Use of Equivalent Building Dimensions (EBD) to Characterize Upwind Terrain Wake Effects for AERMOD

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ABSTRACT

A new stack with Flue Gas Desulphurization (FGD) is being designed to replace an existing stack at the Reliant Energy Cheswick Generating Station (CGS) located in the Allegheny River valley, 15 miles northeast of Pittsburgh. Since the terrain to the south of the new stack rises 178 m above stack base, there was concern that terrain wakes may affect ground-level concentrations. Since AERMOD can currently only model building wake effects, a wind tunnel modeling study was conducted to determine the appropriate building dimension inputs (i.e., Equivalent Building Dimensions or EBD) for modeling upwind terrain wake effects with AERMOD. Even though this modeling is not currently required by EPA, CGS wanted to ensure that concentration levels due to terrain wake effects would not pose a problem after the stack was constructed.

In order to conduct the wind tunnel simulations, a detailed physical model of the CGS and terrain was constructed. The flue gas velocity and temperature and ambient wind conditions were then simulated for various wind directions and the resulting concentration patterns were measured at ground level. Tests were then conducted with the terrain and structures removed to find an EBD that would give the same concentration distribution as measured with all structures and terrain present. Comparisons of AERMOD predicted concentrations with and without EBD input values are provided. Overall, the study showed that upwind terrain wake effects can significantly increase ground level concentrations and this effect can be modeled using EBD in AERMOD.

INTRODUCTION

This paper describes the wind tunnel study that was conducted for the Reliant Energy Cheswick Generating Station (CGS) located in the Allegheny River valley, 15 miles northeast of Pittsburgh. A new stack with FGD is being designed to replace the existing stack at CGS. To ensure that ground level concentrations do not exceed allowable limits after the stack is constructed, Reliant Energy decided to conduct this wind tunnel modeling evaluation of wake effects created by nearby terrain and the existing 229 m (750 ft) tall stack. The formula GEP stack height due to nearby structures for the new stack is 168.5 m (552.5 ft). Since the terrain to the south of the new stack is nearby and rises 178 m (583 ft) above stack base, there was concern that terrain wakes may affect ground level concentrations. In addition, there was concern that the existing 229 m (750 ft) tall stack, which will be left in place, may create adverse dispersion conditions due to localized downwash effects from the tall stack. This paper will focus on the results pertaining to terrain wake effects.

Since AERMOD can currently only model building wake effects, a wind tunnel modeling study was conducted to determine the appropriate building dimension inputs (i.e., Equivalent Building Dimensions or EBD) for modeling upwind terrain wake effects with AERMOD. The Environmental Protection Agency (EPA) has approved the use of EBD using ISC for building wake applications. Petersen[1,2] describes the first such study for which a protocol was reviewed and accepted by the EPA (Region V and Research Triangle Park) and for which a permit was ultimately obtained[3]. Also, the EPA[4,5] approved the EBD concept for regulatory modeling use on the basis that it is a source characterization study, which is under the purview of the Regional Offices. Even though this situation involves upwind terrain wake effects, the same concepts and principles as for building wake effects should apply. With the development and promulgation of AERMOD with the PRIME downwash model, it is now possible to specify EBDs that are located at some distance from the stack[6]. This increases the flexibility and accuracy of the EBD procedure and is particularly important for this application since the terrain is about 1 km upwind of the CGS.

TECHNICAL CONSIDERATIONS

Determination of Equivalent Building Dimensions

The basic modeling approach for determining equivalent building dimensions is to first document, in the wind tunnel, the dispersion characteristics as a function of wind direction at the site with all significant nearby terrain and structure wake effects included. Next, the dispersion is characterized, in the wind tunnel, with an equivalent building positioned at various positions upwind of the stack in place of all nearby terrain and 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 equivalent building, consider Figure 1 which shows a typical result from this study. The figure shows the maximum ground-level concentration versus downwind distance for two different equivalent buildings and the maximum concentration measured with terrain and site structures in place (annotated NS-Max, New Stack, Maximum Load). Within this figure, the concentration profile for EBD 11 “1:2:1” 40 cm (11 is building height in model cm, 1:2:1 is the building height to width to length ratio and 40 cm is the distance from the stack to the building downwind face) meets the first criterion in that the maximum measured concentration is at least 90 percent of the maximum concentration measured with the site terrain and structures in place. The EBD 11 "1:2:1", 40 cm profile also meets the second criterion (note: the criteria was assumed to be met at the second downwind distance) in that the lower bound of the error bar equals or exceed the EBD values at each downwind distance. The equivalent building for the test case shown in Figure 1 was specified to EBD 11 "1:2:1" 40, since this is the smallest equivalent building that meets both criteria.

