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COMPARISON OF THORNEY ISLAND DATA WITH HEAVY GAS DISPERSION MODELS

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Summary

The major objectives of this work were to provide information on the dispersion of large-scale instantaneous releases of heavier-than-air gases and to quantify the predictive capabilities of the various classes of dispersion models. Five analytical methods for comparing the test data to model calculations were developed. The methods compared various physical characteristics of the trial gas cloud to the predicted physical characteristics of the model cloud. Four models that represent state-of-the-art techniques were selected for comparison with data from the Thorney Island trials. The models were divided into three categories: box, extended box, and three-dimensional fluid dynamic models. From the box model group, the Cox and Carpenter model and the Eidsvik model were selected. The Colenbrander model, HEGADAS II, is an extension of the box model concept, considers concentration and velocity profiles, and uses the K-theory eddy diffusivity approach. From the fluid dynamic group of models that use K-theory for turbulent closure, the MARIAH II model was selected for this study.

1. Introduction

Methods to compare experimental data with the predictive results from four heavier-than-air gas dispersion models are discussed and the models evaluated within this paper. The ability to accurately predict the dispersion of heavier-than-air gases has become a primary concern of project planners and government regulators due to the increasing amount of flammable and/or toxic materials being transported and stored throughout the world.

To determine the predictive capabilities of models, the data from Phase I of the Thorney Island trials [1] were analyzed for this study. From the sixteen trial data sets, the data were divided into six wind speed and stability categories and the best data within each category were selected for comparison with predicted results of the four heavy gas dispersion models.

The comparison of the model predictions and experimental results was accomplished using several graphical techniques performed for the analysis. With the completion of the analysis, several specific conclusions were made

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about the ability of the various models to predict an isothermal release of denser-than-air gas under several atmospheric conditions.

The computerization of the Thorney Island data, data processing techniques, factors determining which models were to be evaluated, and the methods by which the models would be judged were presented in detail in an earlier paper [2]. This paper will deal with the model results compared against the trial data. A step-by-step analysis of one test (Trial 7) will be performed, and the results from the other five trials analyzed will be presented.

2. Thorney Island test results

The Phase I Thorney Island trials consisted of sixteen tests of unobstructed instantaneous gas spills. Table 1 is a summary of the trial number, average wind speed, Pasquill stability, initial relative density, and the number of gas sensors responding to the gas clouds. Data in Table 1 were taken from the summary and the sensor response plots of the Phase I Thorney Island trials by the United Kingdom Health and Safety Executive [3]. Trial 4 was a neutrally buoyant release, and Trial 17 was made with pure Freon-12 with a relative density to air of 4.2. The remaining tests had a range of 1.41 to 2.31 density relative to air, and a variation in wind speed from 1.7 to 7.5 m/s. Atmospheric stability ranged from moderately unstable (Pasquill B) to moderately stable

TABLE 1

Summary description of Phase I heavy gas trials

Trial number	Wind speed (m/s)	Pasquill stability category	Initial relative density	Number of gas sensors which responded to gas
004	3.8	B	0.97	22
005	4.6	B	1.69	26
006	2.6	D/E	1.64	46
007	3.2	E	1.78	57
008	2.4	D	1.72	73
009	1.7	F	1.73	62
010	2.4	C	1.97	11
011	5.1	D	2.03	26
012	2.6	E	2.31	65
013	7.5	D	1.96	47
014	6.8	C/D	1.98	50
015	5.4	C/D	1.41	38
016	4.8	D	1.68	45
017	5.0	D/E	4.20	62
018	7.4	D	1.87	60
019	6.4	D/E	2.12	67

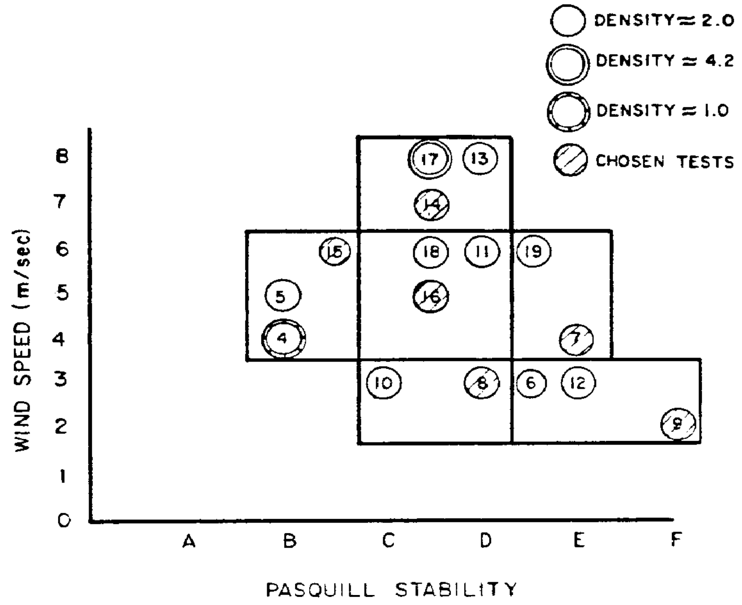

Fig. 1. Distribution of tests by wind speed and stability.

(Pasquill F). Figure 1 shows the distribution and grouping of tests by wind speed versus stability.

Six trial data sets were selected for comparison with model predictions. The data were grouped into wind speed categories of low (1.0–3.0 m/s), midrange (4.0–6.0 m/s), and high (7.0–8.0 m/s), and stability categories of moderately to slightly unstable (Pasquill B–C), slightly unstable to neutral (Pasquil C–D), and slightly to moderately stable (Pasquill E–F) to include as many combinations of conditions as possible that are commonly used in risk assessment studies. The sets within each category were compared with each other, and one test within each category was selected for comparison with model predictions. The six sets are marked with diagonal lines in Fig. 1 for each wind speed–stability category.

3. Heavy gas dispersion models

For this study, four models were selected which we believe represent state-of-the-art techniques. The models can roughly be divided into three categories: box, extended box, and three-dimensional fluid dynamic models. From the box model group, the Cox and Carpenter model [4], with modifications by Bradley et al. [5], and the Eidsvik model [6,7] were selected. The label, box, is derived from the uniform distribution assumed in the gas cloud which yields a box type profile for any cross-sectional view of the cloud's concentration profile. The two models differ in the way the coefficients are specified for the top and frontal air entrainment of the spreading cloud, and in the way the models make the transition to passive scalar dispersion. The Cox and Carpenter model uses a Gaussian method to account for the passive scalar dispersion, and the Eidsvik model makes the transition by the continuous adjustment of the air entrainment coefficients. The Colenbrander model [8], HEGADAS II, with extensions reported by Puttock et al. [9], was selected because it is an extension of the box model concept, considers concentration and velocity profiles, and uses the eddy diffusivity approach. From the three-dimensional fluid dynamic models, the model developed by Taft et al. [10], MARIAH II, was selected as the representative model for this study.

