AERMOD BUILDING DOWNWASH THEORETICAL LIMITATIONS AND POSSIBLE SOLUTIONS

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Ronald L. Petersen, Ph.D., CCM and Anke Beyer-Lout, M.S.
CPP, Inc., 1415 Blue Spruce Drive, Fort Collins, CO 80524

ABSTRACT

While AERMOD has been shown to provide reasonably accurate concentration estimates for many building configurations, the following situations may not be modeled accurately: 1) very complicated building geometries, porous or lattice type structures and cylindrical structures; 2) building aspects ratios significantly different than those for which the model was developed and tested; 3) wind directions where the stack and upwind building corners are in alignment (enhanced downwash due to corner vortex); or 4) when terrain wake effects are important. The AERMOD building dimension inputs are calculated using the Building Profile Input Program (BPIP). The ultimate goal for BPIP should be to try and find the building shape and position that places the stack of concern into the correct Snyder and Lawson data base flow region (i.e., the data base used to develop the PRIME downwash algorithm). For the situations discussed above, there is no assurance that the current BPIP algorithms achieves that goal. This is because the PRIME building downwash algorithm in AERMOD was developed and tested using concentration and flow field measurements obtained in wind tunnel simulations for a limited range of building aspect ratios and did not consider building porosity, streamlined type structures (cylindrical or spherical), extremely short buildings with a large footprint, or nearby terrain features. Currently, AERMOD is applied with BPIP inputs for any building regardless of shape, porosity or building aspect ratio. The effect of upwind terrain wakes is completely neglected. This paper lists the theorectical limitations of AERMOD/PRLIME, presents example problem areas for AERMOD/PRIME and discusses an approach that can used to overcome these problems, the use of Equivalent Building Dimensions in place of BPIP.

INTRODUCTION

In December 2006 AERMOD[1] officially became the EPA preferred model for regulatory dispersion modeling applications and replaced the predecessor ISC3[2]. Since then AERMOD, has been improved continuously. One of the major enhancements of AERMOD was the addition of the PRIME building downwash algorithm[3] 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[3]. 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.

AERMOD/PRIME, as with all models, has certain limitations that users, industry and regulators should be aware of. The building wake algorithms within the model were developed based on a limited set of building shapes and configurations, but the model is applied for all shapes and building configurations based on building dimension inputs determined by BPIP[4] (Building Profile Input Program). In those situations where AERMOD's theoretical foundation is broken, the model may over or underestimate the expected concentration levels. In the former case, industry will have to apply various mitigation measures to their operation to show compliance with NAAQS when in fact such costly mitigation measures may not be needed. In the latter case, the model will show no mitigation is necessary when in fact ambient air quality may not be protected.

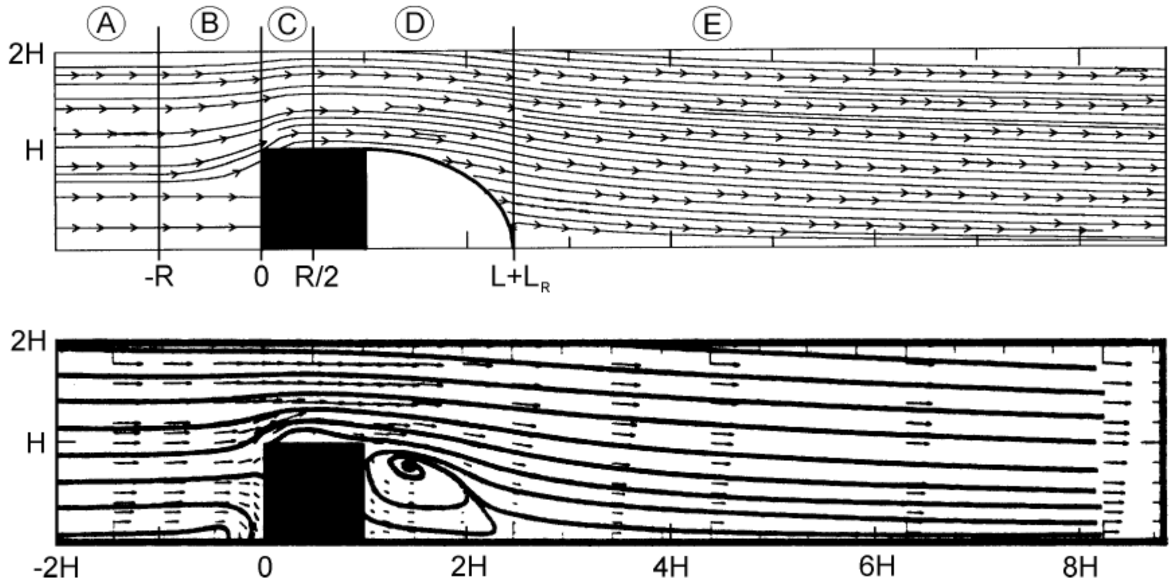
This paper will discuss the site conditions where the algorithms in AERMOD currently do not provide accurate concentration estimates. This paper will also briefly discuss a method whereby the limitations in AERMOD can be overcome. That method, which has been utilized on numerous occasions with ISC3[5,6,7,8] and a few occasions with AERMOD[9,10,11] consists of providing the building dimension inputs that accurately define the site building wake configuration (referred to as EBD). This method should be even more accurate with AERMOD/PRIME since this model has advanced building downwash and plume rise capabilities. With these enhancements, is seems it would be safe to assume that if the correct building dimensions are input (i.e., those that conform to the assumptions under which the model was developed) the model will provide accurate estimates.

