Consequence Analysis for Adoption of PRIME: an Advanced Building Downwash Model

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ABSTRACT

PRIME (Plume Rise Model Enhancements) is an advanced module that includes formulations involving plume rise and flow around building obstacles. This long-neglected, but important area of modeling applications can often lead to the highest short-term ground-level concentrations. The new PRIME model accounts for the stack/building geometry much better than the existing Industrial Source Complex (ISC) model algorithm in that it internally accounts for the plume rise and trajectory around building obstacles. It is a technique (as installed in the current ISCST3 model) that is being proposed for adoption as a preferred modeling procedure by the U.S. EPA at the 7th EPA Modeling Conference, to be held in 1998.

One element of reviewing new model submittals is an analysis of the consequence of replacing the existing model (in this case, the ISCST3 algorithm) with the new model, ISC-PRIME. The analysis described in this paper consists of a series of typical emission scenarios that cover the spectrum of expected applications. A year of meteorological data has been applied with the existing and proposed techniques to obtain a set of predicted concentrations for the two models on a grid of receptors for each scenario modeled. The results of this analysis are reviewed to determine the expected regulatory impact of the adoption of the new ISC-PRIME model.

INTRODUCTION

Aerodynamic building downwash is a phenomenon caused by eddies created by air movement around building obstacles. Through the use of the Industrial Source Complex (ISCST3) model[1], United States Environmental Protection Agency (USEPA) modeling guidelines have incorporated these effects in ground-level concentration calculations. Unfortunately, the current ISCST3 model retains numerous discontinuities and has not been adequately evaluated.

In 1992, the Electric Power Research Institute (EPRI) initiated a program to design a new downwash model to correct several deficiencies in the current ISCST3 model noted above. The emphasis on the study of plume rise effects as influenced by building downwash led to the name for the new model, based upon "Plume Rise Model Enhancements": PRIME. The implementation of PRIME within ISCST3 results in a model called "ISC-PRIME". A technical description of the ISC-PRIME model as developed by Earth Tech is provided by Schulman et al.[2].

A protocol for an independent evaluation of ISC-PRIME was negotiated with EPA (Paine[3]). The independent evaluation was recently completed (Paine and Lew[4]). The evaluation involved four separate data bases:

- a 1-year data base for a steam electric plant,
- an intensive tracer data base involving two gas compressor stations,
- a tracer data base involving a nuclear facility, and
- a wind tunnel study involving a steam electric plant, simulating both neutral and stable conditions.

In each case, predictions by ISC-PRIME were conservatively high (for the first three data bases) or relatively unbiased (for the wind tunnel data base). ISC-PRIME had a better evaluation performance than did ISCST3 because its predictions, while generally conservatively high, were not as high as those of ISCST3. This was particularly true for stable atmospheric conditions. For each data base, ISC-PRIME had a performance that was statistically different from ISCST3, and which was better in each case.

As a result of the favorable independent evaluation results and the better technical formulation of ISC-PRIME, EPRI formally submitted the model to USEPA in early 1998. As part of that submittal, a document addressing several aspects of a consequence analysis associated with adopting ISC-PRIME as a replacement for ISCST3 was also provided (Paine and Lew[5]). The design of the consequence analysis was reviewed and approved by USEPA, and is considered by USEPA to be a necessary element in a formal submittal package for public review of new models proposed for guideline status. While this consequence analysis is not an indication of how well a model performs relative to ambient concentrations (since it only involves a model-to-model comparison), it is useful for determining expected changes in concentration estimates for regulatory applications that one would expect should ISC-PRIME be adopted as a guideline model. This paper provides a review of the consequence analysis.

STUDY OBJECTIVE

The USEPA has established recommended procedures for use of air quality dispersion models for use in regulatory permitting activities. Documentation supporting any revision to these procedures as described in the Guideline on Air Quality Models (Revised)[6] is usually quite extensive. Besides the primary supporting material (model user guide, model evaluation(s), etc.), USEPA usually provides a comparison of the model predictions from the existing guideline technique and the proposed model. This comparison, which encompasses a variety of typical model applications that the newly proposed technique is applicable for, provides the USEPA and the public with a look at comparative prediction levels between the two models. The comparison can then be used to determine the likely regulatory consequences of replacing the existing guideline model with a new technique.

