Improved Building Dimension Inputs for AERMOD Modeling of the Mirant Potomac River Generating Station

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ABSTRACT

This paper describes a wind tunnel modeling study conducted for the Mirant Potomac River Generating Station (MPRGS) located in Alexandria, Virginia. The study was commissioned because a screening-level model indicated potential for plume impacts at a nearby uniquely-shaped high-rise building within a few hundred meters of the station, constructed long after the station started operation in 1949. Due to the complex interaction between the two buildings, both a computer dispersion modeling study using AERMOD and a wind-tunnel modeling study were undertaken to help answer questions about potential impacts. The wind-tunnel study was conducted to obtain a better understanding of the concentration spatial distribution on and around the high-rise building and to provide site-specific building dimension inputs (i.e., Equivalent Building Dimensions or EBD) for AERMOD, to account for the complex building interactions in a form that AERMOD could handle. The study also had the important goal to help MPRGS design modifications to the plant that would help reduce potential ambient impacts on the high-rise building and other areas in the vicinity of the plant.

INTRODUCTION

This paper describes a wind tunnel study conducted for the Mirant Potomac River Generating Station (MPRGS) located as shown in Figure 1. The study was commissioned by Mirant because a USEPA recommended computer dispersion model, AERMOD[1], predicted high impacts of plant emissions on a nearby high-rise tower (Marina Towers) as shown in Figure 2. The tower was built near the plant without the benefit of site-specific modeling or a wind tunnel study in the 1970s, long after the MPRGS was built in 1949. The heights of the stacks at MPRGS were restricted due to the proximity of the power plant to Reagan National Airport.

Since AERMOD was predicting high concentration levels on the Marina Towers (MT) and at various ground level locations surrounding MPRGS, a wind tunnel study was undertaken to obtain a better understanding of the concentration spatial distribution on and around MT and to provide site-specific building dimension inputs for AERMOD.[2]

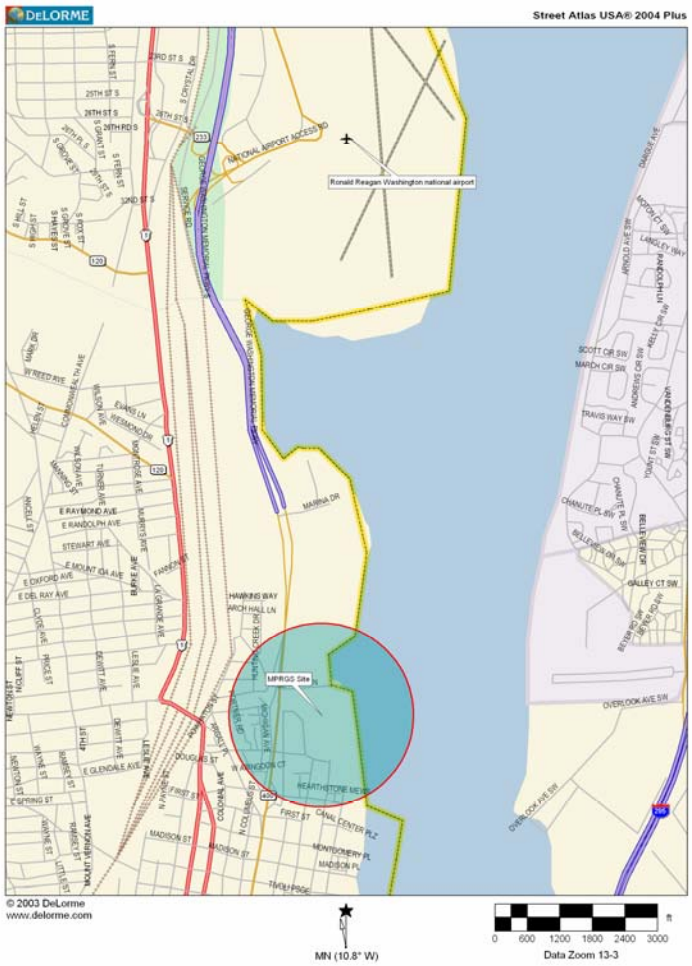

Figure 1. Location of area modeled in wind tunnel

Since AERMOD has advanced building downwash and plume rise modeling capabilities, it was anticipated that if the "correct" building dimensions are input into the model it will produce accurate concentrations estimates. The EBD values are the building height, width, length and position that should be input into AERMOD to allow the model to produce an accurate representation of concentration spatial distributions due to all site building wake effects. When a single solid rectangular building is adjacent to a stack and the wind flow is perpendicular to a building face, the actual building dimensions are the appropriate inputs. An estimate of these dimensions for each wind direction is normally determined using the Building Profile Input Program (BPIP). For more complicated situations, such as for this application, the use of EBD values for model input will result in more accurate concentration estimates, and hence, an optimal determination of any required mitigation.

The only practical manner for determining EBD is through the use of wind tunnel modeling.[3,4,5,6,7] To conduct the wind tunnel simulations, a detailed physical model of MPRGS and nearby structures (including MT) was created to test their impacts on plume dispersion. The wind tunnel testing was divided into two main phases for both the current and future design of the MPRGS: EBD determination for predicting ground-level impacts; and EBD determination for determining MT impacts. For the first phase of testing, EBD values were determined to account for the combined effect of MT and the MPRGS. The second phase of testing involved obtaining EBD values for characterizing the impact on MT due to the effect of MPRGS. These EBD values were used as an input for AERMOD to obtain a better representation of building effects on concentration estimates on MT and at ground level.