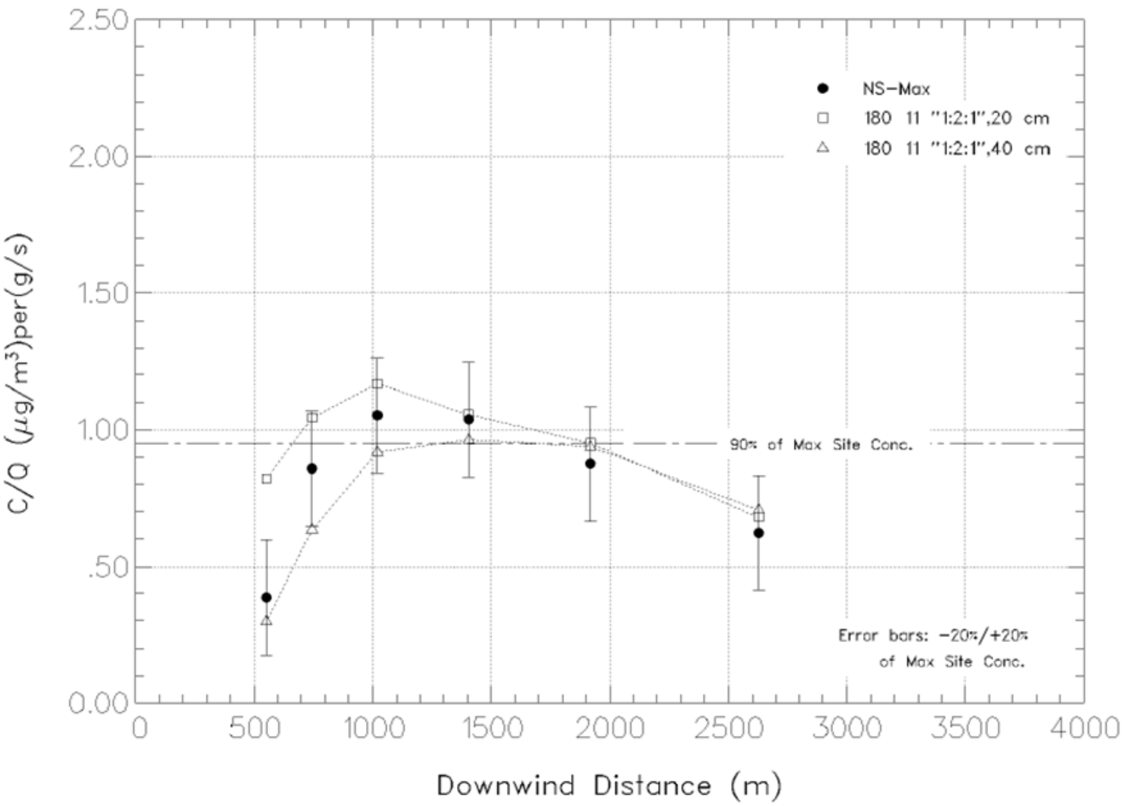

Figure 1. Chart used to determine EBD for the 180 degree wind direction

Hence the building dimension input for AERMOD for this wind direction is a H= 132 m, W = 264 m, L = 132 m, XBADJ = - 612 m (all model units have been multiplied my the model scaling factor of 1200 to obtain the full scale values).

Similarity Requirements

To model plume trajectories for all EBD testing, 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 terrain, the following criteria were met as recommended by EPA[7]: 1) a:1200 model scale reduction was used; 2) an appropriate mean and turbulent approach boundary layer was established; 3) terrain Reynolds number independence was verified through wind tunnel testing; 4) a neutral atmospheric boundary layer was established that simulated an approach surface roughness of 0.74 m for all wind directions with significant upwind terrain.

