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A COMPARISON WITH EXPERIMENTAL DATA OF SEVERAL MODELS FOR DISPERSION OF HEAVY VAPOR CLOUDS

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Summary

A comparison is reported between experimental data obtained from spills of heavy gas or volatile liquids and predictions of five different models of heavy vapor cloud dispersion. The models chosen for comparison and their sources are: MARIAH (Deygon—Ra, Inc.), ZEPHYR (Energy Resources Co., Inc.), HEGADAS-II (Shell), Eidsvik's "top hat" model (Norwegian Institute for Air Research), and the Germeles and Drake "top hat" model (Cabot Corp.). They are compared with the experimental LNG spills by Esso Research and Engineering Co. on water at Matagorda Bay, Texas (specifically Esso Runs 11, 16, 17) and the releases of heavy gas at Porton Down, Gt. Britain, sponsored by the Health and Safety Executive (specifically HSE Trials 6, 8, 20).

It was found that the eddy diffusivity (K-theory) type of models, MARIAH and ZEPHYR, were best able to fit the HSE Porton Down data (for both near and far, high and low sensors). The HEGADAS-II model predictions best fit Esso Runs 11 and 17. However, HEGADAS-II cannot describe the calm wind cases, Esso Run 16 and HSE Trial 8.

The Eidsvik model is recommended as one of the most advanced of the "top hat" class of models. It generally matches well the HSE Porton Down data for which it was calibrated. However, both HEGADAS-II and Eidsvik's model poorly fit sensor responses close to the source in the HSE trials; more distant sensors are matched better.

The Germeles and Drake model seriously overpredicts air entrainment for HSE Trial 8, and overpredicts cloud dimensions for Esso Run 16. It reverts to the neutrally buoyant Gaussian form for four of the six experiments considered.

Introduction

It has been recognized in recent years that models developed for the dispersion of neutrally buoyant clouds are inadequate to describe the dispersion of heavy vapor clouds formed, for example from accidental spills of volatile liquids. Subsequently, numerous models have been developed to describe heavy vapor clouds, often with little or no comparison with experimental data beyond that used to adjust or "calibrate" model parameters. Five models are compared here against the same sets of experimental data to assess the range of model validity.

Previous model comparison studies have concentrated on the ability of models to predict the effects of very large (25,000 m^3 of liquid) spills over water (Bowman et al. [2], Havens [8] and Taft and McBride [14]). For this purpose, the available data base is clearly inadequate (since the required extrapolation for spill sizes is over four orders of magnitude). Yet the available data may be adequate for the more limited purpose of testing the adequacy of models to predict the effects of relatively small spills on land or water. In these cases, minor differences in model predictions can be important, and it is to these differences that this model comparison is addressed.

Five of the many models available were selected for evaluation: MARIAH, ZEPHYR, HEGADAS II, and models by Eidsvik [4], and Germeles and Drake [7]. These models are representative of two types, the K-theory (or eddy diffusivity) type (MARIAH and ZEPHYR), and the "top hat" or uniform concentration cloud type (Eidsvik and Germeles and Drake). The HEGADAS II model by Colenbrander [3] can be described as an "advanced top hat" model, which assumes a particular form of concentration profile, although it also utilizes an eddy diffusivity (K-theory) approach. The Germeles and Drake (GD) model typifies "first generation" models which incorporate air entrainment in the vertical via constant coefficients. The GD model requires that a transition be made to a neutrally buoyant Gaussian model for the far field solution. The Eidsvik model typifies "second generation" top hat models which incorporate horizontal (cloud edge) and vertical air entrainment via non-constant coefficients which are dependent on the Richardson number. The Eidsvik model does not require transition to a Gaussian model. The ZEPHYR model of Energy Resources Co., and the MARIAH model of Deygon—Ra, Inc. are three-dimensional numerical solutions of the partial differential equations of mass, energy, and momentum transfer. Both ZEPHYR and MARIAH are similar to the SIGMET model documented by Havens [9]. Although these models solve the same set of equations, there are significant differences in the numerical solution methods. ZEPHYR uses a particle-in-cell technique coupled with an explicit finite difference approach. MARIAH uses an implicit finite difference method which allows larger step sizes thereby reducing computer costs.

Experimental data for verifying model predictions are very limited in scope and accuracy. The available data sets are summarized in Blackmore, Herman and Woodward [11]. Of these, most proved inadequate for model comparison purposes and only a few were selected for our model comparison study. Those selected (see Table 1 for details) are:

(1) The Health and Safety Executive (HSE) releases of 40 m^3 of freon/air mixtures at Porton Down, Gt. Britain (Picknett [13]), specifically HSE Trials 6, 8, and 20.

TABLE 1

Experimental data utilized in the comparison study

Data set	General description	Spill size (m^3)	Spilling time (s)	Atmospheric stability [a]		Wind speed (m/s)	Amb. temp. (°C)	Rel. hum. (%)
				Reported	Used for MARIAH			
HSE 6	Freon 12/Air (Specific gravity 1.7) onto land.	40 (Vapor)	"Instantaneous"	C—D	A	2.8[b]	8	87
HSE 8	Ditto, S.G. = 2.0	40 (Vapor)	"Instantaneous"	F—G	F	Calm	Unavail.	Unavail.
HSE 20	Ditto, S.G. = 2.1	40 (Vapor)	"Instantaneous"	C	A, C	5.3[b]	12	49
Esso 11	LNG onto water	10.2 (Liquid)	35	D	D, F	8[c]	27	78
Esso 16	LNG onto water	7.57 (Liquid)	28	B	D	Calm	18	62
Esso 17	LNG onto water	8.37 (Liquid)	31	D	D	4[c]	18	85

(a) Pasquill Stability Class
(b) At 2.0 m height
(c) At 5.5 m height
(d) At 10 m height

(2) The Esso/API spills of LNG onto water at Matagorda Bay, Texas (Feldbauer et al. [6]), specifically Esso Trials 11, 16, and 17.

These experiments include instantaneous releases and finite-time releases; spills both on land and over water; and spills occurring during very low (calm), low, and medium wind speeds.

Approach

Model comparisons are desired for both cloud dimensions and concentrations in order to determine areas of hazard. Of particular value would be comparison plots of plan view iso-concentration contours, particularly LFL or toxic limit contours. Unfortunately, observations are too limited to allow comparisons of plan view contours. Separate comparisons of cloud dimensions and sensor responses at a wide variety of heights and distances as a function of time is next best, and this is the approach used here.

