

***ISC-PRIME Versus Wind-Tunnel Observations For Multi-tiered, Sloped, Porous Structures**

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Abstract

This paper evaluates the validity of ISC-PRIME for modeling multi-tiered, sloped, porous structures. ISC-PRIME was proposed for use to model a pair of such structures that were to be located near two proposed combustion turbines. The local agency questioned the use of BPIP determined building dimensions as inputs to the model due to the complexity of the surrounding structures. Hence, wind-tunnel testing was conducted to determine the equivalent building dimensions for ISC-PRIME input. During the course of the study, building dimensions were defined using both the BPIP analysis program and wind-tunnel determined "equivalent building dimensions" (EBD). ISC-PRIME was then run for 36 wind directions and one wind speed using both sets of building dimensions as input. The predicted concentrations were compared with wind-tunnel measurements obtained using a scale model of the facility. The results indicate that ISC-PRIME tends to over-predict maximum concentrations for this type of structure when BPIP generated building dimensions are used. ISC-PRIME with EBD inputs performed exceptionally well when compared to the wind-tunnel database and provided lower concentration estimates than ISC-PRIME/BPIP.

INTRODUCTION

The Industrial Source Complex model (ISC3)¹ has been the EPA approved model for estimating concentration levels when building wakes affect pollutant dispersion. The ISC3 model was developed largely based on data^{2,3} for neutral stability, moderate to high wind speeds, winds perpendicular to the building face and for a building with height to width to length ratios of 1:2:1. Some of the main limitations of ISC3⁴ are: 1) the location of the stack relative to the building is not considered; 2) the effect of streamline deflection on plume trajectories is not considered; 3) the effect of the velocity deficit in the building wake on plume rise is neglected; 4) no accounting for plume material captured by the near wake on far wake concentrations is not included; 5) there are discontinuities at the interface between two downwash algorithms; 6) wind direction effects are not properly considered for squat buildings; and 7) large concentrations are predicted during stable conditions with light wind speeds. A new model developed by Electric Power Research Institute (EPRI)^{5,6} has been recommended as the new "EPA approved model"⁷ for building downwash situations. This model is referred to as ISC-PRIME and addresses the shortcomings in ISC3 mentioned above. One independent evaluation of PRIME⁸ showed that it provides overall better performance than ISC3 and has a better scientific basis. Another evaluation⁹ showed that ISC-PRIME performed better for cubical building shapes while ISC3 performed better for buildings with height to width to length ratios of 1:2:1. A more recent evaluation¹⁰ showed that ISC-PRIME provides reasonable concentration estimates for cases when stacks are one to six building heights upwind, directly downwind and one building height downwind of the building under certain restricted conditions.

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The past performance evaluations of ISC-PRIME considered field and wind-tunnel databases with the stack located near the building^{8,9} and at various distances from the simple building shape for which ISC3 was designed,¹⁰ but no evaluation has been presented to date, that the authors are aware of, showing how well ISC-PRIME performs for unusual building shapes. It seems this would be an important area to investigate, since many facilities using the model have unusually shaped and/or porous structures in close proximity to the stack (i.e., lattice support structures, architectural shrouds to hide the stacks, etc.). In some cases, the porous structure may be neglected by BPIP even though this structure may be the dominant feature affecting plume downwash. In other cases it may be valid to neglect the effect of the porous feature. Since ISC-PRIME provides good estimates for simple building shapes,^{8,9} the Equivalent Building Dimension technique^{11,12} may be an appropriate method for improving the predictive capability of the ISC-PRIME model for complex sites, complex structures or porous structures for which ISC-PRIME was not designed.

This study was carried out to provide limited evidence regarding the validity of ISC-PRIME for multi-tiered, sloped, porous structures. To carry out the evaluation, a database of ground-level concentrations was obtained due to plume dispersion from a single stack located: 1) near a multi-tiered, sloped porous structure, and 2) near various buildings of simple geometric shape (i.e., 1:2:1 height to width to length ratio) to determine the EBD. The ISC-PRIME model was run, using building dimensions generated using the Building Profile Input Program (BPIP)¹³ as well as the EBD, for the exhaust parameters simulated in the wind tunnel. Comparisons between the ISC-PRIME/BPIP model predictions, the ISC-PRIME/EBD model predictions and the wind-tunnel observations were made. The database, the evaluation methods and results are discussed below.

WHY USE WIND-TUNNEL MODELING

There are several reasons why wind-tunnel modeling should be used as the primary tool for evaluating the validity of dispersion models like ISC-PRIME: theoretical, dispersion comparability, controlled conditions and expense. The first and most important reason is theoretical. A wind-tunnel simulation is, in effect, a solution to the basic equations of motion.¹⁴ The basic equations are solved by simulating the flow at a reduced scale and then the desired quantity (i.e., concentration) is measured. This solution to the basic equations (i.e., the wind-tunnel simulation) is a steady state solution with a complete record of the time varying velocity and concentration fields. It should be noted that the Gaussian dispersion model also predicts steady-state average concentrations. Another way of looking at the wind tunnel is that it is an analog computer with near infinitesimal resolution and near infinite memory. As stated in EPA,¹⁴ “if a mathematical model cannot simulate the results of an idealized laboratory experiment, how can it possibly be applicable to the atmosphere?”