Of the four models selected to be analyzed in this project, all but the MARIAH II three-dimensional fluid dynamic model were coded by Energy Analysts, Inc., from literature descriptions. The results from the MARIAH II model were supplied to Energy Analysts, Inc., by Spectra Research Systems. The other three heavy gas dispersion models (Cox and Carpenter, Eidsvik, and HEGADAS II) conform exactly to the literature descriptions available.

4. Graphical representation of model results

A total of five graphical representations were developed for the Thorney Island trial data and the applied model results. The five methods were interrelated through the time after gas release variable, yet each of the five demonstrated different phenomena occurring within the gas cloud. A brief description of each graphical method and its usefulness in analyzing the trial/model results is presented. A more complete description is given in an earlier work [2].

4.1 Graphical method no. 1: Horizontal gas concentration contours versus time

For specific times during the course of the testing, trial data for each gas sensor were extracted from the trial data and plotted on an x,y rectilinear grid. In addition to the test data, model results for gas concentration were calculated at the same point in time. The model predictions were then plotted in the same rectilinear grid as the trial results.

Such a plot can be used to observe the location of the model as a function of time. The fluid dynamic phenomena worthy of observation resulting from this type of presentation were the radial gravity spreading and how it related to a specified cloud concentration boundary, and the advection of the total cloud mass with the passage of time.

In the analysis presented here, the horizontal level of interest was that of 0.4 m. The reason for this choice was two-fold. First, this was the lowest sensor location for acquiring the experimental results. The ideal location would be ground level; however, the structure of the tests was such that this was not possible. In addition, extrapolation from 0.4 m down to ground level by using the other sensor location data (2.4 m, 4.4 m, and 6.4 m) could prove erroneous based upon how the models treat the concentration versus height. Second, most of the data acquired from the tests were located along the 0.4 m plane. This allowed for a more accurate representation of the cloud at any point in time.

4.2 Graphical method no. 2: Vertical gas concentration contours versus time

Analogous to the contour mapping performed in method no. 1 was that of plotting the vertical contours of the cloud over the duration of the test. Several problems arose when developing these contours, primarily in the model predictions of concentration. In the Eidsvik model and the Cox and Carpenter model, the cloud height was used as the "floating" variable which was used to satisfy the mass balance once the radius and air entrainment values for a particular point in time were evaluated. In addition, due to the nature of these box models, there was no concentration gradient in the vertical direction; thus, any predictive distribution arising from an interpolation scheme would not accurately reflect the model results.

The definition of the cloud height in the HEGADAS II model, once the gas cloud was removed from the source location, was defined with a Gaussian distribution with respect to the ground level gas mass concentration.

4.3 Graphical method no. 3: Maximum gas concentration versus time

The variation of maximum gas concentration versus time was an important measure of how the predictive values of the models compared with the trial data. This method also eliminated the need to accurately predict the cloud advection. This representation demonstrated how the rate of air entrainment affected the dilution of the gas cloud. Although the model predictions of maximum concentration versus time were smooth curves, the test data might oscillate due to movement of the cloud off the centerline and the non-uniform mixing of gas within the cloud.

4.4 Graphical method no. 4: Maximum gas concentration versus distance

The companion plot to the maximum concentration versus time plot was that of maximum concentration versus distance. The maximum concentration versus distance will be affected by the cloud advection. If a model predicts the maximum concentration versus time correctly but uses a wrong prescription for advection velocity, the maximum concentration versus distance will be modeled incorrectly (and vice versa). This representation showed how the downwind movement of the cloud was related to the dilution of the gas cloud without regard for the time elapsed.

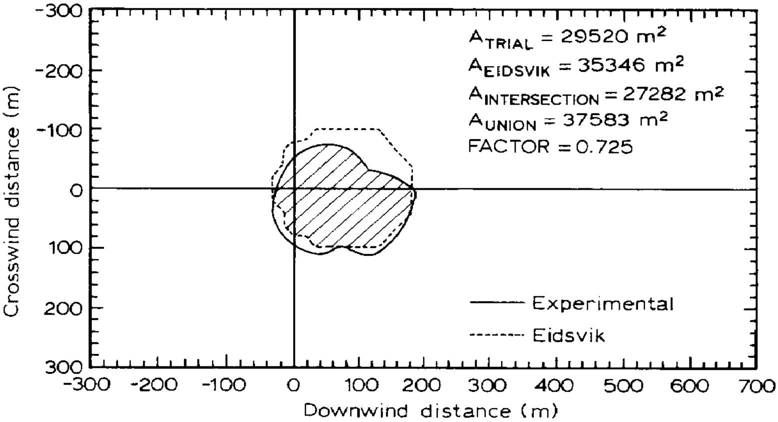

Fig. 2. Example calculation for the predicted Eidsvik cloud and the trial cloud from Trial 8 at 60 s after release.

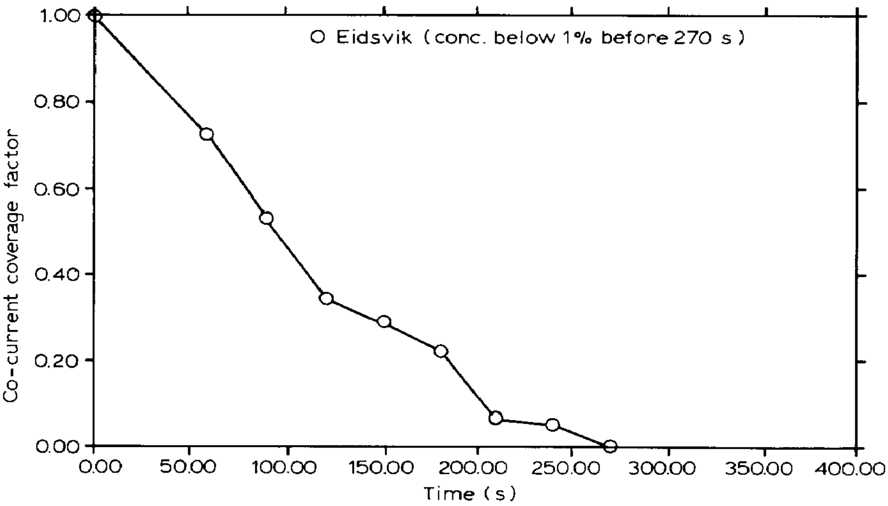

Fig. 3. Co-current coverage factor versus time using the Eidsvik model for Trial 8.

