Is AERMOD/PRIME Overpredicting for Short Buildings with a Large Footprint?

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ABSTRACT

The PRIME building downwash algorithm used in AERMOD was developed and tested for a range of building dimensions with relatively small aspect ratios of W/H = 0.33 to 1 and L/H = 0 to 4 where W, L and H are the building width, length and height. For short buildings with a large footprint (i.e., a large aspect ratio), AERMOD/PRIME concentration estimates may be not valid. This paper discusses an evaluation of one such facility, the Alcoa Davenport Works (DPW). The DPW is a complex of low, large attached structures with an average building height of 20 m, a width of 600 m and an overall length of 1700 m. The structure dimensions calculated by BPIP for input into the AERMOD/PRIME algorithm have aspect ratios (e.g., W/H and L/H) ranging from 5 to 50 - well outside the range for which PRIME was developed and tested. A wind tunnel modeling study was conducted to determine Equivalent Building Dimensions (EBD) for AERMOD/PRIME input for five stacks. The EBD values represent the building inputs for which PRIME was originally developed and tested. AERMOD was then run using these EBD for building dimension inputs and was compared to the concentration estimates using BPIP. The resulting maximum ground-level concentrations were over a factor of three lower using EBD. This paper discusses the methods used to obtain EBD as well as presents some evidence on why AERMOD with BPIP is overestimating ground level concentrations.

INTRODUCTION

In 1991 the American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee (AERMIC) was formed to introduce state-of-the-art modeling concepts into the EPA's air quality models. AERMOD, a modeling system that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts was developed. AERMOD includes the treatment of both surface and elevated sources, and both simple and complex terrain. For more information on the AERMOD modeling system see Cimorelli et al. (2005)[1]. In December 2006 AERMOD officially became the EPA prefered model for regulatory dispersion applications and replaced the predecessor ISC3. Since then AERMOD, has been improved continuously. One of the major enhancements of the preferred EPA dispersion model was the addition of the the PRIME building downwash algorthm to predict ground-level concentrations near structures more accurately.

The PRIME model incorporates enhanced plume dispersion due to the turbulent wake behind sharp-edged rectangular buildings and reduced plume rise due to descending streamlines behind these obstacles and entrainment of the plume in the building cavity[2]. PRIME calculates fields of turbulence intensity and wind speed, as well as the local slope of the mean streamlines as a function of the building dimensions, and coupled with a numerical plume rise model, determines the change in plume centerline location with downwind distance. For this study it is assumed that AERMOD/PRIME with the advanced building downwash and plume rise capabilities produces accurate concentration estimates, if the correct building dimensions are input.

This study focusses on an industrial facility with low building heights and a large footprint - Alcoa Davenport Works (DPW). The DPW is a complex of low, large attached structures located adjacent to the Mississippi River near Davenport, IA. The plant has a length of about 1700 meters parallel to the river and 600 meters perpendicular to the river. The building heights are generally about 15-20 meters above grade. A photograph of the facility is shown in Figure 1.

Figure 1: Aerial photograph of the Alcoa Davenport Works facility.

AERMOD/PRIME was run for the facility and high ground-level concentrations near the property line were predicted. The predictions showed that five short stacks on the facility cause the largest contributions to the highest calculated ground-level concentration fields. Closer examination of the problem revealed unreasonalby large building dimension inputs into AERMOD/PRIME that fall outside the range for which PRIME was developed. Therfore a wind tunnel study was conducted to determine equivalent building dimensions (EBD) to input into AERMOD/PRIME.

This paper first describes current methods to determine building dimensions for input into AERMOD. Then, the wind-tunnel methodology is summarized. The AERMOD/PRIME maximum ground-level concentration results using both EBD and BPIP values are compared for the five stacks of concern. A more detailed analysis compares ground-level concentration using EBD and BPIP to wind-tunnel results. Finally, conclusions and potential future work are described.

THEORETICAL CONSIDERATIONS

Flow fields around isolated rectangular or block shaped obstacles are qualitatively well understood[3]. As the main flow approaches a rectangular building it decelerates longitudinally and accellerates laterally and vertically to pass around the obstacle. At the leading edge of the building roof and sides the flow seperates, creating recirculation zones. If the obstacle is long enough the seperated streamlines reattach on the roof and the sides of the building. Seperation occurs again at the trailing edges of the obstacle. The seperation streamlines for both cases curve inward downwind of the obstacle creating the building cavity. This ellipsoidal-shaped recirculation zone immediately behind the obstacle is characterized by low mean wind speed and high turbulence intensity[3]. The entrainment of even only part of an exhaust plume into the building cavity region causes high ground-level concentrations.

