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HEAVY GAS DISPERSION AND ENVIRONMENTAL CONDITIONS AS REVEALED BY THE THORNEY ISLAND EXPERIMENTS

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Summary

Time plots of average concentration values from the Thorney Island field experiments were used to draw cloud outlines. After the initial slumping, and a more or less pronounced formation of a vortex ring, redistribution of mass took place. At later stages the highest concentrations were found to be well inside the cloud.

The wind speed increment with height shears the cloud in the wind direction and creates a high front and a low trailing edge. Distances to specific concentration levels seemed independent of wind speed and air stability as assumed in the Eidsvik (NILU) box model. Distances to 1% concentration were predicted well. A too high decrease in concentration with time could be offset by applying in the model a too high transport speed, set equal to the wind speed at the 10 m level.

1. Introduction

The objectives of this work have been to study the dependence of heavy gas dispersion on environmental conditions as revealed by the Thorney Island experiments, and how well this can be predicted by the Eidsvik (Norwegian Institute for Air Research, NILU) model.

Only Thorney Island Phase I data will be considered, as Thorney Island Phase II involved physical obstacles. These gave flow effects not considered in the model.

The instantaneous release of a cloud heavier than air is characterized by a rapid slumping followed by the formation of a vortex ring (or rings). This formation is most pronounced in calm conditions. To model this phase realistically involves physical and numerical problems which are not yet satisfactorily solved.

The vortex ring soon dissipates. During the next, intermediate phase, frontal entrainment no longer dominates the dilution process. Gravity is still the main driving force and turbulence tends to smooth concentration distributions. The entrainment is now mainly through the larger upper surface. It is for this phase Eidsvik has developed his box model [1]. This he tested against the Porton Down experiments [2] with good results. The model contains a minimum number of experimental coefficients, and predictions are not overly sensitive to variations in the coefficients over their normal range of uncertainty. This is especially important in practical applications, say, in forecasting hazard distances.

In the following, we will use the same numerical values used for the Porton data, and perform a test of the physical assumptions involved.

2. Experimental data

Data evaluation was based on the information in the hard copy records provided by the Health & Safety Executive (HSE) [3], which give time plots of 0.6 s averaged values. Concentration values at specific times were read off and plotted on the horizontal grid system. Isolines and cloud outline were drawn subjectively. This is believed to be the best way, considering the relatively few data points available.

At Thorney Island the initial phase lasted from 40 to 100 seconds. After that period, maximum concentrations were found well inside the cloud outline.

Figure 1 shows cloud outlines at the 0.4 metre level. Concentration values at 40, 80, 140, 200, 300, 400 . . . seconds after time of release were taken from the graphs. Only grid points with observed concentrations equal to or above 0.1% were considered. Cloud outlines at the 0.4 m level were then drawn, and the location of the maximum concentration was estimated. Figures 1(a)–(h) show examples from Trials 8, 12 and 15.

Trial 15 had the lowest cloud release density. The cloud moved relatively fast, stayed rather narrow and hence each outline contained only a few grid points. Height of the cloud rapidly reached above the upper, 6.4 m, measuring level.

Trial 8 is representative of most of the trials. A stretching of the cloud in the wind direction is evident. The cloud moved slowly, and up to 9 grid points are within a specific outline. A particular feature is the small area of high concentrations at 200 seconds, lagging behind the main center. The cloud height was here at minimum. It is an open question, whether areas of high concentrations below 0.4 m were lost by capture of the gas in the grass. The same question arises especially in Trial 12 in which parts of the cloud lingered behind and 0.5% concentration was observed 100 m away from the release point at 900 seconds after release. The cloud could be followed for 900 seconds and cloud heights were the lowest. Concentrations were measured at 0.4 m, 2.4 m, 4.4 m and 6.4 m. All but traces of gas, 0.2% or less, were measured at the three upper levels and may be due to the vortex ring. No other trial showed similar low cloud heights. (In Trial 17, with density 4.2, the cloud center did not stay completely within the grid of masts, probably due to a change in wind direction.)