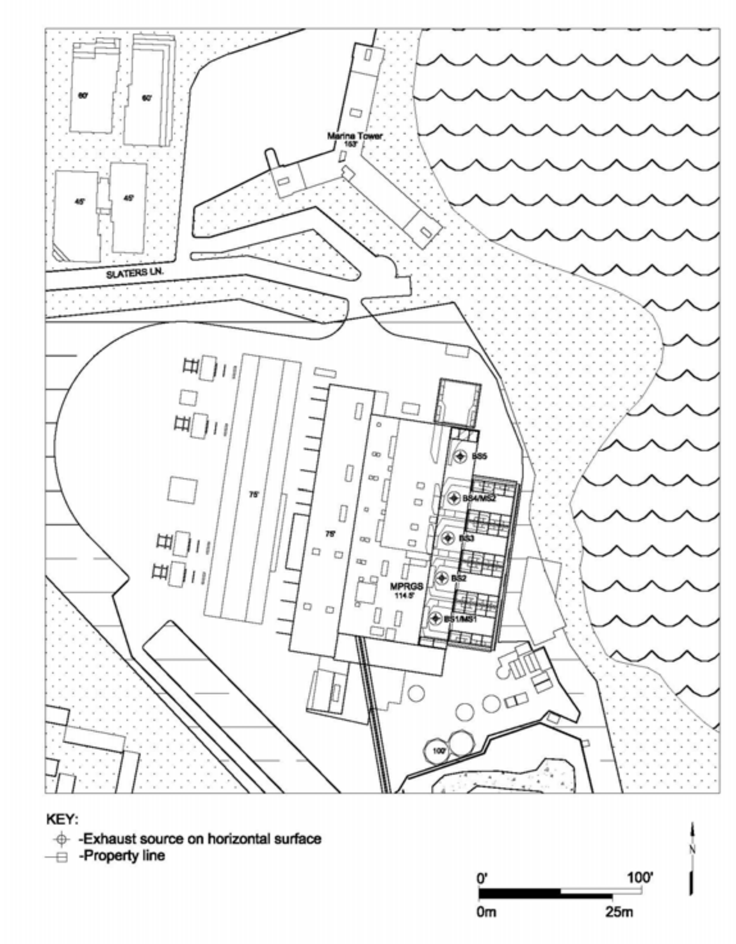

Figure 2. Close up view of area modeled

This paper focuses on the methods used to obtain the EBD and provides a comparison between the EBD and BPIP determined building dimension inputs values. The general use of the EBD values in AERMOD is discussed in a paper by Petersen.[8] The use of the EBD values developed in this study for AERMOD application is discussed in Shea.[9]

SIMILARITY REQUIREMENTS

To model plume trajectories for the EBD determinations, the velocity ratio, R (V_e/U_h), and density ratio, λ (ρ_s/ρ_a) were matched in model and full scale where 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), and ρ_a = ambient air density (kg/m^3). In addition, the stack gas flow in the model was fully turbulent upon exit as it is in the full scale.

To simulate the airflow and dispersion around the buildings, the following criteria were met as recommended by EPA[10]: 1) all structures within a 518-m (1700-ft) radius of the stacks were modeled at a 1:300 scale reduction; 2) appropriate mean and turbulent approach boundary layer was established; 3) building Reynolds number independence was verified through testing; 4) a neutral atmospheric boundary layer was established simulating an approach surface roughness of 0.79 m for wind directions of 175-360 (urbanized sector) and 0.15 m for all other wind directions (water and low roughness sector).

The above scaling parameters were used to determine the model operating conditions. It should be noted that the use of these scaling parameters is the recommended method for determining GEP stack heights by EPA[11] and have been used on past EBD studies. The use of these scaling parameters does not include an exact simulation of full buoyancy, and as a result, full-scale plume rise is underestimated (i.e., a conservative scaling approach). If one wants to compare the wind tunnel results with AERMOD, the full scale source parameters have to be back calculated from the conditions set in the wind tunnel by using the appropriate buoyancy and momentum scaling method.[10] These full scale conditions are provided in Table 1.

Table 1. Model Inputs

Exhaust Stack Parameters

Source ID:	Existing Boilers		Future Merged Boilers*	
	BS1, BS2	BS3, BS4, BS5	MS1	MS2
Exit Diameter, d (m)	2.59	2.44	2.59	3.05
Stack Height, H_s (m)	48.2	48.2	48.2	48.2
Exit Temperature, T_s (K)	304.9	303.7	304.9	303.7
Volume Flow Rate, V (m^3/s)	111.5	86.0	223.1	257.9
Exit Velocity, U_s (m/s)	21.2	18.4	42.3	35.4
* MS1 consists of merging the BS1 and BS2 exhaust in to the BS1 exhaust flue and MS2 consists of merging BS3, BS4 and BS5 exhausts into the BS4 exhaust flue.				

Ambient Parameters

Wind Direction	1-174	175-360
Stack Height Wind Speed, U_h (m/s)	12.52	10.8
Approach Roughness, z_o (m)	0.15	0.79
Ambient Temperature, T_a (K)	298.15	298.15

DETERMINATION OF EBD VALUES

Ground Level

The basic modeling approach for determining EBD values is to first document, in the wind tunnel, 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 building positioned directly upwind of the stack in place of all nearby structures. 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 (within the constraints defined below) to that with all site structures in place.

