

Comparison of ISC3 and Prime Model Predictions Against Wind Tunnel Observations

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ABSTRACT

At present, the ISC3 model is used for estimating concentration levels when building wakes affect pollutant dispersion. A new model developed by EPRI, referred to as PRIME (or as ISCPRIME), is in the process of being recommended as an "EPA approved model" for building downwash situations. This model has been designed to simulate stacks located at various distances upwind or downwind of structures and has improved dispersion and plume rise algorithms. This study was carried out to evaluate the relative improvement in concentration predictions for the PRIME model versus the ISC3 model for various simple building configurations. To meet this objective, a series of wind tunnel tests were carried out using individual buildings with height to width to depth ratios of 1:2:1. This is the building shape used by EPA to develop the downwash algorithms in ISC3 and used to conduct Equivalent Building Dimension evaluations. A cube shaped building was also assessed. Ground level concentrations due to an elevated point source release were obtained for various stack height to building height ratios with the building at various orientations and heights. Plots of model predictions versus wind tunnel observations were then developed and the normalized bias and root-mean-square error between ISC3 and PRIME model predictions and wind tunnel observations were computed. The statistical evaluation showed that ISC3 tends to overpredict and PRIME tends to under predict when compared to the wind tunnel observed concentrations. The study also showed that both models agree well with wind tunnel observations for certain building arrangements and show less favorable agreement in other cases. Although the PRIME model is vastly superior to the ISC3 model from a theoretical standpoint, the results of this study show that further improvements can be made.

INTRODUCTION

The Industrial Source Complex model (ISC3)¹ is presently the EPA approved model for estimating concentration levels when building wakes affect pollutant dispersion. The ISC3 model was developed largely based on data for neutral stability, moderate to high wind speeds, wind 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 ISC3² are: 1) the location of 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 wake on plume rise is neglected; 4) there is no accounting for plume material captured by the near wake on far wake concentrations; 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)^{3,4} is in the process of being recommended as an "EPA approved model"⁵ for building downwash situations. This model is referred to as PRIME (Plume Rise Model Enhancements) and addresses the short-comings in ISC3 mentioned above. Independent evaluations of PRIME⁶ have shown that it provides overall better performance than ISC3 and has a better scientific basis.

Past performance evaluations of PRIME considered field and wind tunnel databases but no results have been presented to date showing how well PRIME performs versus ISC3 for the simple building shapes for which ISC3 was designed^{7,8}. This is an important assessment because an Equivalent Building Dimension technique has been developed^{9,10} whereby ISC3 can be improved. Equivalent Building Dimensions (EBD) are those building dimensions (of a single building) that provide the same ground level concentration profile of maximum concentration as when all site structures are present. EBD are determined through the use of wind tunnel modeling. If PRIME provides good estimates for simple building shapes, the Equivalent Building Dimension technique would also be an appropriate method for improving the predictive capability of the PRIME model for complex sites, complex structures or porous structures for which PRIME was not designed.

Hence, the purpose of the this study was to evaluate the performance of PRIME and ISC3 using a wind tunnel database of plume dispersion about buildings of simple geometry. For these cases, plume rise was insignificant so the main feature of the model being evaluated is the wake dispersion. Most of the building geometries evaluated had height to width to length ratios of 1:2:1 with the stack located in the center of the downwind face of the building. This is the geometry used to develop the original ISC3 wake algorithm. One test was conducted with the stack centered on the building and a cube was also evaluated with the stack centered on the downwind face. No tests were conducted with the stack some distance from the building. The following sections describe the wind tunnel database in more detail, the PRIME and ISC3 model runs and the comparisons between the model predictions and the wind tunnels observations.

WIND TUNNEL DATA BASE

A series of seven wind tunnel tests were conducted to obtain maximum ground level concentrations versus downwind distance due to emissions from a 42 m stack. The simulated source parameters and building dimensions for all tests are provided in Table 1. Figure 1 shows a schematic of the wind tunnel setup.