Using the full scale conditions in Table 1, The above scaling parameters were used to determine the model operating conditions.

Table 1 **Full Scale Source and Modeling Information**	
Stack height, H_s (m)	168.5
Exit temperature, T_s (K)	322.6
Exit diameter, d (m)	8.23
Exit velocity, V_e (m/s)	17.0
Ambient temperature, T_a (K)	283.7
Airport wind speed at 10 m, U_a (m/s)	7.5
Approximate stack top wind speed, U_s (m/s)	11.0

Test Wind Speed

For Good Engineering Practice (and also EBD) studies, the maximum wind speed tested is frequently set at the 2% wind speed[8]. The 2% wind speed of 9.8 m/s for CGS was based on meteorological observations (scaled to a 10 m height) at the Pittsburgh International Airport anemometer for the period 1961-2001. In conducting EBD evaluations, stack tip downwash conditions are usually avoided. This condition occurs when the stack velocity ratio (ratio of exhaust velocity to wind speed at stack top) is less than 1.5. Since the stack velocity ratio is below 1.5 at the 9.8 m/s airport wind speed (stack top speed of about 15 m/s), the maximum airport speed simulated was 7.5 m/s (11 m/s at stack top), since at this lower wind speed, the stack velocity ratio is slightly higher than 1.5.

MODEL CONSTRUCTION AND SETUP

A 1:1200 scale model of the CGS, surrounding structures and terrain was constructed. The model included all terrain and significant structures within a 2073 m (6800 ft) radius of the new stack location. The model was placed on a turntable so that different wind directions could easily be evaluated. Additional terrain was installed upwind of the turntable area for each wind direction evaluated to ensure an accurate simulation of the approach flow. Figure 2 shows the entire terrain area that was modeled. The appropriate upwind terrain was installed for each wind direction evaluated. Figure 3 shows a photographs of the model installed in the wind tunnel with terrain and site structures in place. For EBD testing, the upwind terrain was removed and replaced by a uniform roughness that simulated a wind and turbulence profile characteristic for a 0.74 m surface roughness length.

Stacks were constructed of aluminum 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.