A second reason relates to dispersion comparability. With the passage of the EPA “good engineering practice” (GEP) stack height regulation, wind-tunnel modeling has been required to determine the GEP stack height for many facilities.^{15, 16, 17} As part of a GEP stack height evaluation, the wind-tunnel modeler must perform what is referred to as an “atmospheric dispersion comparability test.” For this test, wind profiles and dispersion measurements are made in the wind tunnel without the presence of structures. A flat, uniform, grassland type roughness is

simulated. These tests have demonstrated that wind-tunnel velocity profiles match profile shapes observed in the atmosphere and the profiles fit similarity theory. The tests have also shown that the horizontal and vertical dispersion coefficients are consistent with the dispersion coefficients used in the ISC-PRIME model for urban and rural dispersion. The horizontal and vertical dispersion coefficients are also consistent with similarity theory and consequently reflect the character of the underlying surface roughness.

The third reason relates to the ability to control and monitor the meteorological and source conditions. When comparing dispersion models against field observations, the errors in the model inputs give one little hope in assessing the real validity of the model. In the field, wind profiles are frequently not available and the wind characteristics at the stack location are often assumed the same as the anemometer. Quite often, the hourly source characteristics are also unknown in the field. You may get good agreement with field observations but often the agreement is fortuitous. When using a wind-tunnel database, these input problems are minimized. The wind direction and wind speed are set and remain constant during a given simulation. The source parameters are also fixed and known. Hence, model input errors are minimized and the true performance of the model can be assessed.

Another good reason for using the wind tunnel is the cost. A high quality data set can be obtained for wide variety of source and building configurations for a fraction of the cost for the same data set collected in the field.

WIND-TUNNEL DATABASE

A series of 36 wind-tunnel tests (i.e., 10 degree wind vector increments) were conducted to obtain profiles of maximum ground level concentrations versus downwind distance due to emissions from a 45.7 m stack with the site structures in place. Figure 1 shows the multi-tiered, porous, sloped site structures. Eight additional tests were conducted to obtain maximum ground level concentrations versus downwind distance for buildings with height/width/length ratios of 1:2:1 (i.e., the “equivalent buildings”) with the significant site structures removed, as shown in Figure 2. The simulated source parameters and building dimensions for all tests are provided in Table 1.

Wind-tunnel model operating conditions were set by matching the following parameters in model and full scale:

- momentum ratio, M_0

Equation 1.

$$M_0 = \frac{\rho_s}{\rho_a} \left(\frac{V_e}{U_h} \right)^2 \left(\frac{d}{z_r} \right)^2 ;$$

- buoyancy ratio, B_0

Equation 2.

$$B_0 = \frac{g d^2 V_e (\rho_a - \rho_s)}{4 z_r \rho_a U_h^3} = \left(\frac{\rho_s}{\rho_a} \right) \left(\frac{R^3}{Fr_s^2} \right) \left(\frac{d}{z_r} \right) ;$$

- Reynolds number independence was ensured with a building Reynolds number in excess of 11,000;
- a neutral atmospheric boundary layer was established (Pasquill-Gifford C or D stability);

where

Equation 3.

$$Fr_s^2 = \frac{\rho_s V_e^2}{g (\rho_a - \rho_s) d} ;$$

and

- ρ_s = stack gas density (kg/m³);
- ρ_a = ambient air density (kg/m³).
- V_e = stack gas exit velocity (m/s);
- U_h = wind velocity at stack top (m/s);
- d = stack diameter (m);
- z_r = reference height (m); and
- g = gravitational acceleration (m/s²).

Ground-level sampling taps were installed downwind of the stack so that up to 48 locations were sampled simultaneously for each simulation. A typical sampling grid pattern is shown in Figure 3. The measured concentrations were converted to full-scale normalized concentrations (i.e., C/Q). The maximum concentration in each horizontal row was then selected to generate a database of maximum concentration versus downwind distance. The overall maximum concentration for each wind vector was also selected to generate a database of maximum concentration versus wind vector.

To determine “equivalent building dimensions” (EBD), the maximum ground level concentration profiles with the site structures in place are compared to those for the various simple geometry buildings. The criteria for defining whether or not two concentration profiles are similar is to

determine the smallest simple geometry building which: 1) produces an overall maximum concentration exceeding 90 percent of the overall maximum concentration observed with all site structures in place; 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 structures in place.¹¹

ISC-PRIME/BPIP AND ISC-PRIME/EBD VERSUS WIND-TUNNEL OBSERVATIONS

Building Dimension Inputs

Building dimensions for input into the ISC-PRIME model were determined using both BPIP and the EBD method. It should be noted that due to the complexity of the site structures, particularly the cooling tower seen in the background of Figure 1, the maximum number of tiers allowed in BPIP was changed to 11 and the source code was re-compiled.

