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VALIDATION OF THE CANADIAN ATMOSPHERIC DISPERSION MODEL FOR THE CANDU REACTOR COMPLEX AT WOLSONG, KOREA

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ABSTRACT

AECL is undertaking the validation of ADDAM, an atmospheric dispersion and dose code based on the Canadian Standards Association model CSA N288.2. The key component of the validation program involves comparison of model predicted and measured vertical and lateral dispersion parameters, effective release height and air concentrations. A wind tunnel study of the dispersion of exhaust gases from the CANDU complex at Wolsong, Korea provides test data for dispersion over uniform and complex terrain. The test data are for distances close enough to the release points to evaluate the model for exclusion area boundaries (EAB) as small as 500 m. Lateral and vertical dispersion is described well for releases over uniform terrain but the model tends to over-predict these parameters for complex terrain. Both plume rise and entrainment are modelled conservatively and the way they are combined in the model produces conservative estimates of the effective release height for low and high wind speeds. Estimates for the medium wind speed case (50-m wind speed, 3.8 ms^{-1}) are conservative when the correction for entrainment is made. For the highest ground-level concentrations, those of greatest interest in a safety analysis, 82% of the predictions were within a factor 2 of the observed values. The model can be used with confidence to predict air concentrations of exhaust gases at the Wolsong site for neutral conditions, even for flows over the hills to the west, and is unlikely to substantially under-predict concentrations.

INTRODUCTION

Risk assessments of radioactive releases from nuclear facilities rely heavily on computer models to extend information beyond the sphere of direct observation. Predictions into the future are made to support decisions about facility siting, the magnitude of routine releases and emergency planning for non-routine releases. The models are also used to extrapolate to locations where direct measurements are impractical or environmental concentrations are below detection limits. But computer models are invariably simplifications of complex natural processes and in many cases must be applied without complete data for the site in question. Model reliability must therefore be evaluated and understood before predictions can play a part in decision making.

In recognition of this need, AECL has undertaken the validation of the suite of key computer codes used in the analysis of hypothetical accidents in CANDU nuclear reactors. This suite includes ADDAM (Atmospheric Dispersion and Dose Analysis Method), the tool used by AECL to calculate radionuclide concentrations in air and on the ground, and inhalation, immersion and groundshine doses to the public following postulated accidental releases to the atmosphere. ADDAM follows the conceptual model outlined in Canadian Standards Association Standard N288.2, "Guidelines for Calculating Radiation Doses to the Public from a Release of Airborne Radioactive Material under Hypothetical Accident Conditions in Nuclear Reactors" (CSA, 1991). Although models similar to ADDAM have been extensively tested in the past, their performance for the geometry of CANDU reactors has not previously been investigated.

This paper describes evaluation of the model against test data from a wind tunnel study of the dispersion of exhaust gases from the CANDU reactors at the Wolsong site in Korea. The work was carried out to establish the credibility of ADDAM's predictions for uniform and complex terrain for exclusion area boundaries (EAB) between 500 and 1000 m. The EAB is the area surrounding a nuclear facility for which population settlement, agriculture and public access are denied. The focus of the effort has been the comparison of model predicted lateral and vertical dispersion parameters, effective release height and air concentrations with measured values.

The observations are compared with model predictions using a variety of statistical and graphical tools. It will be shown that the methods used in ADDAM are unlikely to result in an underestimate of concentrations or public doses for exclusion area boundaries as small as 500 m and for CANDU sites of moderate topographical complexity. The results apply to the use of ADDAM to model atmospheric dispersion at domestic or offshore CANDU sites.

EXPERIMENTAL METHODS

The Wolsong reactor complex is located on the southeast coast of the Republic of Korea on the shore of the East Sea. It consists of four reactor units and includes several large buildings spread over an area 750 m by 250 m on a narrow coastal plain between the sea and a range of hills inland to the west. The coastal plain is fairly flat and uniform. To the south, it is farmed and occupied by small towns whereas to the north it is largely uninhabited. The hills to the west are tree-covered and rise to elevations of 150 m within 1000 m of the reactors.