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

C momentum ratio, M_o

$$M_o = \frac{\rho_s}{\rho_a} \left[\frac{V_e}{U_h} \right]^2 \left[\frac{d}{z_r} \right]^2; \quad (1)$$

C buoyancy ratio, B_o

$$B_o = \frac{gd^2V_e(\rho_a - \rho_s)}{4z_r\rho_aU_h^3} = \left(\frac{\rho_s}{\rho_a} \right) \left(\frac{(V_e/U_h)^3}{Fr_s^2} \right) \left(\frac{d}{z_r} \right) \quad (2)$$

C Reynolds number independence was insured with a building Reynolds number in excess of 11,000;

C A neutral atmospheric boundary layer was established (Pasquill–Gifford C or D stability);

where

$$Fr_s^2 = \frac{\rho_s V_e^2}{g(\rho_a - \rho_s)d}; \quad (3)$$

and

- d = stack diameter (m);
- g = gravitational acceleration (m/s^2);
- U_h = wind velocity at stack top (m/s);
- z_r = reference height (m);
- V_e = stack gas exit velocity (m/s);
- ρ_s = stack gas density (kg/m^3);
- ρ_a = ambient air density (kg/m^3).

For each test, a tracer gas mixture was released from the model stack and ground level concentrations were measured in horizontal arrays at five downwind locations. The appropriate building was installed upwind of the stack or centered on the stack as indicated in Table 1 and Figure 2. Roughness elements were installed upwind and downwind of the building and stack as shown in Figure 1 to represent a rural surface roughness ($z_0 = 0.1$ m). Flow conditioning devices consisting of a 2-dimensional trip and spires were placed at the beginning of the test section to aid in the development of a representative boundary layer.

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 1. 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.

ISC3 AND PRIME VERSUS WIND TUNNEL OBSERVATIONS

ISC3 and PRIME were run for each of the building configurations in Table 1 and Figure 2. Runs 1-4 kept the building height approximately constant (at 32.4 m or 34.2 m) while the building width, length and stack position varied. Runs 1 and 5-7 were designed to assess the models' predictive behavior as the building height varied, holding constant the building shape, stack height and stack location. For these latter tests the building height to width to length ratio was 1:2:1. This is the same building shape used to develop the ISC3 building downwash algorithm and is the building shape used for Equivalent Building Dimensions (EBD) evaluations.

Figure 3 shows the predicted and observed normalized concentrations (C/Q) versus downwind distance for Runs 1-4. Both models tend to underestimate close to the stack when a wide building is upwind, but agree with wind tunnel predicted concentrations farther downwind (Run 1). ISC3 tends to overpredict, and PRIME tends to underpredict for the case with a long building upwind of the stack (Run 2). PRIME and ISC3 give almost identical agreement with each other and with the wind tunnel for the cube-shaped building (Run 3) and the case with the stack centered on the building (Run 4). Run 4 is essentially a cube shaped building both upwind and downwind of the stack. In general, these runs show a tendency for ISC3 to predict higher concentrations and PRIME to predict lower concentrations than those observed in the wind tunnel.

Figure 4 shows predicted and observed concentrations versus downwind distance for the cases with varying building height while holding the building shape and stack height constant. For the short building (stack height to building height ratio of 1.67 - Run 5), ISC3 agrees well with the wind tunnel observations while PRIME tends to under-predict near the stack. With a slightly taller building (stack height to building height ratios of 1.3 and 1.46 - Runs 1 and 6, respectively), both models show relatively poor agreement near the stack and better agreement farther downwind. For the tallest building (stack height to building height ratio of 1.17 - Run 7), ISC3 does the best job estimating the overall maximum concentration while PRIME agrees best with wind tunnel observations beyond 400 m.

To provide an overall qualitative assessment of PRIME and ISC3, a scatter plot of predicted versus observed C/Q was prepared considering all runs. The scatter plot in Figure 5 shows that the models tend to underestimate the high concentrations and overestimate the low concentrations, with ISC3 generally predicting higher concentrations than PRIME. A significant fraction of the predictions for both models are within a factor of two of the wind tunnel measurements.

