

95-WA75A.05

Equivalent Building Dimensions for ISC2 Modeling Applications

Ronald L. Petersen and Brad C. Cochran
Cermak Peterka Petersen, Inc.
Fort Collins, Colorado

David E. Keen
Radian Corporation
Morrisville, North Carolina

Ronald N. Walton
Cape Industries
Wilmington, North Carolina



AIR & WASTE MANAGEMENT
A S S O C I A T I O N

◆
SINCE 1907

For Presentation at the
88th Annual Meeting & Exhibition
San Antonio, Texas
June 18-23, 1995



INTRODUCTION

The treatment of downwash in the ISC2¹ model is based on wind tunnel studies conducted by Huber and Snyder^{2,3} in which a solid structure with a width twice that of the height and depth was positioned directly upwind of a source stack as shown in Figure 1. While the downwash algorithm is appropriate for this simple configuration, it may not be appropriate for the more complex site configurations typically found at industrial facilities, such as when the structure is located at a distance from the stack or is tiered, porous, non-rectangular or otherwise varies from the basic configuration assumed in the ISC2 downwash algorithm. The ISC2 User's Guide¹ acknowledges this building wake prediction problem with the following statement concerning the building wake algorithm:

“Their suggestions (Huber and Snyder) are principally based on the results of wind-tunnel experiments using a model building with a crosswind dimension double that of the building height.... Thus, the data reported by Huber and Snyder reflect a specific stability, building shape and building orientation with respect to the mean wind direction. It follows that the ISC2 Model wake-effects evaluation procedures may not be strictly applicable to all situations.”

The ISC2 User's Guide further requires using the dimensions of the largest nearby building for the building dimension input for each wind direction modeled. Nearby in this case is defined as $5 L_b$ upwind, $0.5 L_b$ crosswind and $2 L_b$ downwind where L_b is the lesser of the building height or crosswind width. Thus, the dominant building need not be adjacent to or even upwind of the modeled stack as assumed in basic algorithm development. An example of this disparity can be demonstrated for an upwind building near the $5 L_b$ criteria. If the building is slightly greater than $5 L_b$ away from the stack it is assumed to have *no* downwash influence on the stack, while the same structure just under $5 L_b$ is assumed to have the *full* downwash influence. This clearly results in a discontinuity in the downwash treatment since the downwash influence of a building is expected to decrease gradually as the distance from a stack approaches $5 L_b$. Any reduction in the downwash which actually takes place due to the separation distance between the building and the stack is not accounted for when following the ISC2 User's Guide procedures for defining the building dimension input.

The geometry of the building can also have a dramatic impact on the resulting vertical dispersion patterns. The ISC2 downwash algorithm inherently assumes that the vertical plume dispersion patterns of “squat” buildings (building width greater than or equal to the building height) do not change with building geometry. Results of wind tunnel measurements recently conducted by Snyder and Lawson⁴ indicate that the downwind vertical flow patterns vary dramatically for rectangular buildings with width to height ratios ranging from 1.0 to 4.0. For a cubical structure the building wake is substantially smaller than for a structure with a width four times the height. This would suggest that the vertical plume dispersion would be less for cubical structures.

The building shape will also affect the building downwash and can be dramatized by investigating the wake region behind a cube and a cylinder. Flow around a cube will separate at the leading edge and results in a relatively large wake region and high dispersion coefficients downwind of the cube. For a cylinder exposed to a turbulent environment, the flow will separate slightly downwind of the center of the cylinder perpendicular to the flow. Therefore, the wake region and subsequently the dispersion coefficients behind a cylinder will be less than that behind a cube. Thus, applying the ISC2 downwash algorithm using the actual dimensions of cylindrical structures may result in overestimates in ground-level concentrations.

The effect of porosity on the flow pattern downwind of a 3-dimensional structure has not been fully investigated. However, wind tunnel tests documenting the wake structure downwind of 2-dimensional windbreaks⁵ confirm the expected premise that the size of the wake region behind the structure is proportional to the porosity of the structure. Thus the effect of the building wake on plume dispersion should be diminished for porous structures.

Based on the above, it is clear that the input of the actual building dimensions according to criteria in the ISC2 User's Guide may give inaccurate concentration estimates for many situations. A major enhancement to ISC2, therefore, could be obtained by adjusting the building dimension input into ISC2 such that the new dimensions allow ISC2 to better replicate the actual downwash when the building configuration is not consistent with the Huber/Snyder^{1,2} geometry (see

Figure 1). These adjusted building dimensions are referred to as “equivalent building dimensions” and can be determined by wind tunnel modeling.

