Evaluation of the Theoretical Problems with Building Downwash Using A New Method to Determine Equivalent Building Dimensions

Extended Abstract # 25
Presented at the conference:
Guideline on Air Quality Models: The New Path
April 12-14, 2016
Chapel Hill, NC

Sergio A. Guerra, Ron Petersen; CPP, Inc., Fort Collins, CO

INTRODUCTION

At present, wind tunnel modeling remains the best available scientific tool for studying fluid dynamics in complex environments, including wind flow patterns around buildings and structures. Wind tunnel modeling has been used for over two decades to develop equivalent building dimensions (EBDs) for input to regulatory dispersion models such as ISC and AERMOD. The theoretical basis for wind tunnel modeling can be derived from the basic equations of motion in dimensionless notation. If the important dimensionless parameters and dimensionless boundary conditions are identical at two different scales (i.e., full scale and model scale), the solution to the equations will be identical. It should also be noted that these equations, if solved exactly, will yield a correct simulation. In performing an EBD study, all important parameters are matched between model and full scale and, consequently, a very accurate simulation of the building wakes and resulting dispersion is achieved. As the EPA Fluid Modeling Guideline[1] so aptly put it: "A well-designed and carefully executed fluid modeling study will yield valid and useful information – information that can be applied to real environmental problems – with just as much and generally more credibility than any current mathematical models."

Petersen, et al.[2,3] describes the first EBD study for which a protocol was reviewed and accepted by the EPA (Region V and the Office of Air Quality and Standards [OAQPS]) and for which a permit was ultimately obtained.[4] That study considered the effect of a nearby lattice type (porous) structure. Also, EPA approved the equivalent building concept, [5] based on a study conducted by CPP,[6] for regulatory modeling use. Petersen et al.[7] summarizes the results of an EBD study reviewed and approved by EPA (approved in March 2007) and Shea et al.[8] describes a companion field validation of the EBD process.

EPA defines the EBD method as a source characterization study that can be reviewed and approved by the EPA Regional Office in coordination with EPA's Model Clearinghouse. Most importantly, these studies are not subject to the requirements of alternative modeling in Section 3.2 from Appendix W to 40 CFR part 51, the Guideline on Air Quality Models, "Use of Alternative Models". EBD studies are currently performed by first characterizing the dispersion profile characteristics at a site for each wind direction of concern and then by finding an equivalent building that provides a profile of maximum ground level (MGL) concentration versus downwind distance that is similar to that with "*all site structures present*". The concentration profiles for the "*all site structures present*" and EBDs are all performed and measured in the wind tunnel. The resulting building dimensions are then used in AERMOD in place of the ones generated by the Building Profile Input Program for Plume Rise Model Enhancements (BPIPPRM) for the wind direction(s) of concern.

While the current EBD method is the best available option to determine correct building dimensions in the model, a different method was suggested by EPA in the 2011 Memo: *Model Clearinghouse Review of EBD for AERMOD.*[9] Attachment B to the 2011 Memo includes an assessment of the Alcoa Davenport Works EBD Study. In this evaluation EPA compared wind tunnel observations with AERMOD derived concentrations. However, this evaluation has important shortcomings. First, to carry out this comparison between wind tunnel and AERMOD concentrations, it is necessary to collect velocity profiles that include longitudinal and vertical turbulent intensity measurements upwind of the stack. These data were not available for the EPA evaluation of the Alcoa Davenport Works EBD Study. Second, the wind tunnel model operating conditions were converted to full scale conditions by using exact similarity. However, exact similarity is not used to specify model operating conditions since only momentum ratios are matched but not buoyancy ones. Whereas EPA did not provide important details on how this study was performed, this paper outlines how to properly carry out this new method where AERMOD is used to determine equivalent building dimensions. The viability of this new method was also evaluated and discussed.