The following sections provide some background on building wake theory within AERMOD/PRIME and examples where the model does not provide accurate estimates. Recommendations on how to solve these problems are included.

AERMOD/PRIME THEORETICAL BASIS

AERMOD/PRIME has equations to predict the exhaust dispersion and plume rise due to the presence of a nearby structure. These equations are based on calculations of the building wake/cavity length and streamline slope which in turn are based on the input building height, width, length and position relative to the stack. For example, the equations used to calculate the building recirculation cavity dimensions use the building height (H), the projected building width across the flow (W) and the projected building length along the flow (L). However, the equations were developed and tested using wind-tunnel data[12] 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, the length to height ratio of the building is limited to $0.3 \leq L/H \leq 3$. Ellipse segments are used to calculate the height and width of the cavity envelope as a function of downwind distance from 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. Figure 1 shows a comparison of AERMOD streamlines with those observed in the wind tunnel[3,12].

Figure 1. From Schulman[3] showing a comparison of streamlines predicted by the PRIME model with thorse observd in wind tunnel simulation of a cubic building.



PROBLEM AREAS AND SOLUTIONS

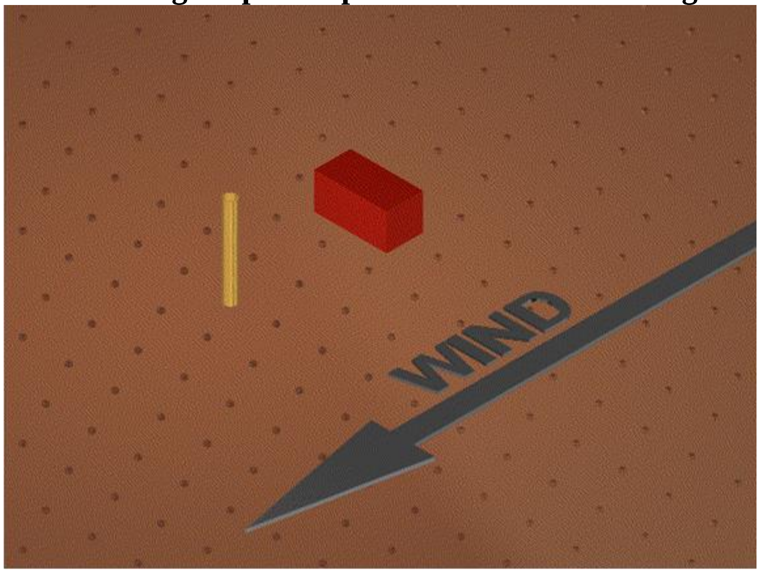
In general AERMOD/PRIME should give reasonable predictions for those cases that fall within the range of building shapes and configurations for which the model was developed and tested against. The following site configurations will most likley provide problems:

- Complicated site building configuration,
- Buildings with a large aspect ratio, short structures with a large fooprint,
- A stack in line with an upwind building corner,
- Porous structures,
- Cylindrical or streamlined structures, or
- Nearby terrain features.

The ideal solution for these problem areas is to find building dimension inputs that match the theoretical assumptions in AERMOD while at the same time match the dispersion for these various site configurations. To do this, first the dispersion characteristics and/or flow fields for each of these site configurations needs to be documented. Next, the dispersion characteristics and flow field need to be compared with the theoretical assumptions in AERMOD/PRIME. The building dimensions and position that match are the ideal inputs. These dimensions are defined as Equivalent Building Dimensions (EBD).

While other methods may be developed in the future for determining EBD, the current method is through the use of wind tunnel modeling.[5,6,7,8,9,10,11] To determine EBD 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 a rectangular-shaped building positioned directly upwind or at various locations upwind and downwind of the stack in place of all nearby structures (i.e., the setup as shown in Figure 3). This testing is conducted for various building geometries 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 and methods for EBD evaluations are described in more detail in Petersen and Reifschneider.[10]

Figure 3: Typical building and stack configuration for equivalent building dimension wind tunnel setup. Note: the building shape and position are varied during testing.