For a more quantitative assessment, two statistical quantities were calculated, the fractional bias (FB) and the normalized mean square error ($NMSE$). The FB and $NMSE$ are defined as follows:

$$FB = \frac{\overline{C/Q_p} - \overline{C/Q_{ob}}}{\frac{1}{2}(\overline{C/Q_p} + \overline{C/Q_{ob}})} \quad (4)$$

$$NMSE = \frac{(C/Q_p - C/Q_{ob})^2}{C/Q_p \cdot C/Q_{ob}} \quad (5)$$

where C/Q_{ob} is the observed normalized concentration (i.e., from the wind tunnel testing) and C/Q_p is the PRIME or ISC3 predicted normalized concentration. Perfect agreement between two methods is indicated when $FB = NMSE = 0$. The FB and $NMSE$ were computed for each run and all runs combined; the results are provided in Table 2. Considering all databases, PRIME tends to under predict and ISC3 tends to overpredict concentrations when compared to wind tunnel observed values. For all buildings with H/W/L ratios of 1/2/1, ISC3 predictions are slightly closer to wind tunnel observations than PRIME predictions. Considering all buildings with stack height to building height (h/H) ratios of 1.3, PRIME tends to under predict by nearly the same amount that ISC3 over predicts. The biggest variations in FB and NMSE between the two models are noted for Runs 2 (the long building upwind) and 5 (the largest stack height to building height ratio).

DISCUSSION AND CONCLUSIONS

The results of this evaluation of PRIME and ISC3 have shown that when considering all building shapes and stack configurations evaluated, PRIME tends to under predict and ISC3 tends to overpredict concentrations when compared to wind tunnel observed values. However, when considering only buildings with H/W/L ratios of 1/2/1 (the EBD configuration), ISC3 performs best. For cube shaped and long upwind buildings (1/1/1 or 2), PRIME more closely matches wind tunnel observations. Therefore, ISC3 appears to be the best model for EBD evaluations. However, this analysis was performed using the approximate scaling discussed earlier and should also be performed using exact wind tunnel scaling (i.e, match the Froude number, velocity ratio and density ratio modeled in the wind tunnel).

The study has also shown that both models agree well with wind tunnel observations for certain building arrangements and show less favorable agreement in other cases. In general both models tend to underestimate the overall maximum concentrations when the stack height to building height ratio is in the mid range of ratios tested (i.e, h/H = 1.30 and 1.46). Although the PRIME model is superior to the ISC3 model from a theoretical standpoint, the results also show that further improvements in PRIME can be made.

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Key Words

Dispersion modeling, wind tunnel, building wake effects, model validation, ISC, PRIME.

Figure 1. Schematic of wind tunnel setup.