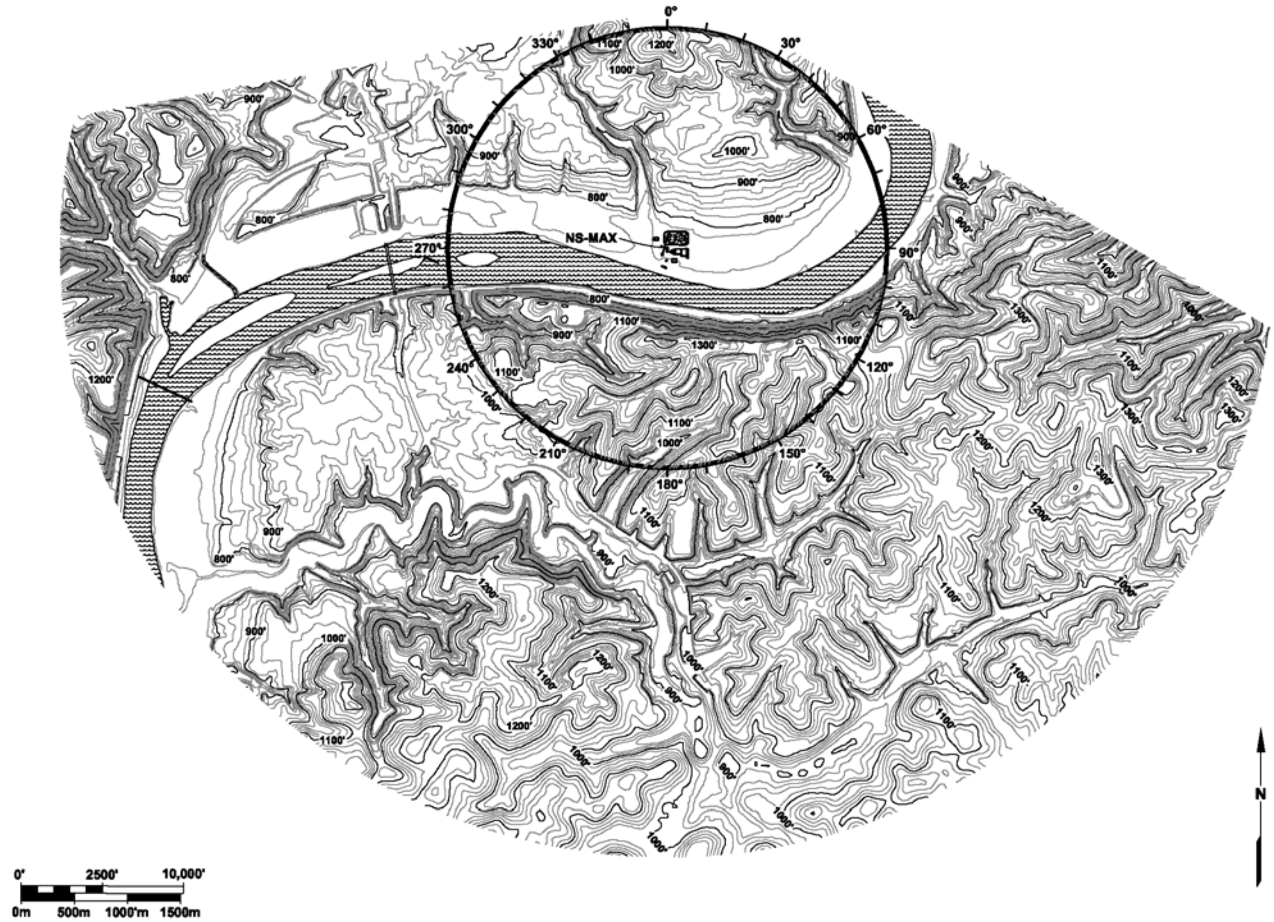

Figure 2. Terrain area modeled in wind tunnel

Figure 3. Photograph of wind tunnel configuration with terrain present

Figure 4. Photograph of wind tunnel configuration for EBD testing

A set of solid rectangular structures was fabricated for placement at various distances upwind of the new stack for EBD testing. The structure shapes evaluated had height to width to depth ratios of: 1:2:1; 1:4:1; 1:8:1; and 1:2:2. For the EBD testing, the new stack in Table 1 and idealized buildings were tested with the upwind terrain removed from the wind tunnel and a uniform roughness installed in its place. The uniform roughness was constructed such that z_o = 0.74 m. Figure 4 shows the wind tunnel configuration with a typical EBD setup.

Concentration sampling taps were installed on the surface of the model so that at least 45 locations were sampled simultaneously for each simulation. A typical sampling grid consisted of 5 to 7 receptors located in each of 7 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 able to be determined in the lateral and longitudinal directions. Initial testing was conducted to confirm the grid design and to alter the design if necessary.

All testing was carried out in an environmental wind tunnel. Testing consisted of releasing a mixture of an inert gas and a tracer (ethane or methane) of predetermined concentration from the stack at the required rate to simulate the desired flow rate and velocity. The flow rate of the gas mixture was controlled by a pressure regulator at the supply cylinder outlet and monitored by a precision mass flow controller. Concentration measurements were then obtained at various ground level measurement locations.

EBD RESULTS

The purpose of testing was to define the EBD values that can be input into AERMOD for the new stack. For this testing, a stack height equal to formula GEP stack height was utilized. This height is lower than the terrain height and was equal to the final height selected for the new stack. Experience has shown that EBD values are rather insensitive to stack height and, if anything, conservative results are obtained if the stack height evaluated is lower than the final height modeled in AERMOD.

A tracer gas was released from the new stack and maximum ground-level concentrations versus downwind distance were determined for wind directions 120 through 260 degrees in 10-degree increments at a 7.5 m/s anemometer wind speed. Tests at 135 and 315 degrees were included to assess the effect of the existing stack, which will be left in place after the new stack is constructed. The existing stack is directly upwind or downwind for these wind directions. After these tests were completed, tests were conducted to determine the EBD values. For these tests, the terrain upwind of the new stack was removed from the wind tunnel and a uniform roughness representative of the terrain was installed in its place. Concentration measurements were then conducted with various solid structures upwind of the new stack. The solid building that produced similar concentrations as with all structures and terrain in place was selected as the EBD. The dimensions of these EBD structures can then be used for AERMOD model input. EBD values were specified by applying the criteria described earlier to the longitudinal maximum concentration profiles like that shown in Figure 1 for the 180 degree wind direction case. Similar figures were determined for each wind direction evaluated.