The effects of obstacles in flow fields have been examined in multiple field and wind tunnel studies[4]. Through dimensional analysis Hosker[3] determined that for a simple flow the length of the building cavity is only a function of the obstacle dimensions - the building width, length and height (W,L,H). However, due to the chaotic nature of the problem only empirical equations for building cavity dimensions have been developed[5,6,7]. These empirical equations are only valid for idealized sharp-edged rectangular obstacles oriented normal to the approach flow.

The equations used in PRIME to calculate the building recirculation cavity dimensions can be found in Schulman[2]. These dimensions are a function of the building height (H), the projected building width across the flow (W) and the projected building length along the flow (L). However, PRIME was developed and tested using wind-tunnel data for a specific range of building dimensions with relatively small aspect ratios of W/H=0.33 to 1 (W=L) and L/H=0 to 4 (W=H). These limitations are reflected in the building cavity dimension equations. To calculate the length of the downwind cavity, for example, length to height ratio of the building is limited to $0.3 \leq L/H \leq 3$. In case the building dimensions fall outside this range, the nearer limit is used. Ellipse segments are used to calculate the height and width of the cavity envelope as a function of downwind distance of the building. However, in these calculations the building width is capped at eight times the building height or vice versa. No studies have been conducted on how accurate these limits are in case building dimensions fall outside the indicated ranges.