The wind tunnel study of the Wolsong site was performed in the boundary layer wind tunnel of the University of Western Ontario in the spring of 1997 (Hangan et al., 1997). The wind tunnel model consisted of the nuclear complex and surrounding topography built at a scale 1:400 (Figure 1). Turbulence measurements made in the tunnel suggest that stability conditions were neutral to slightly stable (stability classes D and E).

The dispersion trials were carried out using a tracer gas mixture of 20% ethane and 80% nitrogen. The gas was sampled at particular locations by aspirating a continuous sample through a Beckman Model 400A Flame Ionization Detector. The concentrations measurements represent one hour means. Results are expressed here as the ratio of the measured concentration minus background to the source concentration.

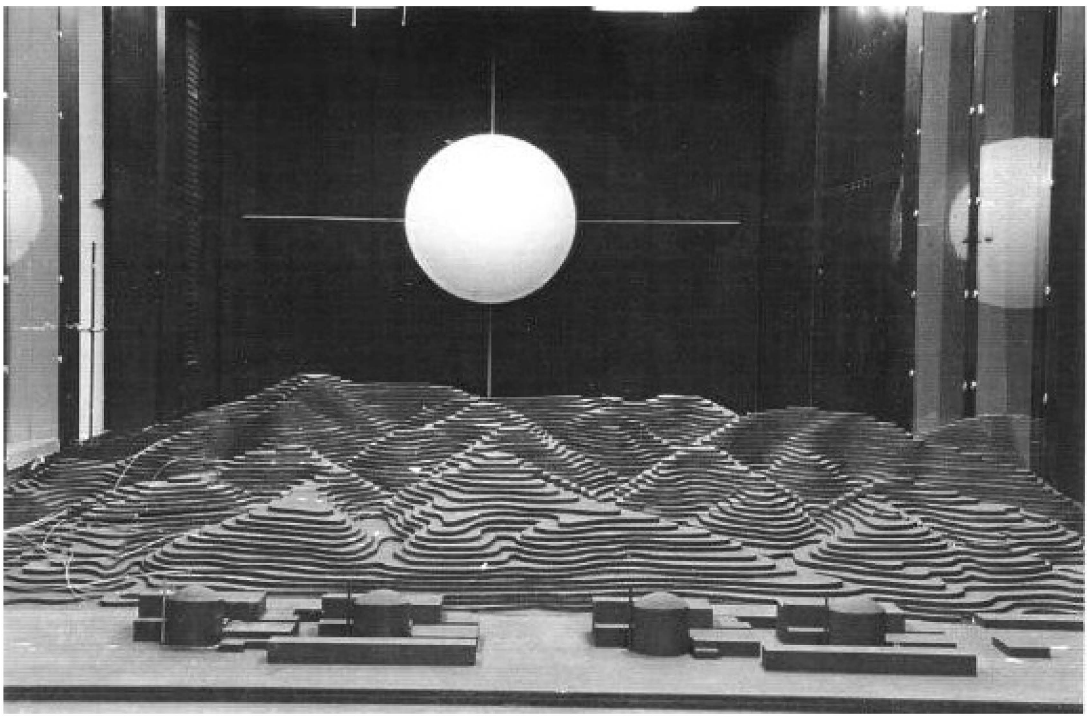


Figure 1. The wind tunnel model of the Wolsong reactor complex and the hills to the west (Hangan et al. 1997).

Releases were made for three sources: the existing 50-m reactor stack, an extended stack 70 m above ground level, and the ventilation inlet on the side of the service building at a height of 15 m. The extended stack was included in the study to provide data on the reduction in ground-level concentrations (glc's) achievable through a higher stack. The effect of stack height on glc's is discussed briefly in Section 3.5. Releases from the stacks were neutrally-buoyant and had exit velocities of 14 m s^{-1}. Releases from the ventilation inlet were also non-buoyant and had exit velocities of 5 m s^{-1} directed horizontally. Building-induced turbulence strongly influenced the ventilation inlet releases but had less effect on the stack releases, which occurred 5 and 25 m above the top of the highest nearby building and had substantial plume rise. Tests were conducted for winds blowing from the north, south and east (Figure 2). For north and east winds, the tracer gas was released from Unit 4 (the most southerly unit) for each of 3 wind speeds (1.25, 3 and

6 m s^{-1} at 10-m height). For south winds, the tracer was released from Unit 1 (the most northerly unit) for speeds of 1.25 and 6 m s^{-1}.