Figure 4 shows the simplification of the multi-tiered, sloped, porous, structure used as input for the BPIP program. Note that both the porous shroud surrounding the stack (Tier 1) and the porous parts of each “wing” (see Figure 1) were assumed to be solid in the simplification. The “wings” were simplified as multiple tiers of decreasing height. The building parameters generated by BPIP indicated that Tier 2 was the dominant structure affecting plume downwash, not the stack shroud (Tier 1). The building parameters were all based on Tier 2.

EBD were determined by plotting the maximum observed C/Q in each receptor row versus downwind distance for the site structures as well as each equivalent building. Based on the criteria discussed above, an equivalent building was selected for each of the 36 wind vectors. Figure 6 is a typical plot used to make an EBD determination.

Figure 7 shows the variation in building height, H , versus wind vector for the various methods. Note that the BPIP determined height is identical to the actual height of Tier 2 for all wind vectors. Several of the EBD determined building heights are slightly higher than the Tier 2 height. This is probably due to the criteria required for the EBD selection and does not suggest that the stack shroud is the dominant feature affecting plume dispersion. If the stack shroud were the dominant feature, the EBD heights would be greater than the Tier 2 height for all directions.

Concentration Results and Discussion

The ISC-PRIME model was run using building parameters generated using both the BPIP program (ISC-PRIME/BPIP) and the EBD technique (ISC-PRIME/EBD). The exhaust and ambient parameters simulated are listed in Table 1. In both model runs, a polar receptor grid with rings of receptors corresponding to each receptor row used in the wind tunnel (i.e., downwind distances of 100 m, 144m, 208 m, 300 m, 433 m, 624 m and 900m) was used. As discussed above, a database of concentrations measured in the wind tunnel with the site structures present was compiled prior to the EBD analysis.

Figures 7 through 12 present the concentration results in various forms. In order to compare the results of the various techniques, graphs of the maximum concentration in each receptor row

versus downwind distance were generated. Figure 8 shows two typical graphs of the maximum concentration in each receptor row versus downwind distance at a specific wind vector. In Figure 8a, the maximum predicted C/Q for both methods matches that observed in the wind tunnel for distances less than about approximately 400 m. At greater distances, both ISC-PRIME/BPIP and ISC-PRIME/EBD tend to under-predict the maximum concentration. Figure 8b shows that ISC-PRIME/BPIP tends to over-predict the maximum C/Q for some wind directions, while still under-predicting at far downwind distances. This under-prediction at far downwind distances is most likely due to the limitation of “Urban” or “Rural” approach roughnesses.

Figure 9 and Figure 10 show the relative performance of ISC-PRIME using two building dimension generation methods. In Figure 9, the maximum concentration predicted for each wind vector is plotted versus the maximum concentration observed in the wind tunnel. All of the maximum predicted concentrations are within a factor of two of those observed in the wind tunnel. In general, ISC-PRIME/BPIP tends to over-predict when compared to both ISC-PRIME/EBD and the wind-tunnel observations. Figure 10 shows the maximum concentrations versus wind vector, normalized by the observed concentration for that wind vector, for each method. Again, ISC-PRIME/BPIP tends to over-predict for most wind vectors. This over-prediction is amplified for several wind vectors, including 30 degrees and approximately 290 through 350 degrees. The models slightly under-predict the maximum observed concentration for wind vectors 100 through 180 degrees. This is likely due to the orientation of the two complex structures, as shown in Figure 5. There are no significant structures upwind of the stack, but the “wing” of the complex structure may be acting as a “trip” that increases the vertical dispersion of the plume. Finally, an apparent wind vector shift between the ISC-PRIME/BPIP and ISC-PRIME/EBD is apparent in the ranges 80 through 110 degrees and 180 through 220 degrees. This may be due to a “bug” in the ISC program or the PRIME algorithm, discussed later.

In practice, a selected number of maximum concentrations (i.e., the 50 greatest concentrations) are used as an assessment of the environmental impact of a given facility. Figure 10 shows the maximum predicted and observed concentrations in increasing rank order. This figure shows that an environmental impact assessment using ISC-PRIME/BPIP for complex structures such as the multi-tiered, sloped, porous structure evaluated here, may needlessly over-predict the maximum concentration actually produced by the facility.