The criteria for defining whether or not two concentration profiles are similar is to determine the smallest building which: 1) produces an overall maximum concentration exceeding 90 percent of the overall maximum concentration observed with all site structures in place; and 2) at all other longitudinal distances, produces ground-level concentrations which exceed the ground-level concentration observed with all site structures in place less 20 percent of the overall maximum ground-level concentration with all site structures in place.

To demonstrate the method for specifying the EBD values, consider Figure 3 which shows a typical result from this study. The figure shows the maximum ground-level concentration versus downwind distance for five different equivalent buildings and the maximum concentration measured with site structures in place. Within this figure, the concentration profile for EBD 11.5 meets the first criterion in that the maximum measured concentration is at least 90 percent of the maximum concentration measured with the site structures in place. (Note, the 11.5 is building height in model centimeters. Multiple by 3 to obtain the full-scale height in meters). However, the EBD 11.5 profile fails the second criterion at the third actual site data point (at approximately 180 m downwind) where the lower bound of the error bar exceeds the interpolated concentration value for EBD 11.5. Therefore, the equivalent building for the test case shown in Figure 3 is EBD 12, since EBD 12 is the smallest equivalent building which meets both criteria.

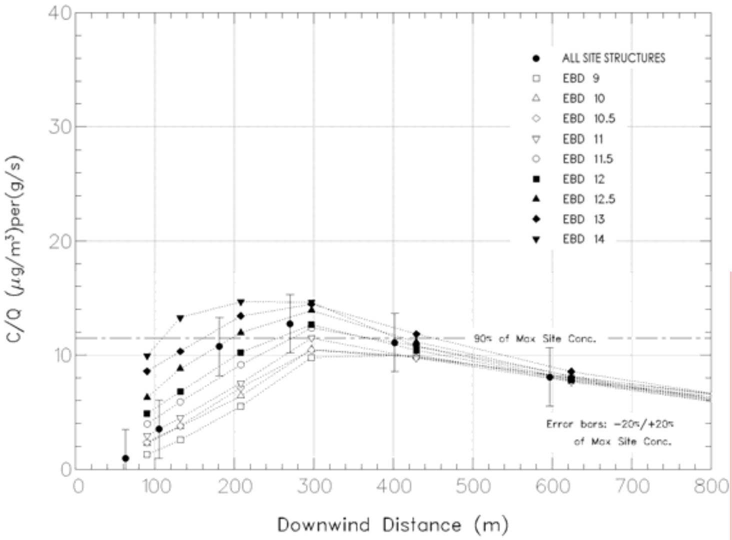

Figure 3. Typical Ground Level EBD Results for BS4

Marina Towers

In addition to traditional ground-level EBD values for the purpose of predicting ground-level impacts, EBD values were also determined to serve as an AERMOD input when the impact of MPRGS on MT is being evaluated. In this case, the approach for determining EBD values was to first document, in the wind tunnel, the concentration levels as a function of wind direction on MT with all significant nearby structure wake effects included. For testing with the EBD structures, the MPRGS and MT were removed, but the rest of the site remained the same (i.e., surrounding buildings, terrain, etc.) MT was replaced with a "flag pole" receptor grid with sampling points at the same locations as those obtained when MT was in place to replicate the way the receptors are represented in the AERMOD model. Then, the stack under evaluation was placed in its respective location with the same height above grade. Various EBD structures were then placed directly upwind of the stack of interest.

The determination of EBD values for the impact on MT is similar to that described in the previous section with the exception of the type of data profile evaluated. For this phase of EBD determination, the data points were ranked from largest to smallest for the site structures and EBD tests. The site structure profiles were then compared with the EBD profiles for EBD determination. The criteria for defining whether two-ranked concentration profiles were similar was the same as that described above.

Figure 4 shows typical results from this study. Within this figure, the profiles for the EBD 8 1:4:1, EBD 9 1:2:1, EBD 9 1:4:1, and EBD 10 1:4:1 meet the first criterion in that the maximum measured concentration is at least 90 percent of the maximum concentration measured with all site structures in place. (Note: the three numbers following the building height, specify the building height to width to length ratios.)