4.5 Graphical method no. 5: Co-current areal coverage of model results with trial results

A method was developed to produce a factor which measured, in part, how well a particular model prediction would match the trial data. The factor measured how well a model matched the trial data areal coverage of the *x,y* horizontal plane (0.4 m was chosen for this work) extrapolated out to a one percent contour. The factor ranged from 0.0 (no co-current areal coverage of the model and trial results) to 1.0 (identical coverage). Figure 2 shows an example calculation for the predicted Eidsvik cloud and the trial cloud from Trial 8 at 60 s after release of the gas bag. The coverage factor was computed from:

$$f=\frac{[A_{\text{model}} \cap A_{\text{trial}}]}{[A_{\text{model}} \cup A_{\text{trial}}]}$$

where: $f=$ factor defining co-current areal coverage with: $f=0.0$; no intersection of the cloud, and $f=1.0$; identical model and trial cloud, $A_{\text{model}}=$area of model cloud, $A_{\text{trial}}=$area of trial cloud, $\cap=$intersection, and $\cup=$union.

After all time steps were computed and the factors for the model were computed, a composite graph was created, as shown in Fig. 3. As shown in the figure, the co-current areal coverage was zero after 270 s, the time the recorded trial cloud concentration dropped below one percent.

5. Analysis and results

When comparing the model predictions and the trial results, several points must be considered. The meteorological data used in the models must represent the average conditions of the experiment. The conditions of wind speed, wind direction, air temperature, relative humidity, and stability were never constant over the dispersion period; therefore, the average conditions were dependent on the time period used to calculate the average. The meteorological parameters required by the models (wind speed, air temperature, and relative humidity) were derived from time averages that included the cloud dispersion, five minutes of readings before the test, and five minutes after the test. The wind direction was averaged over the same period, but was used only in the rotation of the sensor coordinates to define the downwind and crosswind coordinates. The stability conditions used in the model predictions were taken from the HSE summary information [3]. Seven methods were presented for the estimation of the stability conditions, and variation based on the various methods was as much as four categories. In some instances, the selected stability class was different than any of the stability conditions estimated from the seven methods. In addition to the atmospheric parameters, data such as surface temperature, surface roughness, and drag coefficients (for the Eidsvik model) were derived from trial observations.

We chose to supply the models with the above level of information since that is the type of information that is generally available for making predictions at a specific site. We recognize that it was possible to supply more trial-specific information for the various models. An example would be friction velocity. The Cox and Carpenter model and the HEGADAS II model use friction velocity in the prediction calculations, and it was possible to calculate an average friction velocity from the three-dimensional anemometer data recorded during the trials.

One must consider what the models predicted. The Cox and Carpenter model and the Eidsvik model predicted a cloud of uniform concentration advected downwind. At a location in the dispersion field, the models predicted a concentration versus time profile that had a trapezoidal shape. The concentration rose rapidly as the cloud front passed over the location and then decreased, either until the trailing edge of the cloud passed causing a rapid decrease to zero concentration, or until the concentration reached a level no longer of concern. The HEGADAS II model predicted a cloud with a uniform concentration over the source and calculated a ground level centerline concentration away from the source. Vertically and laterally, the concentration was distributed by a predefined concentration profile, with coefficients also predicted as a function of downwind distance. The MARIAH II model predictions gave a value of concentration as a function of time for each grid volume that surrounded the release and dispersion area.

For the experimental results, the values of concentration at the sensor locations were affected by the time period used for the averaging. A longer time averaging period caused greater smoothing of the data. A 0.6 s time period was used to retain the shape of the sensor responses and to numerically filter the sensor response noise. A trial represented only one release at the stated conditions. Due to the variability of the atmospheric parameters (wind speed, wind direction, etc.), other experiments released under the same average conditions would produce different results. The average of the replications of the experiment would smooth out some of the recognized sharp features of the cloud, thereby altering the dynamics of the cloud. Due to the impossibility of performing replications of the trials under the same atmospheric conditions, we believe that the only alternative was to consider each trial as representative of the cloud produced under the conditions. For each wind speed and stability category, we attempted to select the trial that we thought was the most representative of the trials within the category and minimized the smoothing of the sensor responses.

5.1 Analysis

Of the five graphical methods described in Section 4, four methods were found to be useful for comparing the ability of the models to predict dispersion behavior. The method that was least helpful dealt with the cloud height. This method produced plots of trial and model cloud heights versus distance (i.e., vertical gas concentration versus time) for a selected time. As was discussed earlier, cloud heights in the Cox and Carpenter, Eidsvik, and HEGADAS II models were defined by mass balance requirements and were not truly representative of actual cloud heights. The HEGADAS II model yielded slightly more representative plots since it allowed a concentration distribution along the edge of the cloud.

The remaining four graphical techniques (horizontal concentration contours, maximum concentration versus time, maximum concentration versus distance, and the co-current areal coverage plots) provided the best tools for comparing the model predictions with the actual trial results. Intertwined among the four graphical representations were the concentration versus time/ downwind distance relationships. We believe that no single measure of a model's ability to duplicate the trial results exists at this time. In order to do this, the method would have to take into account five factors: time, downwind distance, lateral extent of the cloud boundaries, maximum concentration, and the concentration distribution. We believe that these five aspects were covered by the four graphical techniques defined. The plots of horizontal concentration contours at selected times yielded information on the rate of lateral spreading and air entrainment as a function of time and location. The plots were instructive in defining the initial cloud motion upwind, downwind, and crosswind of the source.

The plots of maximum concentration versus time were representative of how the cloud diluted in time, without defining its location at any point in time. The plots were representative of how well the model predicted the total air entrainment into the cloud and the diffusion of the gas into the surrounding atmosphere.

The plots of maximum concentration versus distance yielded information concerning how well the model predicted the maximum concentration of the cloud, without regard for how long it took the cloud to travel the distance. The plots presented the important "maximum downwind travel" parameters used in safety studies to evaluate the risk to surrounding populace from a release of toxic and/or flammable gas. The plots yielded information as to whether a particular model underpredicted or overpredicted the maximum downwind range of a cloud.

Co-current areal coverage plots for the model predictions versus the trial results were also employed in the analysis of results. This type of plot tied together the downwind location of the cloud, time after release, and horizontal limits of the cloud to a particular concentration limit. Indirectly, concentration profiles for the model predictions and trial results were used to help define the lateral cloud boundaries. The plots were particularly useful when visually comparing the location and lateral dimensions of the model cloud to the trial cloud at a particular time. By the nature of the definition of the co-current coverage factor, the observer must be wary of misinterpretation of the results. The factor was forced to 0.0 for any one of three reasons: (1) the trial cloud concentration dropped below one percent; (2) the model cloud concentration dropped below one percent; or (3) there was no co-current coverage between the model clouds. In order to use these types of plots effectively, area plots of the model and trial clouds discussed in Section 4.1 must be referenced.