At present, the only method the Environmental Protection Agency (EPA) has concurred with for determining EBD is through the use of wind tunnel modeling. Petersen^{6,7} describes the first such study for which the protocol was reviewed and accepted by the EPA (Region V and RTP) and for which a permit was ultimately obtained.⁸ That study considered the effect of a nearby lattice type (porous) structure. More recently, the EPA⁹ has approved the equivalent building concept for regulatory modeling use on the basis that it is a source characterization study which is under the purview of the Regional Offices.

APPLICATION OF EBD TO THE CAPE INDUSTRIES FACILITY

This paper describes the application of the equivalent building concept for a regulatory modeling study of the Cape Industries Facility in Wilmington, North Carolina. Cape Industries is in the process of evaluating current operations to define their baseline emissions inventory as part of a 5 year Waste and Release Reduction (WARR) program. The initial phase of the WARR program was to develop an accurate estimate of emissions from current operations. Future modifications and expansions of the facility rely on accurate estimates of ground-level concentrations from existing sources. In addition, Cape Industries, along with the entire chemical manufacturing community, will be subjected to increasingly more stringent environmental controls as a result of current and future legislation. Therefore, the accuracy of the model used to determine emissions and subsequent compliance has become increasingly more important.

The Cape Industries Facility (CIF) consists of several chemical processing lines, each of which contains one or more emission sources. Many of these exhaust stacks are either directly adjacent to, or nearby open lattice-type structures. Initial dispersion modeling conducted with ISC2 using actual building dimensions (i.e., those determined using the suggested procedures in the ISC2 User's Guide¹) showed that high concentrations would result due to building downwash effects.

The equivalent building dimensions for different exhaust stacks located at CIF were determined through physical modeling of plume dispersion and the atmospheric boundary layer. A 1:240 scale model of CIF shown in Figure 2 was constructed and placed in the open-circuit atmospheric boundary layer wind tunnel. The ISCST2 model was then run with the equivalent building dimension inputs to provide a more accurate assessment of the ground-level concentrations downwind of each of the exhaust stacks. This enhancement to the ISCST2 model allowed Cape Industries the opportunity to evaluate future plant modifications and expansions using more accurate ground-level concentration estimates.

A draft fluid modeling protocol for this study¹⁰ was prepared and submitted to the State of North Carolina Department of Environment, Health and Natural Resources (DEHNR) for review and approval. The study was then conducted and the final report was subsequently approved by the EPA¹¹.

TECHNICAL BACKGROUND

Determination of Equivalent Building Dimensions

As discussed in the introduction, equivalent building dimensions are the dimensions (height and width) that should be input into the ISC2 model to allow the model to produce realistic concentration estimates for sites where the actual building geometry is not consistent with the assumptions in the ISC2 wake algorithm. Figure 3 illustrates the discrepancy between the downwash created by the actual building site and the assumed configuration. The figure shows the downwind concentration profile for an exhaust stack with the actual site configuration (open circles) and two equivalent buildings. For this wind direction the dominant building is a 24 m tall by 48 m wide lattice structure located approximately 50 m upwind of the stack. Following the ISC2 procedures, the downwash due to this structure would be modeled as if a 24 m × 48 m solid structure was located directly upwind of the stack. Figure 3 shows that the downwash resulting from this solid structure (solid triangles) overestimates the downwind concentrations. The figure also indicates that the actual concentration profile can be modeled more accurately using an equivalent solid structure with dimensions 15.2 m × 30.5 m (open triangles).

To determine the equivalent building dimensions for CIF, wind tunnel tests were first conducted for 18 wind directions (at 20 degree increments) with all plant structures in place for each source. Ground-level concentration measurements were obtained at between 40 and 48 receptor locations along lateral grids at a minimum of 5 downwind distances. The 18 concentration tests were then repeated with the nearby structures removed (structures were classified as nearby when the stack is closer than five times the lesser of the height or width of the structure).

The initial determination of the EBD used the following EPA¹² definition for an excessive concentration:

“A maximum ground-level concentration due to emissions from a stack due in part or whole to downwash, wakes, or eddy effects produced by nearby structures or terrain features which individually is at least 40% in excess of the maximum concentration experienced in the absence of such downwash, wakes, or eddy effects and which contributes to a total concentration due to emissions from all sources that is greater than an ambient air quality standard.”

Therefore, when the maximum ground-level concentration with all structures in place was no more than 40% greater than the maximum ground-level concentration with the nearby structure removed, the concentration was not considered to be excessive for that specific exhaust stack/wind direction combination, and the EBD was set equal to zero. An example of this analysis is shown in Figure 4. In the plot, the maximum concentration with the structures present is less than 1.4 times the maximum concentration with the nearby structures removed. Hence, for this wind direction the downwash is not considered excessive and thus the equivalent building height is zero.