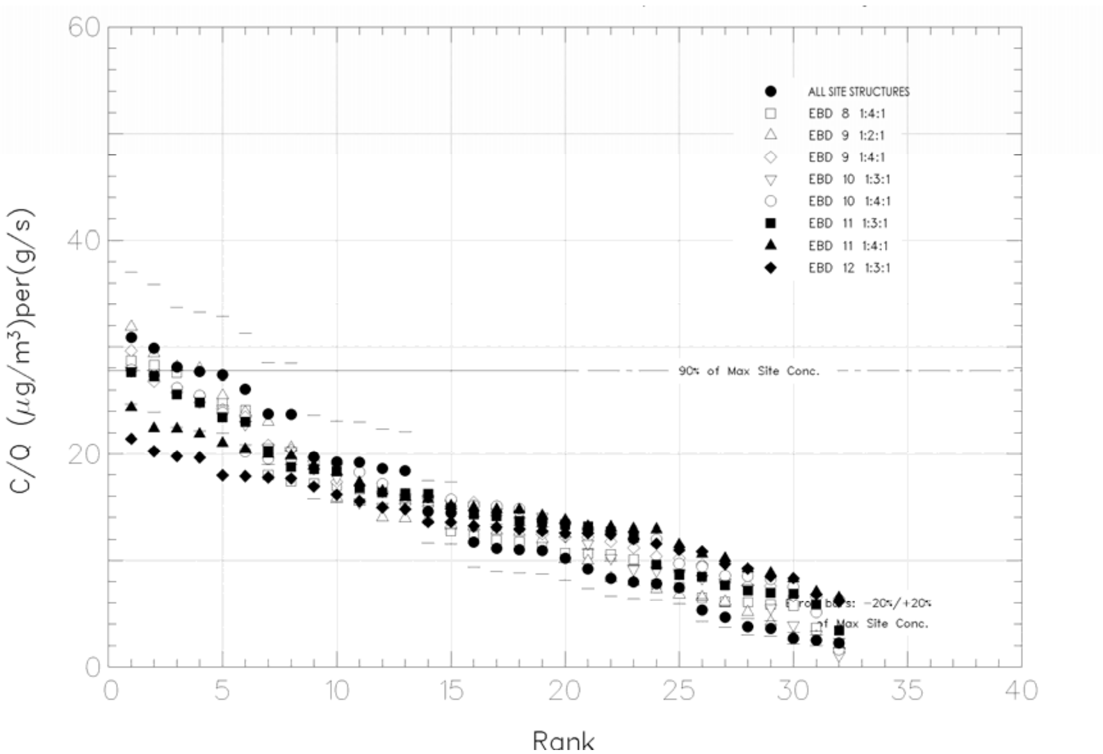

Figure 4. Typical Flagpole EBD Results for BS4 Stack with BS5 operating, 160 degree wind direction

However, EBD 8 1:4:1 and EBD 9 1:2:1 both fail the second criterion of 20 percent of the overall maximum ground-level concentration with all site structures in place. Of the two profiles that meet both criteria, the lowest value can be chosen as the EBD structure. Therefore, the EBD for this case is EBD 9 1:4:1 denoted by a white diamond.

MODEL CONSTRUCTION AND SETUP

A 1:300 scale model of the MPRGS and surrounding structures and terrain was constructed. The model included all significant structures within a 518-m (1700-ft) radius of the center of the MPRGS. A close-up of a portion of the area modeled is shown in Figure 2. The model was placed on a turntable so that different wind directions could be easily evaluated. Photographs of the model are provided in Figures 5, 6 and 7. Stacks were constructed of plastic and were supplied with a helium–hydrocarbon (or nitrogen-hydrocarbon) mixture of the appropriate density. Measures were taken to ensure that the flow was fully turbulent upon exit. Precision gas flow meters were used to monitor and regulate the discharge velocity.

A set of solid rectangular structures was fabricated for placement directly upwind of each stack for EBD testing. The structure shapes evaluated had height-to-width-to-length ratios of: 1:2:1; 1:3:1; and 1:4:1. For the ground-level EBD tests, the stacks in Table 1 and idealized buildings were tested with the turntable model removed from the wind tunnel and a uniform roughness installed in its place. The uniform roughness was constructed such that it provided the same surface roughness as the surroundings (i.e., 0.79 m for the urbanized approach, and 0.15 m for the water and lower roughness approach). For the ground-level EBD testing, concentration sampling taps were installed on the surface of the model so that at least 46 locations were sampled simultaneously for each simulation. A typical sampling grid consisted of 5 to 7 receptors located in each of 7 rows that were spaced perpendicular to the wind direction. Two background samples were 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.

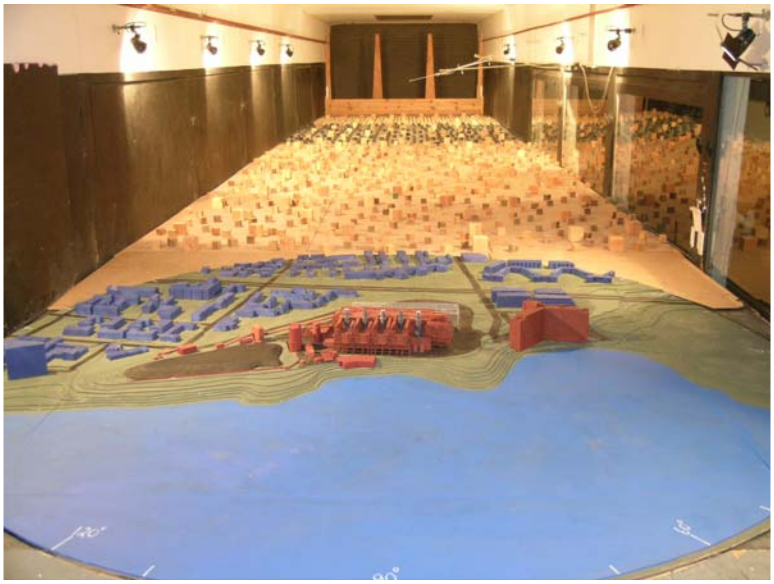

Figure 5. Photograph of model

For the site structures portion of MT testing, MT was instrumented with 46 sampling taps that closely matched the locations modeled with AERMOD (see Figure 6). Roof-top, side-wall and ground-level locations were evaluated. For the EBD portion of MT testing, a "flagpole" receptor grid was constructed such that sampling locations were the same as when MT was in place (see Figure 7). The same EBD structures were used for the EBD portion of MT testing, and were placed directly upwind of the stack evaluated on the model turntable with the MPRGS removed.