DESIGN OF CONSEQUENCE ANALYSIS

Stack and Building Combinations

ISCST3's building downwash algorithm handles three separate types of building tier shapes:

- "tall" (building height exceeds its crosswind dimension, or width);
- "squat" (building width exceeds its height, but by a factor less than 5); and
- "supersquat" (building width exceeds its height by a factor of at least 5).

ISCST3 also has different downwash algorithms for stack height to building height ratios that are above/below 1.5. In addition, different treatments for plume rise and dispersion are provided for urban and rural conditions. Therefore, combinations of all of these factors were considered in the consequence analysis design to account for these various treatments in ISCST3, as shown in Table 1.

For hypothetical tall, squat, and supersquat buildings, the consequence analysis employed stack heights in categories below 1.5 and above 1.5 times the building height (except for the supersquat case, where the combination of a tall stack and a supersquat building was considered to be unlikely). For each of these cases, model runs using rural and urban switches were both conducted.

An additional set of model runs was made for the categories described above to test the sensitivity of the models, especially ISC-PRIME, to the displacement of the stack from the building. While most of the runs considered a stack adjacent to the test building, the additional set tested a stack displaced four building heights away from the controlling structure. As a control measure, a set of model runs was also conducted without buildings present. The entire set of model runs conducted is listed in Table 1.

The emission parameters for the two stacks involved (35 and 100 meters tall) were designated as follows:

Stack #1 (used for stack height to building height ratios less than 1.5):

- stack height is 35 meters,
- stack gas exit temperature is 432°K,
- stack gas exit velocity is 11.7 m/sec, and
- inner stack diameter is 2.4 m.

Stack #2 (used for stack height to building height ratios exceeding 1.5):

- stack height is 100 meters,
- stack gas exit temperature is 416°K,
- stack gas exit velocity is 18.8 m/sec, and
- inner stack diameter is 4.6 m.

For both stacks, a fixed pollutant emission rate of 100 g/sec was used.

The plan view of stack location relative to the building tier being modeled in each case is shown in several figures:

- Figure 1 for the tall building with the stack at the northeast corner of the building tier,
- Figure 2 for the tall building with the stack displaced four building widths to the northeast of the northeast corner of the building tier,
- Figure 3 for the squat building with the stack at the northeast corner of the building tier,
- Figure 4 for the squat building with the stack displaced four building heights to the northeast of the northeast corner of the building tier,
- Figure 5 for the supersquat building with the stack at the northeast corner of the building tier, and
- Figure 6 for the supersquat building with the stack displaced four building heights to the northeast of the northeast corner of the building tier.

The appropriate building tier data as a function of each 10° direction were established for each model with the use of separate Building Profile Input Program (BPIP)[7] versions applicable for ISCST3 as well as for ISC-PRIME.

Meteorological Data

A 1-year meteorological data base was obtained from USEPA for Pittsburgh, 1964 that has been used in other consequence analyses. The associated wind rose is plotted in Figure 7. The quadrant between south and west has the highest incidence of winds. Therefore, the positions of the stacks relative to the building tiers as shown in Figures 1 through 6 were designed for the predominance of the winds in the southwest sector, testing the case where the flow reaches the building before encountering the stack. Conversely, winds from the northeast tested the ISC-PRIME model formulations for flow reaching the stack before the building.

Receptor Grid

For each case modeled, the source was always located at the grid origin (0,0). The building location was offset to the southwest of the grid origin. The receptor grid featured a nested array of points as shown in Figure 8. Points within a 2-km square centered at the origin were placed 100 meters apart. Beyond this area, points within a 4-km square were placed 200 meters apart. Receptors in a 10-km square centered at (0,0) and beyond the inner squares described above were placed 500 meters apart. Beyond the three inner squares, receptors in a 20-km square were placed 1,000 meters apart.

MODELING RESULTS

For each of the 24 scenarios described in Table 1, 1-year model runs of ISC-PRIME and ISCST3 were conducted. Separate runs of SCREEN3[8] were also made for the 20 building downwash cases to provide concentration calculations in the cavity region within 3 building heights of the stack. (For the case of a physical separation between the stack and the building, especially of more than 3 building heights, it is not clear whether the cavity predictions are relevant, or whether they are to be interpreted as being applicable near the stack as opposed to the building location. Therefore, the incorporation of cavity effects into ISC-PRIME removes an ambiguity in cavity modeling applications that has been a problem up until now.)

Results of the modeling runs were tabulated and plotted for the highest, second-highest 3-hour and 24-hour concentrations as well as for the highest annual concentration. These averaging periods were selected because they account for regulatory averages and statistic used for the standard for SO_2 and NO_2. The 3-hour averaging time tends to address the 1-hour and 8-hour averaging times for carbon monoxide. The highest, second-highest concentration is a surrogate for the percentage-based particulate matter standards.