The top hat and HEGADAS II models were programmed from the literature descriptions. No adjustments were made to the model parameters originally reported. Discussions were held with the authors to clarify some points of detail not included in the original papers. For example, the precise height to use with wind speed calculations is often unspecified (we used half of the cloud height for cloud advection), as is the treatment of humidity and water condensation. A complete description of each of the models, how they were programmed, and how input data were obtained is left to a later paper (Havens [10]).

MARIAH and ZEPHYR model calculations were performed by the model originators (Deygon—Ra, Inc. and Energy Resources Co., Inc. respectively). An effort was made to use the same wind speed profiles and vapor generation rates for a given case with all models. However, Deygon—Ra made an independent assessment of the atmospheric stability for each experiment based on reported vertical temperature gradients and used some different values from those listed in Table 1. To evaluate the significance of this revision, the sensitivity of the Deygon—Ra model to atmospheric stability was determined for two cases. This sensitivity proved to be small.

Reference was made to the original experimental data. The British Health and Safety Executive supplied unpublished information on the exact location of sensors for the HSE tests.

Model and data limitations

One of the first conclusions to emerge is that each model is limited in its range of applicability. In addition, the selected data sets are incomplete and of limited range as summarized in Table 2. This table indicates there are no gas sensor data available for Esso Trial 16 (a serious limitation). As indicated by a G in Table 2, the MARIAH and ZEPHYR models are unable to predict responses of the very low (5 and 10 cm) sensors used in HSE Trials 6, 8, and 20 without the use of a finer, high-resolution grid (thereby tripling computer cost/run).

TABLE 2

Applicability of models to chosen data sets

Model \ Data set	Wind speed (see Table 1)	Calm 0	Calm 0	Low 2.8 m/s	Medium 5.3 m/s	High 8 m/s	Low 4 m/s
		HSE 8	Esso 16	HSE 6	HSE 20	Esso 11	Esso 17
MARIAH		G	S	*, G	*, G	*	*
ZEPHYR		G	S	*, G	*, G	*	*
Eidsvik		*	S	*	*	*	*
HEGADAS		N	N	Q	Q	*	*
Germeles & Drake (GD)		*	S	N	N	N	N

* = Applies (at least for some sensors)
N = Not applicable, model limitations[(a)]
G = Grid limitations to matching sensor data
Q = Questionable to apply model for instantaneous release
S = No sensor data available
(a) The HEGADAS model relies on "observers" which float with the wind, therefore zero wind cases cannot be modelled. The heavy gas portion of the GD model is not invoked by the GD "transition criterion".

The HEGADAS II model (hereafter referred to as HEGADAS) assumes a quasi-steady representation of the cloud and appears less applicable for instantaneous releases such as the HSE trials. It is marked in Table 2 as questionable (Q) for such cases. The HEGADAS model does not apply for calm wind conditions, and is marked with an N.

The Germeles and Drake model is shown in Table 2 as not applicable for four of the six experiments. This is because the model consists of two submodels, a "gravity spreading" or heavy gas submodel and a neutrally buoyant (Gaussian) submodel. The required transition from the former to the latter is made (according to the originally published version of the model) when the cloud edge speed falls below the wind speed. This is a highly restrictive requirement, since in some cases the cloud speed is always below the wind speed. In other cases, the transition occurs very early in the experiment, and the heavy gas portion of the model, which is of primary interest here, has little influence on GD model predictions.

In spite of our attempts to keep all adjustable inputs and outputs of the models consistent, some inconsistencies arose. These are summarized below, and explained, in context, later:

1. Different values were assumed for ZEPHYR and MARIAH for the visible edge concentrations in the HSE trials.
2. Without using high-cost high resolution runs, MARIAH and ZEPHYR results are available only for 28 cm high and are compared with sensors at 5 and 10 cm high for HSE runs 6 and 20.

3. MARIAH used different atmospheric stability class assumptions (with justification) as summarized in Table 1.
4. MARIAH used a different wind profile for HSE 6 and HSE 20 (a curve drawn by the computer through the midpoints of the observed range of wind speeds at each anemometer height).
5. Only ZEPHYR and HEGADAS results are reported at the 0.38 m sensor height for Esso Runs 11 and 17. The other models are for 0.5 m height.

Nearly all of the experimental data available apply to flat terrain situations without obstacles and structural wake effects. It is not yet possible to test whether models calibrated against such data can be applied to more complex cases including obstacle effects.

Model comparison results—Cloud dimensions

Figure 1 compares several model predictions with observed cloud half widths as a function of time for HSE Trial 8. This is a near zero wind speed case, in which an initial column of gas spreads with radial symmetry upon release. The MARIAH and ZEPHYR models fit observed data very well, assuming that a concentration of between 0.5 and 2% (normally 1%) represents the visible edge of the cloud. Since the cloud was made visible with a smoke grenade, and the initial ratio of smoke particle concentration to freon gas concentration was not determined, the "correct" visible edge concentration is unresolvable. Since such an arbitrary choice is involved, the comparison of K-theory models with cloud width data would be meaningless except for the fact that these models predict a sharp concentration gradient at the edge of the cloud (at least early in the response). Concentrations be-

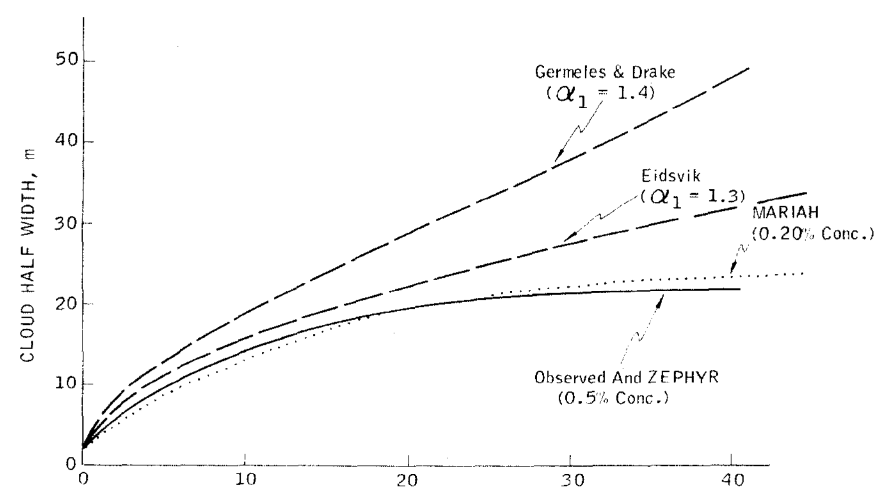

Fig.1. Predicted and observed cloud radius for HSE Trial 8.

tween 0.5 and 2% fall within the same grid cell (7.5 m wide by 5.0 m long) for the ZEPHYR model.