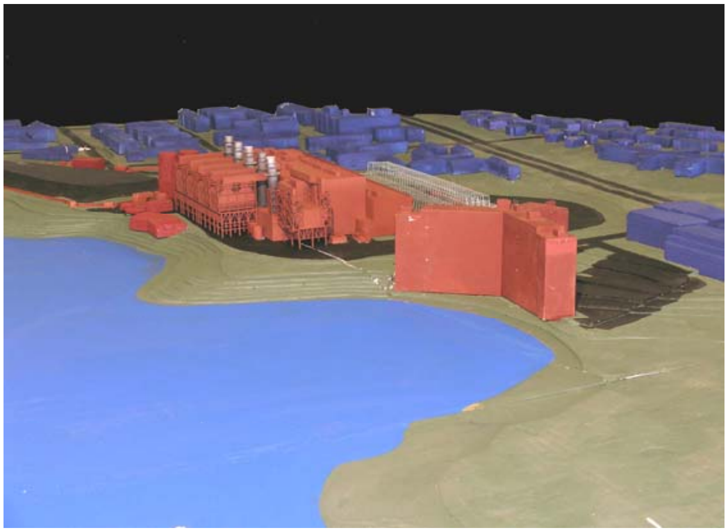

Figure 6. Close-up of all Site Structures

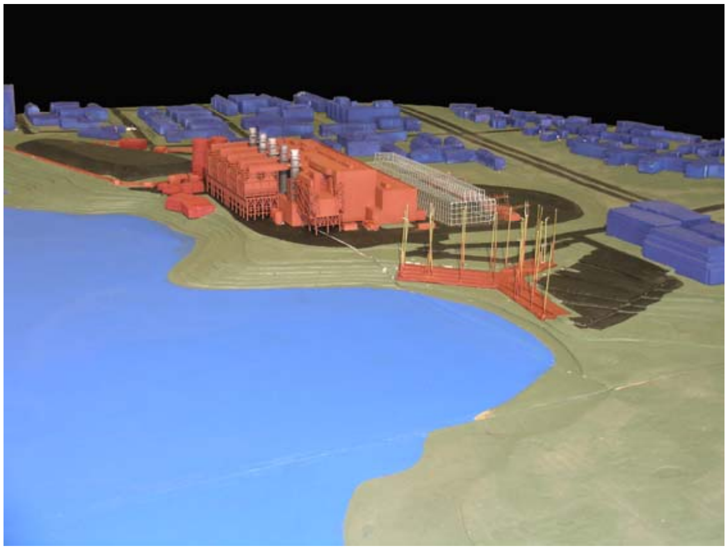

Figure 7. Close-up of Power Plant and Flagpole Receptor Grid

RESULTS

EBD Results - Ground Level

For the ground-level EBD portion of the study, wind tunnel tests were first conducted for the existing and merged exhaust stacks for the wind directions of interest with all site structures in place as shown in Figure 6. The full-scale exhaust information for the various exhausts is listed in Table 1. The MPRGS consists of five boiler exhaust stacks with stack identification labels of BS1, BS2, BS3, BS4, and BS5 representing stacks one through five as shown in Figure 2. The stacks, BS1/BS2, were simulated with the same source parameters (i.e., exit diameter, volume flow, temperature, etc.) while BS3/BS4/BS5 were simulated with the same source parameters.

Due to the proximity of the airport, MPRGS cannot significantly raise the stack heights to increase the plume height and escape building wake effects. However, it is possible to merge the exhaust streams to accomplish the desired objective of redesigning the plant to reduced impacts on the Marina Towers. Therefore, merged exhausts were evaluated at the stack positions normally occupied by stacks BS1 and BS4 having the stack identification labels of MS1 and MS2, as shown in Figure 2. MS1 represents combining the BS1 and BS2 exhausts through one merged-flue stack, while MS2 represents combining the BS3, BS4, and BS5 exhausts through another merged-flue stack.

Ground-level concentrations were measured at a minimum of 46 locations for each test. The receptor grid was designed so the maximum ground-level concentration versus downwind distance could be defined within acceptable uncertainty. The stacks, BS1/MS1 and BS4/MS2 were evaluated for wind directions of 10 through 360 degrees at ten degree increments.

For the next phase of the EBD determination for the various stacks, the site model was removed from the wind tunnel and replaced with a uniform roughness representative of the surface roughness of the actual site. Since this site has two roughness approaches, EBD had to be determined for both. For each test, a single rectangular building was placed upwind of the stack under evaluation and the maximum ground-level concentrations versus downwind distance were measured as described above. This process was repeated for various building shapes until an EBD was found that had a similar ground-level concentration profile as with all buildings present. The idealized rectangular structures (EBD structures) initially tested had height-to-width-to-length ratios similar to those used by Huber and Snyder[12,13] for development of the ISC2 downwash algorithm (H:W:L = 1:2:1). For cases where the traditional EBD did not provide an adequate concentration profile, alternate EBD configurations were assessed. For example, wider EBD structures with the ratios of "1:3:1","1:4:1", etc. were very effective. For certain cases, the best EBD configuration that resulted in the proper profile was with the EBD turned at a 45-degree angle to the approach flow resulting in a corner vortex bringing the exhaust plume downward. Unfortunately, AERMOD does not allow this type of configuration for input. Petersen[2] provides a listing of building dimensions that were evaluated and the values chosen for each exhaust stack and wind direction scenario evaluated.

To illustrate the difference between the BPIP and EBD determined building dimension inputs, only the results for BS4 will be discussed in detail. The variation in building dimensions and building location versus wind direction for the two methods are shown in Figures 8-12.