A summary of the EBD values for the new stack for direct input into AERMOD for the wind directions evaluated is presented in Table 2.

Table 2. Summary of EBD values for the New Stack

Flow Vector (Deg.)	Wind Direction (Deg.)	EBD ID (# "H:W:L")[2]	BUILDHGT[3] (m)	BUILDWID[4] (m)	BUILDLEN[5] (m)	XBADJ[6] (m)	YBADJ[7] (m)
300	120	0	0.0	0.0	0.0	0.0	0.0
310	130	12 "1:2:2"	144.0	288.0	288.0	-1092.0	0.0
315	135	11 "1:2:1"	132.0	264.0	132.0	-372.0	0.0
315[1]	135	11 "1:2:1"	132.0	264.0	132.0	-372.0	0.0
320	140	12 "1:2:1"	144.0	288.0	144.0	-948.0	0.0
330	150	10 "1:2:2"	120.0	240.0	240.0	-1044.0	0.0
340	160	12 "1:2:2"	144.0	288.0	288.0	-1092.0	0.0
350	170	11 "1:2:1"	132.0	264.0	132.0	-372.0	0.0
360	180	11 "1:2:1"	132.0	264.0	132.0	-612.0	0.0
10	190	10 "1:2:1"	120.0	240.0	120.0	-480.0	0.0
20	200	11 "1:2:1"	132.0	264.0	132.0	-936.0	0.0
30	210	13 "1:2:1"	156.0	312.0	156.0	-960.0	0.0
40	220	11 "1:2:1"	132.0	264.0	132.0	-936.0	0.0
50	230	11 "1:2:1"	132.0	264.0	132.0	-936.0	0.0
60	240	0	0.0	0.0	0.0	0.0	0.0
70	250	0	0.0	0.0	0.0	0.0	0.0
80	260	0	0.0	0.0	0.0	0.0	0.0

Notes:
1) Neighboring existing stack removed
2) # "H:W:L" denotes the model scale EBD building number and height, width, length ratio
3) BUILDHGT is the full scale building height
4) BUILDWID is the full scale building width
5) BUILDLEN is the full scale building length
6) XBADJ is the full scale EBD position in the x direction
7) XBADJ is the full scale EBD position in the y direction

The table shows that for all of the wind directions evaluated, the EBD heights were less than the 178 m maximum upwind terrain height. The overall largest EBD was 156 m high and occurred for the 210 degree wind direction. It should be noted, however, that significant building dimension inputs were observed for wind directions 130 through 230 degrees. Inputting these values into AERMOD should produce higher concentration estimates than would be obtained using just BPIP inputs, since BPIP does not account for upwind terrain effects.

VISUALIZATION OF TERRAIN AND EBD DOWNWASH

Photographs of plume behavior with the upwind terrain, without the upwind terrain out, and with an upwind EBD are shown in Figure 5. The figures clearly show that the upwind terrain tend to bring the plume down to the ground sooner than when the upwind terrain is not present. The dispersion pattern with the EBD in place instead of the upwind terrain (Figure 5c) also shows a similar dispersion pattern as the terrain-in case in Figure 5a.