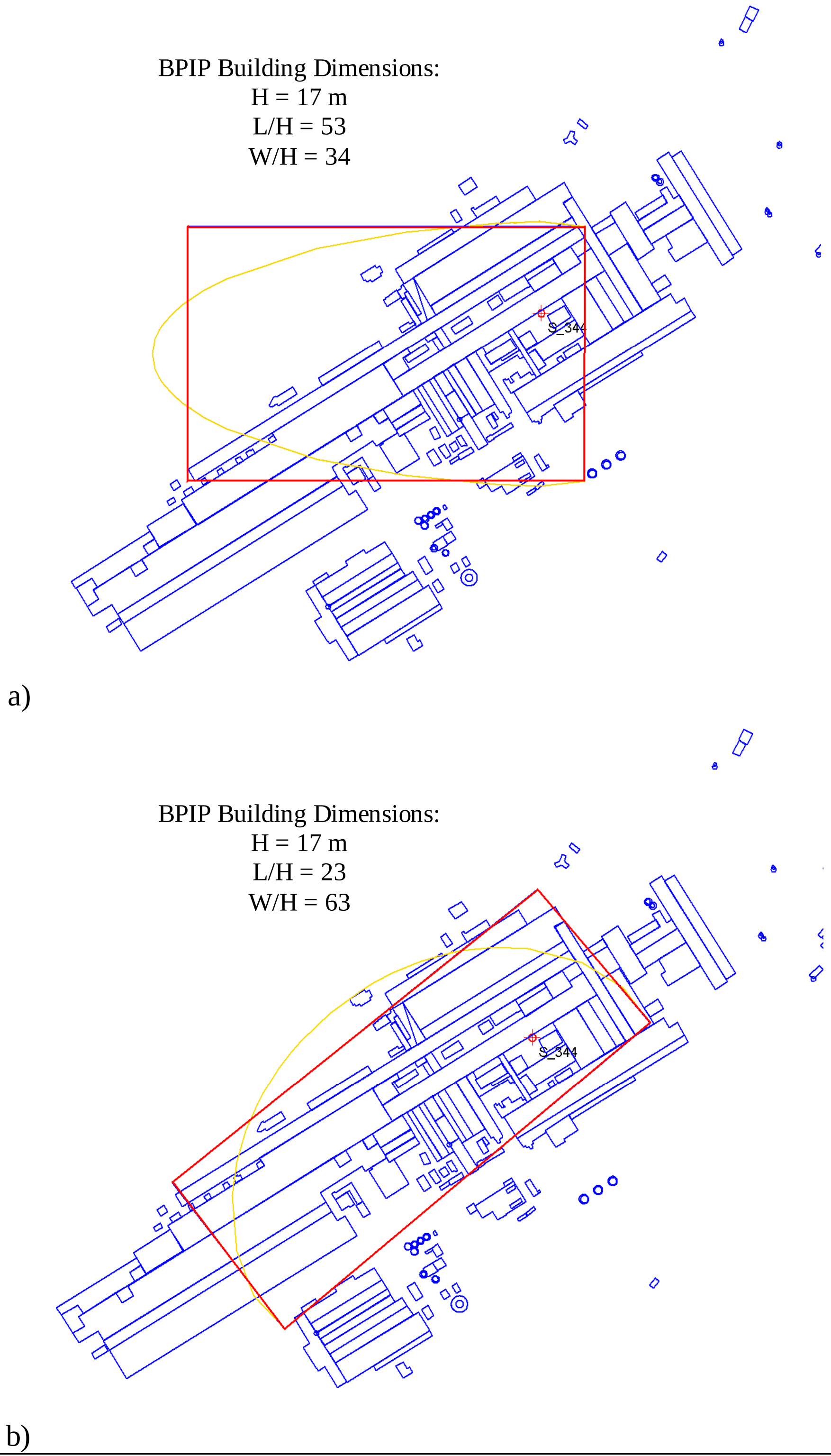
BPIP building dimensions

To convert real buildings with multiple tiers and complex architecture into idealized rectangular shaped obstacles that are always oriented normal to the wind the Building Profile Input Program (BPIP)[8] was developed. BPIP first identifies stacks that could be influenced by wake effects from by nearby structures. Then, for every stack of concern BPIP determines the projected width, length, height and position of the dominant structure for every direction, merging adjacent buildings into a single massing if appropriate.

AERMOD/PRIME uses these BPIP building dimensions for the building downwash algorithm. However, PRIME was only developed and tested for a range of building dimensions with relatively small aspect ratios, as mentioned above.

Figures 2a and b illustrate the BPIP building dimensions for the DPW facility for wind directions of 90 and 140 degrees for stack S-344.

Figure 2: DPW facility (blue), BPIP building dimensions (red) for stack S-344 (red) and horizontal envelope of the building cavity calculated by PRIME (yellow) for a) a wind direction of 90 degrees; and b) a wind direction of 140 degrees.

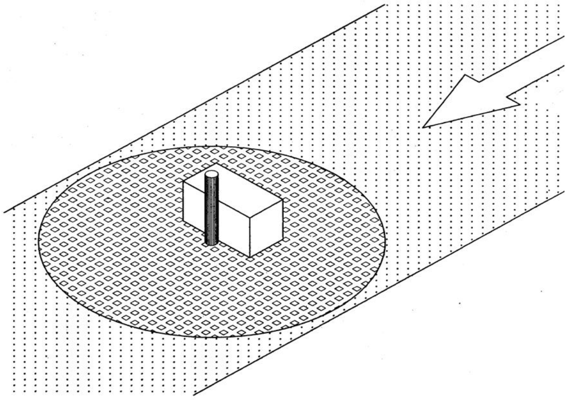


The DPW facility buildings are displayed in blue. The BPIP bilding dimensions for the specific direction are displayed in red. For a wind direction of 90 degrees the BPIP building height was calculated to be 16.6 m. With a length to height ratio of L/H=53 and a width to height ratio of W/H=34 the BPIP building dimensions fall outside of the dimensions used to develop and test PRIME. The same holds true for the 140 degree wind direction, with a BPIP building height of H=16.6 m, a length to height ratio of L/H=23 and a width to height ratio of W/H=63. The other wind directions yield similar results. With these building dimensions, the horizontal envelope of the building cavity was calculated using the PRIME equations. The cavity envelope for both wind directions is shown in yellow in Figures 2a and b. Due to the limitations in the PRIME equations discussed above, the cavity size is smaller than the BPIP building.

Determination of Equivalent Building Dimensions (EBD)

To determine equivalent building dimensions in the wind tunnel, the basic modeling approach is to first document the dispersion characteristics as a function of wind direction at the site with all significant nearby structure wake effects included. Next, the dispersion is characterized, in the wind tunnel, with an equivalent rectangular-shaped building positioned directly upwind of the stack in place of all nearby structures (i.e., the setup as shown in Figure 3).