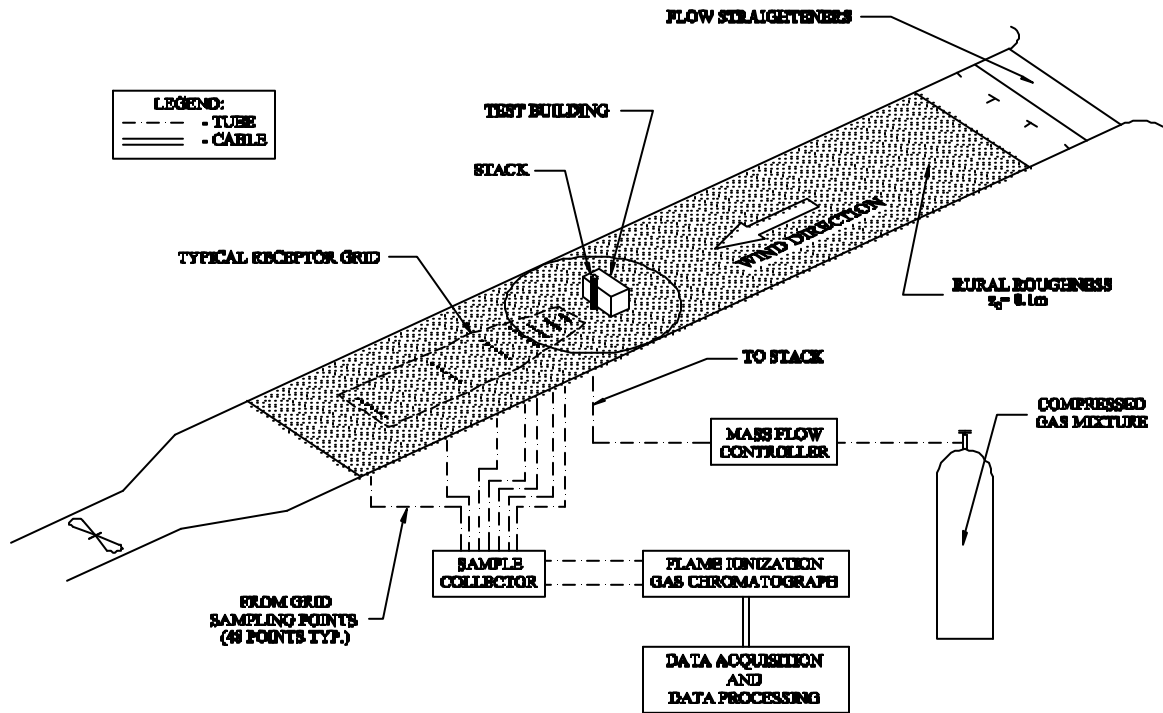


Figure 2. Plan view of building/stack arrangements and coordinate system.

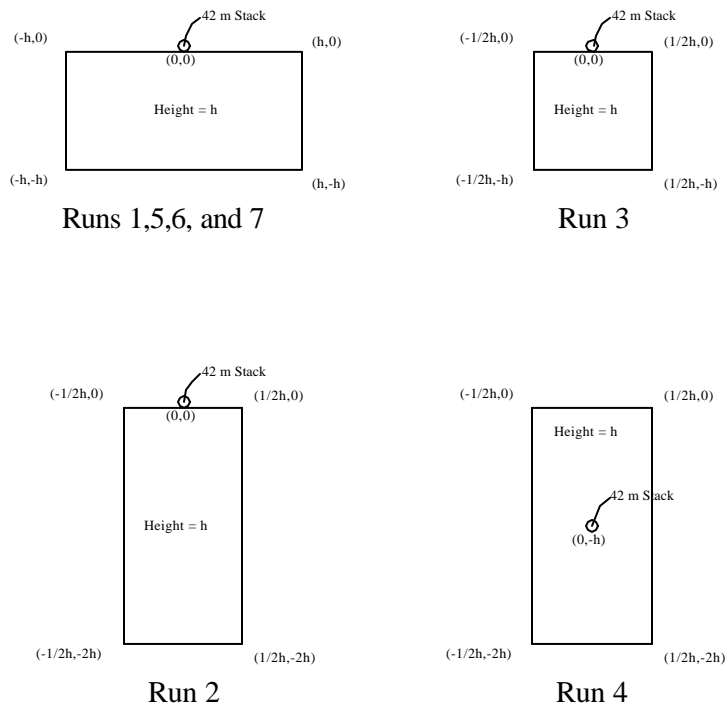


Figure 3. Maximum ground-level concentrations versus downwind distance for ISC3, PRIME and the Wind Tunnel - various building geometries.