METHODOLOGY ON HOW TO USE AERMOD TO DETERMINE EBD

A potential new method that uses AERMOD to determine EBD would follow the four steps described below. This method was indirectly suggested by EPA in the 2011 Clearinghouse Memo.[9]

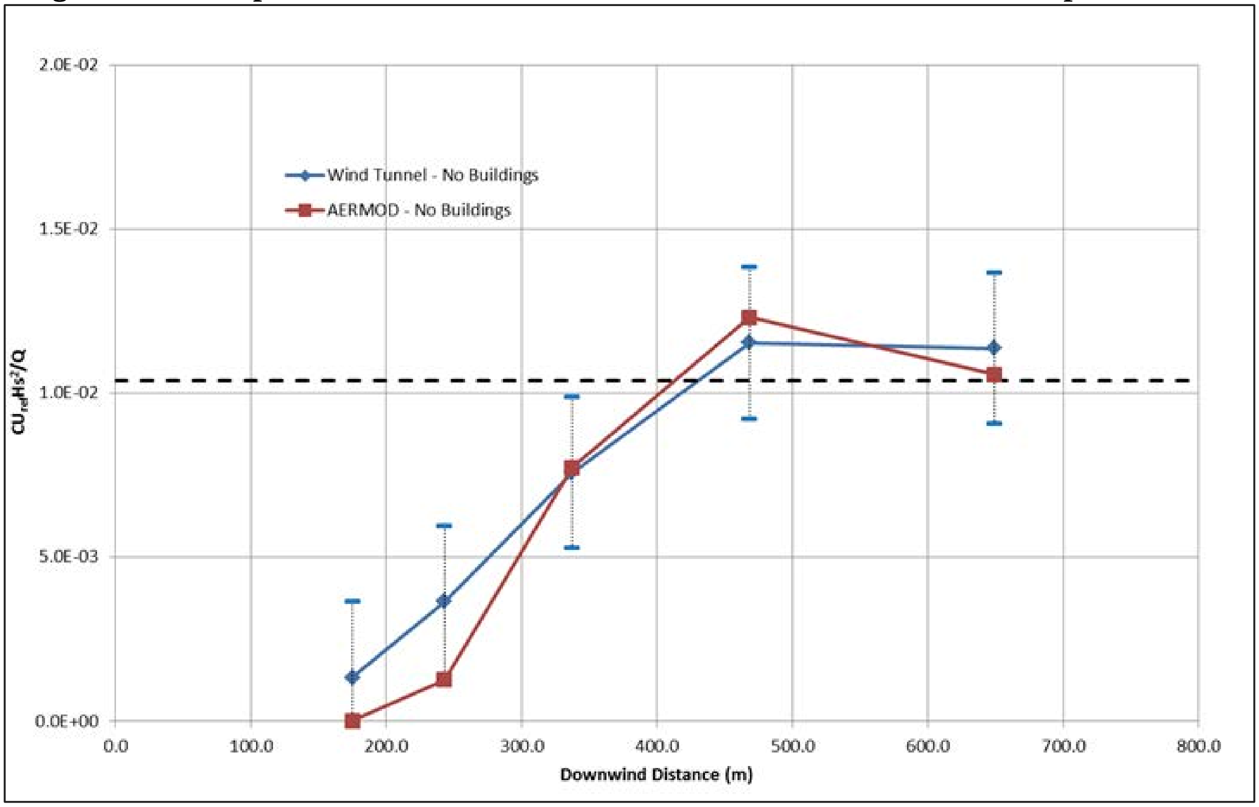
Step 1: Wind Tunnel Study to Establish Maximum Ground-Level Profile Mapping with the *No Site Structures Present* Case

In this step there are no structures in place in the wind tunnel other than the stack being tested. A tracer gas is released from the stack under evaluation and the maximum ground-level concentrations versus downwind distance are determined using the traditional method as described previously. In addition, the wind and turbulence profile approaching the stack are measured in the wind tunnel for use as inputs to AERMOD.

Step 2: Adjust AERMOD Inputs for the *No Site Structures Present* Case

AERMOD is then run using the source parameters and wind profiles from the wind tunnel and the results are compared to the wind tunnel observations with *no site structures present*. Since the wind tunnel can approximately replicate the theory in AERMOD, for the no-building case, the agreement should be very good (Figure 1). However, the predicted AERMOD and the observed wind tunnel concentration profiles may not match exactly due to slight variations in some of the wind profile input parameters (i.e., sigma-y, sigma-z, stack temperature, friction velocity) in the surface (*.sfc) and profile (*.pfl) meteorological files used by AERMOD. These parameters can be adjusted until acceptable agreement (i.e., within the 20% error bars) between the wind tunnel observations and the AERMOD results is achieved. Once good agreement is achieved, all AERMOD input parameters for the EBD evaluation will have been defined for the remaining steps. It is important to note that the full-scale source inputs to AERMOD are based on scaling the wind tunnel conditions back to full scale using Momentum and Buoyancy ratio similarity.