5.2 Results for Trial 7

In order to reduce the number of trials for comparison with the model predictions, six of the sixteen Phase I Thorney Island Trials were selected for six wind speed–stability categories. The six trials selected were considered to be

TABLE 2

Selected trials for wind speed-stability categories

Trial number	Category
7	Midrange wind speed (4.0–6.0 m/s) and slightly to moderately stable (Pasquill E–F) category
8	Low wind speed (1.0–3.0 m/s) and slightly unstable to neutral (Pasquill C–D) category
9	Low wind speed (1.0–3.0 m/s) and slightly to moderately stable (Pasquill E–F) category
14	High wind speed (7.0–8.0 m/s) and slightly unstable to neutral (Pasquill C–D) category
15	Midrange wind speed (4.0–6.0 m/s) and moderately to slightly unstable (Pasquill B–C) category
16	Midrange wind speed (4.0–6.0 m/s) and slightly unstable to neutral (Pasquill C–D) category

the best representative trials within the categories. Table 2 shows the trial number that was selected for each category. The summary of results obtained from the comparison of the trial data and model predictions from Trial 7 are presented below. Due to the length of the analysis and number of graphical aids required, Trial 7 is presented as an example of how the six trials chosen were analyzed.

Trial 7

The Trial 7 concentration results are presented graphically in Figs. 4 and 5. Figure 4 is a plot of the maximum concentration in the trial cloud versus time. The general trend of the data showed a rapid decrease in the maximum cloud concentration during the initial portion of the trial. The scatter of the data was due to the non-uniformity of the mixing occurring in the trial cloud. Figure 5 presents the maximum concentration within the trial cloud as a function of downwind distance. Since sensor locations were laid out in a rectilinear grid, a few gas sensors recorded the maximum gas concentration during several time pictures. As seen in Fig. 5, the location of the maximum concentration is consistently observed at the same sensors (i.e., same downwind distance). Three of the fifty-seven sensors which recorded gas concentrations consistently recorded maximum concentrations for Trial 7 for the time steps selected.

Figure 6 contains a series of plots presenting horizontal one percent contours 0.4 m above ground. The time steps selected for comparison were 15 s, 30 s, 60 s, 90 s, 120 s, 150 s, 180 s, 210 s, 240 s, 270 s, and 400 s. Only the results for 30 s, 60 s, 90 s, and 180 s are plotted in Fig. 6 for illustration. The trial data did not produce any sensor readings at the 15 s time step; therefore, only the model clouds were plotted at that time. The next time step selected, 30 s, yielded

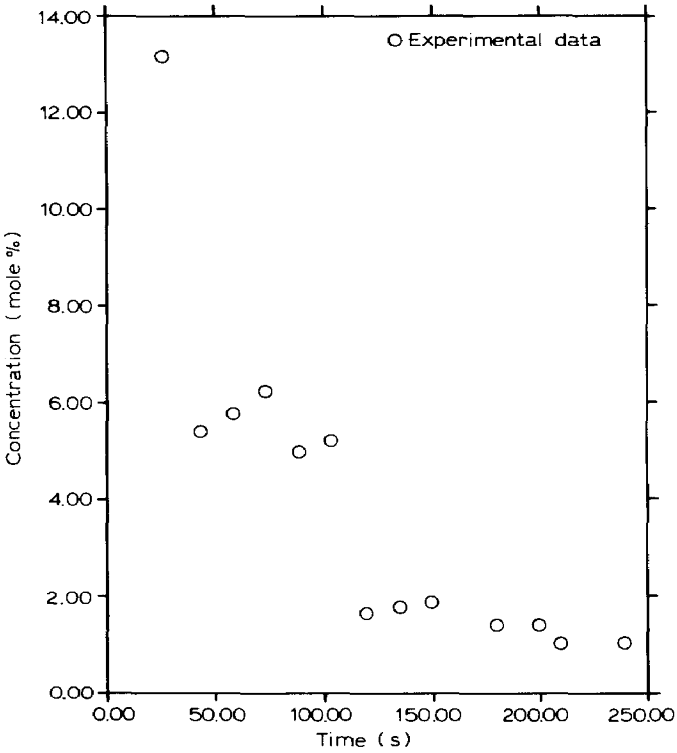

Fig. 4. Maximum concentration in the cloud versus time for Trial 7.

contour plots for the trial data and all three model results. Due to the nature of the Eidsvik model and the Cox and Carpenter model, these clouds were instantaneously accelerated to a velocity less than the reference wind speed. The trial cloud also appeared to follow this type of instantaneous acceleration. The HEGADAS II model did not allow the vapor cloud to be accelerated downwind during the transient source definition phase of the model, thus accounting for the stationary cloud over the source. Once the air started stripping gas off the source cloud, the stripped gas/air mixture was accelerated downwind with a velocity less than the reference wind speed. By 90 s after the release, the HEGADAS II cloud was seen to be removed from the source. The MARIAH II cloud had a width approximately equal to the trial cloud; however, the trial cloud was much more elongated.

From the plots at 60 s on, the Eidsvik model and Cox and Carpenter model overpredicted the downwind location of the gas cloud. The HEGADAS II model did a better job of predicting the location of the cloud up through 150 s after release. The HEGADAS II gas cloud, defined by the one percent contours at 0.4 m above ground, disappeared sometime between 150 and 180 s after release.

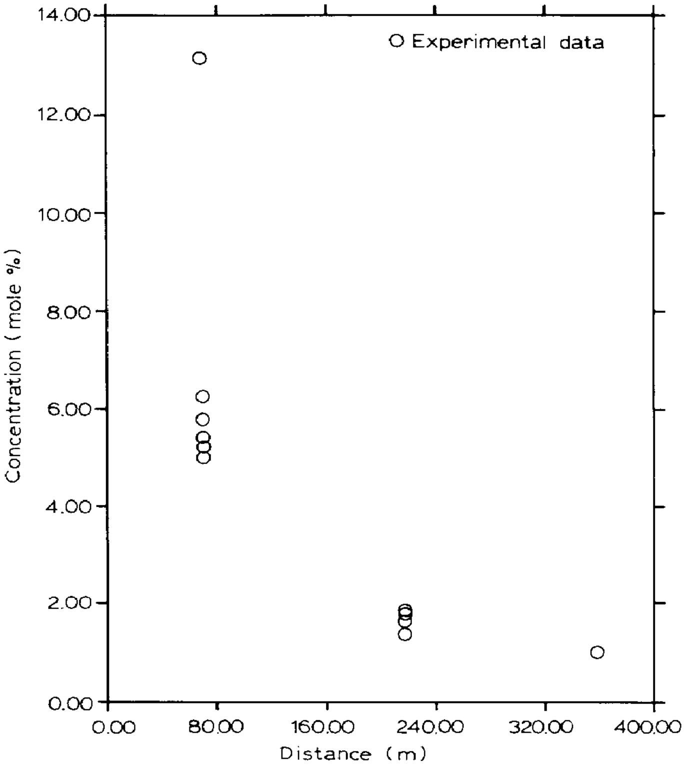

Fig. 5. Maximum concentration in the cloud versus downwind distance for Trial 7.