The results of the ISCST3, the ISC-PRIME, and the SCREEN3 (cavity) runs are provided in detail by Paine and Lew[5]. Comparisons of the results of the ISCST3 and ISC-PRIME modeling (without SCREEN3 cavity predictions) are listed in Table 2.

The SCREEN3 cavity predictions were scaled to the 3-hour, 24-hour, and annual concentrations using EPA-approved factors of 0.9, 0.4, and 0.08, respectively. In all cases, the scaled SCREEN3 results were higher than the corresponding ISCST3 value (which covers receptor distances beyond three building heights). The resulting model comparisons including the SCREEN3 results are provided in Table 3. These cavity predictions are applicable only out to three building heights, a distance of no more than 150 meters.

The model runs involving no buildings were conducted as a control measure, and showed identical results between ISCST3 and ISC-PRIME, as expected. The comparison of results between the two models for each of 20 additional combinations of stack heights, building shapes, building displacements from the stack, and urban/rural environments, are summarized below.

- In all cases, the SCREEN3 cavity predictions were higher than the ISCST3 predictions beyond the cavity zone.
- The SCREEN3 cavity predictions were almost always higher than the ISC-PRIME results, with the exception of urban cases when a stack was adjacent to a squat or tall building.
- For rural dispersion, short stack cases, ISCST3 predictions were usually higher than those of ISC-PRIME, especially for the cases where the stack was displaced from the building. One exception to this rule occurred for longer averaging periods for the stack adjacent to the tall building.
- For urban dispersion, short stack cases, ISCST3 predictions were generally lower than those for the companion rural cases, while ISC-PRIME predictions were higher in urban vs. rural conditions (apparently responding to increased ambient turbulence).
- The ISCST3 predictions for the stack height to building height ratio of 2.0 were only slightly higher (or equal to) the predictions for the no building case. The ISC-PRIME predictions were higher than ISCST3 for these situations.

- Both ISCST3 and ISC-PRIME peak predictions decreased when the stack was displaced from the building, but ISC-PRIME was much more sensitive to this change, sometimes resulting in much lower predictions as the stack was moved away from the building. This was especially true for the low stack height case. For the tall stack case, the ISCST3 predictions changed very little between the two stack positions relative to the building location. The ISC-PRIME behavior resulted in a smoother transition as the assumed no downwash influence stack-building separation case of 5 building heights (or widths, whichever was less) was approached. (Note that with use of a modified BPIP, ISC-PRIME assumes no building influence in a manner consistent with ISCST3 if the separation distance is large enough.)
- The concentration patterns for ISC-PRIME generally showed more responsiveness of the model to the flow characteristics around the building and the relative positions of the stack and the building. ISCST3's building downwash algorithms did not take these spatial considerations into account.
- The location of the ISC-PRIME peak concentration was often farther from the stack than that of ISCST3. This was especially true for tall stack releases when the stack was displaced from the building location (when there was probably little or no aerodynamic building effect).

CONCLUSIONS

It is important to remind the reader that this analysis is not intended to show how well ISCST3 and ISC-PRIME perform relative to real-world concentrations. Rather, this analysis shows the changes one would expect from the regulatory adoption of ISC-PRIME, and it provides information regarding model sensitivity to varying operational settings. In summary, the change in predicted concentrations as a result of using ISC-PRIME instead of ISCST3 depends upon the application. For small stack height to building height ratios (e.g., less than 1.5), ISC-PRIME appeared to result in lower predictions, especially in rural dispersion conditions. For stack height to building height ratios approaching 2.5, ISC-PRIME appeared to result in higher predictions since slight downwash effects can linger in ISC-PRIME for such stack height to building height ratios.

The inclusion of the cavity predictions within ISC-PRIME removes a modeling discontinuity and an application ambiguity in the current modeling system. The ISC-PRIME cavity predictions were usually lower than the SCREEN3 values.

ISC-PRIME predictions were more sensitive to stack-building displacement variations than ISCST3. The ISC-PRIME concentration patterns around a building are more complex than those of ISCST3, in response to the additional flow field formulations built into the ISC-PRIME model. As a result, changes in the peak concentration value (possibly either higher or lower) as well as the location of the peak are to be expected with the use of ISC-PRIME in lieu of ISCST3.

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