Figure 1. : Example: wind tunnel versus AERMOD for the *no site structures present* case



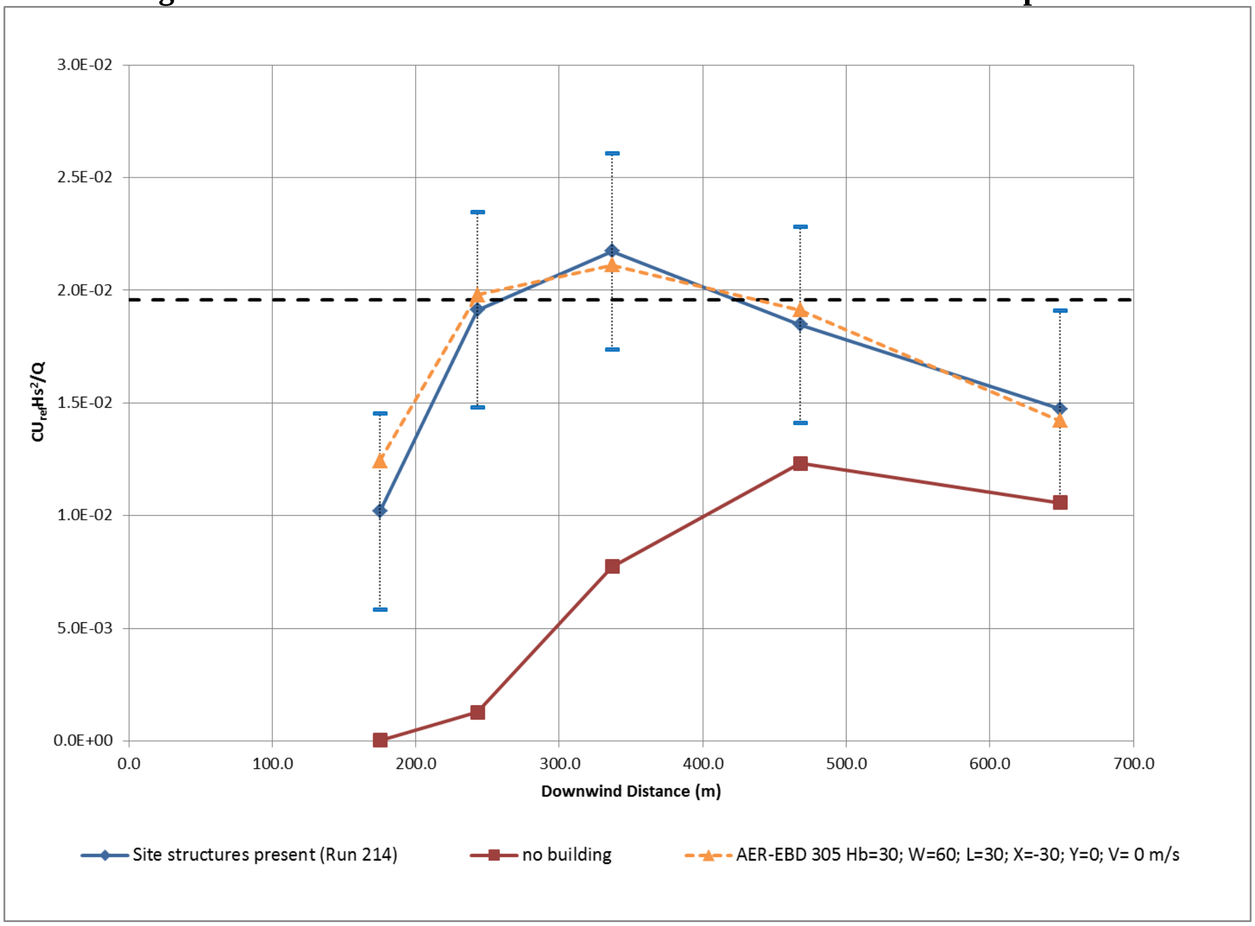
Step 3: Wind Tunnel Study to Establish Maximum Ground-Level Profile (MGL) Mapping with Site Structures Present

Similar to Step 1, for each wind direction and source evaluated, a tracer gas will be released from the stack including all site structures present to determine the maximum ground-level concentrations versus downwind distance using the method described previously. These tests define the actual effect of the structures on the dispersion characteristics (i.e., downwash) and will be used as the basis from which to define the building dimension inputs for AERMOD.