Concentrations were measured at 1) 10 points on the mean centreline at 100 m intervals to downwind distance 1000 m, 2)10 points on the crosswind arcs at downwind distances of 500, 700 and 1000 m, and 3) 6 points on the vertical axis at downwind distances of 200, 500 and 1000 m. The maximum observed concentration on each crosswind arc was taken as the centreline concentration. The dataset provides a good test of the model for releases from a complex of CANDU-6 reactors over both flat and moderately complex terrain.

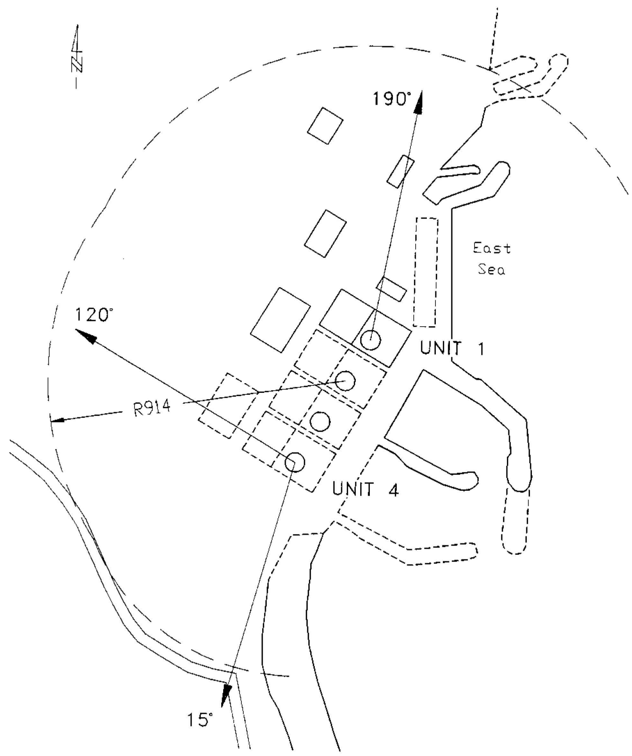


Figure 2 Plan-view of the reactor complex showing test wind directions and release locations. The dashed line shows the 914 m (1000 yard) exclusion area boundary.

The ADDAM Model and Input Parameter Values

ADDAM follows the guidelines published by the Canadian Standards Association for calculating public doses from a postulated accidental release of radioactivity to the atmosphere from nuclear reactors (CSA, 1991). It is a Gaussian model in which the plume centreline is assumed to follow the direction of the mean wind. The lateral and vertical dispersion parameters are calculated using the methods of Briggs (1974) and Smith-Hosker (Smith, 1972; Hosker, 1974), respectively. These parameters can be modified if necessary to account for enhanced spreading due to building-induced turbulence. The effective release height of the plume is determined by considering the physical height of the release point, downwash, building entrainment and plume rise. Reflection from an elevated inversion, and from the ground, is handled by introducing virtual sources above and below the real source. The amount of radioactivity deposited on the ground surface due to dry and wet deposition is calculated using deposition velocities and washout coefficients, respectively. In this study, the downwind distances considered are too short for significant deposition to occur. If necessary, concentrations in the airborne plume are reduced with distance from the source to account for activity lost to the ground surface using the source depletion method.

All of the input data needed to run ADDAM for the trials discussed here was available. This included values for release rate, release duration, building dimensions, stack gas exit velocity, stack gas temperature, the downwind distance at which samples were collected and the meteorological conditions in effect during each trial (wind speed, stability class, air temperature, vertical temperature gradient and inversion height). The wind speed used in the calculations was the 10-m height speed for the Wolsong ventilation inlet releases and the 50-m height speed for the Wolsong stack releases. These were considered to be the heights most representative of the transport speed of the centre of mass of the plume.