EXAMPLES

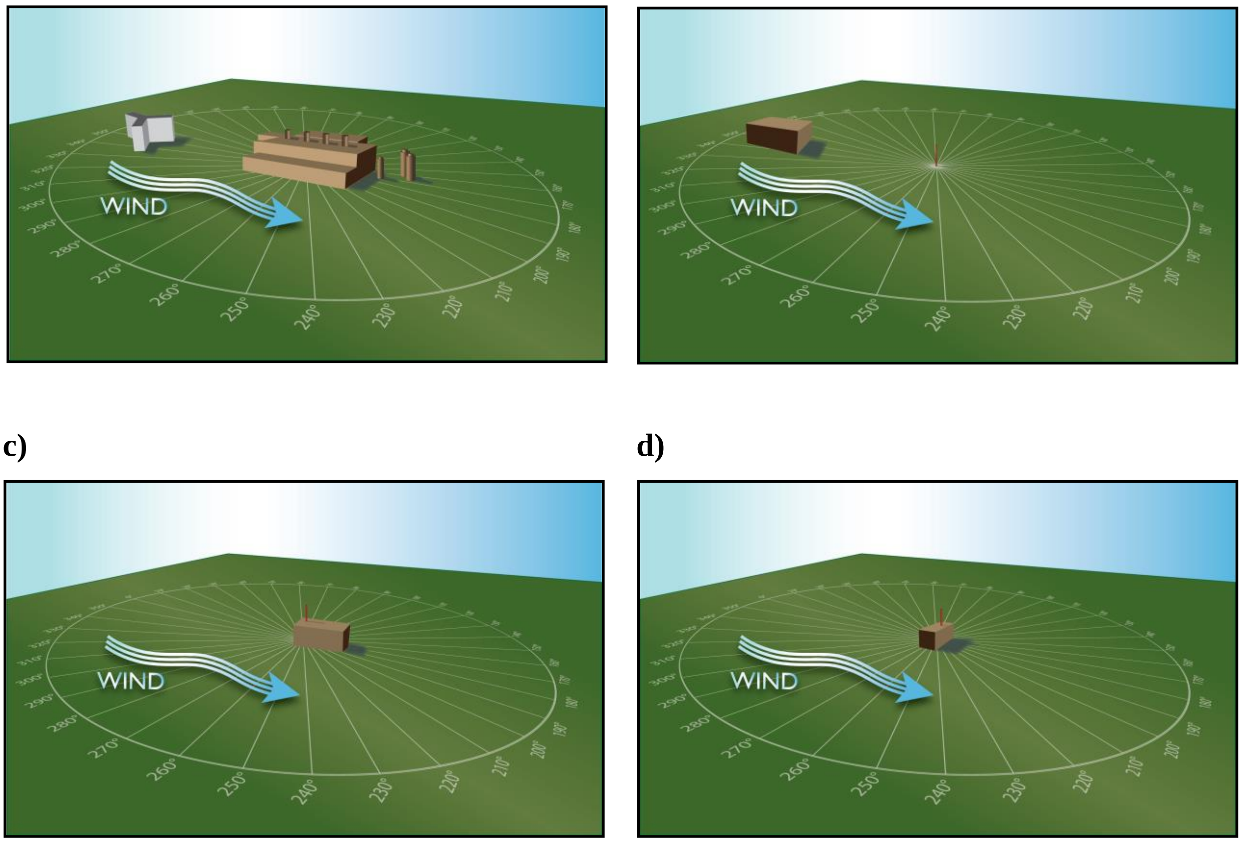
Picking the Wrong Dominant Building - BPIP Issues

The Building Profile Input Program (BPIP) was designed to calculate the building height, width, length and position for input into the AERMOD/PRIME building downwash algorithms. As discussed above, the ultimate goal for BPIP should be to try and find the building shape and position that places the stack of concern into the correct Snyder data base flow region (i.e., the data base used to develop the PRIME downwash algorithm). There is no assurance that the current BPIP algorithms do this. These calculated dimensions can have several problems (i.e., picking the wrong dominant building, merging structures incorrectly, not accounting for lattice and/or cylindrical structures).