Following the actual site and nearby building-out concentration tests, the site model was removed from the wind tunnel and replaced with a uniform roughness that was representative of the plant roughness. A single rectangular building with height to width to depth ratios of 1:2:1 was then placed upwind of the stack under evaluation (similar to the configuration shown in Figure 1) and the ground-level concentrations versus downwind distance were measured. This setup was specifically designed to reproduce the wind tunnel configuration used by Huber and Snyder.^{2,3} The process was repeated for various sized buildings until a building was found that gave a similar (as defined below) longitudinal ground-level concentration profile as that measured with the actual site present.

Figure 5 shows the ground-level concentration profile for an exhaust stack/wind direction combination for which an excessive concentration was observed. For this source, and all others where an excessive concentration was demonstrated to exist, the equivalent building was determined by first comparing the overall maximum concentration for the various equivalent building tests to the test with the actual site structures present. The equivalent building is then taken to be the smallest building that produces an overall maximum concentration that is within 90% of or greater than the overall maximum concentration with the actual site structures in place. The corresponding equivalent building for the exhaust stack/wind direction combination shown in Figure 5 is BH6 following this selection criteria.

Since this study was conducted, the EPA⁹ has recommended a different procedure for determining EBD. The new procedure abolishes the use of the excessive concentration demonstration to define a zero building height and redefines the selection criteria for determining whether or not two concentration profiles are similar. Under the new provision, the equivalent building is defined as the smallest building for which: 1) the overall maximum concentration with the equivalent building configuration exceeds 90% of the overall maximum concentration observed with all site structures in place; and 2) the maximum concentration with the equivalent building configuration at all other longitudinal distances exceeds the maximum ground-level concentration observed at that distance with all site structures in place less 20% of the overall maximum ground-level concentration with all site structures in place.

An example of this new selection criteria is shown in Figure 6 using the same data set shown in Figure 5. The figure indicates that the new EPA defined selection criteria has been met for both BH6 and BH7. Since BH6 is the smaller of the two buildings it is selected as the equivalent building, which gives the same result as the previous selection criteria. This will not necessarily be true for all cases but does indicate that the differences between the two criteria will be small.

Model Similarity Requirements

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind tunnel study of diffusion from an industrial facility. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. A detailed discussion on these requirements is given in the EPA fluid modeling guideline.¹³

The gas flow simulation was designed around the criteria of matching momentum and exhaust density ratios. This criteria has been approved by the EPA¹¹ for use in equivalent building dimension studies and is consistent with the requirements for a “Good Engineering Practice” (GEP) stack height analysis. In both types of studies the wake structure and its influence on the subsequent plume behavior is evaluated rather than actual ground-level concentration values. The GEP guideline recommends neglecting plume buoyancy and setting the momentum ratio and density ratio equal in model and full scale. This approach allows the best simulation of the air flow characteristic around structures.

EXPERIMENTAL METHODS

Model Construction

A 1:240 scale model of CIF was designed and constructed. The model included all significant buildings and structures within a distance of 520 m radius of CIF. A photograph of the model is shown in Figure 2. Brass tubing was used for the each of the circular exhaust stacks. Each stack was supplied with a premixed helium–hydrocarbon mixture using a precision gas flow meter to monitor and regulate the discharge velocity. Where appropriate, in-stack trips were used to assure turbulent flow.

Wind Tunnel Configuration

After construction, the CIF model was placed in an open circuit atmospheric boundary layer wind tunnel. Upwind and downwind of the model, roughness elements were installed to represent the surrounding roughness. Flow conditioning devices consisting of a 2-dimensional trip and a pair of spires were also placed upwind of the model to aid in the development of a representative boundary layer. Ground-level sampling taps were installed downwind of the exhaust stacks so that up to 48 locations were sampled simultaneously for each simulation.

The equivalent building dimensions were determined using a set of solid structures fabricated for placement directly upwind of each centrally located exhaust stack. The full scale building heights of the solid structures ranged from 9.15 m to 36.6 m with widths ranging from 18.3 m to 73.2 m. These structures were specifically designed to match the building height to width to depth ratio of 1:2:1 used by Huber and Snyder^{2,3} in the validation study for the ISC2 downwash algorithm.

Concentration Measurement Techniques

After the desired atmospheric boundary layer was established in the wind tunnel, a mixture of inert gas and a tracer (ethane, methane and/or propane) of predetermined concentration was released from the stacks at the required rate to simulate plume rise. Samples of the gas were withdrawn from the receptor locations using a gas sampling system. The samples were then analyzed with a flame ionization gas chromatography to determine the tracer gas concentration. The concentrations measured in the wind tunnel were related to full-scale concentrations using standard scaling techniques¹³.