Model Evaluation

The accuracy of the concentration predictions largely depends on the ADDAM estimates of: i) lateral and vertical dispersion parameters, σ_y and σ_z, and ii) the effective release height of the plume, *H*. Therefore, a two step approach is used to evaluate ADDAM. First model estimates of σ_y, σ_z and *H* are compared against the measured parameter values. The measured values were determined by fitting the theoretical crosswind and vertical concentration profiles to the measured data. Then ADDAM estimates of air concentrations are compared with measured concentrations. Results for uniform and complex terrain were analyzed separately and compared to isolate the effects of complex terrain on plume dispersion.

The comparison is shown visually as scatter plots of predictions (P_i) against observations (O_i). In addition, a quantitative evaluation of model performance was obtained through the use of the following statistical measures:

- the correlation coefficient arising from linear regression analysis,
- the mean fractional error, MFE = $(2/n)\ \Sigma\ (P_i - O_i)/(P_i + O_i)$, where n is the number of samples in the comparison (Rao and Visalli, 1981). The MFE provides a measure of the magnitude of the error in the predictions and indicates whether or not the model is biased, and
- the fraction of predictions lying a given distance (e.g., 50%, a factor of 2) from the observations.

The experimental uncertainty in the observed centreline concentrations was estimated to be about 20% in both the field and the wind tunnel studies. The uncertainty in the CSA N288.2 model on which ADDAM is based is given as a factor of 2 for the downwind distances considered here (CSA, 1991). More recently, the method of expert elicitation has been used to estimate as rigorously as possible the uncertainty in the predictions of Gaussian dispersion models (NUREG, 1994). Results of this study indicate that the ratio of the 95th to 5th percentiles of the centreline concentration is about a factor of 10 for downwind distances of 500 to 1000 m.

RESULTS AND DISCUSSION

Lateral and Vertical Dispersion

For uniform terrain, model-predicted lateral and vertical dispersion parameter values were generally in good agreement with the measured values (Figure 3). The model predicts σ_y due to atmospheric turbulence well, but underestimates the spread due to building wake effects for the entrainment correction used here. At 1000 m where building wake effects are negligible, 92% of the predicted values were within 25% of the measurements. At 500 and 700 m where building wake effects are more important, 60% of the predicted values were within 25% of the measured and the average ratio of predicted to measured was 0.8. The measured σ_y values showed much more variation than the predictions, suggesting that the correction for building wake effects should vary with release location and wind speed. For σ_z, 85% of the predicted values at 1000 m were within 25% of the measurements and overall 68% of the predictions were within 25% of the observations. There was no tendency for over or under-prediction at shorter distances, suggesting that the entrainment correction applied is suitable for vertical dispersion.

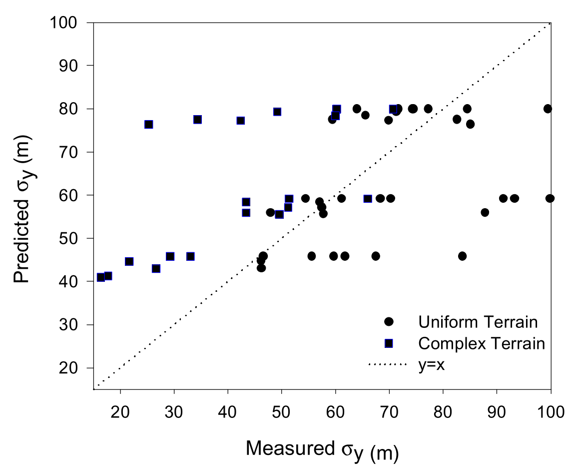
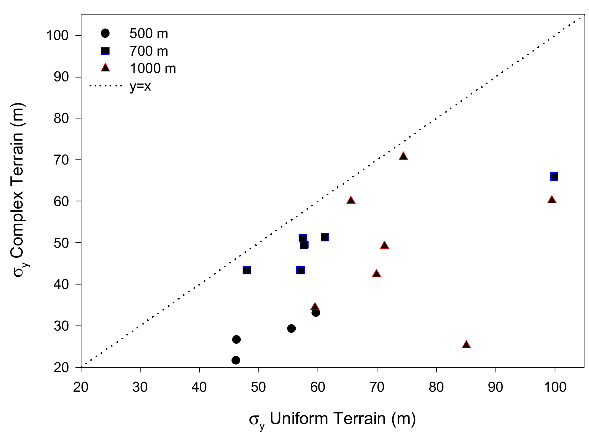


Figure 3 Scatter plot of predicted and measured σ_y values at downwind distances 500, 700 and 1000 m for all release locations and wind speeds. The data are segregated according to terrain type. The dashed line is the line of perfect agreement between predicted and measured values.