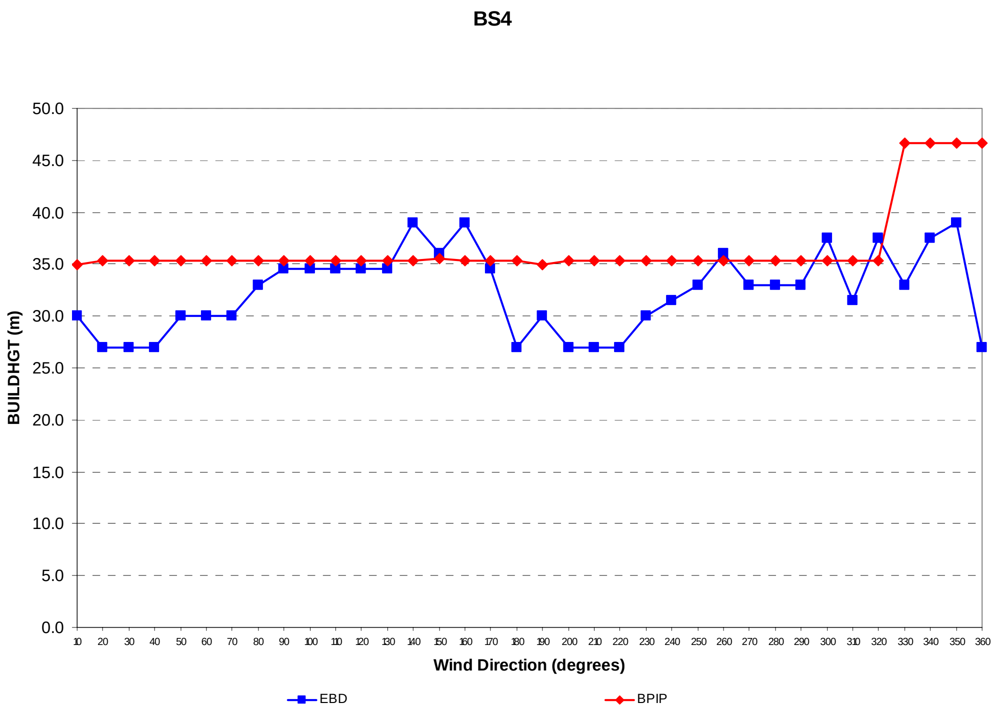

Figure 8. Building height, BUILDHGT, determined using BPIP and EBD methods

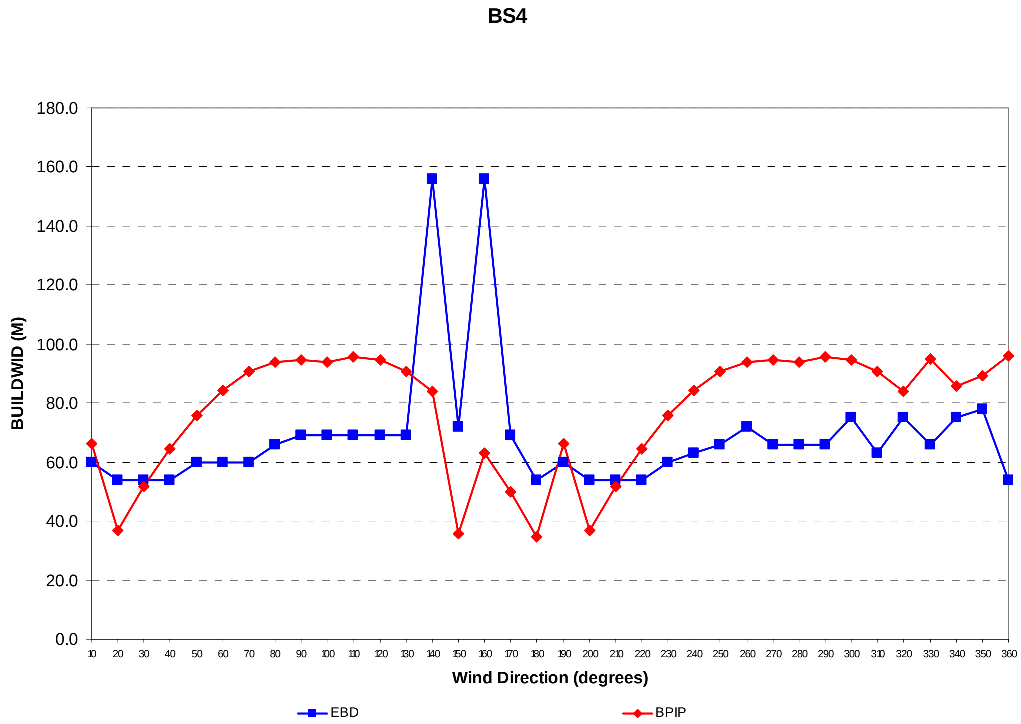

Figure 9. Building width, BUILDWID, determined using BPIP and EBD methods