RESULTS

“Equivalent” building dimensions were determined for 18 wind directions in 20 degree increments for each exhaust stack using the procedures described in the preceding sections. Since ISC2 requires building dimension inputs for 36 wind directions, the equivalent building height for the remaining wind direction inputs were obtained based on the wind-tunnel determined results at the 18 primary wind directions. The building dimensions for the non-tested wind directions (10, 30, 50 degrees, etc.) were determined by using the dimensions of the larger of the EBD on either side (± 10 degrees). For example, if the wind tunnel determined equivalent building at 0 degrees was 21.3 m \times 42.7 m (BH5) and the equivalent building at 20 degrees was 24.4 m \times 48.8 m (BH6), the equivalent building for 10 degrees is also 24.4 m \times 48.8 m (BH6).

Comparison of Equivalent Building Dimensions Versus ISC2 Building Dimensions

A comparison between the equivalent building dimensions as determined using the wind tunnel simulation and the actual building dimensions for CIF as defined by the ISC2 User's Guide is presented in Figure 7 for three of the stacks evaluated. The figure illustrates that for many wind directions the equivalent building heights are substantially lower than the actual heights. In one rare instance the equivalent building was slightly taller than the actual building. At this particular wind direction a large solid structure is located upwind of the stack at a distance slightly greater than $5 L_b$.

Comparison of Concentration Estimates Using Equivalent Building Dimensions Versus ISC2 Building Dimensions

A comparison between ISCST2 modeled 3-hour concentrations for the Cape Industry Facility using the actual building dimension inputs and the equivalent building dimension inputs is presented in Table 1. The results indicate that using the equivalent building dimensions reduced the concentration estimates for the individual stacks by as much as a factor of 7.3 for this facility. For all six stacks listed in Table 1 the concentration estimates using the equivalent building dimensions were equal to or lower than estimates using the actual building dimensions. Assuming the emission rate for all stacks is equivalent, Table 1 also indicates that overall concentration estimates for CIF were reduced by a factor of 2.6 using the equivalent building dimensions rather than the actual building dimensions for input into ISCST2.

CONCLUSIONS

The results of this study have indicated that the ISCST2 approach of modeling the exhaust stacks at the Cape Industries Facility using the actual dimensions of the surrounding structures (open lattice-type structures and/or buildings removed from the stack location) for building dimension input into ISCST2 does not represent the actual dispersion from sources. In addition, this study has demonstrated that the wind tunnel can be used, following an EPA approved protocol, to determine equivalent building dimensions.

The results of this study show that concentration estimates from individual stacks were lowered by as much as a factor of 7.3 when the equivalent building dimensions were used for input instead of the actual building dimensions for the Cape Industries Facility. While these results are certainly site specific, similar reductions can be expected for facilities with building configurations similar to that evaluated in this study.

Since this study was conducted, the EPA has redefined the criteria for selecting equivalent building dimensions. It appears that the impact of the new criteria does not significantly affect the results of this study.

From these findings it is clear that the input of the actual building dimensions according to criteria in the ISC2 User's Guide may give inaccurate concentration estimates when the building configuration is not consistent with the Huber/Snyder^{1,2} geometry. A major enhancement to ISC2, therefore, can be obtained by adjusting the building dimension input into ISC2 such that the new dimensions allow ISC2 to better replicate the actual downwash. The EPA has currently recognized that these adjusted building dimensions, referred to as "equivalent building dimensions," can be determined through wind tunnel modeling.

REFERENCES

1. EPA, *User's Guide for the Industrial Source (ISC2) Dispersion Models*, EPA-450/4-92-008a, USEPA Office of Air Quality, Research Triangle Park, 1992.
2. A.H. Huber and W.H. Snyder, "Building Wake Effects on Short Stack Effluents," *Preprint Volume for the Third Symposium on Atmospheric Diffusion and Air Quality*, American Meteorological Society, Massachusetts, 1976.
3. A.H. Huber and W.H. Snyder, "Wind Tunnel Investigation of the Effects of a Rectangular-Shaped Building on Dispersion of Effluents from Short Adjacent Stacks," *Atmospheric Environment*, 16(12): 2837-2848 (1982).