Figure 12 presents the maximum predicted and observed concentrations versus wind vector. The wind vector shift mentioned in the discussion of Figure 10 is quite obvious here. Since the EBD for each wind vector is determined based on wind-tunnel observations for that wind vector, the curve of maximum concentration for the ISC-PRIME/EBD model should match the wind-tunnel observed concentration curve. Note that in Figure 12, the ISC-PRIME/EBD curve is shifted slightly right for wind vectors from 0 through 210 degrees and slightly left from 230 through 250 degrees. To this point, both the ISC-PRIME/BPIP and ISC-PRIME/EBD models were run with the receptor grid origin at the center between the two units shown in Figure 1 (also see Figure 5). Based on these observations, several more ISC-PRIME/EBD model simulations were run with the stack location and receptor grid origin varied as indicated in Figure 13.

Figure 13a is the same as Figure 12, but with the ISC-PRIME/BPIP data removed. The stack was located at coordinates (-35.26, -80.45) and the receptor grid origin was located at (0, 0). Note that

the ISC-PRIME/BPIP data was not included in this analysis due to the lack of exact correlation between the ISC-PRIME/BPIP and wind-tunnel observed results. In Figure 13b, the stack location and receptor grid origin were co-located at coordinates (0, 0). In Figure 13c, the stack location and receptor grid origin were co-located at coordinates (-35.26, -80.45). The curves of ISC-PRIME/EBD and wind-tunnel observed results match quite well in both of these figures. In Figure 13d, the original stack location and receptor grid origin were switched. The stack was located at coordinates (0, 0) and the receptor grid origin was located at (-35.26, -80.45). The results discussed for Figure 13a are exactly reversed. This suggests an error in the translation of the building dimensions as the wind vector is rotated through its' full range. This error may be either in the original ISC program or in the newer PRIME algorithm. This inconsistency could produce results significantly different from the "true" results when "real" meteorological data is used. Alternatively, the results may show a limitation in the polar receptor grid such that a polar grid should not be used if the source is not located at the origin of the receptor grid. Additional testing is required to determine the source of the error.

CONCLUSIONS

The results of this study show that the ISC-PRIME model using BPIP generated building dimensions tends to over-predict concentrations for complex structures such as the multi-tiered, sloped, porous structure evaluated. When "Equivalent Building Dimensions" (EBD) are used, the ISC-PRIME model performed exceptionally well in predicting the overall maximum concentrations for the complex structure evaluated. However, the ISC-PRIME model tends to under-predict concentrations at distances far downwind no matter the technique used to generate the building dimensions. This under-prediction at downwind distances is most likely due to the limitation to "Urban" or "Rural" approach roughnesses. It is expected that this limitation will not be present when the PRIME algorithm is incorporated in the AERMOD¹⁸ model.

When comparing the maximum concentration at each wind vector, a possible "bug" in either the ISC-PRIME program was identified. Specifically, the wind vector producing the maximum concentration depends on the relative location of the source and receptor origin. This inconsistency could produce results significantly different from the "true" results when "real" meteorological data is used. This possible "bug" may also be an artifact of the polar grid selected and may suggest that polar grids should not be used when the source is not located at the origin of the receptor grid.

In general, this study shows that the ISC-PRIME model performs exceptionally well for complex structures if the building parameters are first determined using the EBD method. If BPIP generated dimensions are used, the model tends to over-predict the maximum concentration for this particular structure. However, this study was limited in scope and additional testing is needed before general conclusions can be drawn.

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KEY WORDS

Dispersion Modeling, wind tunnel, building wake effects, model validation, ISC, PRIME

FIGURES

Figure 1. Close-up view of the multi-tiered, sloped porous structures in the wind tunnel.

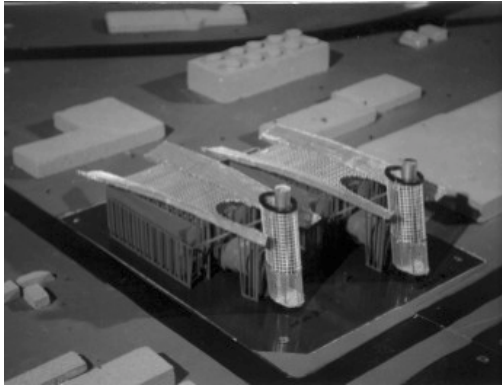


Figure 2. Close-up view of a typical equivalent building setup in the wind tunnel.

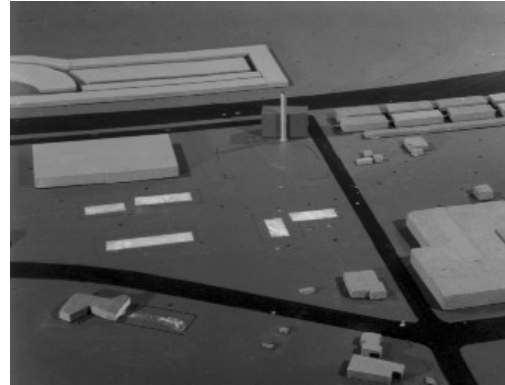


Figure 3. Wind-tunnel schematic showing a typical equivalent building setup in the wind tunnel.