The top hat models match cloud width primarily by adjusting the parameter, α_1, in the "gravity intrusion formula":

$$\frac{dR}{dt} = \alpha_1 \left[g \left(\frac{\rho - \rho_a}{\rho} \right) H \right]^{1/2} \tag{1}$$

where R is cloud radius, H is cloud height, ρ and ρ_a are cloud density and air density, and g is the gravitational acceleration. Figure 1 shows that for HSE Trial 8, $\alpha_1 = 1.3$ (used by Eidsvik), produces a better fit with observed data than does $\alpha_1 = 1.4$ (used by Germeles and Drake). In addition, the GD model also invokes the Boussinesq approximation in eqn. (1) (ρ_a can be substituted for ρ in the denominator).

Unfortunately, a favorable comparison of model prediction against cloud radius alone, as in Fig.1, is not an indication that the models will correctly predict concentrations in the cloud. This is because the relationship of cloud radius to time is insensitive to the amount of air entrained in the cloud. This was shown for isothermal clouds experimentally by Britter [1] and theoretically by Picknett [13], who rearranged eqn. (1) in terms of the initial (constant) values of cloud height, radius and cloud density, H_o, R_o, and ρ_o, to:

$$R\,\frac{dR}{dt} \simeq \alpha_1 \left[g\,H_o \left(\frac{\rho_o - \rho_a}{\rho_a} \right) \right]^{1/2} R_o = \text{constant} \tag{2}$$

Thus, models in general and top-hat models in particular can predict cloud radius vs. time without reference to air entrainment terms. (Air entrainment is directly related to cloud height in top-hat models.) Comparison with sensor data is much more important than comparison with cloud dimensional data.

Wind profile assumptions

Figures 2 and 3 illustrate that, in general, model predictions are very sensitive to wind profile assumptions. Wind speeds, measured at four heights, in HSE Trial 6 produced a range of values as shown by the horizontal bars in Fig. 2. Any number of wind speed profiles having the formula:

$$\frac{u}{u_o} = \left(\frac{z}{z_o} \right)^p \tag{3}$$

(or a logarithmic formula) can be drawn through the data in Fig. 2. Two such profiles are shown, both with the same reference height, $z_o = 1$ m, but differing in u_o and p. These profiles, labeled "Run 1" and "Run 2" were used with the ZEPHYR and Eidsvik models to produce the model predictions in Fig. 3. labelled correspondingly. Model predictions change appreciably with the two wind profiles, thus making model treatment of wind profile very important.

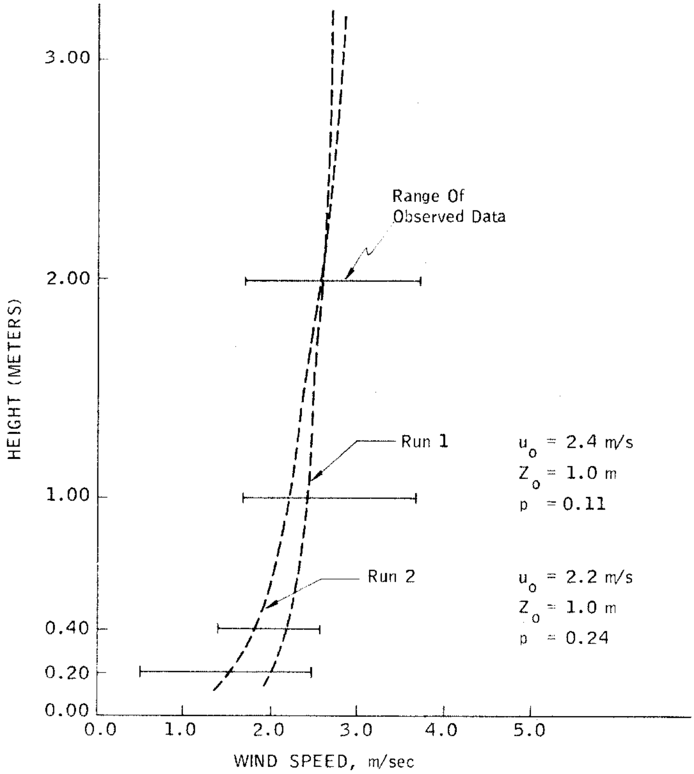

Fig.2. Wind speed profiles used in simulating HSE Trial 6.

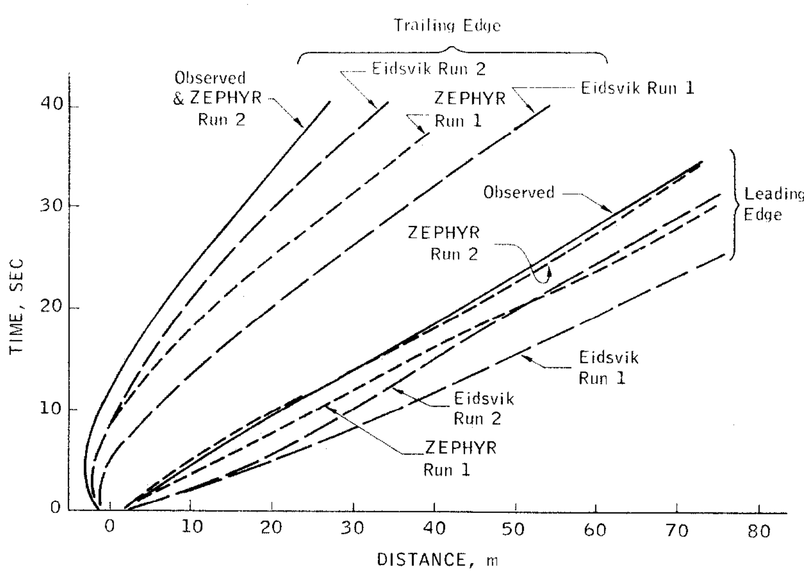

Fig.3. Leading and trailing edge comparison for HSE Trial 6.

Figure 3 shows that the Run 2 wind profile, which corresponds to a greater surface roughness, provides the better fit with data for both models. The ZEPHYR model using the assumed cloud edge concentration of 0.5—2% matches data better than the Eidsvik model for both wind profile assumptions. The MARIAH model also fits observations well, but is not shown to simplify the plot. In each case, model predictions tend to lead the data, for both the leading edge and the trailing edge. This would be expected for trailing edge data because heavy gas tends to move very slowly next to the ground where wind speeds approach zero. Models generally use a wind speed vertically averaged over some distance above the ground, thus erring toward high wind speeds.