4. W. H. Snyder and R.E. Lawson, Jr., "Wind-Tunnel Measurements of Flow Fields in the Vicinity of Buildings," *Eighth Joint Conference on Applications of Air Pollution Meteorology with AW&MA*, American Meteorological Society, 1994, pp 244–250.
5. B.J.B. Stunder and S.P.S. Arya, "Windbreak Effectiveness for Storage Pile Fugitive Dust Control: A Wind Tunnel Study," *JAPCA*, 38: 135–143 (1988).
6. R.L. Petersen, D.N. Blewitt and R. Panek, "Lattice Type Structure Building Height Determination for ISC Model Input," *85th Annual AWMA Conference*, Missouri, 1992.
7. R.L. Petersen and M.A. Ratcliff, "Site Specific Building Height Determination for Amoco's Whiting Refinery," Report No. 90–0703, CPP, Inc., Colorado, 1991.
8. D. Blewitt, AMOCO Corporation, IL, personal communication, 1995.
9. J. Tikvart, United States Environmental Protection Agency, NC, letter to Brenda Johnson, Regional Modeling Contact, Region IV and Douglas Neeley, Chief Air Programs Branch, Region IV, July 25, 1994.
10. Cermak Peterka Petersen, Inc., "Equivalent Building Height Determinations for Cape Industries of Wilmington, North Carolina," Protocol Report No. 93–0955, CPP, Inc., Colorado, 1993.
11. D. Neeley, United States Environmental Protection Agency, Region IV, GA, letter to Alan Klimek, Chief Air Quality Section Division of Environmental Management, North Carolina Department of Environment, Heath, and Natural Resources, July 28, 1994.
12. EPA, *Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulation)*, EPA–45014–80–023R, USEPA Office of Air Quality, Research Triangle Park, 1985.
13. W.H. Snyder, *Guideline for Fluid Modeling of Atmospheric Diffusion*, Report No. EPA600/8–81–009, USEPA, Environmental Sciences Research Laboratory, Research Triangle Park, 1981.
14. Sigma Research Corporation, *Hazard Response Modeling Uncertainty (A Quantitative Method), Volume I, User's Guide for Software*, Publication No. 4545, American Petroleum Institute, Washington, DC, 1992.

Table 1. Comparison of ISCST2 modeled concentrations using the actual building height versus using the equivalent building dimensions (EBD).

Source ID	Maximum 3-hour Concentration @ 1 g/s Emission Rate*		
	Using ISC-ACT Dimensions ($\mu\text{g}/\text{m}^3$)	Using ISC-EBD Dimensions ($\mu\text{g}/\text{m}^3$)	Reduction Factor (ISC-ACT/ISC-EBD)
B1	47.0	15.5	3.0
H1	5.8	5.8	1.0
H3	4.4	4.1	1.1
H4	5.2	2.2	2.4
H5	3.1	2.1	1.5
TO	20.5	2.8	7.3
ALL	86.0	32.5	2.6

* Based upon meteorological data for 1991.