Figure 3: Equivalent building and stack configuration in wind tunnel.



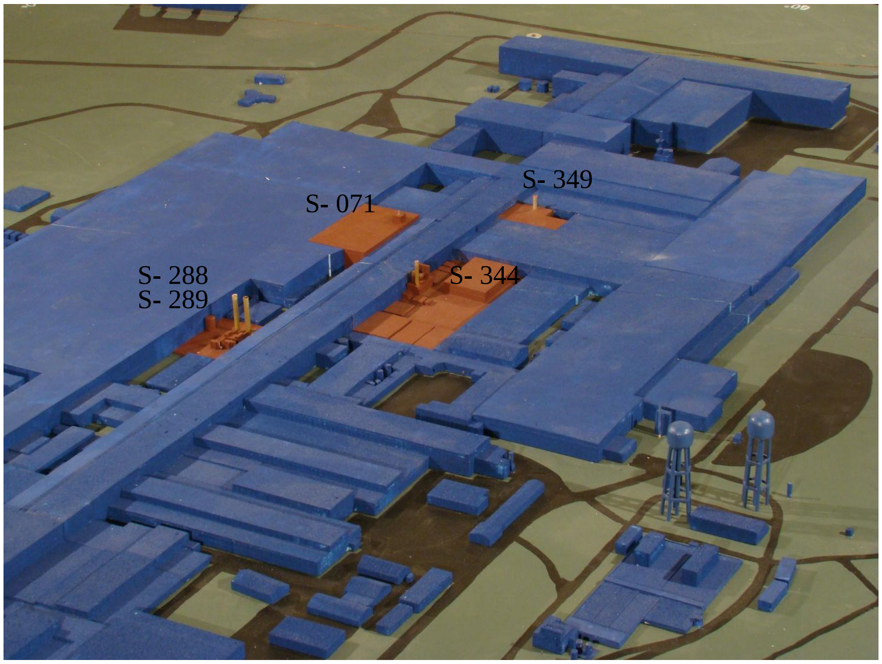
This testing is conducted for various equivalent buildings until an equivalent building is found that provides a profile of maximum ground level concentration versus downwind distance that is similar to that with all site structures in place. The similarity constraints are descibed in Petersen and Reifschneider[9].

METHODOLOGY

Wind Tunnel Modeling

A 1:400 scale model of DPW and surrounding structures and terrain was constructed. The model included all significant structures (i.e., structures whose critical dimension, lesser of height or width, exceeds 1/20th of the distance from the source) within a 732 m (2266.7 ft) radius of the center of the stacks of concern at the DPW facilities. A photograph of the model is shown in Figure 4.

Figure 4: Photograph of the DPW model in the wind tunnel. The brass tubes at the center of the facility are the five stacks evaluated in this study.



The five stacks evaluated in the wind tunnel are designated S-071, S-288, S-289, S-344 and S-349. Source parameters are listed in Table 1.

Table 1. Full-scale Exhaust and Modeling Information

Source ID	Source Height Hs (m)	Stack Inside Diameter d (m)	Stack Exit Velocity V (m/s)	Stack Exit Temperature Ts (K)	Volume Flow Rate (m^3/s)	Emission Rate (g/s)
S-071	23.16	1.07	17.8	294.1	15.9	0.2
S-288	26.33	2.74	11.1	315.2	65.7	1.6
S-289	26.33	2.74	11.4	310.8	67.3	1.6
S-344	25.91	2.24	17.9	302.4	70.4	1.2
S-349	21.34	2.46	17.8	310.9	85.0	1.9

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 were obtained from dimensional arguments derived from the basic equations governing fluid motion. For this study the Momentum ratio in full scale and in the model was matched. A detailed discussion on similarity requirements is given the EPA fluid modeling guideline[10]. Additionally, Reynolds number independence was ensured: Reynolds number independence tests were conducted to determine the minimum acceptable operating speed for the wind tunnel.

To determine the equivalent building dimensions, the site model was removed and replaced by roughness elements (see Figure 3). A set of solid structures, all with height to width ratios similar to those used by Huber and Snyder[4], was fabricated for placement directly upwind of each stack. These structures were used to determine the equivalent building dimensions as mentioned above. Since AERMOD is not limited to this building shape or positioning, other building shapes/positions were also investigated as appropriate to obtain the best match for the case when all site structures are present.