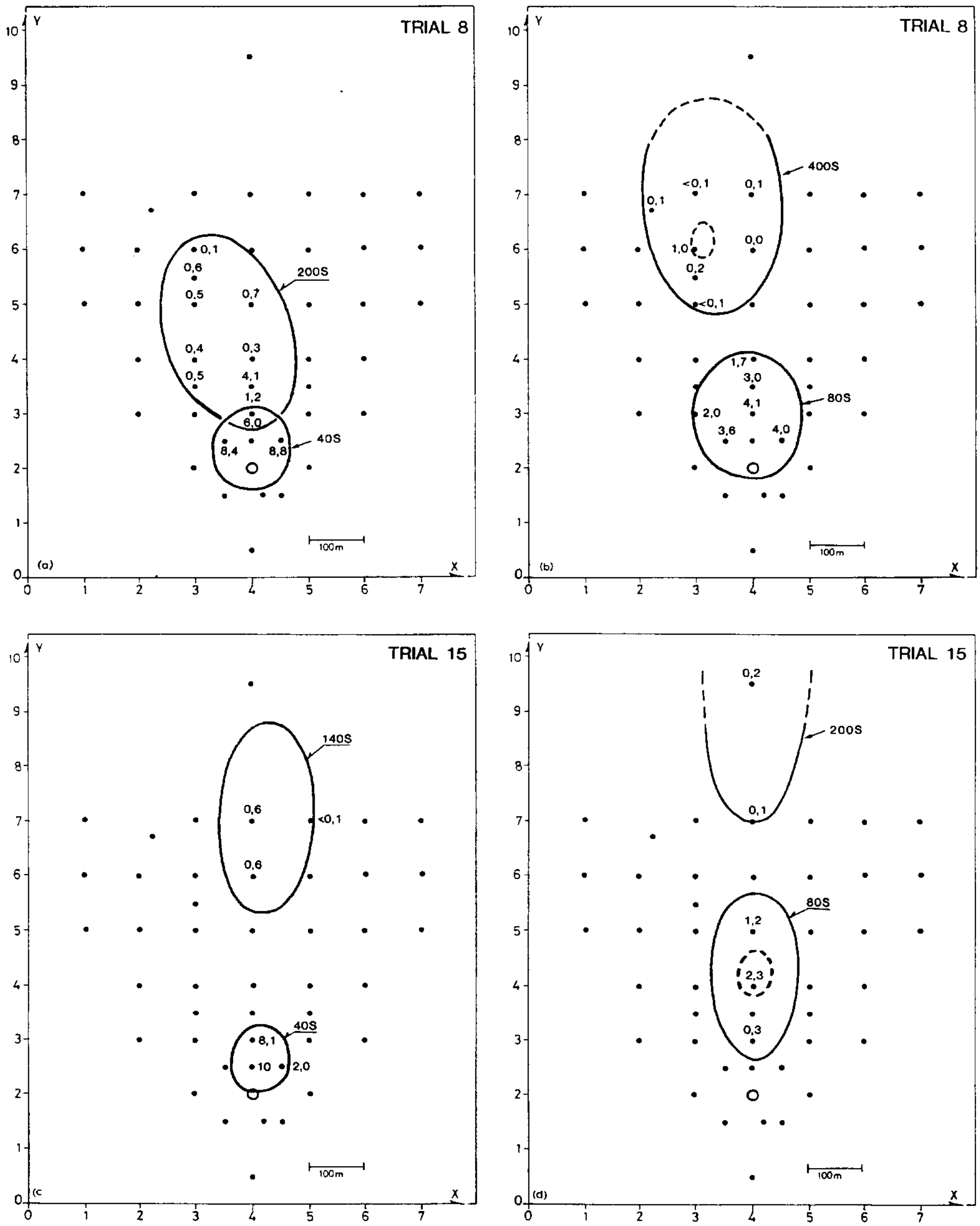


Fig. 1. Cloud outlines at 0.4 m and observed concentrations superimposed on 100 m grid of masts.

(a), (b) Trial 8: wind speed at 10 m level 2.4 m/s, relative density 1.63; near neutral stability (D).

(c), (d) Trial 15: wind speed at 10 m level 5.4 m/s, relative density 1.41; neutral stability (C/D).