Complex terrain effects included reductions in lateral and vertical dispersion parameters of 40% and 25% respectively. Figure 4 shows scatter plots of the measured lateral and vertical dispersion parameters for complex and uniform terrain. The reduction in lateral dispersion is attributed to limits imposed on the lateral spread of the plume by valley walls. The reduction in vertical dispersion suggests the plume is being compressed as it flows over the hills. No trend to reduction in vertical dispersion was observed at 200 m. This is because complex terrain first starts at approximately 300 m from the reactor buildings. The model over-predicted σ_y and σ_z for releases over complex terrain by approximately 50% and 40% on average. The predicted and measured σ_y values for complex terrain are included in Figure 3. The ratio of predicted to measured σ_y values ranged from 0.9 to 3.0 and only 26% of the predicted values were within 25% of the measured. The ratio of predicted to measured σ_z values ranged from 0.93 to 2.18 and only 30% of the predicted were within 25% of the measured values.



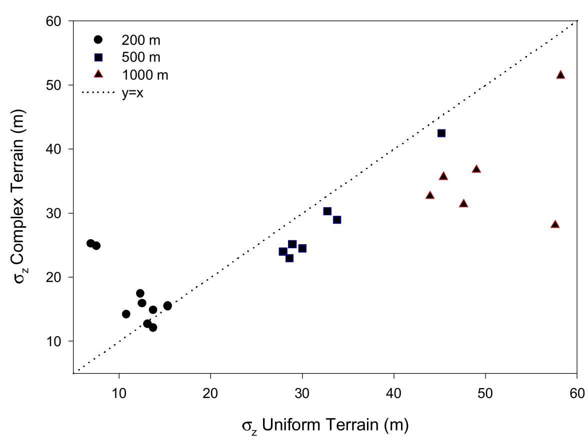


Figure 4 Scatter plot of σ_y (top)and σ_z measurements (bottom) for releases from unit 4 over complex and uniform terrain, all release locations and wind speeds.

Effective Release Height

ADDAM under-predicted effective release height, *H*, for low and high wind speeds but over-predicted *H* for medium wind speeds (Figure 5). Under-prediction of effective release height leads to conservative estimates of ground-level concentrations and is therefore desirable. For low and high wind speed releases over both uniform and complex terrain, the ratio of predicted to observed *H* ranged from 0.44 to 0.99. For these cases, both plume rise and entrainment are modelled conservatively and the way they are combined in the model produces a conservative result. For medium wind speeds, the predicted to observed ratio ranged from 0.9 to 1.48. The measured data suggest that entrainment probably occurs for wind speeds lower than the 5 m s^{-1} threshold recommended by ADDAM. With the entrainment correction for the medium wind speed case (50-m wind speed 3.8 ms^{-1}) predictions would be conservative. In complex terrain, the effective release height decreased by 15-25% between 500 and 1000 m.

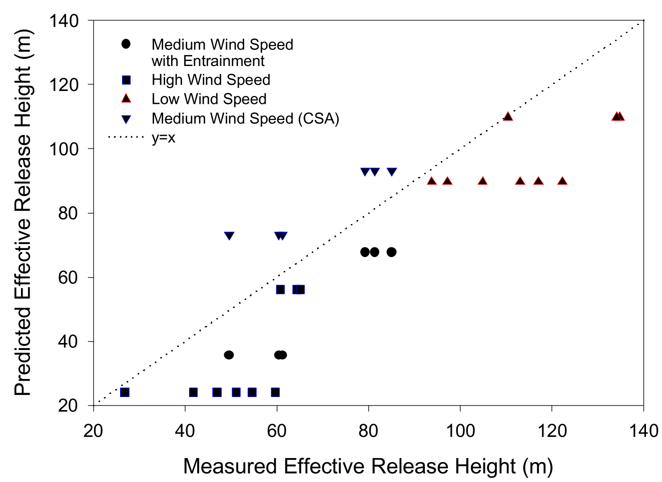


Figure 5 Scatter plot of predicted and measured effective release height for both short and tall stack releases over uniform terrain