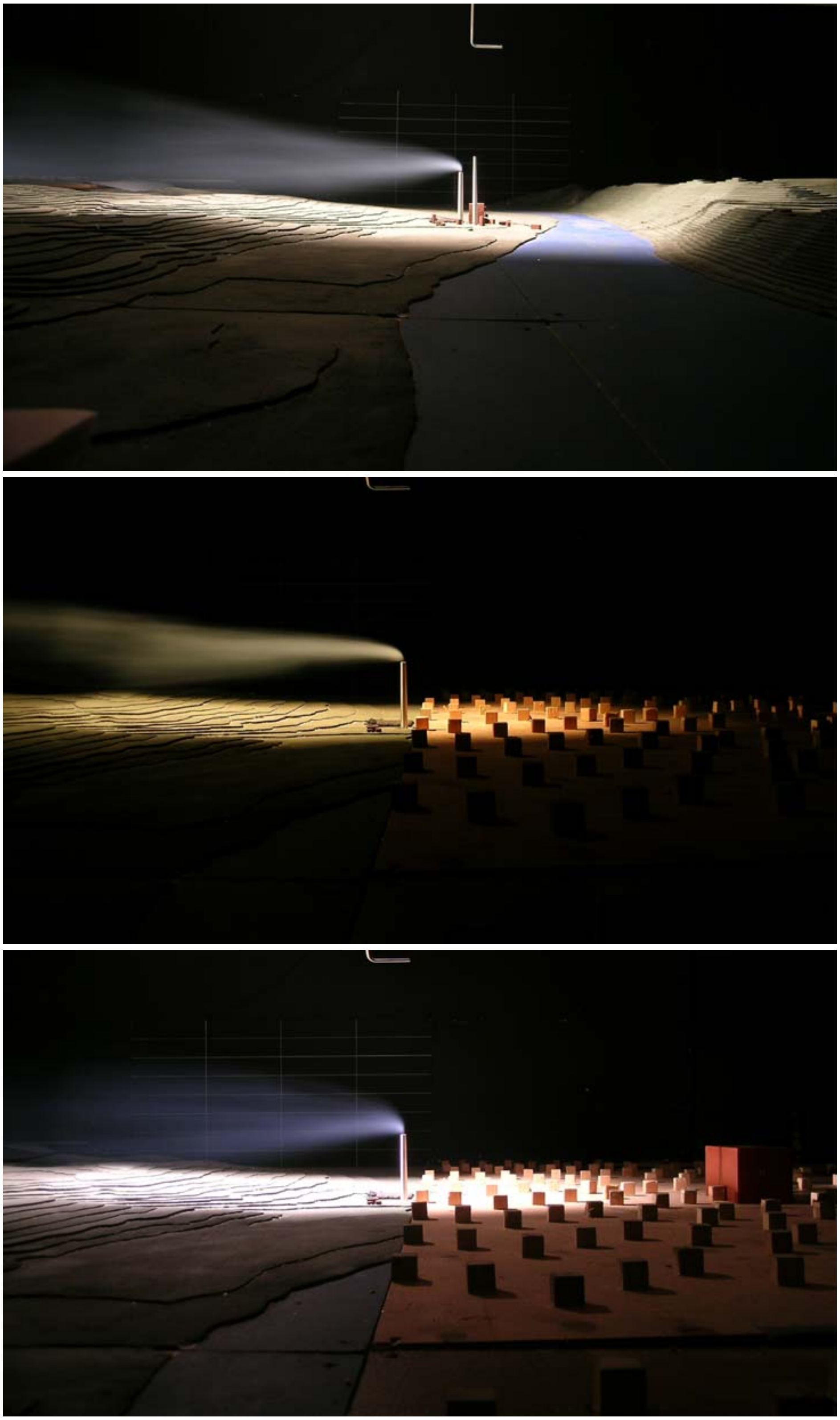
a)
b)
c)

Figure 5. Photographs of plume behavior: a) with upwind terrain in; b) without upwind terrain; and c) with upwind EBD.

USE OF EBD IN AERMOD

To assess the importance of the use of EBD values to account for the effect of upwind terrain, AERMOD was run with and without the EBD values. For all wind directions not tested in the wind tunnel, the Building Dimension Inputs were set at 0.0 since the stack is at the Formula GEP stack height. One year of Met data from Pittsburgh, Pennsylvania Airport was used for this run and a 1 g/s emission rate was assumed. Figure 6 shows AERMOD concentration contour plots without and with EBD. Figure 6a shows that without EBD, the overall maximum hourly concentration of 0.47 ug/m^3 occurs on the elevated terrain to the south. The airport speed is 5.7 m/s, the effective speed is 17.1 m/s and the atmosphere is stable (very high positive Monin Obukhov Length). With EBD, the overall maximum concentration of 0.71 ug/m^3 occurs to the north of the stack with a 1.5 m/s airport speed, 9.9 m/s effective wind speed and slightly stable (very high positive Monin Obukhov Length).