Detailed features and operational characteristics of CPP's environmental wind tunnel are described by Petersen and Reifschneider[9]. The test section of the open circuit wind tunnel has a length of 22.7 m and a width of 3.7 m. A trip and spires at the entrance of the wind tunnel as well as roughness elements placed in a repeating pattern on the floor of the tunnel ensured that neutral atmospheric boundary layer was established.

To accurately represent 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 DPW site were specified using AERSURFACE[11] with a 3 km radius. Two approach flows were necessary; a low roughness approach with a z_o of 0.084 m representing the Mississippi river to the south and east of DPW and a hight roughness approach with a z_o of 0.74 m due to the industrial and suburban areas to the southwest of the facility. The uniform roughness for the equivalent building tests was constructed such that it provided approximately the same surface roughness as the test site, i.e. the area within the 732 m (2266.7 ft) radius of the center of the stacks of concern at the DPW facilities. Again, AERSURFACE was used to determine this surface roughness.

The wind speed for all concentration tests was set at the 2% wind speed, as has been the practice in past EBD studies[9]. The 2% wind speed for DPW was based on meteorological observations at the Moline Airport 10.0 m (32.8 ft) anemometer for the period of 2000-2004. The anemometer is located approximately 6 miles south of the DPW facilities. The 2% wind speed is 9.0 m/s (20.1 mph) at the anemometer.

Concentration sampling taps were installed on the surface of the model so that at least 47 locations were sampled simultaneously for each simulation. A typical sampling grid consists of 9 receptors located in each of 5 rows that are spaced perpendicular to the wind direction. Two background samples are located upwind of the stacks. The lateral and longitudinal spacing of receptors was designed so that the maximum concentration was defined in the lateral and longitudinal directions.

AERMOD/PRIME Modeling

The AERMOD/PRIME model was run in regulatory default mode with the source parameters given in Table 1. The simulation was conducted with rural dispersion coefficients, flat terrain and the building downwash option turned on. One year of surface and upper air meteorological data from the Moline Airport and a uniform cartesian grid with 3600 receptors was used.

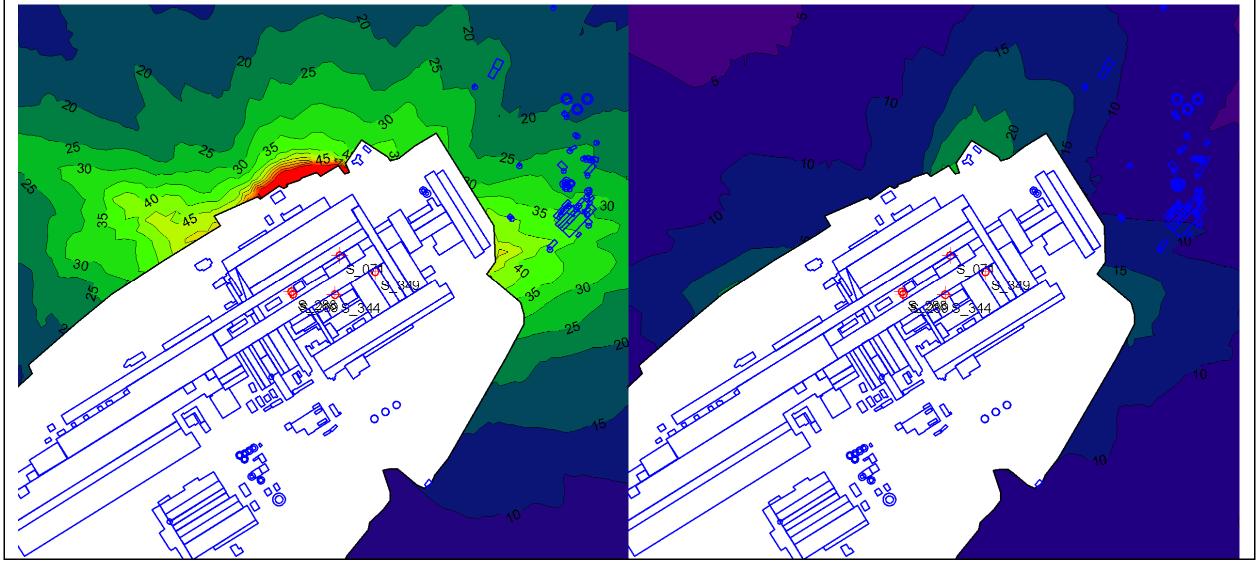
With these model configurations, AERMOD/PRIME was first run with the standard BPIP building dimensions to obtain 4th highest maximum 24-hr PM10 concentration estimates at each receptor. Then, the BPIP building dimensions were replaced by the EBD determined by the wind-tunnel study to detemined more accurate 4th highest maximum 24-hr PM10 estimates.