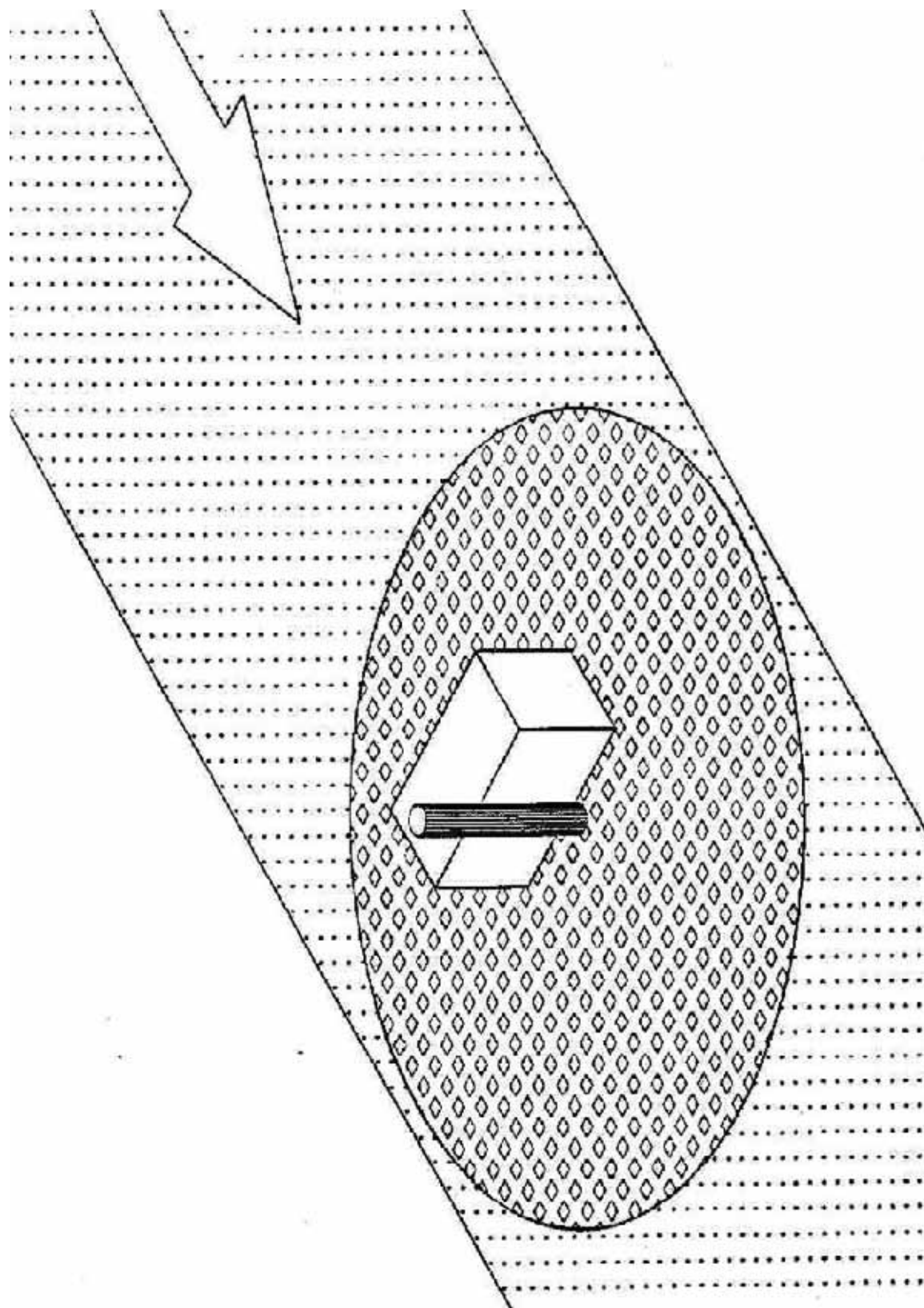


Figure 1. Building configuration (Huber/Snyder) assumed in ISC2 models.



Figure 2. Photograph of Hoechst Celanese model.

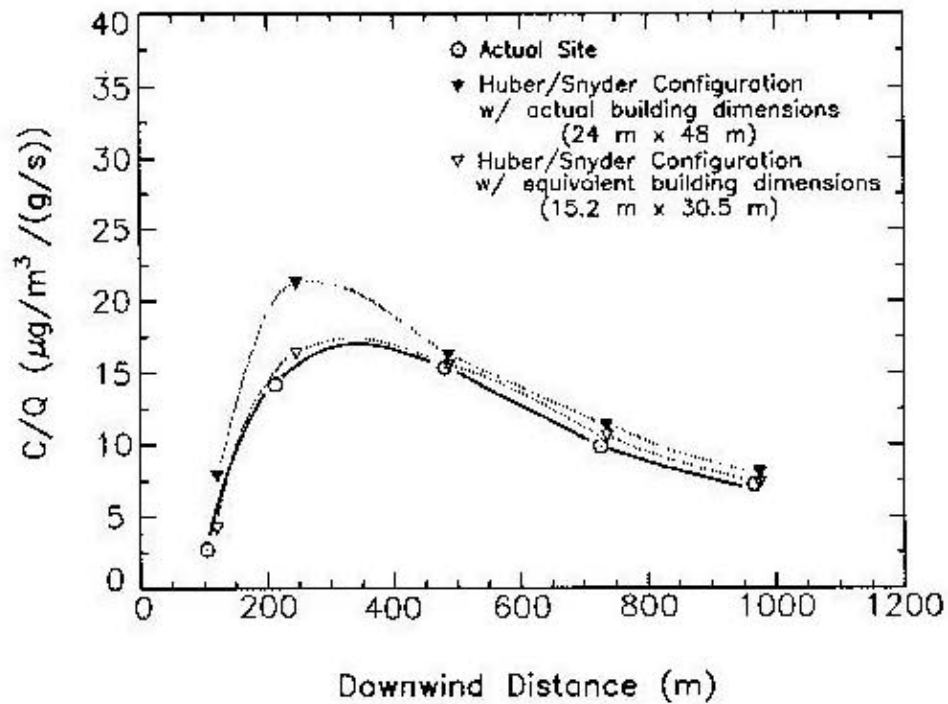


Figure 3. Longitudinal ground-level concentration profiles for an actual site and two different equivalent building (Huber/Snyder) configurations.