The trial gas cloud still existed at 180 s after release; however, from 210 s through 240 s, only a small pocket of the trial gas cloud existed at the 0.4 m level. The MARIAH II cloud had the best match of cloud shape at the 60 s time interval. The MARIAH II cloud continued to provide the best match of cloud shape with the trial cloud up through the 180 s time interval.

Starting with the 90 s time plots, the Eidsvik model and Cox and Carpenter model consistently overpredicted the lateral extent of the gas cloud. This was due primarily to the box type concentration profile. Up until the 90 s time period, all three models predicted the lateral extent of the trial cloud.

Even though the last portion of the trial gas cloud diluted below one percent concentration between 240 and 270 s, the Eidsvik model and Cox and Carpenter model continued to predict a cloud above one percent concentration past 400 s after release. In this sense, the Eidsvik model and Cox and Carpenter model overpredicted the downwind travel of the gas cloud, as well as its lateral extent. Conversely, the HEGADAS II model predicted that the cloud would dilute below one percent between 150 and 180 s after the release. The MARIAH

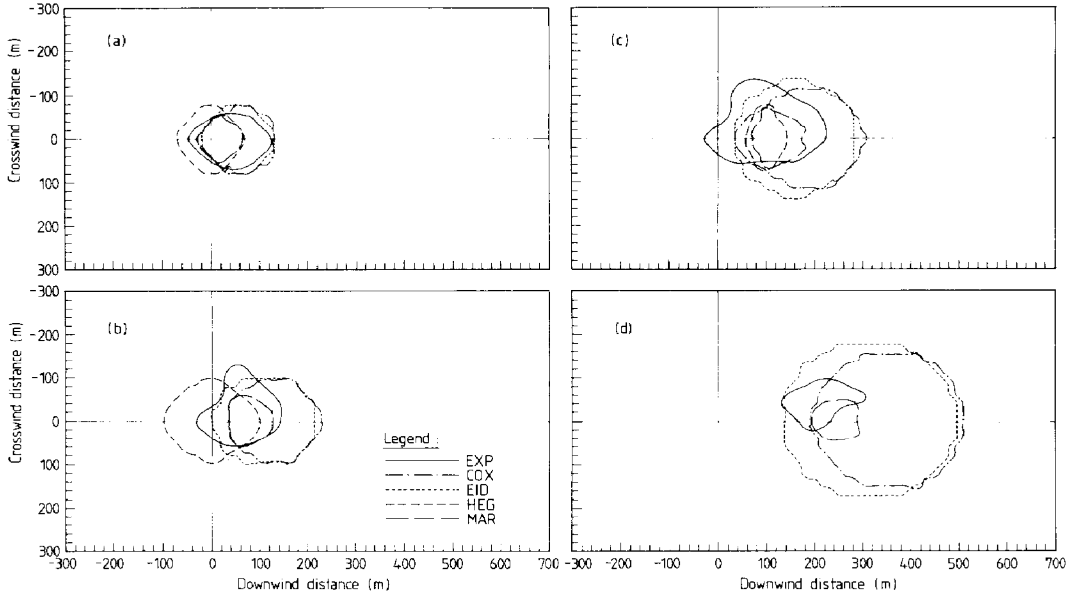

Fig. 6. Comparison of experimental results and model predictions of 1% concentration contour at 0.4 m height at different times after release: (a) 30 s; (b) 60 s; (c) 90 s; and (d) 180 s.

II cloud dropped below the one percent concentration level at approximately the same time after release as the trial cloud.

In general, for the times specified in the analysis and presented in Fig. 6, the HEGADAS II and MARIAH II models predicted the location of the cloud center when the cloud diluted below one percent concentration better than the Eidsvik model and Cox and Carpenter model. The MARIAH II model predicted the time after release to dilution to one percent concentration better than any of the other models. The Eidsvik model and Cox and Carpenter model overpredicted the downwind travel and lateral extent of the gas cloud.

Figures 7 and 8 present the maximum concentrations of the various models and trial data. Figure 7 graphically presents the maximum cloud concentration versus time for the model predictions and trial results. From this plot, it is clear that the Eidsvik model significantly overpredicted the concentration of the gas cloud as a function of time. The Cox and Carpenter and HEGADAS II models both initially predicted the rate of dilution of the gas cloud fairly well; however, once the analysis passed the 150 s time period, significant differences existed. The HEGADAS II model predicted that the maximum concentration of the cloud dropped below one percent before the actual trial cloud, whereas the Cox and Carpenter model predicted that the cloud contours had concentrations above one percent past the time when the trial cloud diluted below one percent. The MARIAH II initial dilution rates were similar to the Eidsvik

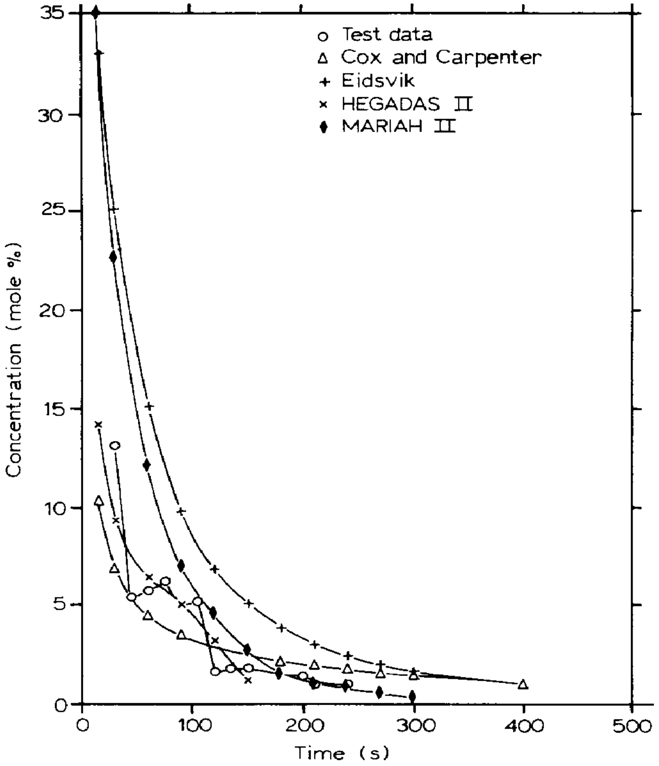

Fig. 7. Comparison of experimental results and model predictions of the maximum concentration in the cloud versus time for Trial 7.

rates. At the 120 s time interval, the MARIAH II cloud dispersed approximately as the trial cloud. In the later part of the trial cloud life, 150 s to 240 s, the MARIAH II cloud and the trial cloud maximum concentrations matched closely.