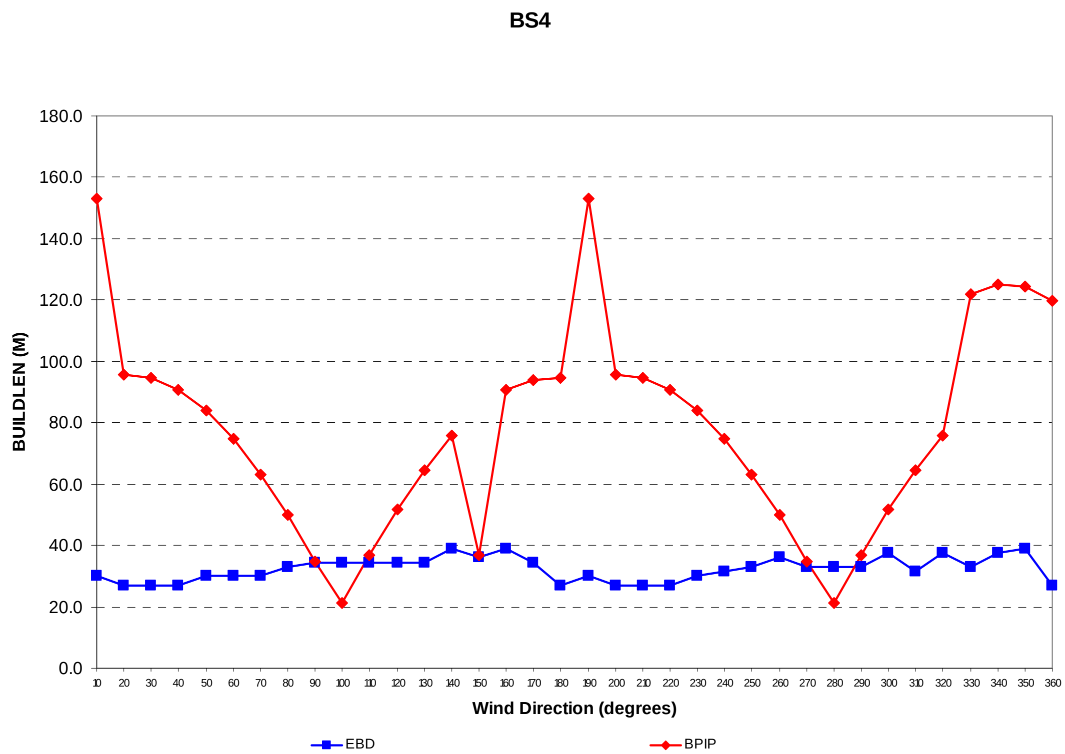

Figure 10. Building length, BUILDLEN, determined using BPIP and EBD methods

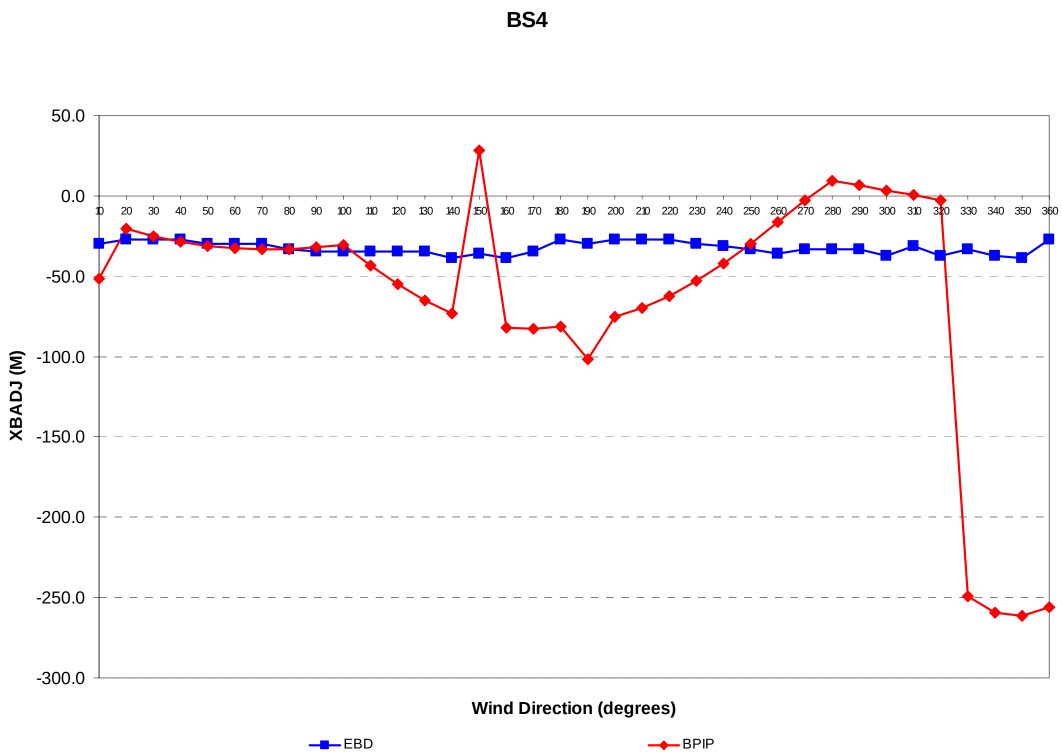

Figure 11. Building position in X direction, XBADJ, determined using BPIP and EBD methods