Model predictions for the leading edge are usually ahead of the observed data because cloud inertia and acceleration to wind speeds are crudely treated. The MARIAH and ZEPHYR models allow for inertia, both of the gas container contents and of the air in the wake of the container, and with the right choice of wind profile are capable of a perfect match with data (ZEPHYR Run 2 in Fig. 3). Top hat models assume instant acceleration to wind speed. This assumption could be improved by using acceleration due to the drag force on a cylinder, since drag coefficients could be estimated.

Non-instantaneous spills over water

Esso Run 16 was a non-instantaneous spill of 7.57 m^3 of LNG over water in which the wind died just as the test began. Consequently, the vapor cloud from the spill did not reach the line of sensors. However, an overhead videotape record of cloud dimensions has been analyzed recently by the Jet Propulsion Laboratories (JPL) using digital photographic processing techniques originally developed for space flight pictures. The resulting data are shown in Fig. 4 as the shaded area for cloud half-width vs. time. With an irregular-shaped cloud, at least four different cloud diameters could be defined: along the axis of the release barge (D_1), perpendicular to this axis (D_2), and the two axes bisecting the first two (D_3 and D_4). Of these, $0.5D_2$ and $0.5D_4$ are plotted and $0.5D_1$ falls between those plotted.

The Eidsvik and GD models significantly overpredict cloud diameter vs. time. The plot for the GD model is shown only for the heavy gas portion which applies for only the first 25 seconds of the response.

The MARIAH and ZEPHYR models, which assume somewhat different cloud edge concentrations, fit the observed data very well. These predictions were made before receiving the data from JPL. Two ZEPHYR runs were made by varying the assumed vaporization rate (ZEPHYR Run 1 assumes no vaporization in the air, Run 2 assumes 75% of the LNG vaporized in the air). The resulting source rate curves for Esso Run 16 are very nearly identical to that shown in Fig. 10 for Esso Run 11.

On the whole, matching observed cloud dimensions alone is insufficient evidence for accepting model accuracy. Matching cloud composition data is more important, and this is discussed next.

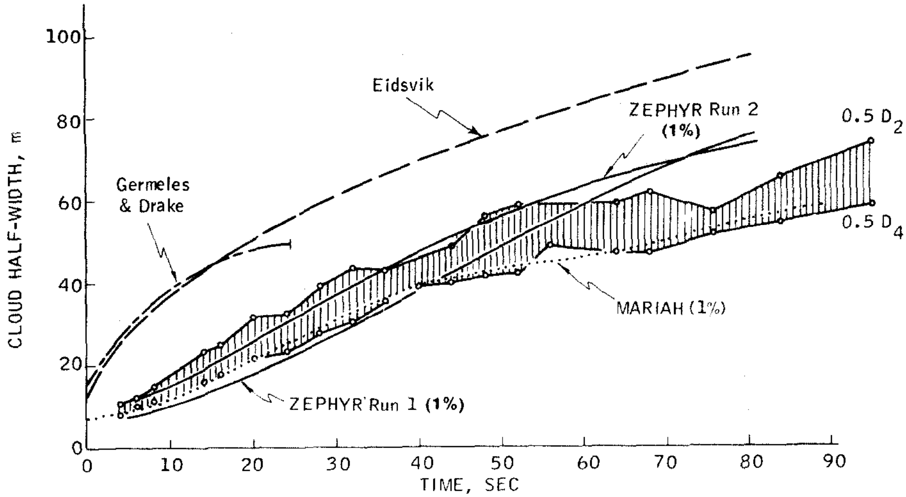

Fig.4. Predicted and observed cloud radius for Esso Run 16.

Model comparison results — Sensor responses

Sensor height is critical with HSE trials

Very few sensor responses were obtained during the HSE trials, and many of those available are from sensors placed very close to the ground (5—10 cm). K-theory models have difficulty matching such low sensors without resorting to a very fine grid which increases computing costs prohibitively. On the other hand, top-hat models fail to predict any response at all for several of the higher sensors (1m and 2 m high), which K-theory models are able to match well.

These points are illustrated in Figs. 5 and 6 for HSE Trial 6. Figure 5 shows that the Eidsvik and HEGADAS models strongly overpredict low-lying sensor responses in the early part of the response, but do better in the tail of the response. Part of the reason for the Eidsvik model overprediction is because it predicts an early arrival of the leading edge of the cloud (see Fig. 3). Since concentration drops rapidly with time, especially close to the release point, an early response will tend to overpredict. In addition, the HEGADAS Model is not designed for an instantaneous release. Since it accounts only for wind entrainment and ignores entrainment caused by the spreading cloud, it would be expected to overpredict concentrations close to the source for an instantaneous release.

The MARIAH and ZEPHYR models also overpredict the responses shown in Fig. 5, even more so than is portrayed in the figure, in that these predictions are for a height of 28 cm. Since concentration decreases vertically, a prediction for a 10 cm height would give even higher concentrations.

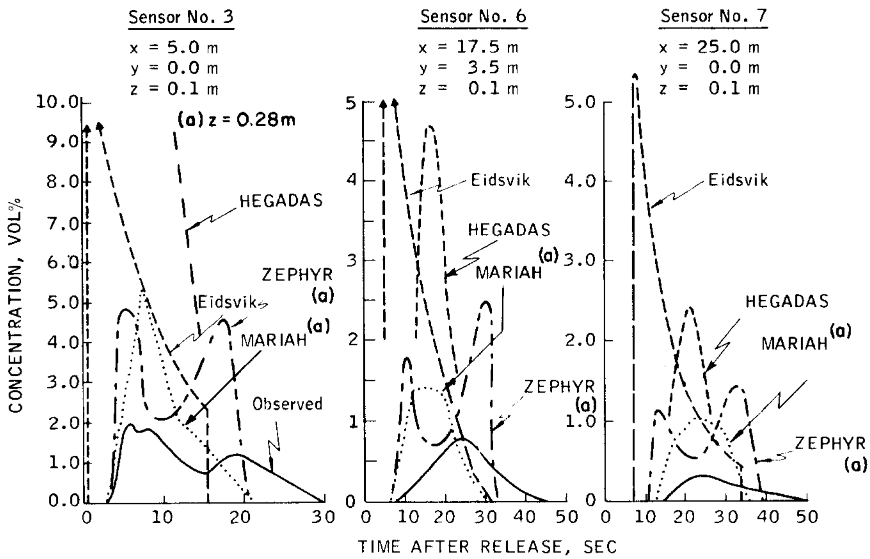

Fig.5. Comparison of concentration responses for HSE Trial 6 (Low sensors).