Figure 8 shows the maximum downwind distance to the one percent concentration limit versus time for the trial and model results. This plot clearly shows that the Eidsvik model and Cox and Carpenter model overpredicted the downwind travel of the gas cloud to the one percent concentration limit. Conversely, the HEGADAS II model predicted the downwind travel of the gas cloud at the concentration level fairly well. The fact that the HEGADAS II model cloud dropped below the one percent limit before the trial cloud is also represented in Fig. 8. The MARIAH II model showed the best match of the distance to the one percent concentration level as a function of time. The MARIAH II predictions closely matched the time the cloud dropped below the one percent concentration level.

The summary plot of the co-current factor calculation, described in Section

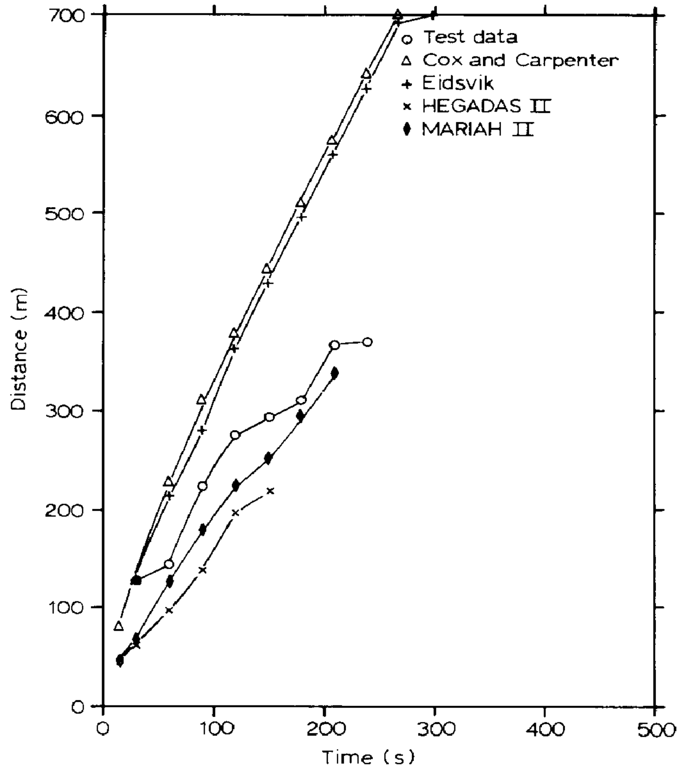

Fig. 8. Comparison of experimental results and model predictions of the maximum distance to the 1% concentration versus time for Trial 7.

4.5, is presented in Fig. 9. The plot shows that initially the Eidsvik model and Cox and Carpenter model predicted the location and lateral extent of the trial cloud better than the HEGADAS II and MARIAH II models. This was due to the ability of the Eidsvik model and the Cox and Carpenter model to instantaneously accelerate the gas cloud to a velocity somewhat less than the reference wind speed. During this initial time period, the HEGADAS II model defined the gas cloud to remain over the source. Once the HEGADAS II model cloud left the source, it more accurately predicted the location of the trial gas cloud than the Eidsvik model and Cox and Carpenter model, until the point in time when the HEGADAS II gas cloud diluted below the one percent concentration limit. The MARIAH II predictions matched the cloud shape better than the other three models after the initial dilution stopped and until the cloud dropped below the one percent concentration level.

In general, for Trial 7, the HEGADAS II model predicted downwind travel and maximum lateral extent of the trial cloud better than the Eidsvik model and Cox and Carpenter model. The Cox and Carpenter model and HEGADAS

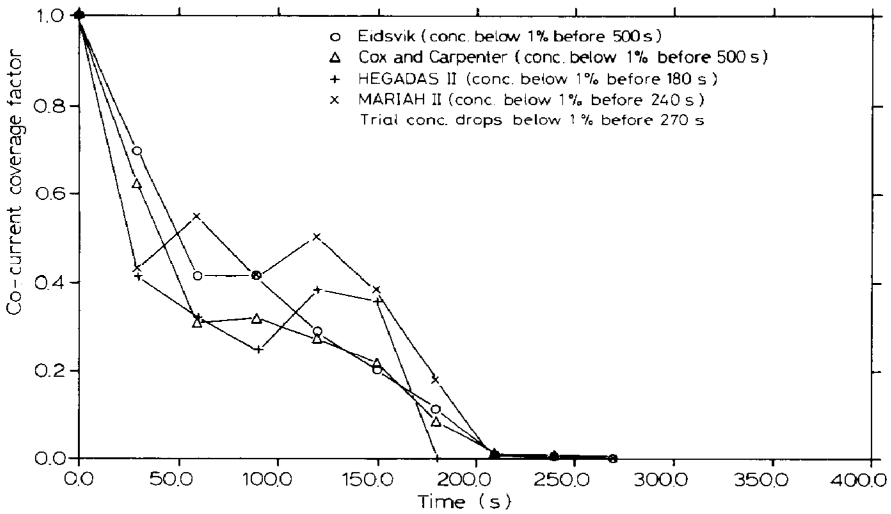

Fig. 9. Co-current coverage factor versus time using the four models and Trial 7.

II model both accurately predicted the maximum cloud concentration versus time. The difference was that the HEGADAS II model cloud dropped below the one percent concentration limit too soon, and the Cox and Carpenter model cloud continued to remain over the one percent concentration level past the time when the trial gas cloud diluted below one percent. For the maximum distance to the one percent concentration versus time and the co-current coverage, the MARIAH II model predicted the cloud behavior better than the other models.

5.3 Summary of results for Trials 8, 9, 14, 15, and 16

Due to the nature of the analysis and the amount of space required to completely describe the analysis of each trial, only a summary statement will be made for each of the remaining trials. A complete description of the analysis for each trial has been published elsewhere [11].