Consider one example. The program may place the structure in question at the wrong location to get the correct dispersion or it may pick the wrong dominant building altogether, as Figures 4a-d demonstrate. Figures 4a-d show the case when a residential tower is upwind of an industrial facility. For this example, AERMOD with BPIP input was predicting the highest concentrations on the nearby residential tower. Ground-level concentrations were also relatively high for some wind directions. Wind-tunnel tests and field observations showed that AERMOD was overestimating concentrations and that the BPIP building dimension input was not appropriate for this specific site.[10] Equivalent building dimensions (EBD) were determined in the wind tunnel and input into AERMOD. Using these inputs, predicted concentrations were lower and agreed better with field observations on the residential tower.[13]

Figure 4: Example of BPIP picking a dominant structure, a) BPIP site input information; b) BPIP building dimensions for the entire site. BPIP picked the upwind tower as the dominant building; c) BPIP building dimensions without upwind tower as input; d) building dimensions (EBD) needed to model dispersion as determined in wind-tunnel study.

a) **b)**



Buildings with Large Aspect Ratio

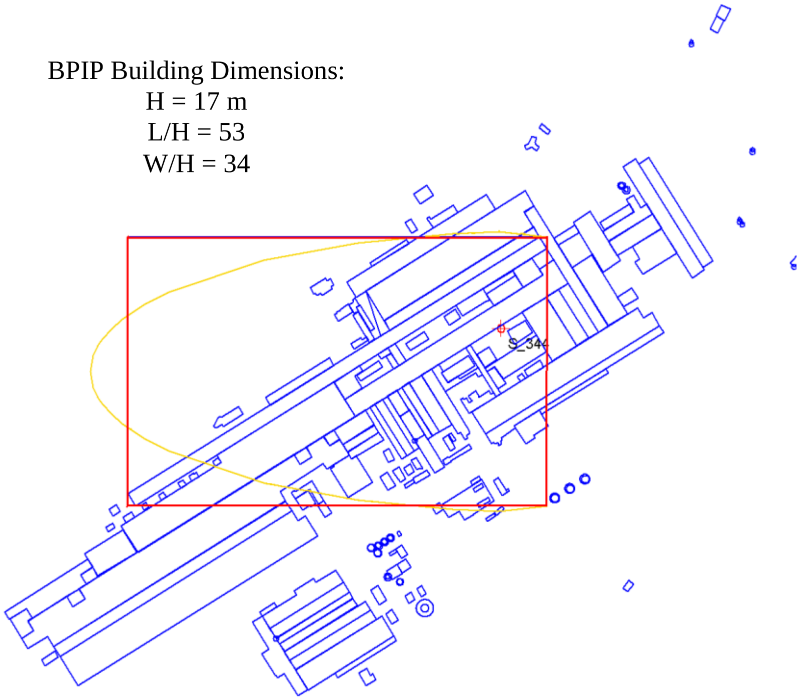
The Alcoa Davenport Works (DPW) shown in Figure 5 is a complex of low, large attached structures with an average building height of 20 m, a width of 600 m and an overall length of 1700 m. The structure dimensions calculated by BPIP for input into the AERMOD/PRIME algorithm have aspect ratios (e.g., W/H and L/H) ranging from 5 to 50 - well outside the range for which PRIME was developed and tested. Example BPIP input calculations are shown in Figure 6.

A wind tunnel modeling study was conducted[11,14] to determine Equivalent Building Dimensions (EBD) for AERMOD/PRIME input for five stacks. 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 two lower using EBD.

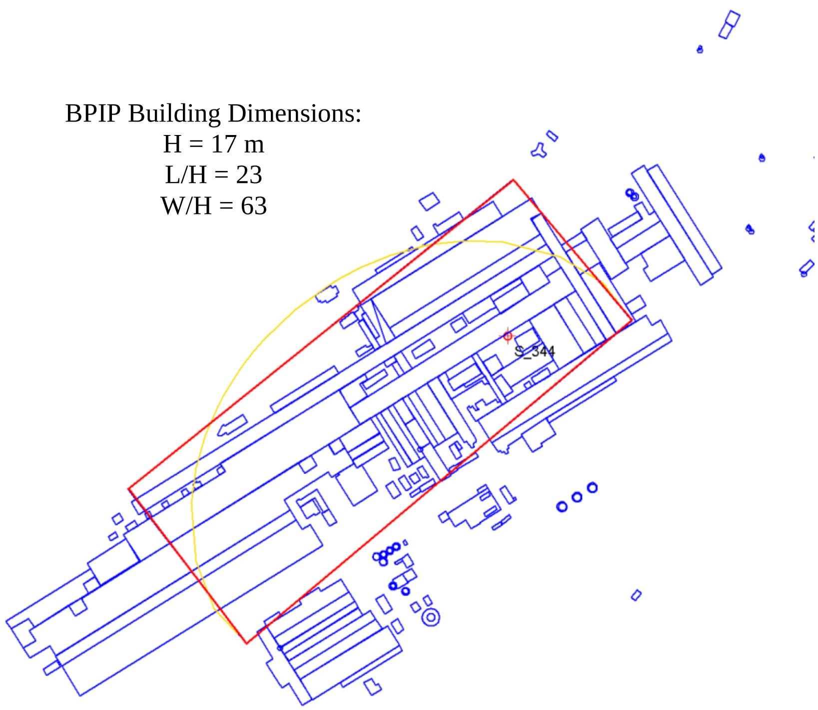
Figure 5: Aerial photograph of the Alcoa Davenport Works facility.