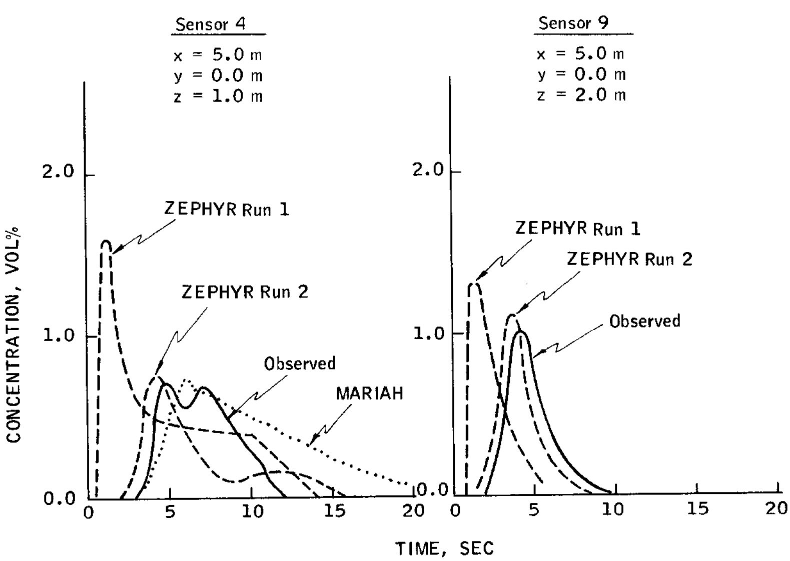

Fig.6. Comparison of concentration responses for HSE Trial 6.

The ZEPHYR model predicts a bimodal response, since the heavy gas tends to concentrate in the edges of the cloud (forming a toroidal shape in calm winds). A bimodal response was observed only for sensors 3 and 4, but photographic records show a generally toroidal-shaped cloud.

The K-theory model predictions at heights of 1 and 2 m (Fig. 6) agree very well with observations. Runs 1 and 2 by the ZEPHYR model refer to the alternate wind speed profiles in Fig. 2. Clearly, concentration predictions are very sensitive to wind speed profile assumptions, just as cloud dimensions are. The Eidsvik and HEGADAS models fail to predict measurable concentrations above 1 m for this case.

Similar conclusions apply for HSE Trial 20 as illustrated in Fig. 7. Again the K-theory models match observations very well. The Eidsvik model predicts a cloud height below one meter (thus no response for 1 and 2 m high sensors). The MARIAH model predictions are shown for two classes of atmospheric stability, A and C.

Figure 8 illustrates that the Eidsvik model matches observations for HSE Trial 8 better for far sensors than for near. In fact, for a sensor at 37.5 m from the source, the agreement with data is excellent. This seems to be a basic property of top-hat models. If entrainment velocity parameters were to be adjusted to provide a better fit with data at the near sensors, then the fit at the far sensors may suffer.

The GD model predictions in Fig. 8 are seriously in error, predicting much faster air entrainment and cloud height than the data indicated. (The GD model also overpredicts cloud radius as shown in Fig. 1.) Figure 9 contrasts the GD model prediction of cloud height with the very low (~50 cm) prediction of the Eidsvik model. The observed cloud heights fall between the Eidsvik and GD predictions. Thus, the Eidsvik model overpredicts cloud radius (Fig. 1) but underpredicts cloud height (Fig. 9), and these compensating errors produce a good match for composition (Fig. 8). Needless to say, compensating error is not a sound basis for model verification in general. In par-

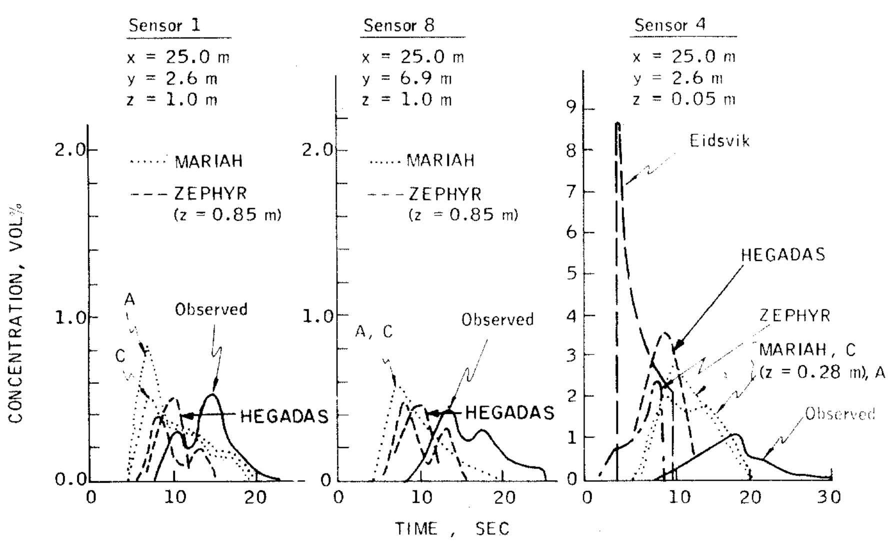

Fig.7. Comparison of concentration responses for HSE Trial 20.