Trial 8

The results from the analysis for Trial 8 can be summarized as follows. The HEGADAS II and Cox and Carpenter models accurately predicted the dilution of the cloud. The MARIAH II model underpredicted the dilution until 150 s after the release, and then accurately predicted the dilution of the trial cloud until the cloud dropped below the one percent level. The Eidsvik model underpredicted the dilution over the entire period. The Eidsvik and Cox and Carpenter models overpredicted the distance to the one percent concentration level over the entire cloud life. The MARIAH II model provided the best prediction of the maximum cloud travel to the one percent concentration level and the time the cloud dropped below the one percent level. The HEGADAS II model slightly underpredicted the maximum cloud travel and predicted that the cloud dropped below the one percent level approximately 60 s before the trial cloud. The co-current cloud coverage showed that the Eidsvik and Cox and Carpenter models predicted the co-current areal coverage during the early phase of the cloud travel. After 120 s, the MARIAH II and HEGADAS II models predicted the co-current coverage slightly better than the Eidsvik and Cox and Carpenter models. The meandering of the cloud after 120 s was, in part, attributable to the lack of agreement of the co-current areal coverage between the model predictions and the trial cloud.

Trial 9

The results from the analysis for Trial 9 can be summarized as follows. The Cox and Carpenter model best predicted the dilution rate of the trial cloud. The HEGADAS II model also accurately predicted the dilution of the cloud in the early phase of the cloud spread. For this particular trial, the fact that the HEGADAS II model cloud did not move downwind during the initial transient growth period favored the model, primarily due to the reluctance of the trial cloud to advect downwind under the low wind speed (2.34 m/s) and stable atmospheric conditions (Pasquill F). The MARIAH II model accurately predicted the downwind edge of the cloud. The HEGADAS II model provided the best co-current coverage of the cloud in the early phase of the dispersion.

Trial 14

The results from the analysis for Trial 14 can be summarized as follows. Based upon the co-current areal coverage factor plot, all four models initially predicted the location and lateral extent of the trial cloud fairly well. This was due to the ability of the Eidsvik, Cox and Carpenter, and MARIAH II models to instantaneously accelerate the gas cloud to a velocity somewhat less than the reference wind speed. During this initial time period, the HEGADAS II model maintained the gas cloud over the source. Once the HEGADAS II model cloud was allowed to leave the source, it predicted the location of the trial gas cloud as accurately as the other models up until the 60 s interval. The co-current coverage factor for the Eidsvik model dropped dramatically to 0.0 at 60 s after release due to the disappearance of the one percent concentration contour at the 0.4 m height and due to the model cloud height being less than 0.4 m. After 60 s, the MARIAH II model accurately predicted the co-current areal coverage.

Trial 15

The results from the analysis for Trial 15 can be summarized as follows. Based on the co-current areal coverage plot, the HEGADAS II model consistently predicted the areal location of the trial cloud better than the Eidsvik, Cox and Carpenter, and MARIAH II models. During the early time periods, the HEGADAS II model defined the gas cloud to remain over the source. For Trial 15, the HEGADAS II model predicted the downwind travel and maximum lateral extent of the trial cloud better than the Eidsvik, Cox and Carpenter, and MARIAH II models. The HEGADAS II model also predicted the maximum cloud concentration versus time better than the Eidsvik and Cox and Carpenter models.

Trial 16

The results from the analysis for Trial 16 can be summarized as follows. Based on the co-current areal coverage plot, all four models performed nearly the same for this trial. The difference in the way the factor was calculated was due to the HEGADAS II and MARIAH II model clouds being too small, and the Eidsvik and Cox and Carpenter model clouds being too large. In general, for Trial 16, the HEGADAS II model predicted downwind travel and maximum lateral extent of the trial cloud better than the Eidsvik and Cox and Carpenter models. The HEGADAS II model also predicted the maximum cloud concentration versus time better than the Eidsvik and Cox and Carpenter models.

6. Conclusions

The Thorney Island Trials were the most comprehensively instrumented series of field experiments that have been performed to date. The placement of sensors and data recordings produced quality data with which it was possible to make meaningful comparisons with model predictions of four state-of-the-art heavy gas dispersion models. An instantaneously released column of heavy gas over flat terrain presented well defined initial conditions for the model predictions. In addition to release and terrain, meteorological conditions were also well defined due to the extensive instrumentation. The evaluation of model predictions for this instantaneous release of a gas column complemented previous studies using models to simulate continuous and instantaneous releases of liquefied gases.

Four models that represent state-of-the-art techniques were selected for the comparisons. The model predictions were made at gas sensor locations that had been translated to the downwind and crosswind coordinate system. The graphical techniques that had been used for the trial results were then available to make comparisons between the model predictions and trial results. In addition, a method was developed to compare co-current areal coverage of horizontal concentration contours. For this study, one percent horizontal concentration contours at 0.4 m height were compared at several time steps during dispersion of the gas cloud. A summary of areal coverage presented as a fraction of coverage versus time and horizontal concentration contours provided an effective method of comparing the model predictions with the trial results.

The analysis of the trial results and model predictions provided a framework to make several specific conclusions about the ability of the various models to replicate actual heavy gas releases. The conclusions were based upon an instantaneous isothermal release of gas forming and dispersing over open, flat, unobstructed terrain. Other aspects affecting releases of heavy gases (i.e., LNG and LPG), such as the thermodynamics due to temperature differential and terrain effects, were not considered.

For the higher wind speed trials, Trials 14–16, the HEGADAS II and MARIAH II models predicted the downwind travel and lateral extent of the cloud versus time better than either the Eidsvik or Cox and Carpenter model. We believe this to be due primarily to the concentration profiles employed by the models. The MARIAH II model predicted the concentration in each cell in the volume encompassing the release, thereby allowing for gradients of concentration within the computed cloud. Also, the HEGADAS II model predicted the lateral extent of the cloud at some defined concentration level (this study used one mole percent) which enabled it to more accurately calculate the areal coverage of the cloud. Since the Eidsvik and Cox and Carpenter models (in the forms employed) assumed a uniform concentration in the cloud boundary, these clouds continued to expand in the horizontal plane until the gas concentration dropped below the one mole percent level, at which time calculations were terminated.