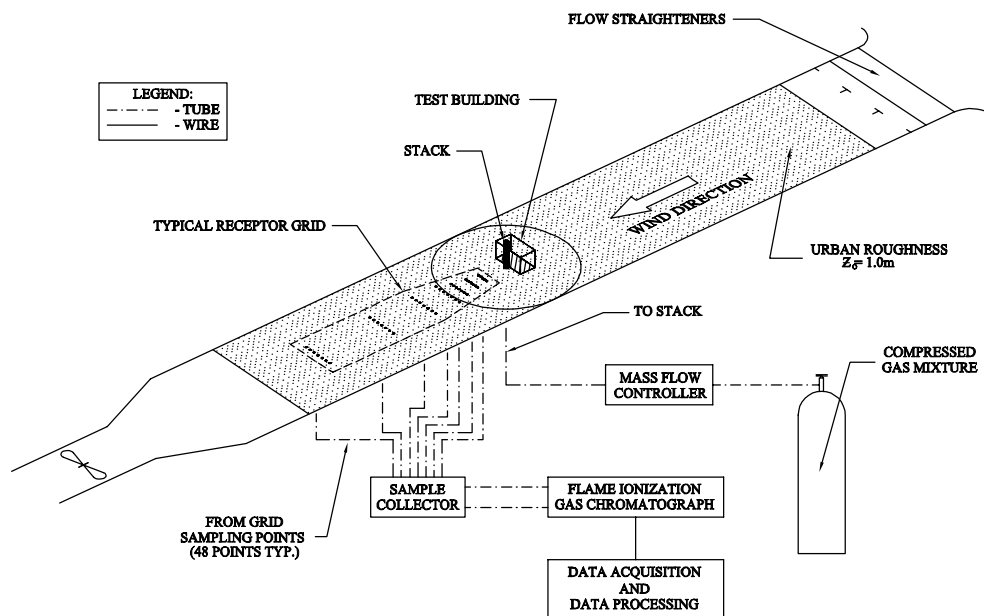


Figure 4. Simplification of the multi-tiered, porous, sloped structure for input into the BPIP program.

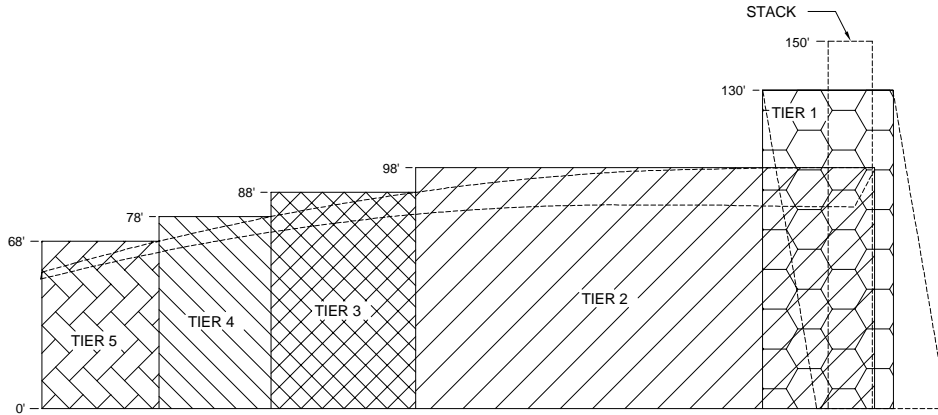


Figure 5. Plan view of area and buildings model on the wind-tunnel turntable.