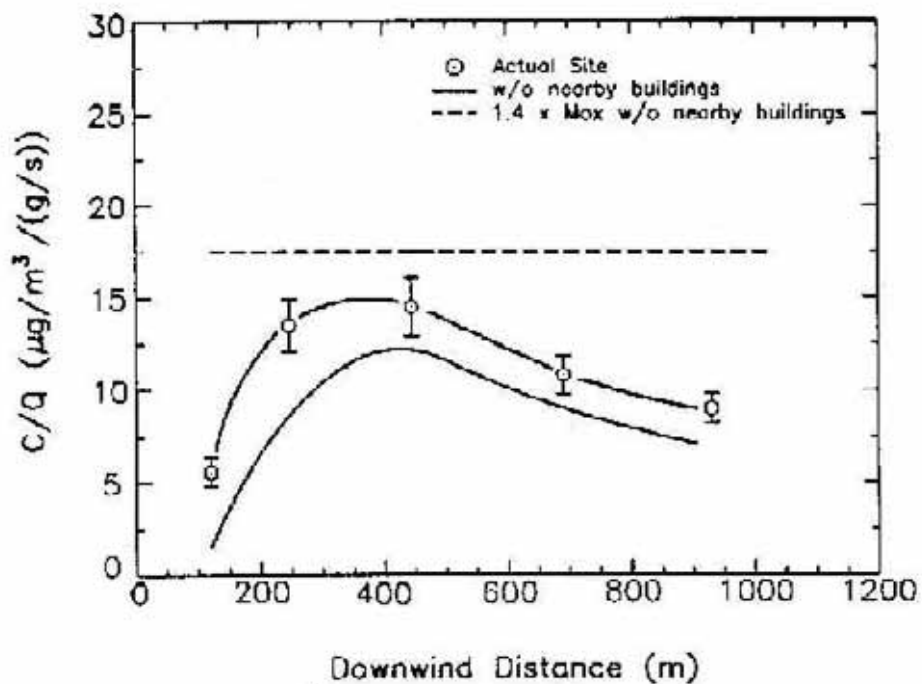


Figure 4. Example showing non-excessive concentrations where equivalent building is set equal to zero.

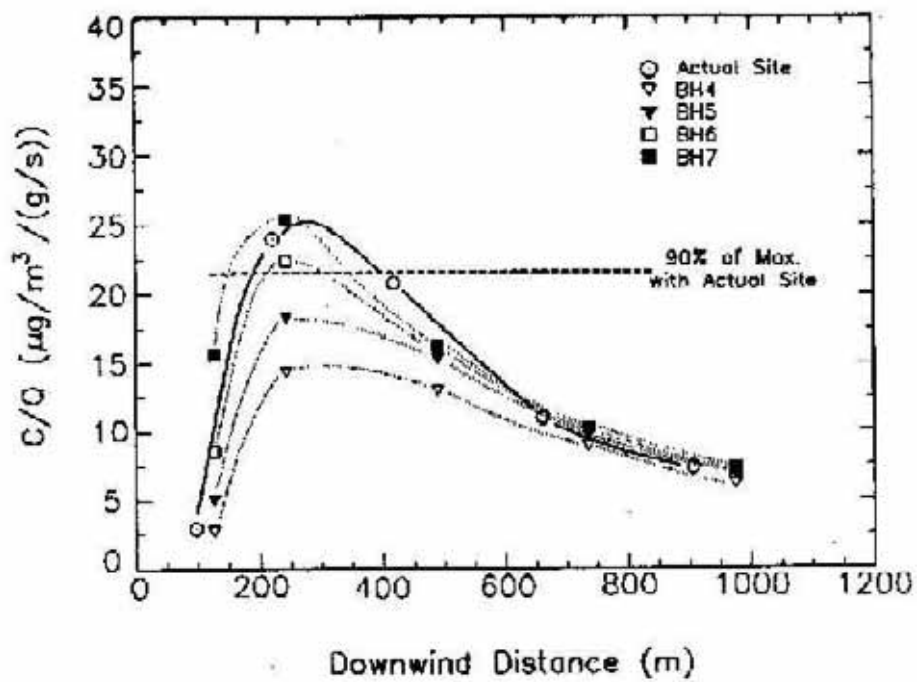


Figure 5. Longitudinal ground-level concentration profiles showing method for selecting the equivalent method.

