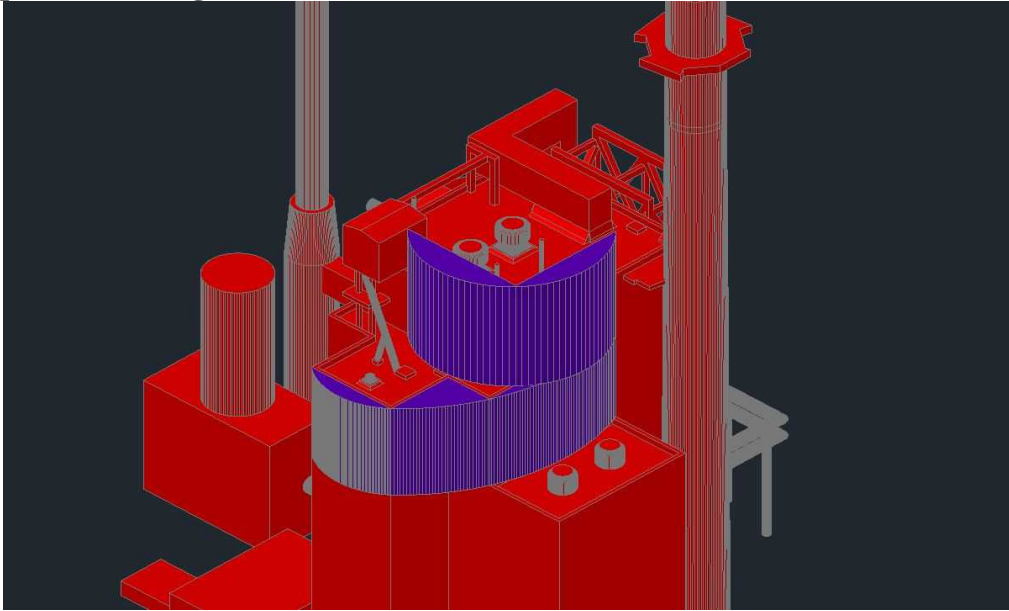


Table 3. Summary of Maximum Concentration Reduction for Various Vortex Mitigation Options Evaluated

Mitigation Description	% concentration reduction
Screens at upwind corners of boiler building	17%
rounded building corners	13%
modified boiler building roof (no equipment)	19%
boiler building removed	33%

Overall, the results of this testing have demonstrated that vortex mitigation will only reduce concentrations by approximately 20%. This reduction is not sufficient to bring the WTM observations into compliance.

Stack Height Evaluation

Since the vortex mitigation did not decrease concentrations at the WTM by the degree needed, additional testing and analysis was conducted for taller stack heights. Using the exhaust parameters for the stacks S09 and S11 shown in Table 1, normalized concentrations (C/m) were predicted at the water tower monitor location using the HYWINMOD approach. Hourly meteorological data for 1998 through 2002 and average stack parameters for three different load scenarios were used to calculate total 1-hour concentrations at the water tower monitor location.

The overall maximum concentrations were predicted for the minimum load scenario. For this critical scenario the maximum 3-year average 99th percentile daily 1-hour maximum concentrations were calibrated to match the concentration at the water tower for the existing stack height. Table 4 summarizes the results. To meet the 1-hr SO₂ NAAQS of 196.5 ug/m³ at

the WTM for this scenario for both stacks operating, a stack height of 96.1 m (based on linear interpolation) is required. The operating parameters obtained for 2009 suggest that S11 operates an insignificant fraction of the time and its contribution to the WTM observations could be assumed equal to zero. Assuming that S11 impacts are insignificant, Table 4 shows that the required stack height to show compliance at the monitor drops to 91.8 m.

Table 4. Summary of Maximum HYWINMOD Predicted Concentrations versus Stack Height at the WTM

Year				Max 3-yr Average
Concentration (µg/m ³)	Monitor	4th highest max daily observed, all sources contribute		472.5
	Back-ground	background		21.8
	Wind Tunnel	Critical Case + Background 4th highest max daily predicted concentration - corrected, S09 and S11 combined at <u>minimum</u> load	63.09 m stack height	500.1
			80 m stack height	394.3
			90 m stack height	251.2
			100 m stack height	180.6

An alternate way of estimating the stack height needed to meet the 1-hr SO₂ NAAQS is to compute the concentration reduction versus stack height observed in the wind tunnel and then apply this reduction factor to the critical WTM measured concentration. The concentration reduction factors versus stack height for the minimum load scenario (un-calibrated) with S09 and S11 operating in Table 4 are as follows:

- 0-m stack: $(500.1-21.8)/(394.3-21.8) = 1.28$
- 90-m stack: $(500.1-21.8)/(251.2-21.8) = 2.09$
- 100-m stack: $(500.1-21.8)/(180.6-21.8) = 3.01$
- Monitor: $(472.5-21.8)/(196.5-21.8) = 2.58$

Based on the maximum 3-year average of the 99th percentile peak daily 1-hour maximum concentration at the monitor for 1998 to 2002 and a background concentration of 21.8 µg/m³, a reduction of the source impact of at least 61% (or a factor of 2.58) would be needed for avoiding future monitoring problems. Based on these results and using linear interpolation, the required stack height is about 95 m, or 100 m allowing for a margin of safety.

SUMMARY AND CONCLUSIONS

Air monitoring data was showing SO₂ concentrations exceeding the 1-hour NAAQS at the Water Tower monitor (WTM). The primary contributor to the ambient air impact at this monitor was determined to be a nearby industrial facility, specifically stack S09. Predicted concentrations using AERMOD cannot reproduce the high measured concentrations at the WTM since the high concentrations were found to be due to upwind building corner vortex. 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. The purpose of this study was to use wind tunnel modeling to evaluate the following two mitigation measures for decreasing concentration levels at the Water Tower Monitor: 1) elimination of the corner vortices; or 2) increasing the stack height. The industrial facility wanted to ensure that whatever mitigation option was selected would in fact reduce the measured concentrations below the 1-hr SO₂ NAAQS.

The conclusions of the study can be summarized as follows:

- For 2009 (the best data set), the wind tunnel (HYWINMOD) predictions of 4th highest maximum daily SO₂ concentration were within 8% (high sulfur coal) to 22 % (average % sulfur coal) of WTM observations. This confirmed that the use of the wind tunnel modeling results should provide a high degree of confidence in the method selected for mitigating the 1-hr NAAQS exceedance.
- Vortex mitigation methods decreased S09 impacts at the WTM on the order of 20%. The mitigation measure alone would be insufficient to bring the measured SO₂ concentration below the 1-hr NAAQS.
- Based on the wind tunnel modeling results (HYWINMOD) plus background, the worst case operating scenario, and 1998-2002 meteorological data, a 100 m stack will be needed to show compliance at the monitor with S09 and S11 operating.

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KEYWORDS

AERMOD, NAAQS compliance, building downwash, corner vortex, wind tunnel