The EBD study was submitted to EPA in early 2009 and in late 2010 EPA issued a Model Clearinghouse Memorandum[15] that rejected the the study based on the following main issues: 1) the roughness used during EBD testing; and 2) a general updating of the EBD methodology since the original method was developed for ISC3 use. It is the authors' opinions that the basic findings of the study will not change once EPA's issues are addressed. The EPA Memoradum did not reject the use of EBD in general but called for review of the past approved method and updating if needed. When the EBD approach is pursued, a protocol will be needed as well as early interaction with the approving agency.

Figure 6: DPW facility (blue), BPIP building dimensions (red) for stack S-344 (red crosshairs) 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.



a)



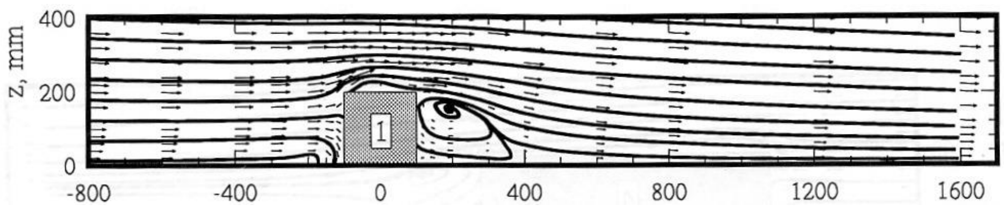
b)

AERMOD/PRIME Underestimation for Corner Vortex

The BPIP program translates structures for any angle of approach into rectangular blocks using the projected width of the structure with the leading wall oriented perpendicular to the wind direction. There is no distinction made for different angles of approach. Hence, the current building wake equations do not account for corner vortices and neglect the resulting enhanced downwash downwind of structures and the potential for resulting higher ground-level concentrations. Therefore, AERMOD/PRIME may under predict the downwash intensity in these cases. Figure 7 shows how the streamline patterns are different when the building is rotated 45 degrees. AERMOD/PRIME is designed to predict the streamline pattern in Figure 7a.

Figure 7: Streamline patterns around cubical buildings; a) wind perpendicular to leading wall; b) cube rotated 45 degrees, so the wind approaches the leading corner. (Snyder and Lawson, 1994)

a)



b)

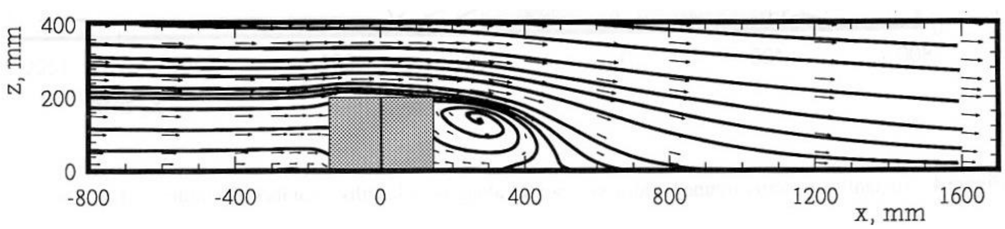


Figure 8 shows AERMOD/PRIME predictions for three different building configurations. For two configurations, the buildings are oriented perpendicular to the flow and for one the building is rotated so the leading corner is pointed into thw wind (the corner vortex situation). The concentration predictions are very similar for all buildings. Figure 9 shows concentrations observed in the wind tunnel for the same building configurations. The figure shows that the maximum concentrations are over a factor of two higher for the case with the rotated building. Hence, AERMOD/PRIME is under predicting for this situation. The author has conducted EBD studies where this corner vortex has shown high concentrations. These evaluations have shown that it is difficult to find a building configuration that is oriented perpendicular to the flow that will provide similar ground level concentration distributions as a building oriented at a diagonal. This points out that a new theoritical algorithm is needed in AERMOD to address to corner vortex condition. Alternately wind tunnel modeling (HYWINMOD) can be used directly to model this condition.[16,17]

Figure 8: AERMOD/PRIME predictions showing the effect of corner vortex is not included in model.