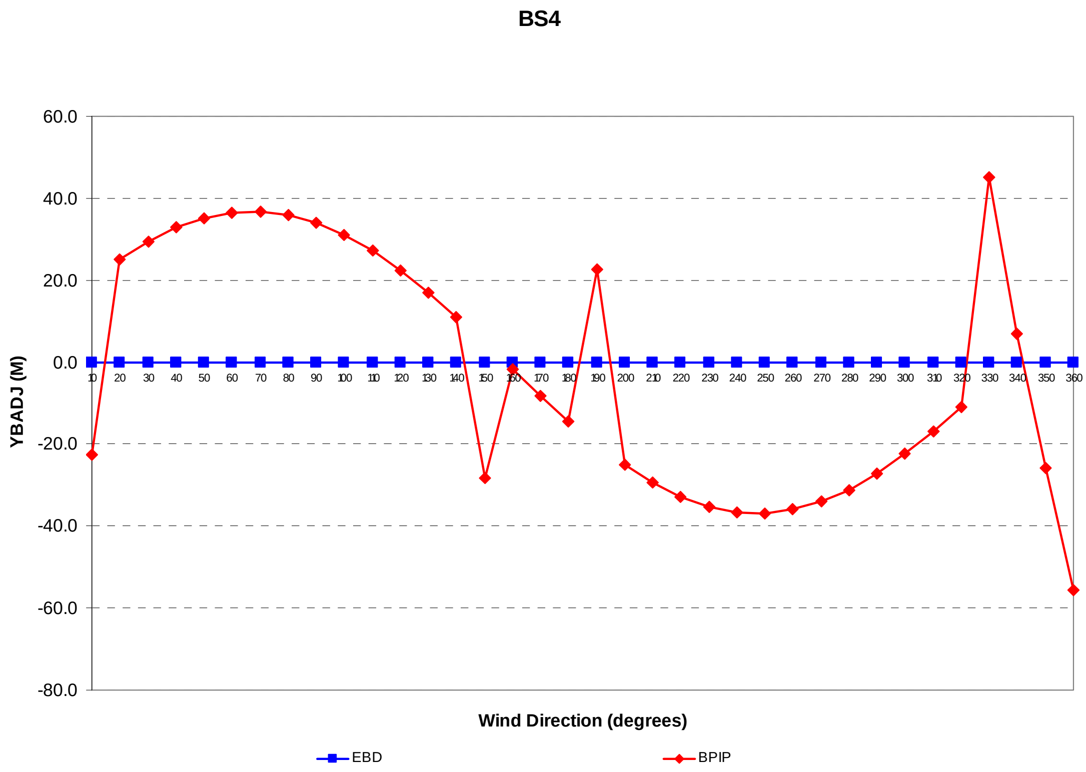

Figure 12. Building position in Y direction, YBADJ, determined using BPIP and EBD methods

For the building height comparison, shown in Figure 8, BPIP designates the same dimension for all wind directions with the exception of 330 to 360 degrees which show an increased dimension that corresponds with the height of the Marina Tower structure that is upwind of the power plant. The EBD values change by wind direction which reflects the true variation of downwash based on the wakes created by all site structures and structure angular positions relative to the wind.

Figure 9 shows the building width comparisons for BPIP and EBD. It is apparent that BPIP is using the long dimension of the power plant for winds from the east and west and the short dimension for winds from the north and south. From this plot, inclusion of the Marina Tower structure upwind of the power plant is not apparent. The BPIP and EBD values show similar trends, with the exception of the 140 and 160 degree wind directions. For these cases, wider EBD dimensions were necessary to replicate the downwash attributed to corner vortex shedding on the power plant structure.

Figure 10 shows significantly different values for the building length component produced by BPIP and EBD. In this plot, BPIP appears to be choosing the long dimension of the power plant when winds are from the north and south and the short dimension when winds are from the east and west. Again, from this plot, inclusion of the Marina Tower structure upwind of the power plant is not apparent. The EBD values do not demonstrate a drastic change in the dominate length component as represented by BPIP.

Figure 11 is an excellent indicator that BPIP is choosing the structure to the north of the power plant as the dominant structure when winds are from 330 to 360 degrees. From 20 to 100 degrees, the BPIP and EBD values are similar. For all other wind directions, the BPIP values are slightly greater or less than the EBD values depending upon wind direction.

Figure 12 shows that all EBD structures were centered on the exhaust stack for all wind directions. The BPIP values, on the other hand shift depending on wind direction. At the 330 through 360 directions, it is likely the values are attributed to the structure upwind of the power plant.

EBD Results - Marina Towers

In addition to traditional EBD values for predicting ground-level concentrations, EBD values were also determined to serve as an AERMOD input when the impact of MPRGS on MT is being evaluated. For these wind tunnel tests, concentrations were measured at 46 locations. These locations correspond to those locations evaluated during AERMOD evaluations of the site[1]. Measurements were obtained for various exhaust stack and wind direction combinations as specified in Petersen.[2]. The wind directions of interest were 150, 160, 170, and 180 degrees as these encompass the wind directions with impacts due to MPRGS on MT.

To determine the EBD, the MPRGS and MT were removed, but the rest of the site remained the same (i.e., surrounding buildings, terrain, etc.) MT was replaced with a “flag pole” receptor grid with collection points at the same locations as those obtained when MT was in place as shown in Figure 7. Then, the stack under evaluation was placed in its respective location with the same stack height above grade. Various EBD structures were then placed upwind of the stacks of interest until a ranked data profile was obtained that was similar to those measured when MPRGS and MT were in place. For these cases, traditional EBD values with the “1:2:1” relationships were initially evaluated and if necessary, other types of EBD configurations were evaluated. The values chosen for each exhaust stack and wind direction scenario are listed in Petersen.[2] Shea[9] discusses the use of these values in AERMOD for estimating the impacts on Marina Tower and also compares the results of the estimates to field observations.

CONCLUSIONS

This analysis has demonstrated that EBD and BPIP determined building dimension inputs are significantly different. The EBD building dimension inputs are based on a characterization of the wake effects created by all site structures. The BPIP determined building inputs are based on logic algorithms that consider building tiers, building spacings, building angles to the flow and from that information a set of building dimension inputs are computed. The problem with these inputs is that they may or may not be appropriate to characterize building wake effects for the site under evaluation. These inputs may cause concentrations to be over or underestimated when utilized in AERMOD.

For this particular study, the impact of the EBD values on concentration estimates is discussed in a companion paper.[9]

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