The HEGADAS II and MARIAH II models also did a better job of predicting the maximum cloud gas concentration versus time than either the Eidsvik or Cox and Carpenter model for the higher wind speed trials. The Eidsvik model continuously underpredicted the amount of air entrained into the cloud, thus overpredicting how long the cloud would remain with a gas concentration over one percent. The Cox and Carpenter model initially overpredicted the amount of air entrainment, but then underpredicted the amount of air entrained in the later portion of the trial. Combined, these two features caused the Cox and Carpenter model predictions of the cloud to remain above the one mole percent limit past the time at which the trial cloud diluted below the one mole percent limit. The MARIAH II model underpredicted the initial air entrainment, but after 60 s, it matched the trial dilution rates closely.

Both the Eidsvik and Cox and Carpenter models significantly overpredicted the maximum distance to one percent concentration versus time for all but the initial time periods used in the analysis. The MARIAH II and HEGADAS II models very closely matched the maximum distance to the one percent concentration level, with the HEGADAS II model usually slightly underpredicting the maximum distance and the MARIAH II model usually slightly overpredicting the maximum distance to one percent concentration. Also, the MARIAH II and HEGADAS II models usually predicted (to within one time interval of the preselected times for analysis) the time for the cloud to dilute to below a maximum concentration of one percent. The Eidsvik and Cox and Carpenter models both overpredicted the time to dilution below the one percent concentration. Once again, we believe this was due to how the models define the gas concentration profiles within the cloud, and the rate of air entrained into the cloud over the life of the trial.

When the trial clouds were centered on the downwind axis, the co-current areal coverage factors were higher for the HEGADAS II and MARIAH II models than for the Eidsvik and Cox and Carpenter models. In the case of Trial 16, where the trial cloud was consistently off the downwind axis, the Eidsvik model provided the best co-current areal coverage prediction over the dispersion of the cloud to the one percent concentration level. We did not attribute this result to the predictive capabilities of the model, but to a possible shortcoming of the method of centering the downwind axis.

For two of the lower wind speed trials, Trials 7 and 8, the general trends found in the higher wind speed trials were apparent, but to a lesser degree. The HEGADAS II and MARIAH II models located the cloud in the downwind direction, with an areal coverage which was closer to the trial cloud movement and expansion, better than the Eidsvik and Cox and Carpenter models. This was due primarily to the nature of the Eidsvik and Cox and Carpenter models overpredicting the time at which the cloud dropped below the one mole percent level, and the downwind travel of the cloud before diluting below the one percent level. Once again, we believe this was due to the definition of the gas concentration profiles and the rate of air entrainment over the period of the trial.

When the maximum gas concentration versus time plots were analyzed, it was seen that the Eidsvik model underpredicted the amount of air entrained into the gas cloud as a function of time. As in the higher wind speed cases, the Cox and Carpenter model initially overpredicted the amount of air entrainment, but then underpredicted the rate once the cloud approached the one mole percent lower concentration limit. The HEGADAS II and MARIAH II models predicted the dilution of the gas cloud as a function of time better than either the Eidsvik or Cox and Carpenter model for the duration of the trial and, in fact, diluted below the one mole percent lower limit at approximately the same time as the trial cloud. The MARIAH II model underpredicted the dilution for the initial 120 s, and then closely matched the dilution rate. The dilution rate for the HEGADAS II model was slightly erratic, but closely followed the dilution rate for the trial cloud.

Trial 9 turned out to be an anomaly. The analysis of the other five trials yielded consistent trends applicable to all. The low wind speed (2.4 m/s) and moderately stable atmospheric stability conditions (Pasquill F) may have contributed to the fact that none of the models evaluated did a good job of duplicating the trial cloud. The movement of the trial cloud initially was very

TABLE 3

Maximum cloud travel distances with gas concentration above one percent

Trial	Observed (m)	Eidsvik (m)	Cox and Carpenter (m)	HEGADAS II (m)	MARIAH II (m)
7	373	700+	700+	218	340
8	253	700+	700+	217	380
9	327	595	700+	202	325
14	347	700+	700+	335	323
15	370	700+	627	405	317
16	320	700+	700+	335	383

slight in the downwind direction, and then appeared to meander about the source. Since the cloud did not instantly advect downwind, the Eidsvik and Cox and Carpenter models significantly overpredicted the downwind location of the cloud as a function of time. The HEGADAS II model cloud remained over the source during the transient source definition phase of the model, thus allowing the co-current coverage factor to remain fairly high during this portion of the trial. However, once the HEGADAS II cloud moved away from the source, it also overpredicted the downwind location of the trial gas cloud. The MARIAH II model predicted the maximum distance to the one percent concentration during the time after the initial spread (120 s) to the time (300 s) the model predicted the cloud would drop to below the one percent level.

Table 3 summarizes the ability of the models to predict maximum downwind distances to the one percent concentration for the six trials. The model prediction calculations were terminated when the predicted distances to the one percent concentration exceeded 700 m. The values in Table 3 are shown as 700+ when the distances exceeded 700 m. As seen from Table 3, the HEGADAS II and MARIAH II models came closest to matching this facet of the experimental results. In particular, for the low wind speed trials, the Eidsvik and Cox and Carpenter models consistently overpredicted the maximum cloud travel distance. For the same low wind speed trials, the HEGADAS II and MARIAH II models consistently underpredicted the travel distance by an average of 31 and 20 percent, respectively. Under the higher wind speed conditions, the Eidsvik and Cox and Carpenter models consistently overpredicted the downwind travel distance. Under the same high wind speed conditions, the HEGADAS II and MARIAH II models did not consistently overpredict or underpredict the maximum downwind travel. On the average, the HEGADAS II predictions varied by 6 percent, while the MARIAH II predictions varied by 13 percent. The most notable difference between the box models of Eidsvik and Cox and Carpenter and the HEGADAS II and MARIAH II models was seen in the results of Trial 14. Under an average wind speed of 6.8 m/s, the highest wind speed trial of those selected, the HEGADAS II and MARIAH II results varied from the trial data by 3 and 7 percent, respectively, while the Cox and Carpenter and Eidsvik results varied by more than 100 percent.

For this set of Thorney Island data, we believe the Eidsvik and Cox and Carpenter models predicted similar results, and the results were conservative in that they predicted larger areal coverages and downwind travel distances than the trial clouds. The Eidsvik and Cox and Carpenter models consistently overpredicted the downwind travel distance to the one percent concentration limit under both low and high wind speed conditions. The HEGADAS II and MARIAH II models predicted the time varying trial concentration data to within 10 to 20 percent, and the maximum distance to the one percent concentration to within 6 to 14 percent. During the time between the initial dispersion (60 s) and the time the cloud dropped below the one percent concentration level (approximately 250 s for low wind speeds and approximately 125 s for high wind speeds), the co-current areal coverage factors ranged from 0.75 to 0.30. The HEGADAS II and MARIAH II models were slightly better for the higher wind speeds than for the lower wind speeds.

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