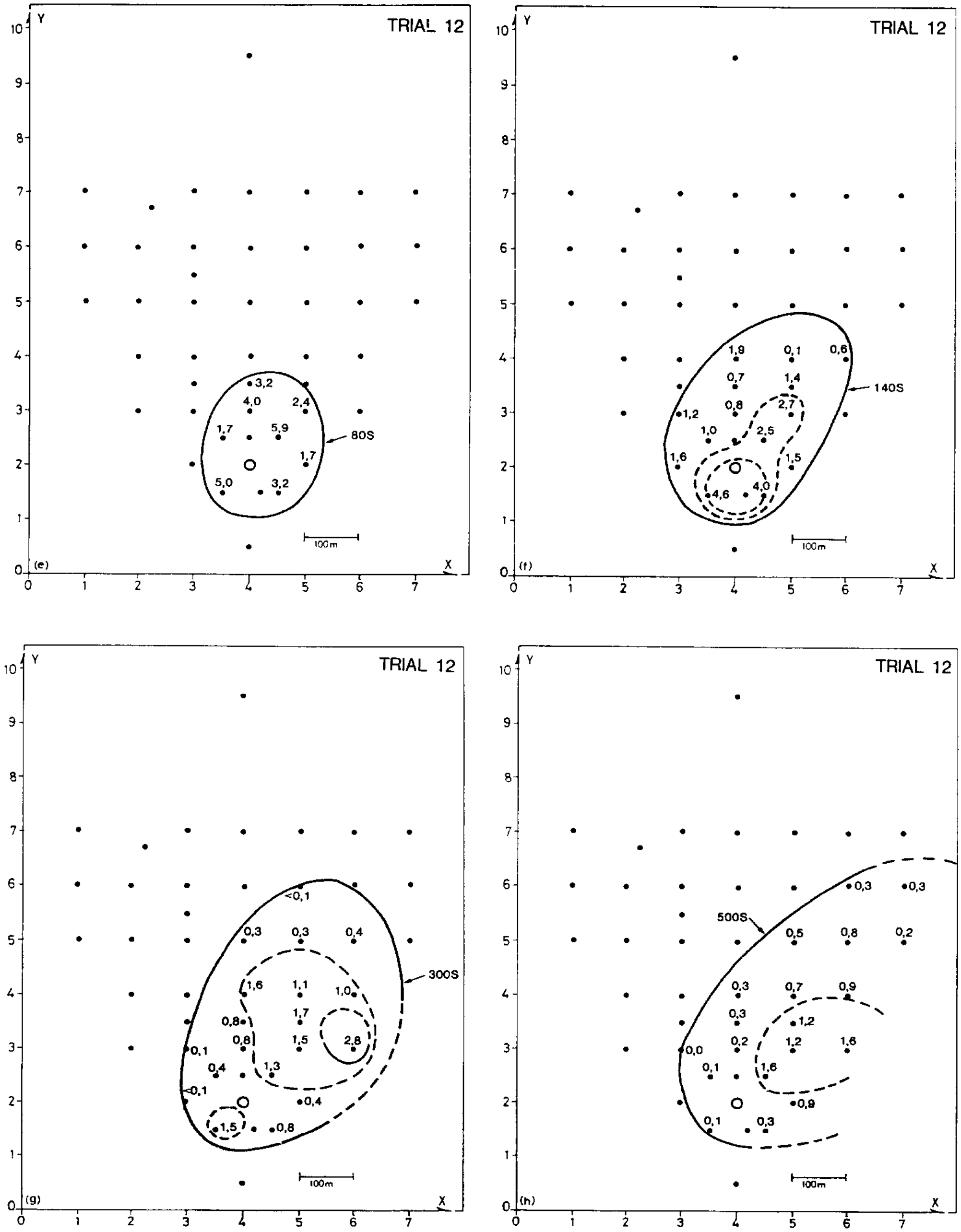
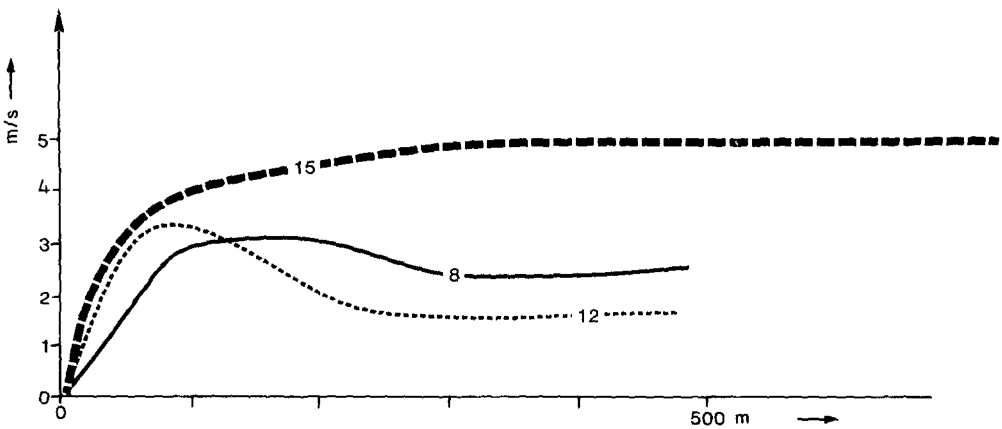