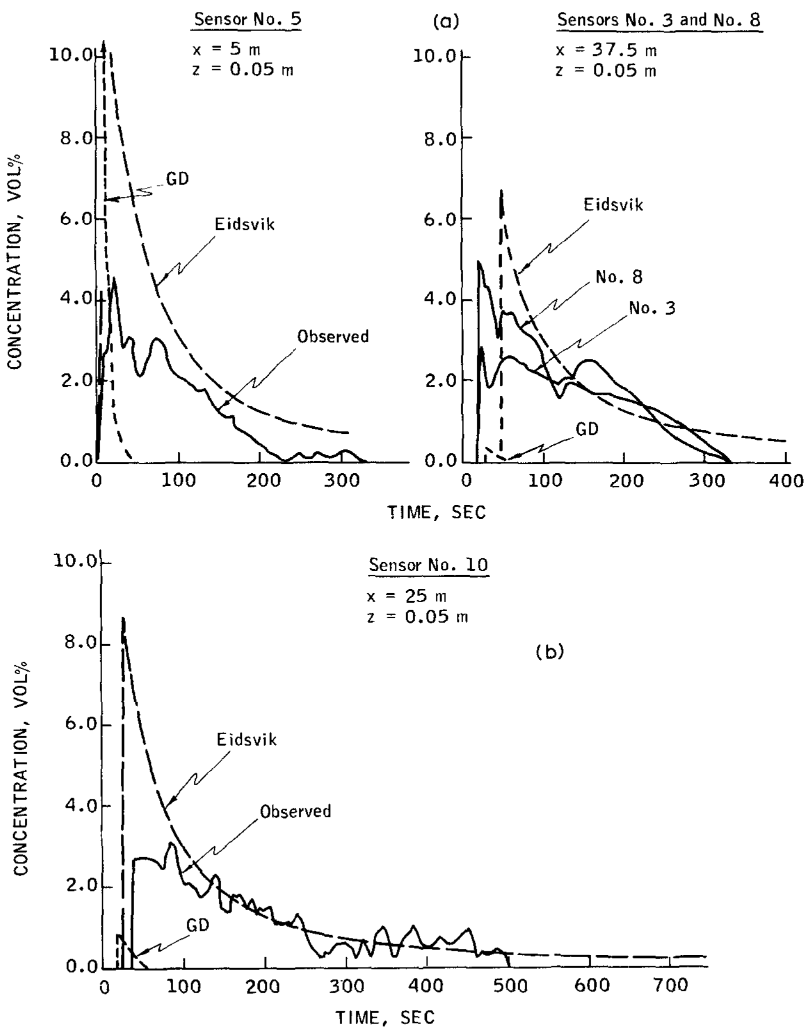

Fig.8. Comparison of concentration responses for HSE Trial 8 with Eidsvik model.

ticular, it is not a good basis for extrapolation to other situations, since the Eidsvik model was calibrated against the HSE trials and would be expected to match these well.

Esso LNG spills

In the Esso/API Matagorda Bay tests, LNG was forced out of a nozzle and traveled in an arched path through the air before reaching the water surface. The liquid pool diameter was visible in the stiff wind (and measured to be 29.3 m) and this fact has been used to establish the LNG vaporization

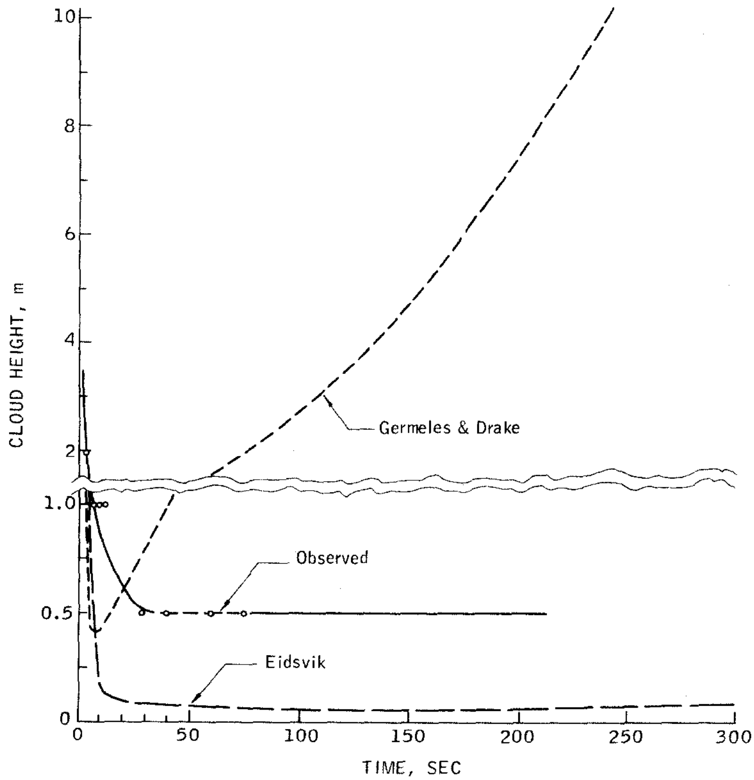

Fig.9. Comparison of cloud height responses for HSE Trial 8.

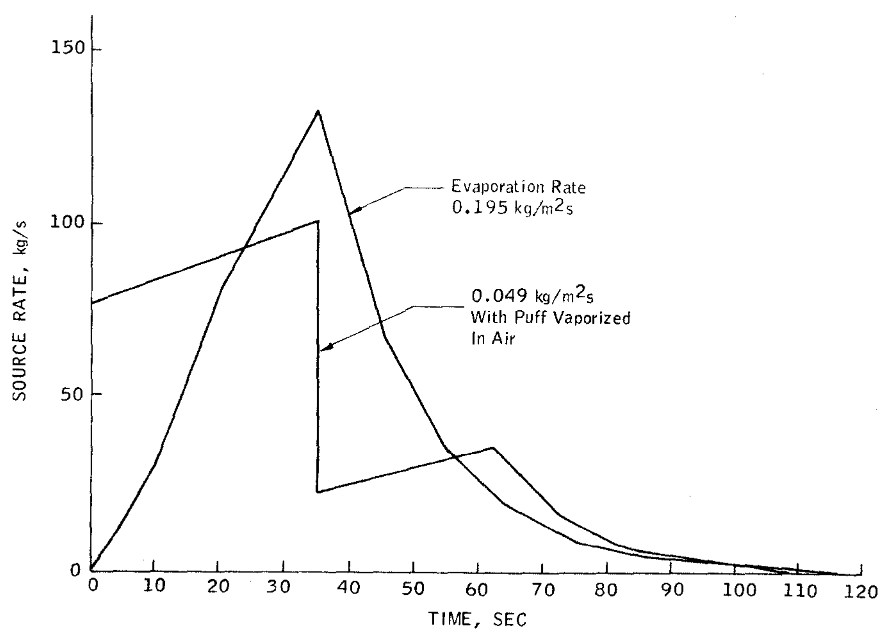

Fig.10. Alternate source rates for Esso Run 11.

rate over water. This vaporization rate is a point of controversy, though, because of uncertainty as to how much LNG vaporized in the air before hitting the water. Estimates range from 17% to 75% vaporized (May [12], Colenbrander [3]).