CONCLUSIONS

This study points out the importance of considering upwind terrain wake effects when evaluating the air quality impact of pollutant sources. Facilities that design and build plants without considering these effects may underestimate the overall maximum concentration and risk air quality problems after the facility is completed. Since CGS did consider terrain wake effects in their air quality modeling assessment, potential problems due to these effects have been addressed during the design phase when any potential problems could be mitigated in advance of construction.

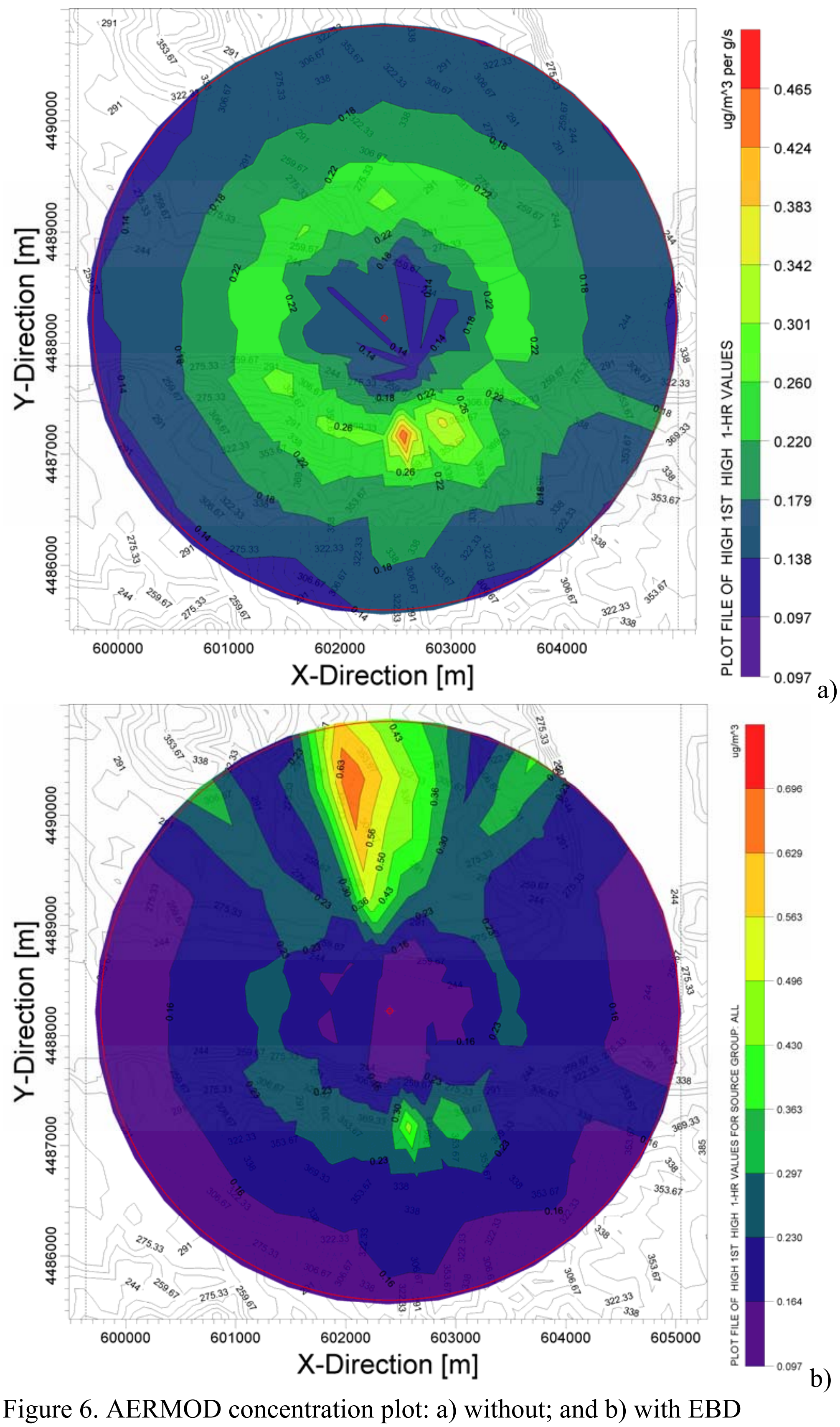

Figure 6. AERMOD concentration plot: a) without; and b) with EBD

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