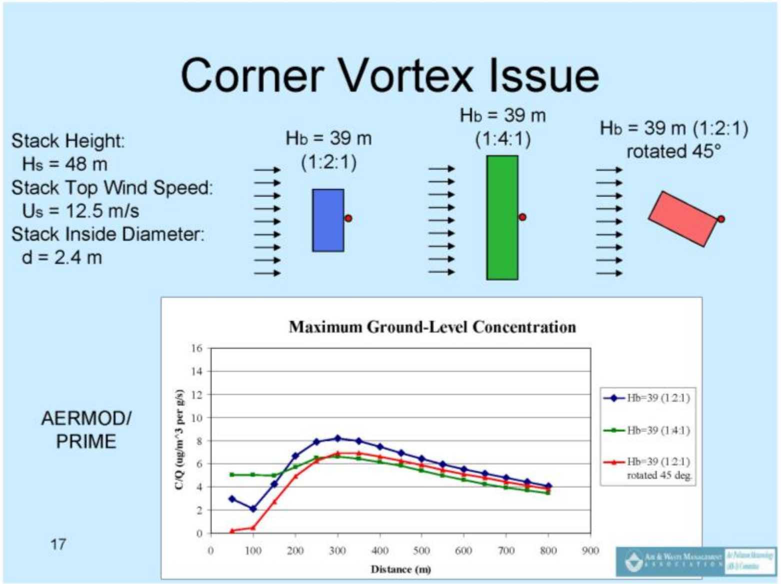
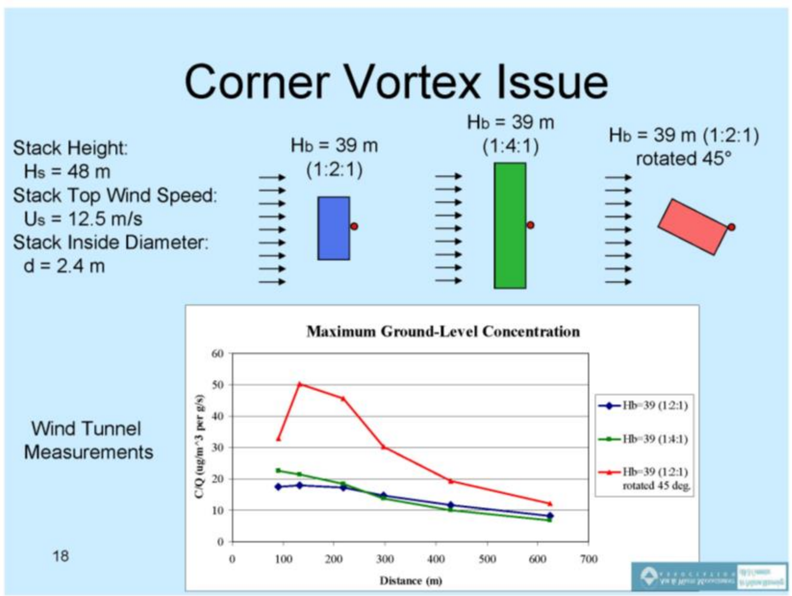


Figure 9: Wind tunnel observations showing that the corner vortex can increase ground level concentrations by a factor of two or more.



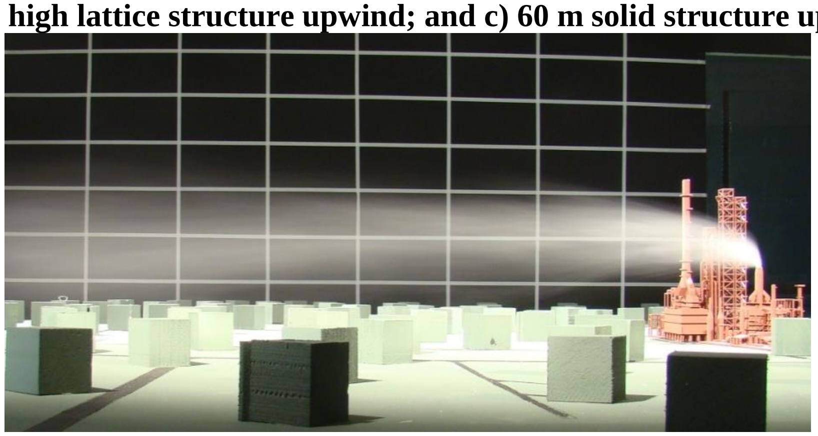
Lattice/Porouse/Streamlined Type Structures

Lattice or porous structures such as those shown in Figure 10 are also not modeled correctly in AERMOD/PRIME. The model assumes the structure is solid and consequently will tend to overestimate the building wake and resulting ground-level concentrations. The same is true for streamlined structures such as hyperbolic cooling towers.