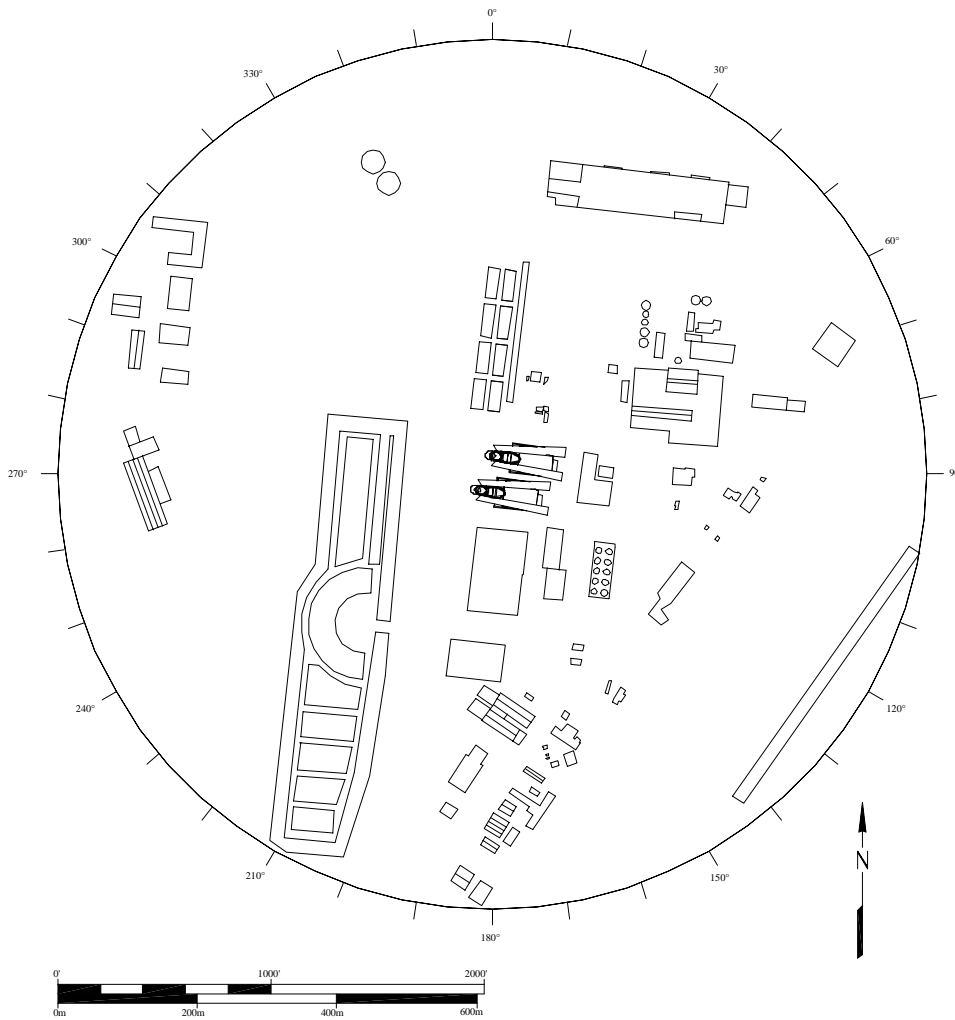


Figure 6. Typical EBD selection plot showing the maximum concentration versus downwind distance for the actual site structures and the various equivalent buildings.

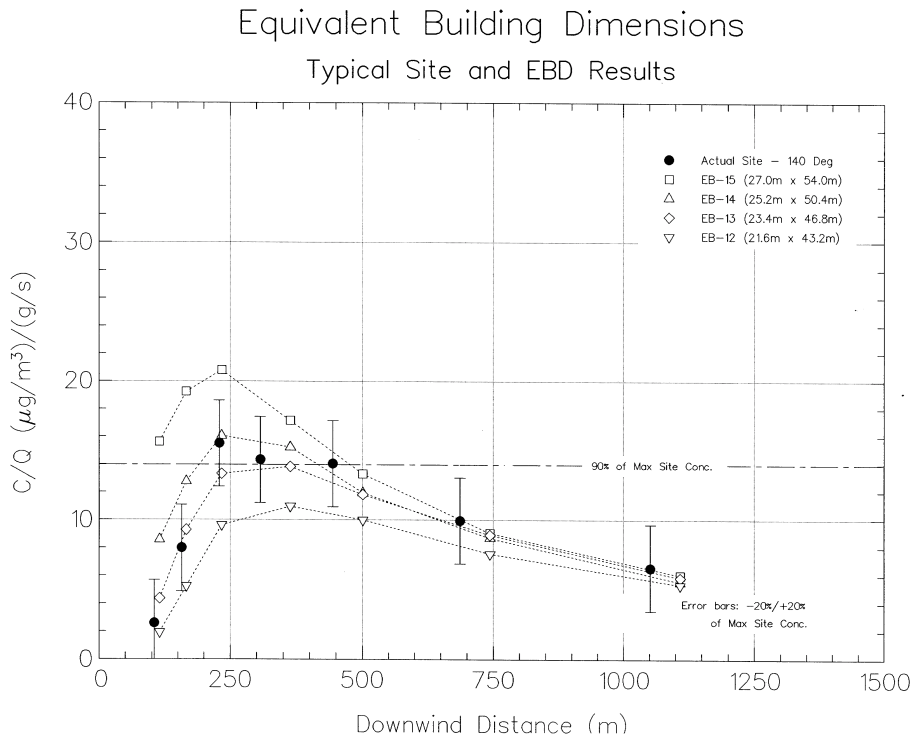


Figure 7. Building Height, H , predicted using the EBD technique, the BPIP program and the actual heights versus wind vector.