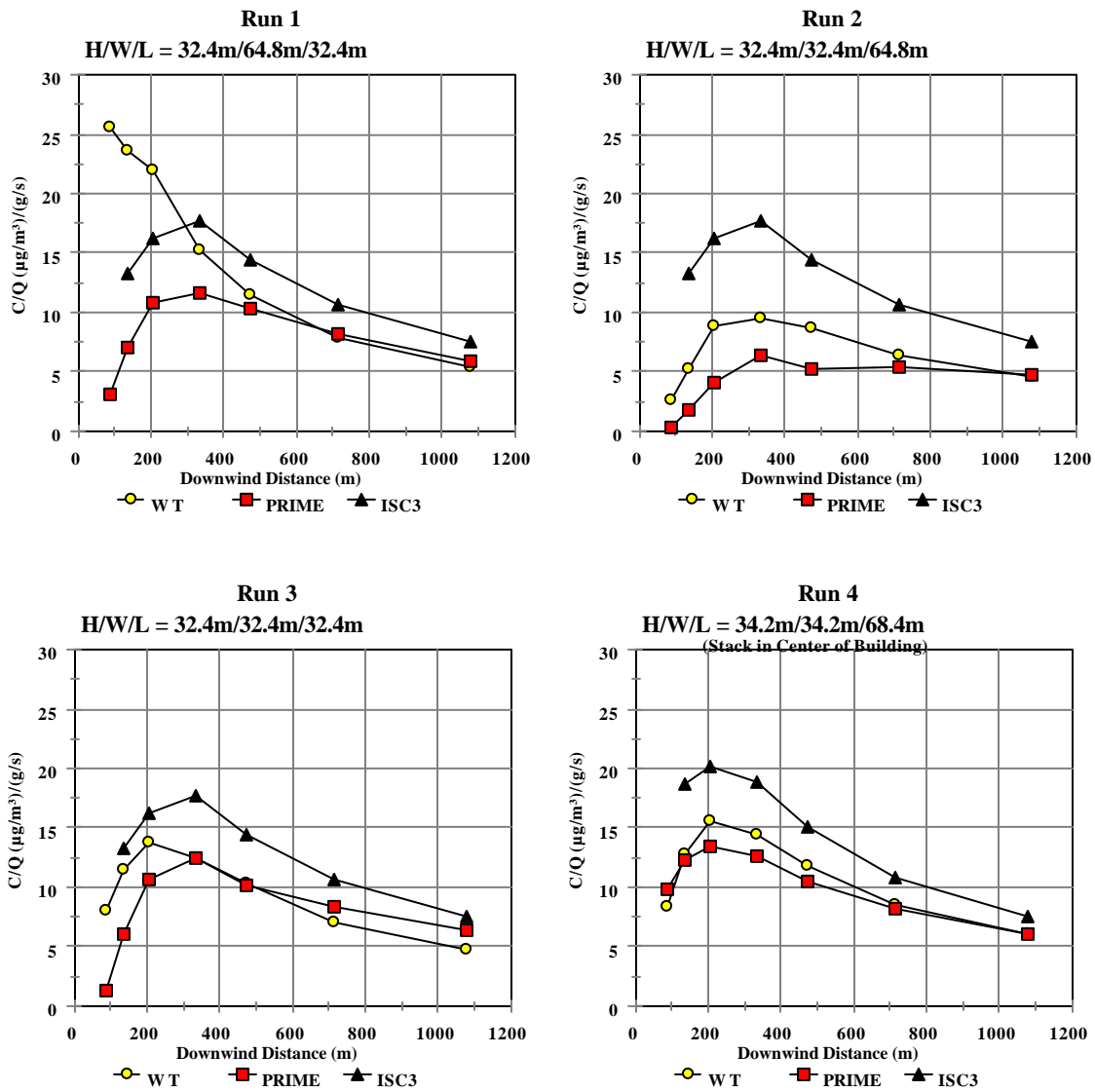


Figure 4. Maximum ground-level concentrations versus downwind distance for ISC3, PRIME, and the Wind Tunnel - various building heights with shape the same.