Step 4: AERMOD-Derived EBD

AERMOD is then run with various building dimension parameters defined in the building block of the input file using the source and meteorological input files determined in Step 2. For each stack and wind direction evaluated with the *site structures present* in the wind tunnel, an EBD will be defined using AERMOD. An example is provided in Figure 2. The EBD determined in this manner essentially makes AERMOD a site-specific model and aims to correct for some of the theoretical problems identified by Petersen.[10]

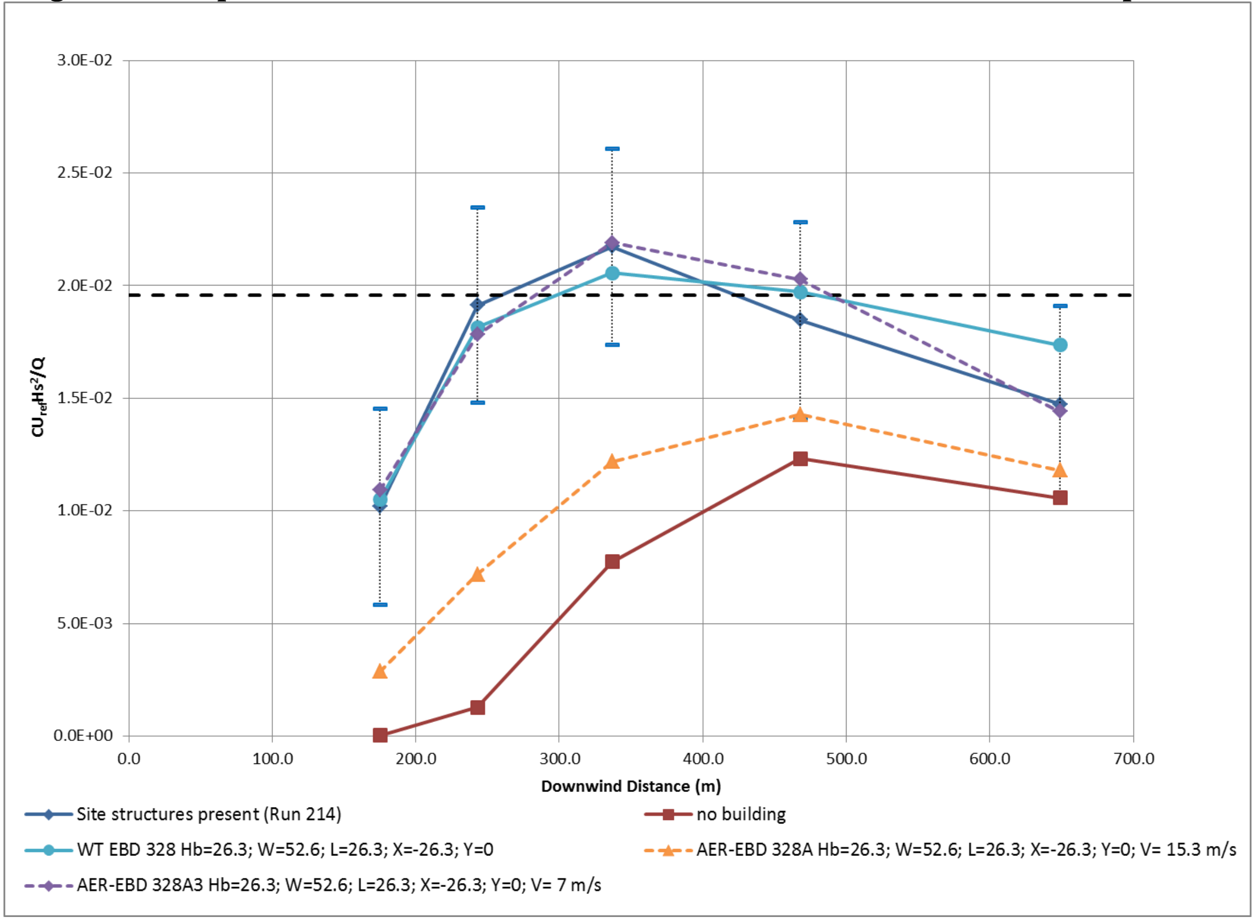
Figure 2. AERMOD EBD versus wind tunnel with site structures present