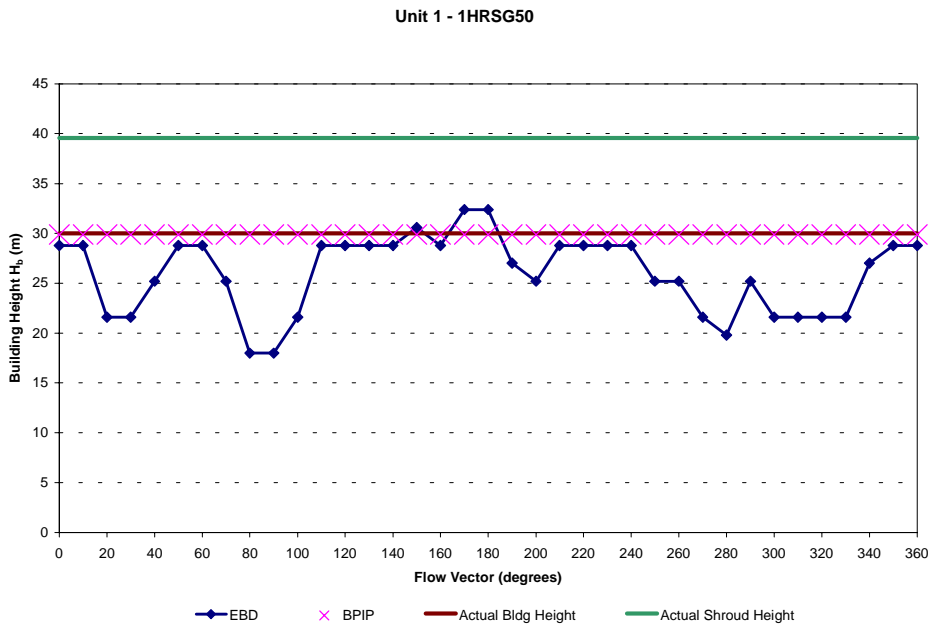


Figure 8. Maximum concentration versus downwind distance predicted using ISC-PRIME/BPIP, ISC-PRIME/EBD and observed in the wind tunnel for selected wind vectors.

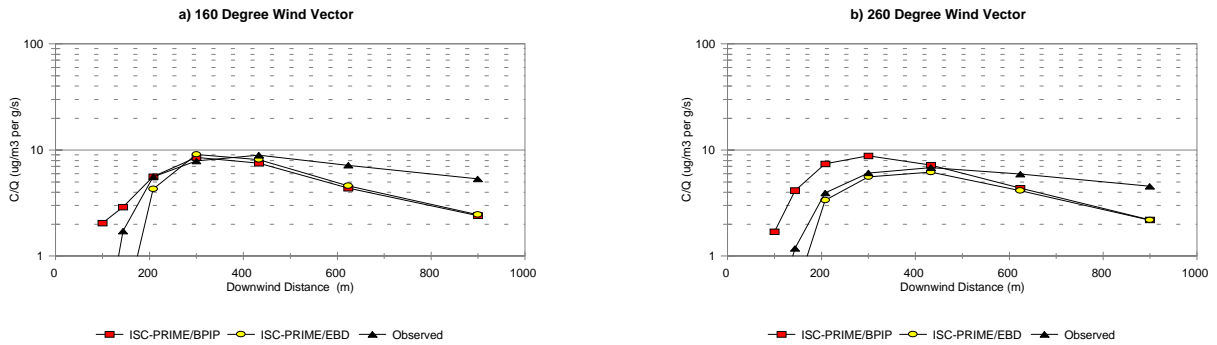


Figure 9. Maximum predicted concentrations versus those observed in the wind tunnel for each wind vector.

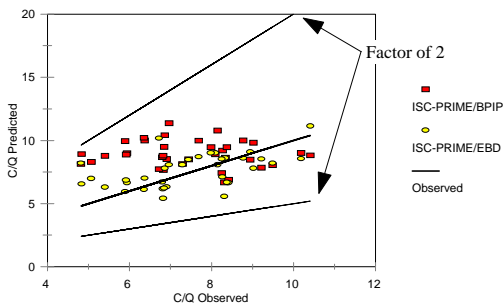


Figure 11. Maximum predicted and observed C/Q normalized by the C/Q observed in the wind tunnel versus wind vector.

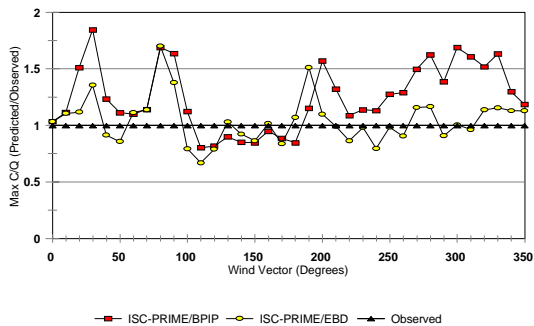


Figure 10. Maximum predicted and observed concentrations in increasing rank order.

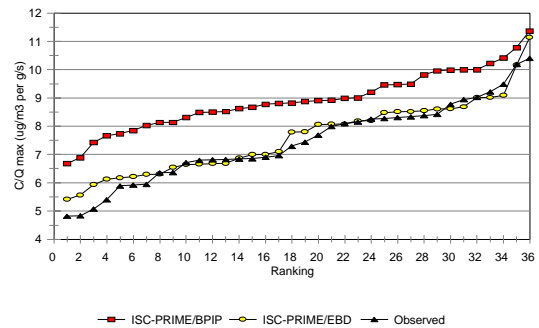


Figure 12. Maximum predicted and observed concentrations versus wind vector.