Additionally, AERMOD/PRIME was run for stack S-288 for the wind directions and wind speeds simulated in the wind tunnel with BPIP and EBD building dimension inputs. Surface and upper air observations with near neutral stability and desired wind conditions were selected and used for this analysis. An emission rate of 1 g/s was used and a uniform polar grid with approximately 1700 receptors ensured that maximum concentration profiles were captured. The purpose of these runs was so that AERMOD/PRIME predictions with BPIP and EBD could be compared to the wind tunnel observations.

RESULTS

The 4th highest 24-hour maximum ground level PM10 concentrations calculated for the DPW facility by AERMOD/PRIME for both the BPIP building input and EBD input are shown in Figure 5. The maximum ground-level concentrations for the BPIP case is 97.0 µg/m^3 almost a factor of four higher than the maximum ground-level concentrations for the EBD case (27.3 µg/m^3).

Figure 5: AERMOD/PRIME 4th highest 24-hr PM10 concentration results for BPIP building inputs (right) with a max. ground-level concentration of 97.0 µg/m^3 and EBD inputs (left) with a max. ground-level concentration of 27.3 µg/m^3.



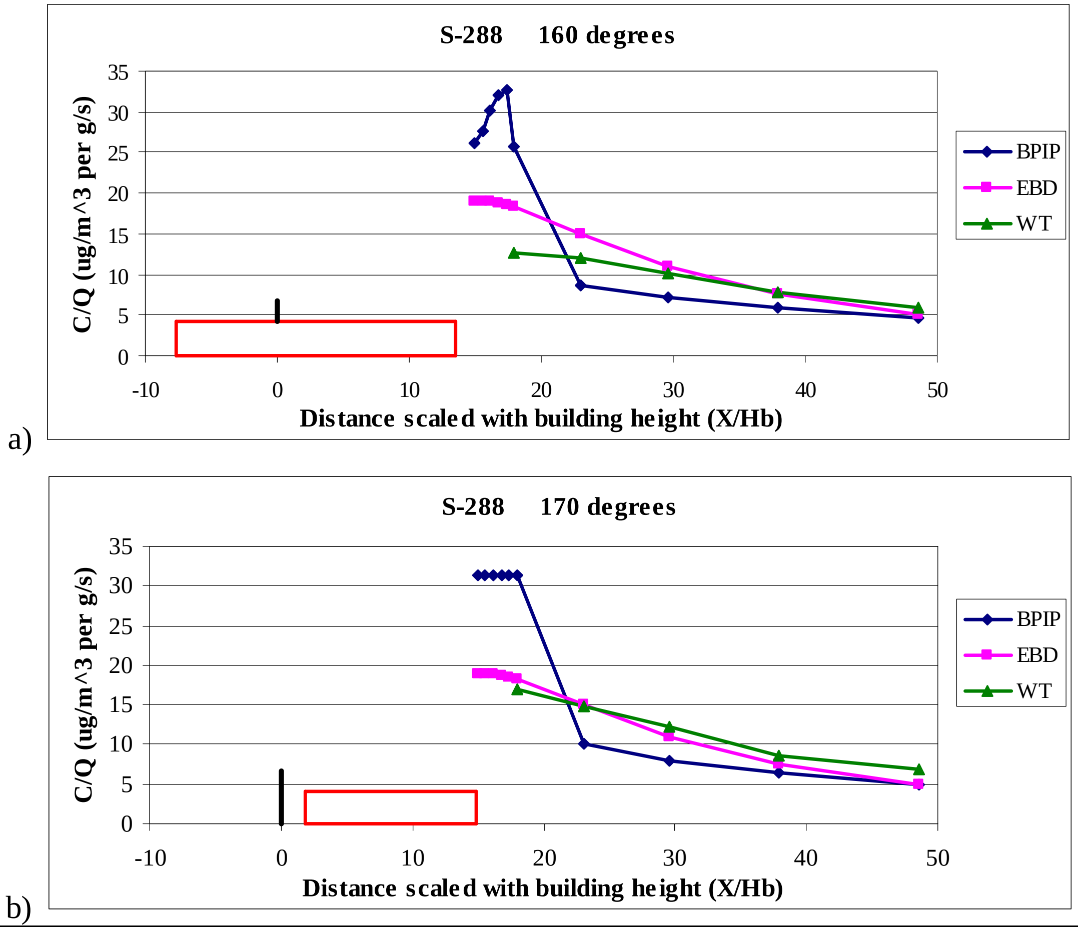
As mentioned above, a refined analysis of building downwash characteristics in AERMOD was conducted for stack S-288. In the wind-tunnel simulations for stack S-288 no building downwash was found for most wind directions, including 160 and 170 degrees. Therefore, no building dimension inputs into AERMOD/PRIME are necessary for these directions. Table 2 lists the BPIP and EBD building inputs for 160 and 170 degree wind directions.