EVALUATION

Whereas the method outlined above seems to show favorable results in adjusting AERMOD to better match wind tunnel observations, it is critical to evaluate how the EBD results obtained from AERMOD and from wind tunnel testing compare to the *all site structures present* case. To do this we found the wind tunnel derived EBD that would best match with the MGL concentration profile from the *site structures present* case (dark blue line with error bars in Figures 2 and 3). In this example, a 1:2:1 in height-width-length (H:W:L) building of 26.3 m in height and placed upwind of the stack was found to be the best match to the MGL concentration profile (light blue line) using wind tunnel test results. This is the true equivalent building for the *all site structures present* case. These same building dimensions were used in AERMOD with the meteorological inputs used in Step 2 to calculate MGL concentrations. The results show that the concentrations obtained by using the wind tunnel EBD in AERMOD yielded a lower curve (orange dotted line) than the ones from the *all site structures present* (dark blue line with error bars) and wind tunnel EBD (light blue line) cases as depicted in Figure 3. These two curves should exhibit a very similar agreement due to the adjustments made on the *no site structures* *present* case (Step 2). However, the profile for the AERMOD-EBD (orange dotted line) has a higher plume rise than the one from the *all site structures present* profile (dark blue line with error bars). To obtain acceptable agreement (i.e., within the 20% error bars) between the wind tunnel-derived EBD and the AERMOD-derived EBD, the plume rise had to be corrected in AERMOD. This was accomplished by adjusting the stack exit velocity in an iterative fashion to obtain acceptable agreement with the *all site structures present* case.

Figure 3. Comparison of wind tunnel-derived EBD and AERMOD-derived EBD profiles.



DISCUSSION

The new EBD method is based on finding agreement between the MGL concentrations from the wind tunnel and AERMOD for the *no site structure* case simulation. This was accomplished by making adjustments to sigma-y and sigma-z in the profile file (*.pfl). Once this agreement was ascertained, the next step is to find with AERMOD the EBDs that result in MGL concentrations that match those collected from wind tunnel for the *site structures present* case. This step was accomplished with a 1:2:1 (H:W:L) building of 30 meters in height placed upwind of the stack. Yet, the question of how these EBDs relate to wind tunnel observations remains. In this evaluation, the wind tunnel EBD that best matched the MGL concentrations from the *site structures present* case was identified to be a 1:2:1 (H:W:L) building of 26.3 meters placed upwind of the stack. These dimensions are smaller than the ones obtained from the AERMOD-derived EBD. The wind tunnel derived EBDs are more accurate since they are based on actual measurements in a properly simulated building wake instead of being based on numerical methods. These same dimensions were used in AERMOD to calculate MGL concentrations. The results showed an MGL profile that was significantly lower than the one obtained with the wind tunnel. Better agreement was obtained by lowering the plume rise in AERMOD to better match the observations from the wind tunnel. This was accomplished by lowering the stack velocity from 15.3 m/s to 7 m/s. The need for this correction suggests that AERMOD's theory may be inaccurate in properly characterizing plume rise. This is the case because the PRIME building downwash algorithm used to calculate the wind speed in the wake (which is used to compute plume rise), is in error for the reasons point out by Petersen[10].

SUMMARY

The wind tunnel method to obtain EBDs is still the preferred source characterization technique to correct the BPIPPRM-generated building dimensions of a site. Evaluating wind tunnel derived-EBDs with AERMOD exhibited plume rise discontinuities that hinder an acceptable agreement between the two unless plume rise adjustments are applied. This plume rise discrepancy, along with other formulation issues in AERMOD, precludes the model from giving acceptable agreement when compared to wind tunnel collected observations. This highlights the need to thoroughly evaluate and update AERMOD and PRIME to improve model performance.

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