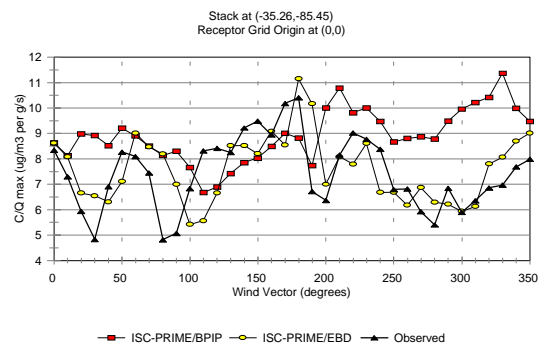
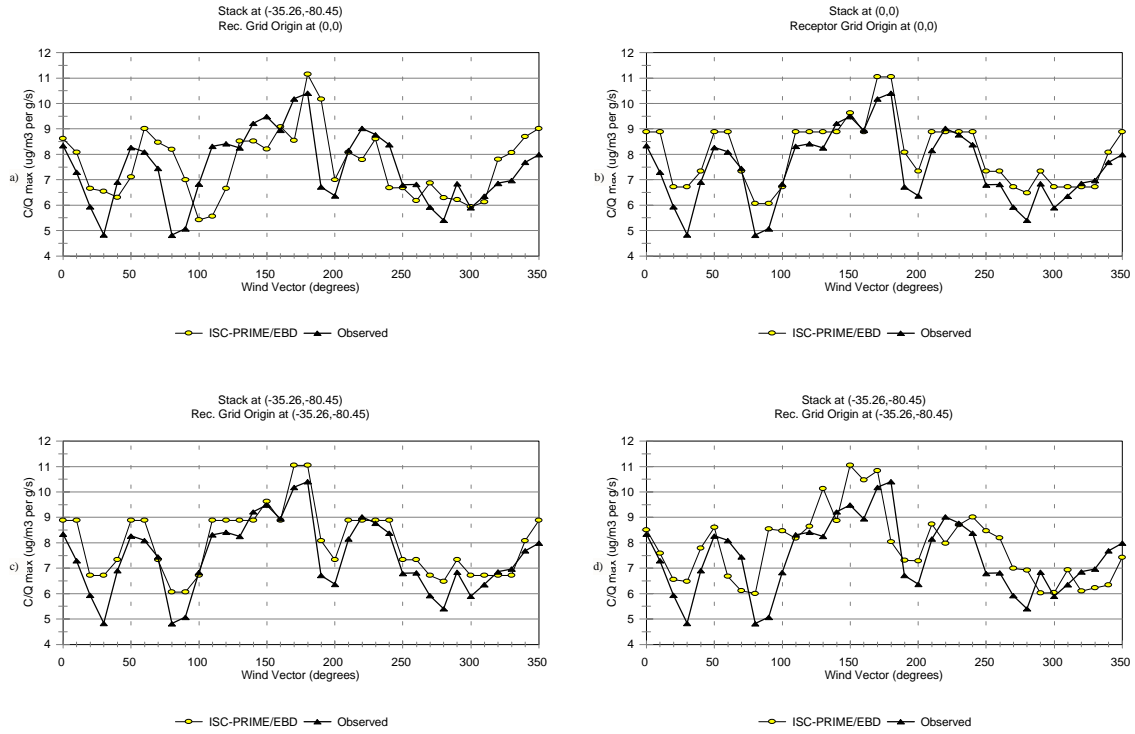


Figure 13. Maximum normalized concentrations predicted for ISC-PRIME/EBD and observed in the wind tunnel versus wind vector for various stack-location/receptor-grid-origin combinations.



TABLES

Table 1. Model Inputs

Exhaust Stack Parameters

Exit Diameter	5.49 m
Stack Height	45.7 m
Exit Temperature	294.4 K
Volume Flow Rate	872.9 m ³ /s
Exit Velocity	36.875 m/s

Ambient Parameters

Wind vector	Varies
Stack Height Wind Speed	28.91 m/s
Approach Roughness	Urban
Ambient Temperature	291.5 m/s

Building Parameters

Run Number	Structure Type	Wind Vector (degrees)	Building Height (m)	Building Width (m)	Building Length (m)
101-136	Site	0-350	N/A	N/A	N/A
301	EBD	N/A	14.4	28.8	14.4
302	EBD	N/A	18.0	36.0	18.0
303	EBD	N/A	21.6	43.2	21.6
304	EBD	N/A	25.2	50.4	25.2
305	EBD	N/A	28.8	57.6	28.8
306	EBD	N/A	32.4	64.8	32.4
307	EBD	N/A	36.0	72.0	36.0
308	EBD	N/A	39.6	79.2	39.6