Table 2. Comparison of BPIP and EBD inputs for stack S-288

Wind direction:	160		170	
AERMOD/PRIME building dimension input	BPIP	EBD	BPIP	EBD
Building height H	16.71 m	0 m	16.71 m	0 m
Building width W	488.22 m	0 m	381.38 m	0 m
Building length L	353.81 m	0 m	217.04 m	0 m
Along flow position XBADJ	-128.35 m	0 m	30.24 m	0 m
Across flow position YBADJ	-85.82 m	0 m	-44.17 m	0 m

Figures 6a and b show normalized maximum ground-level concentrations with distance from stack S-288 for the wind directions of 160 and 170 degrees.

Figure 6: Comparison of AERMOD/PRIME ground-level concentration results for BPIP inputs (blue) and EBD inputs (pink) with the wind-tunnel (WT)ground-level concentration results with site structures in place. The stack location is shown in black and the BPIP building location is shown in red.



AERMOD/PRIME results using BPIP (blue) and EBD (pink) are compared to the wind-tunnel results with site structures in place (green). The stack location (black) and the BPIP building location and length (red) are indicated. Stack and building heights are not drawn to scale.

For both wind directions shown, AERMOD/PRIME with BPIP building inputs predicts the highest ground-level concentrations directly downwind of the idealized BPIP building. With increasing distance from the stack the ground-level concentrations drop off sharply. AERMOD/PRIME with EBD input and the wind-tunnel results show lower maximum concentrations, however, the concentrations do not drop off as rapidly with distance. At a distance of 23 to 40 building heights from the stack the AERMOD/PRIME predicted concentrations using EBD are actually higher than the predicted concentrations using BPIP building dimensions. The figures also show that AERMOD/PRIME with EBD inputs agrees well with the wind tunnel observations.

CONCLUSIONS

Equivalent building dimensions (EBD) for input into AERMOD/PRIME for a facility with short buildings with a large footprint - Alcoa Davenport Works (DPW) - were determined in the wind tunnel. AERMOD was then run with BPIP and EBD building dimension inputs. Maximum ground-level concentrations for both model runs as well as the wind-tunnel data were compared.

As a result of the study, the following conclutions can be drawn.

- AERMOD with BPIP building dimension inputs overpredicts maximum ground-level concentrations for short buildings with a large footprint within approximately 20 building heights downwind of the facility.
- AERMOD predictions can be reduced and improved by using the wind tunnel to determine equivalent building dimensions (EBD) for input into AERMOD in place of BPIP.
- Beyond approximately 30 building heights, the difference between AERMOD predictions with BPIP and EBD building dimension inputs becomes less significant.
- The use of EBD for short buildings with a large footprint has the potential for significantly decreasing the predicted maximum concentration thus decreasing the resulting emission control or other mitigation (e.g., taller stacks) that may be needed.

A significant amount of additional work and research is needed in order to make the BPIP program work correctly for this type of building. Until BPIP can correctly specify the building dimensions, a wind-tunnel study should be conducted to determine EBD for input into AERMOD/PRIME especially when more accurate concentration estimates are needed.

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KEY WORDS

Building Downwash, Exhaust Dispersion, Equivalent Building Dimensions