Figure 10. Typical lattice/porous type structure not treated by AERMOD/PRIME

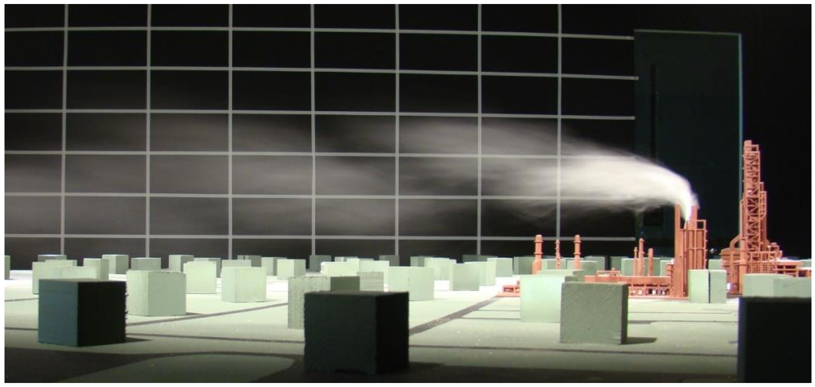
Figures 11a-c illustrate the problem in more detail. Figure 11a shows plume behavior when a lattice structure is directly downwind of a stack. The plume goes through the structure with some enhanced dispersion. Figure 11b shows plume behavior for the same exhaust stack only the lattice structure is upwind. For this case some enhanced dispersion is noticed due to the upwind structure but not as much as the solid structure shown in Figure 11c. Figure 11c is the condition modeled in AERMOD/PRIME. The plume comes to the ground much closer to the stack which will result in higher predicted maximum concentrations.

Figure 11. Visualization of the plume behavior with: a) 92 m high lattice structure downwind; b) 92 m high lattice structure upwind; and c) 60 m solid structure upwind

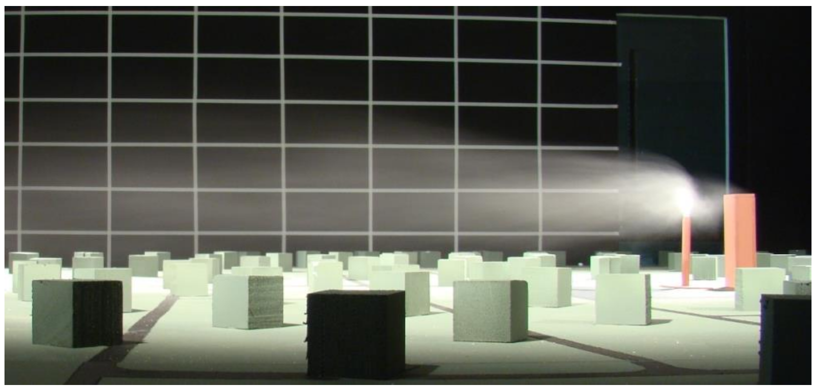


a)

b)



c)



Because of this problem, an EBD study was conducted to evaluate the structure shown in Figure 10. The unit pictured is Fluid Cracking Unit 6 at Amoco's Whiting Refinery. This happens to be the first EBD study that was conducted and approved. At the time of the study, ISC3 modeling was showing exceedances of the 24-hr NAAQS for SO_2 of 365 ug/m3 at the fenceline. The lattice structure height is 50 m which is the height that was input into ISC3. The EBD study determined that the proper dispersion was obtained with a maximum height of 33.5 m when the lattice structure is directly upwind. For other wind directions, the EBD determined building height inputs were lower and for several directions (when the structure was not upwind), the appropriate height input was zero. With the use of EBD in ISC3, predicted concentrations descreased significantly.

Terrain Wake Effects in AERMOD

The GEP stack height regulation[18] defines nearby terrain for the purpose of limiting stack heights. If sources do not build their stacks to the GEP height based on nearby terrain, upwind terrain wake effects may cause high ground-level concentrations. Figure 12 shows an example of increased turbulence and mixing on the lee side of a ridge tested in a wind tunnel. Figure 13 shows the results from some past research[19,20] that could be used to develop terrain amplification factors.

Even though AERMOD incorporates terrain, it is only used to characterize the direct interaction of the plume with the terrain features downwind of the stack. The effects of terrain upwind of the stack are not considered in AERMOD. Since AERMOD does allow for placing a building some distance upwind of the stack, EBD could be determined to account for this effect. On a recent study[21], EBD values were determined to account for upwind terrain. The study showed that overall maximum concentrations increased by nearly a factor of two when upwind terrain wakes effects were accounted for. This points out a condition where the use of AERMOD/PRIME may not be protecting ambient air quality.

Figure 12: wind tunnel model of downwash behind a ridge.