The effect of these various assumptions on the vapor source rate for Esso Run 11 is illustrated in Fig. 10. If no LNG is assumed to vaporize in the air. the peak-shaped curve results, and the evaporation flux is 0.195 kg/m^2 s. If 75% of the LNG evaporates in the air, the evaporation flux is 25% of 0.195

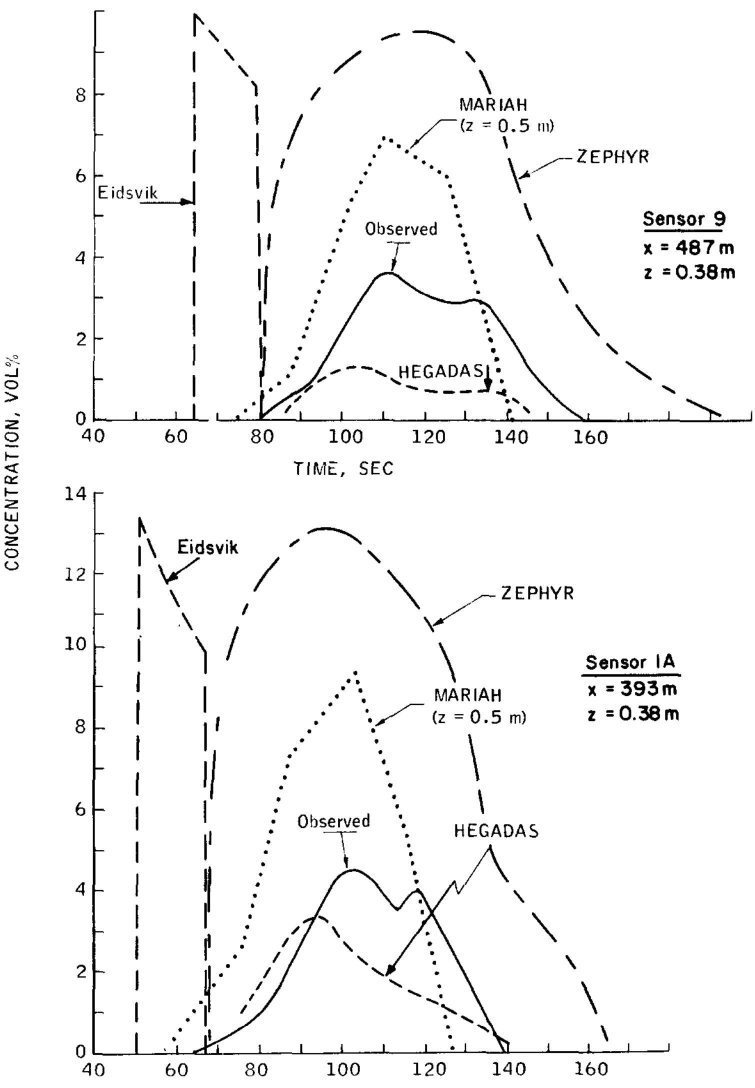

Fig.11. Comparison of compositional responses for Esso Run 11.

or 0.049 kg/m^2 s. Because of the contribution from air evaporation, the source rate is high during LNG discharge (for 35 seconds) followed by an abrupt drop-off to a lower value. To standardize model comparisons, we used the peak-shaped curve (no air evaporation) in Fig. 10 to produce the results in Figs. 11 and 13. Since model responses are strongly affected by peak source rates, and fortunately, both source rates have nearly the same shape and peak values, model predictions are not too sensitive to the assumptions affecting vaporization rate. This was shown at least for cloud dimension for Esso Run 16 in Fig. 4.

Figures 11 and 12 compare predictions with observed data for Esso Runs 11 and 17 at Sensors 1A and 9. In both runs, these sensors gave the highest peak values and, although at the end of the line of sensors, are assumed to be in the cloud centerline. Unfortunately, only the ZEPHYR and HEGADAS model predictions are for the same height as the observations, 0.38 m. The other model's responses are for 0.5 m high. The data for Esso Run 17 are

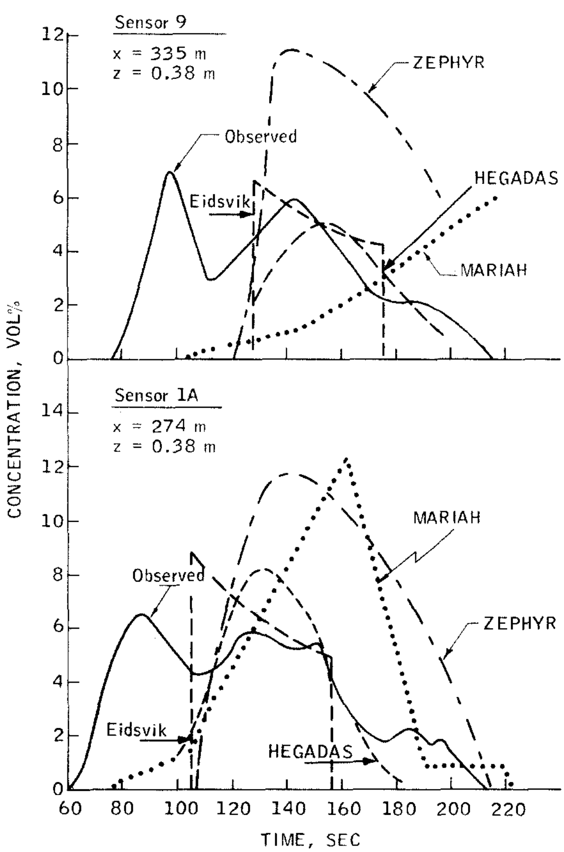

Fig.12. Comparison of compositional responses for Esso Run 17.

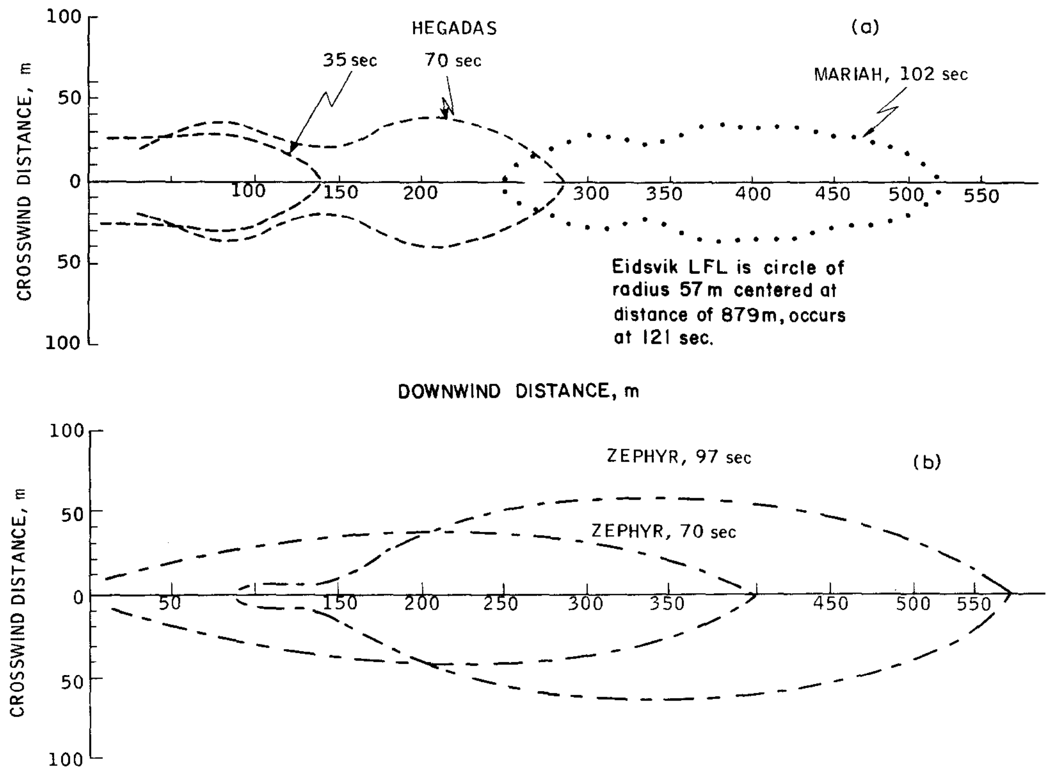

Fig.13. Plan view LFL contours for Esso run 11 at 50 cm height.