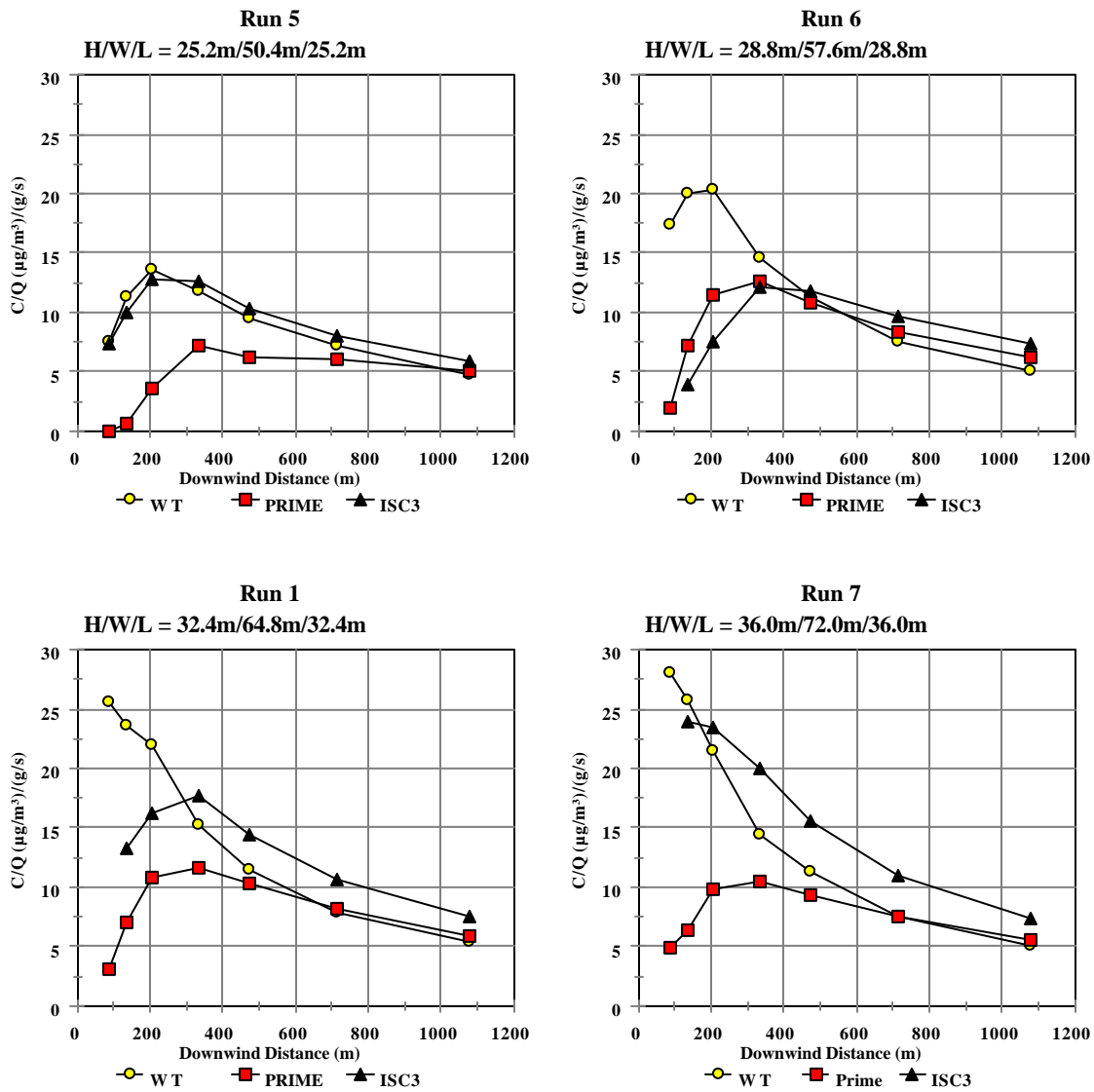


Figure 5. PRIME and ISC3 versus wind tunnel maximum concentrations - all cases.