Air Concentrations

The comparison of predictions and observations for the Wolsong data is given in terms of the dilution factor (air concentration divided by source concentration). Pointwise comparisons were made for ground-level centreline concentrations (glc's) at distances 500, 700 and 1000 m. As well, qualitative comparisons of predicted and measured downwind, cross wind and vertical concentration profiles were made. Figure 6 shows scatter and residual plots of the results. The data points are identified according to terrain type. Note that a number of data points lie one on top of the other in the figures.

Table 1 lists correlation coefficients and mean fractional errors for the complete data set and for data subsets grouped according to terrain and release type. For the statistics provided, 9 of 66 data-points where concentrations were close to background and large under- and over-predictions occurred have been excluded. These points occur close to the stack where the lower edge of the plume has just reached the ground. The predicted glc's at these locations are very sensitive to the effective release height *H* and the vertical dispersion parameter σ_z and the uncertainties are very large. The excluded data points are for: i) short stack low wind speed releases at 500 m, ii) tall stack low wind speed releases at 500 and 700 m, and iii) tall stack medium wind speed releases at 500 m. Good performance of the model for these conditions is not essential because the concentrations are so low.

The model provided adequate predictions of ground-level concentrations over both uniform and complex terrain for downwind distances 500 to 1000 m. The ratio of predicted to measured values ranged from 0.18 to 4.07. Overall, 50% of the predictions were within 25% of the measurements and 81% were within a factor 2. The level of agreement is consistent with the expected uncertainty in the model predictions. Significant under- and over-predictions occurred only on the edges of the plume where concentrations were very low. For the highest concentrations, those of greatest interest in safety analysis, the model performance was similar; 45% of the predictions were within 25% of the measured and 82% within a factor of 2.

The bias in the model towards over- or under-prediction is very small except for stack releases at medium wind speeds for which the model consistently under-predicted concentrations. The ratio of predicted to measured maximum concentrations for these cases ranged from 0.3 to 0.77. The under-prediction can be corrected by including entrainment in the calculation of the effective release height. However, for the short stack release at downwind distances less than 500 m, the model over-predicts measurements by more than a factor 2 when entrainment is included.

The model over-predicted concentrations for downwind distance less than 500 m for all vent releases and for short stack releases under high wind speeds. In both cases, the over-prediction was due to under-prediction of the effective release height near the source. These differences are not considered serious as they occur close to the release point where they have no impact on public dose.

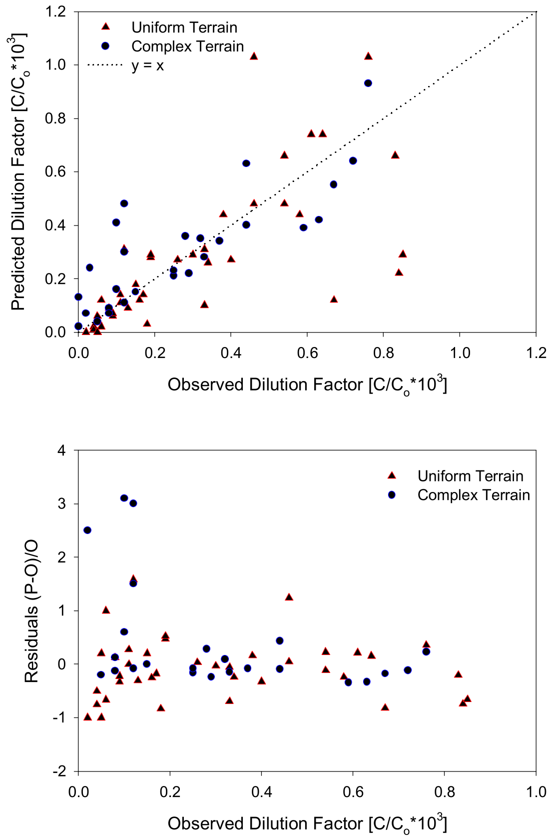


Figure 6 Scatter plot (top) of predicted and observed centreline dilution factors and residual plot (bottom). Data points are segregated with respect to terrain type.