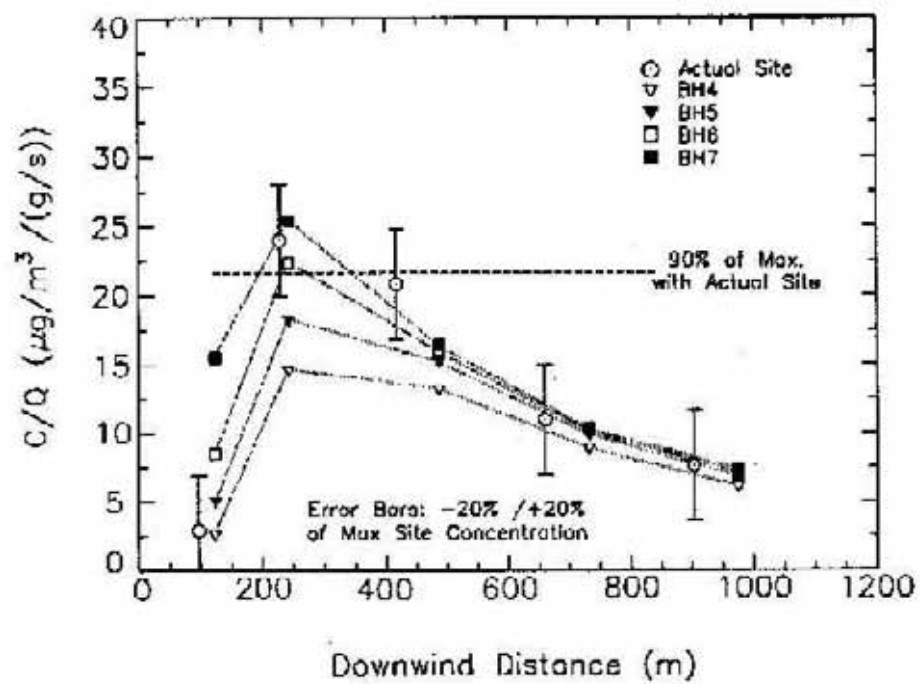


Figure 6. Showing revised method for selecting the equivalent building.

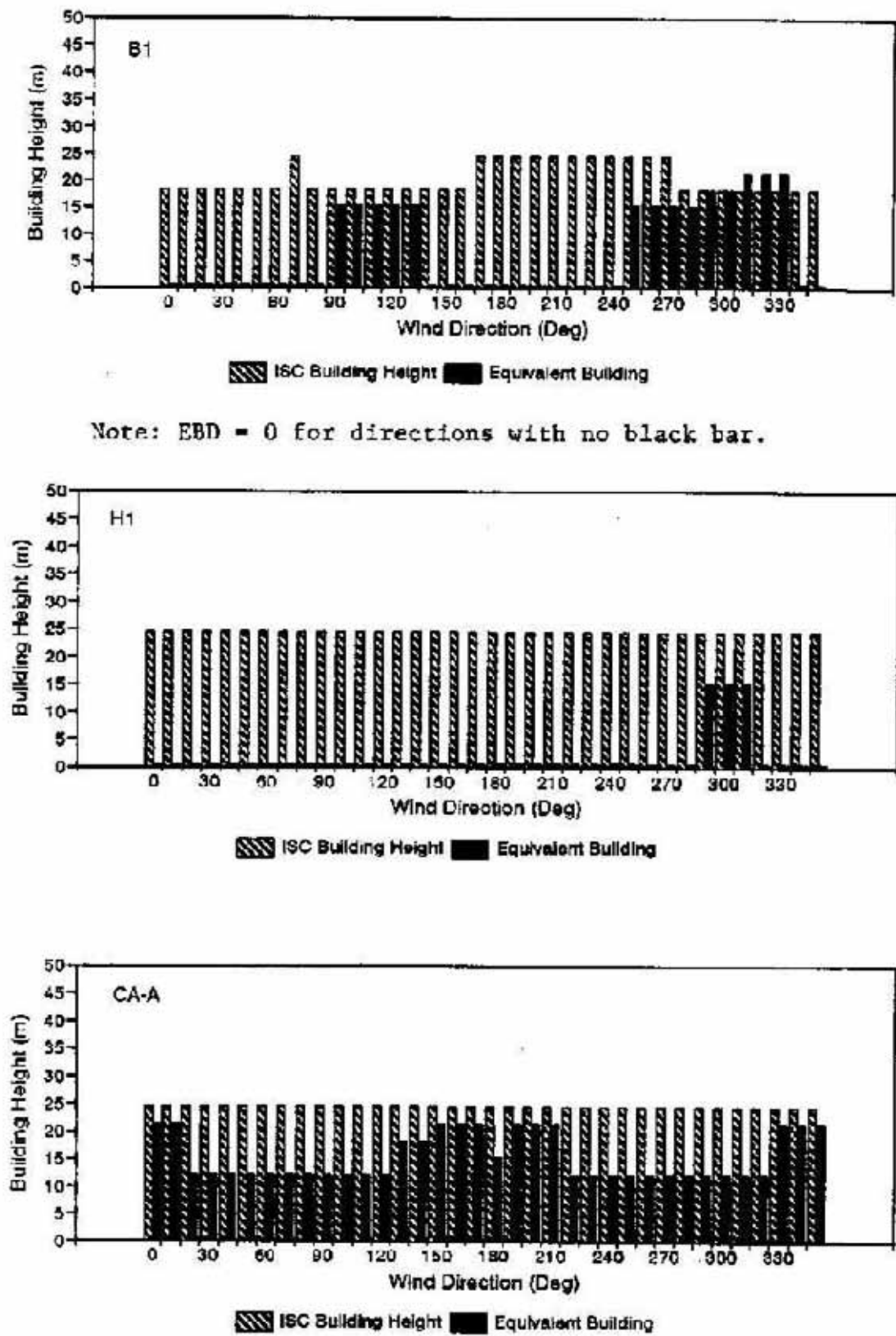


Figure 7. Wind direction specific equivalent building height versus actual (ISC) building heights.