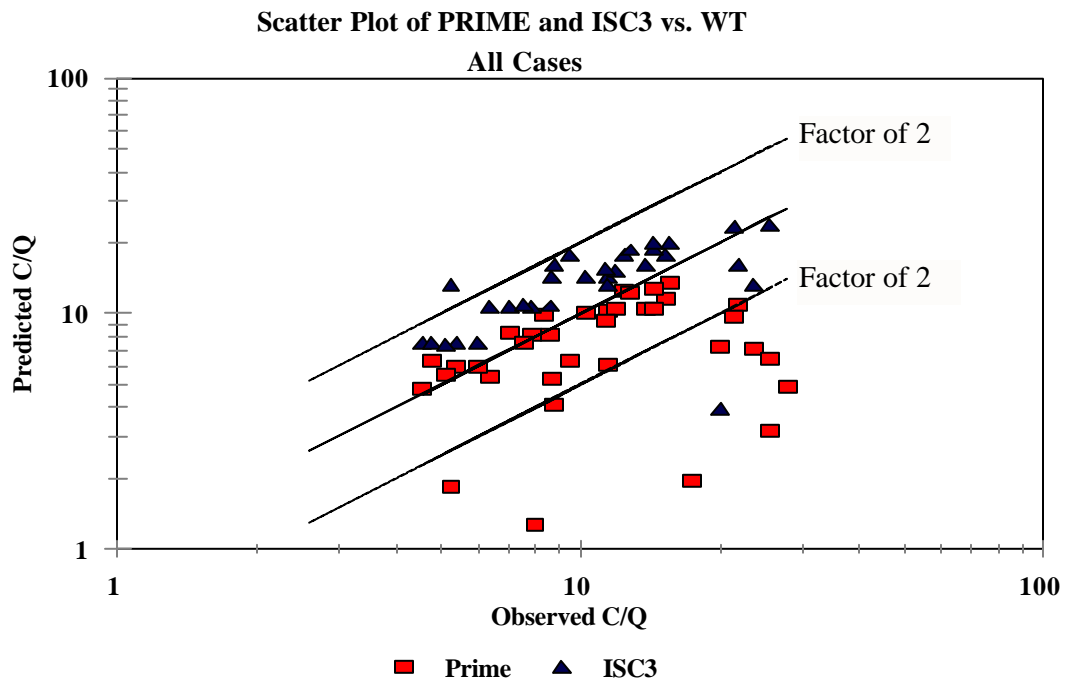


Table 1. Model Inputs

Exhaust Stack Parameters

Exit Diameter	3.05 m
Stack Height	42.0 m
Exit Temperature	351.5 K
Volume Flow Rate	77.49 m ³ /s
Exit Velocity	10.6 m/s

Ambient Air Flow parameters

Wind Vector	0 Degrees
Stack Height Wind Speed	8.47 m/s
Ambient Temperature	298 K

Building Parameters

Run Number	Building Height (m)	Building Width (m)	Building Length (m)	Stack Height to Building Height Ratio
1	32.4	64.8	32.4	1.30
2	32.4	32.4	64.8	1.30
3	32.4	32.4	32.4	1.30
4*	34.2	34.2	68.4	1.23
5	25.2	50.4	25.2	1.67
6	28.8	57.6	28.8	1.46
7	36.0	72.0	36.0	1.17

* - Exhaust stack positioned at the center of the building. For all other cases the exhaust stack is centered on the downwind face of the building.

Table 2. Summary of Statistical Analysis

Buildings with h/H = 1.3

Run #	H/W/L	PRIME vs. WT		ISC3 vs. WT		Difference
		FB	NMSE	FB	NMSE	FB
1	1/2/1	-0.42	0.40	-0.09	0.14	0.33
2	1/1/2	-0.35	0.17	0.58	0.39	0.93
3	1/1/1	-0.05	0.06	0.27	0.08	0.32
4	1/1/2*	-0.07	0.01	0.26	0.07	0.33
	Combined	-0.30	0.17	0.22	0.14	0.52

Buildings with H/W/L = 1/2/1

Run #	h/H	PRIME vs. WT		ISC3 vs. WT		Difference
		FB	NMSE	FB	NMSE	FB
7	1.17	-0.51	0.58	0.15	0.04	0.66
1	1.30	-0.42	0.40	-0.09	0.14	0.33
6	1.46	-0.29	0.24	-0.41	0.66	0.22
5	1.67	-0.61	0.69	0.02	0.01	0.63
	Combined	-0.60	0.44	-0.15	0.16	0.45

ALL	-0.46	0.31	0.03	0.15	0.49
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* -Exhaust stack positioned at the center of the building. For all other cases the exhaust stack is centered on the downwind face of the building.