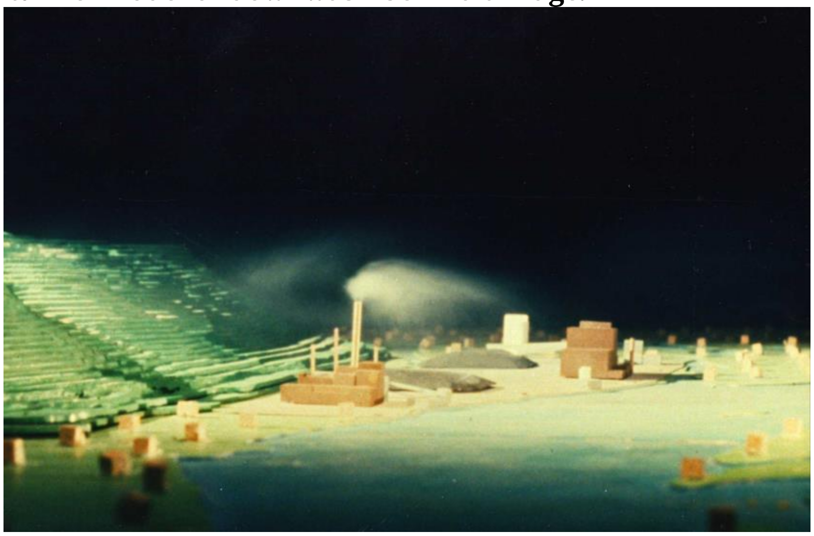
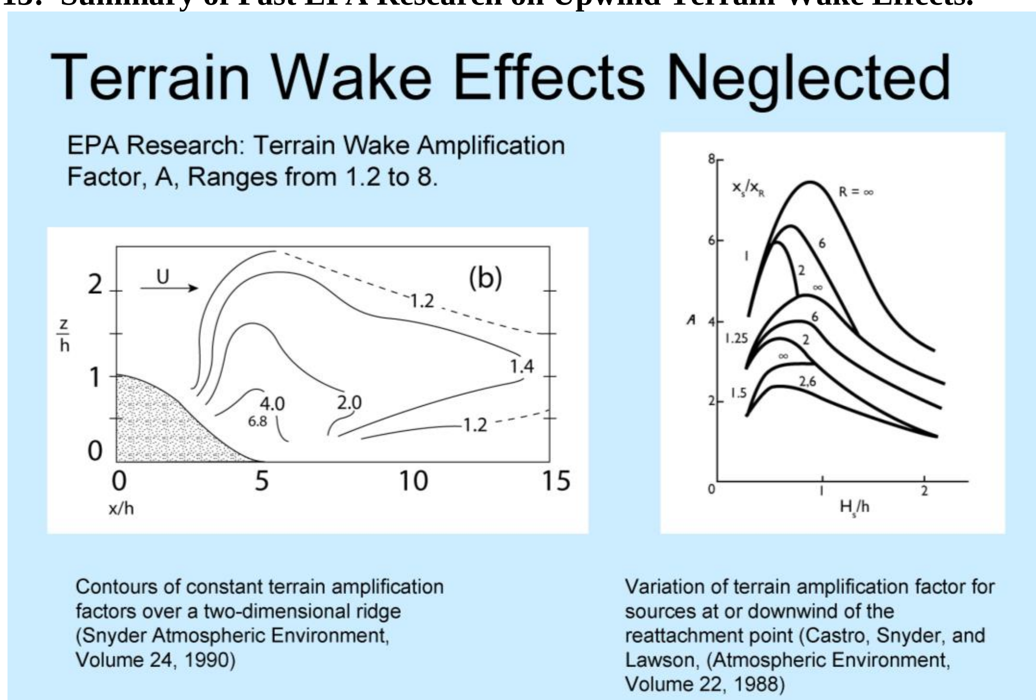


Figure 13: Summary of Past EPA Research on Upwind Terrain Wake Effects.



SUMMARY

This paper has pointed out site configurations where AERMOD/PRIME will either over or underestimate.The site configurations include: complex building geometries; lattice/porous or streamlined structures; low building with a large footprint; stacks with a building corner directly upwind; and nearby upwind terrain. Until new methods are developed for estimating the appropriate building dimension inputs for these situations, the use of EBD in place of BPIP generated building dimensions will overcome most of these problems. For the corner vortex condition, the use EBD may not be sufficient without a new algorithm added to AERMOD/PRIME.

Areas of investigation that are still needed to improve AERMOD/PRIME's predictive capabilities:

- Research on ways to improve BPIP so building dimensions and position match assumptions in AERMOD algorithms. Wind tunnel testing can be used to determine Equivalent Building Dimension (EBD) for complex and/or questionable situations.
- Develop algorithms for the corner vortex situation. Currently the model is underestimating for this situation.
- Develop method to account for upwind terrain wake effects. Past EPA research could be used to develop terrain amplification factors. Alternately, wind tunnel testing can be conducted to determine EBD.
- Updated guidance on the use of EBD in AERMOD/PRIME to account for structures and upwind terrain so that the EBD process can be conducted consistently and in a timely manner.

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