somewhat suspect since very little dilution seems to occur as the cloud travels between the two lines of sensors. In addition, wind speed changes may have occurred which extended the response duration. In light of such uncertainties, all of the models compared in Fig. 12 can be considered adequate. For Esso Run 11 (Fig. 11) the Eidsvik model, which applies the assumption of instantaneous release to a distinctly finite release time situation, is unsatisfactory. It predicts far too narrow a cloud (and short duration response) and overpredicts peak concentrations. For Esso Run 11, the MARIAH and HEGADAS predictions of peak concentration are within a factor of two of observed. ZEPHYR and Eidsvik overpredict by more than a factor of two which is unsatisfactory, though conservative.

Plan view LFL contours

Available experimental data are inadequate to test what is probably the most useful form of model output. Modellers would like to predict hazard areas for a given spill, rather than the time response of several sensors. Of particular value are predictions of plan view concentration contours at various times, or even better, the envelope of all such contours for all times when the cloud is hazardous. Experimenters should be encouraged to provide data which would test such model predictions.

Examples of model output given as plan view contours of the lower flammable limit (LFL) at various times are shown in Figs. 13 and 14 for Esso Runs 11 and 17. Such a plot reveals the true power of the HEGADAS and K-theory models. These produce presumably realistic-looking contours, as opposed to top-hat models where the LFL contour is a single circle (the Eidsvik model prediction in Figs. 13 and 14). Even so, the envelope of all hazardous clouds predicted by the Eidsvik model would be similar to envelopes developed by the other three models. (This envelope is approximated by drawing straight lines from the original source width of ~15 m radius tangent to the Eidsvik prediction shown in Figs. 13 and 14.) HEGADAS, MARIAH, and ZEPHYR predict long-narrow LFL contours in a high wind (Fig. 13) and wider, rounder contours which are advected less distance in a low wind (Fig. 14). Unfortunately comparison is imprecise since the contours for ZEPHYR and MARIAH are plotted for the 38 cm sensor height, whereas for HEGADAS the contours are for 50 cm height (Eidsvik contours are independent of height within the cloud).

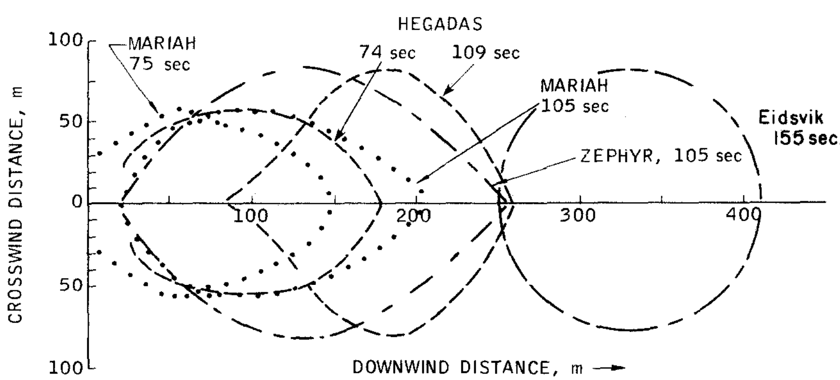

Fig.14. Plan view LFL contours for Esso run 17 at 50 cm height.

Conclusions

On the basis of comparisons with the six experiments considered here, the MARIAH, ZEPHYR, HEGADAS, and Eidsvik models agree acceptably well with sensor response beyond 35 meters from the source. In addition, the MARIAH and ZEPHYR models match well sensor responses close to the source. The Eidsvik and HEGADAS models seem to be considerably better than first generation top-hat models. Both match experimental data in the far field better than close to the source. Both match the low lying sensors in the HSE trials. The Eidsvik model does not match the higher (1—2 m) sensors. The K-theory models, on the other hand, do well against higher sensors, and reasonably well against low sensors in spite of grid size limitations.

The K-theory models are more versatile than top-hat models, but have been more costly in computer time. This cost disadvantage is rapidly decreasing, however, and with costs under $100—200 per run, MARIAH and ZEPHYR must now be considered practical. Top-hat models cost even less to run, and are readily programmed and "transportable". In addition, top-hat models are largely free from concerns over numerical diffusion, which may affect K-theory models in applications requiring simulation to far distances and very low concentrations (as with toxic substances).

The Eidsvik and HEGADAS models are complimentary, since HEGADAS does not apply for calm winds or instantaneous releases, yet Eidsvik does. However, Eidsvik does not do well with non-instantaneous releases. These points are summarized in Table 3.

The GD model strongly overpredicts air entrainment for HSE Trial 8. It also predicts there will be no important gravity spread phase with high wind speeds. The other models studied, including the Eidsvik top-hat model, predict otherwise. The heavy gas portion of the GD model is not applicable to four of the six experiments we analyzed. The Eidsvik model is superior to the GD model in providing a smooth transition to neutral buoyancy and in providing for heat transfer and both top and edge entrainment.

Model responses should be compared against compositional data, preferably over a wide field of sensors and not only against cloud dimensional data. Hopefully, future data will allow validation of model predictions of iso-concentration contours and the time-independent envelope of such contours.

The comparisons made here apply only for relatively small spills. In as much as models adequately describe physical principles, they can predict behavior beyond the original data base for which they are calibrated. However, the limitations to such extrapolation are not yet clear.

TABLE 3

Recommended range for choosing between Eidsvik and HEGADAS models

Release rate	Wind speed: Calm & low < 2 m/s	Wind speed: Medium to high > 2 m/s
Instantaneous	Eidsvik	Eidsvik
Finite (> 20 s)	Neither*	HEGADAS

*K-Theory models are also not validated for this case except by comparisons of cloud dimensions.

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