Fig. 1 (continued). Cloud outlines at 0.4 m and observed concentrations superimposed on 100 m grid of masts.
(e)–(h) Trial 12: wind speed at 10 m level 2.6 m/s, relative density 2.37; stable air (E).

Speeds of the cloud fronts are shown in Fig. 2. They were affected by both the wind speed increment with height above the ground, and by cloud density. In Trial 12 the gravity markedly affected the front speed during the first 200 seconds. In Trial 15 the top of the gas cloud was picked up by the higher wind speeds.

Downward mixing created a relatively high, vertical cloud front. The trailing edge, on the other hand, consisted of slow moving gas and kept close to the ground.



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Heavy gas dispersion and environmental conditions as revealed by the Thorney Island experiments.

Fig. 2. Speed of cloud fronts — Trials 8, 12 and 15.

3. Influence of atmospheric parameters

The Eidsvik model predicts hazard distances for release of an explosive, heavy gas to be fairly independent of wind speed and air stability. The decrease of concentration with time, however, will depend highly on these parameters. We have chosen to look how distances to the concentration levels 5%, 1% and 0.5%, and the time to reach 1% depend on wind speed and turbulence at 10 m height. Figure 3 shows remarkably similar distances for Trials 8, 12 and 15.

The commonly used Pasquill stability classes are not suited for numerical treatment. We therefore used vertical velocity fluctuations, closely related to the top entrainment. The r.m.s. values were also closely related to the inferred atmospheric stability conditions given by HSE.

Table 1 shows the said distances, time to reach 1% concentration, environmental factor, and front and centre speeds. The table confirms the rather

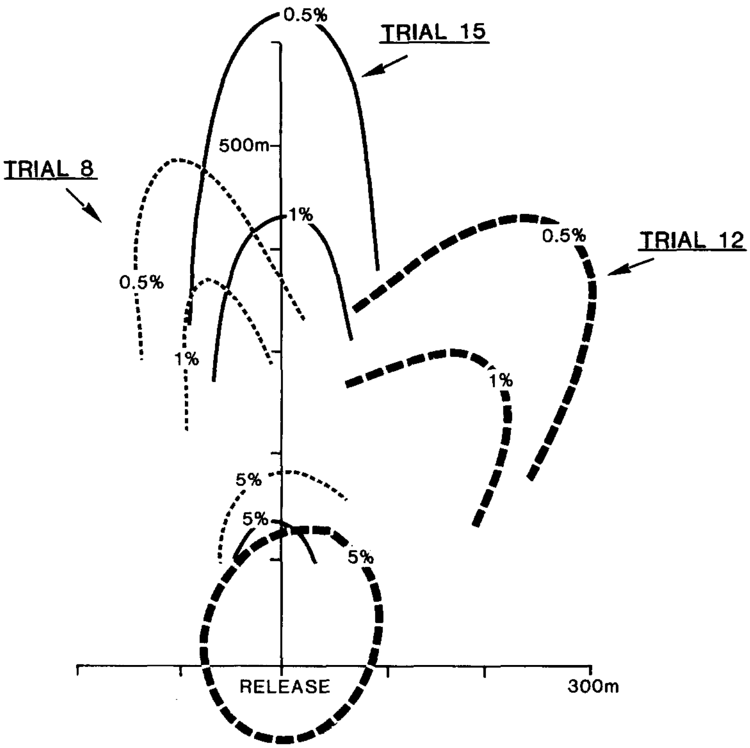

Fig. 3. Maximum distances to 5%, 1% and 0.5% concentrations — Trials 8, 12 and 15.