Table 1 Correlation coefficients and mean fractional errors for measured and predicted ground-level centre-line concentrations (downwind distances 500, 700 and 1000 m only). Positive values of the MFE indicate over-prediction.

Test Configuration	Mean Fractional Error	Correlation Coefficient	Sample Size n
Vent Releases	-0.04	0.95	24
Short Stack Releases	-0.01	0.36	21
Tall Stack Releases	-0.02	0.11	12
Low Wind Speed	0.09	0.85	17
Medium Wind Speed	-0.38	0.50	16
High Wind Speed	0.09	0.89	24
Uniform Terrain Releases	-0.12	0.64	34
Complex Terrain Releases	0.06	0.84	23
All Test Configurations	-0.03	0.68	57

Correlation coefficients for all release types and wind speeds ranged from 0.11 to 0.95. Correlation coefficients were less than 0.5 for the short stack (0.36) and tall stack (0.11) releases. These low values result from a few large under and over-predictions close to the release point where concentrations were much less than the maximum. The residual plots show that, with the exception of the large over-predictions for small observed concentrations, the residuals are uncorrelated with the observations, indicating that the model performs equally well for all other conditions tested.

Complex Terrain Effects

The effect of the hills on atmospheric dispersion was limited to the reduction in lateral and vertical dispersion discussed earlier. The test data did not show consistent evidence for plume channeling through the valleys nor did the hills substantially modify the effective release height of the plume. At a given downwind distance, maximum measured ground-level concentrations were similar for flows parallel to the shore (uniform terrain) or onshore flows over the hills to the west (complex terrain). The mean fractional difference between centre-line concentrations over complex and uniform terrain is -0.14 indicating that on average observed concentrations were slightly lower over complex terrain than uniform terrain.

The similarity between ground-level concentrations for stack releases over complex and uniform terrain is in accordance with theory. Maximum ground-level concentrations are a function of

$$\frac{\exp(-(H^2/2\sigma_z^{\ 2}))}{\sigma_z\sigma_y} \tag{1}$$

A reduction in lateral dispersion as was observed always leads to an increase in centreline concentrations. However, this effect is offset by reduced vertical dispersion which leads to a decrease in ground-level concentrations near the release point for elevated releases as downward diffusion of the plume is slower.

For vent releases, which are essentially ground-level releases, the observed reductions in σ_y and σ_z should lead to an increase in ground-level concentrations of a factor 2. This increase was not observed.

The wind tunnel results indicate that the model is suitable for describing the dispersion of exhaust gases from a nuclear facility over complex terrain. The mean fractional error for predictions over uniform and complex terrain was small in both cases, -0.12 for uniform and 0.06 for complex terrain (Table 1).

Effect of Stack Height on Ground-Level Concentrations

In the absence of plume rise and building wake effects, the Gaussian plume model predicts that the maximum glc's vary as h_s^{-2}, where h_s is the stack height. An increase in stack height from 50 to 70 m should therefore decrease glc's by a factor 1.96. The decrease predicted by the model was in good agreement with the wind tunnel observations for the existing 50 m and extended 70 m stacks. For releases over uniform terrain, the increase in stack height led to a decrease in maximum glc's by factor of 2.2 to 2.7. For releases over complex terrain, maximum glc's decreased by a factor of 2.1 to 3.7. The larger observed values probably arise from the fact that the true maximum concentrations were in many cases not observed within 1000 m of the stack.

CONCLUSIONS

The ADDAM model has been evaluated against test data from a wind tunnel study representing a variety of release locations from the CANDU reactor complex at Wolsong, Korea. Releases were performed at low medium and high wind speeds over uniform and hilly terrain. For the highest concentrations, those of greatest interest in safety analysis, 45% of the ADDAM model-predictions were within 25% of the measurements and 82% within a factor of 2. It is unlikely that the model will substantially under-predict concentrations for EAB's as small as 500, even for flows over the hills to the west of the site. These results are for neutral and slightly stable conditions. They probably also apply to unstable conditions but may not apply to stable conditions when the effects of topography are more pronounced.

ACKNOWLEGEMENTS

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