TABLE 1

Experimental data — Thorney Island

Trial No.	Distance (m)			Time C=1%	Rel. dens.	Wind speed (m/s)	Turb. (m/s) vert.-r.m.s.	Speed (m/s)	
	C=5%	C=1%	C=0.5%					Front	Centre
7	150	400	520	270	1.75	3.2	0.27	3.2	1.8
8	150	385	500	350	1.63	2.4	0.25	2.5	1.1
9	125	360	475	800	1.60	1.7	0.08	2.5	0.4
10	110	–	–	–	1.80	2.4	0.26	–	–
11	160	280	340	190	1.96	5.1	0.44	4.0	1.6
12	130	350	525	750	2.37	2.6	0.14	2.0	0.4
13	140	400	550	130	2.00	7.5	0.47	7.0	4.0
14	125	425	500	120	1.76	6.8	0.43	5.0	4.3
15	190	450	550	140	1.41	5.4	0.47	4.9	4.3
16	150	400	550	190	1.68	4.8	0.35	3.5	2.8
17*	(80)	(220)	(320)	(150)	(4.20)	(5.0)	(0.43)	(3.5)	–
18	100	300	450	60	1.87	7.4	0.58	6.2	3.8
19	120	320	450	130	2.12	6.4	0.44	4.5	3.2
Mean	138	370	492	285	1.83	4.6	0.35	4.1	2.5
St. dev.	23	51	60	243	0.25	2.0	0.14	1.5	1.4

*Values omitted in calculations of means and standard deviation.

TABLE 2

Correlations (Trial 17 omitted)
U-10 m = wind speed at 10 m (m/s)
U-front = mean speed of cloud front (m/s)
U-center = mean speed of cloud center (m/s)

Dist-5%	1.00								
Dist-1%	0.49	1.00							
Dist-0.5%	0.21	0.83	1.00						
Time-1%	0.12	0.07	0.08	1.00					
Rel.dens.	−0.44	−0.56	−0.24	−0.17	1.00				
U-10 m	−0.06	−0.06	−0.08	−0.83	–	1.00			
Turb.	0.26	−0.02	−0.11	−0.42	–	−0.03	−1.00		
U-front	−0.14	0.04	0.02	−0.76	0.15	0.94	−0.03	1.00	
U-centre	0.04	0.34	0.22	−0.85	−0.21	0.90	0.04	0.88	1.00
	Dist-5%	Dist-1%	Dist-0.5%	Time 1%	Rel. dens.	*U*-10 m	Turb.	*U*-front	*U*-center

small variation in "hazard" distances. Variation in time to reach 1% concentration is, on the other hand, considerable.

Although the sample size is small, considering stochastic variabilities, we have made a statistical analysis. Table 2 shows calculated correlation coefficients. Coefficients below 0.5 are considered not significant. When we further omit self-evident correlations, the significant results are:
(1) critical distances are independent of atmospheric conditions;
(2) time to 1% concentration decreases with wind speed.

An increase with atmospheric stability (turbulence) may not be considered significant.

There is also a tendency for critical distances to decrease with increased density. This can be explained by higher clouds moving faster due to the vertical wind shear. Air entrainment through the upper surface then has shorter time to dilute the cloud.

4. Model predictions of the Thorney Island trials using the Eidsvik box model

The model predicts time to reach specific concentration levels, cloud radius and cloud heights.

When comparing with observed values it must be considered that the model assumes a homogeneous concentration distribution within the cloud at all times. This is done by using mean concentrations at the 0.4 m level. A characteristic cloud height can be estimated applying a constant vertical dis-

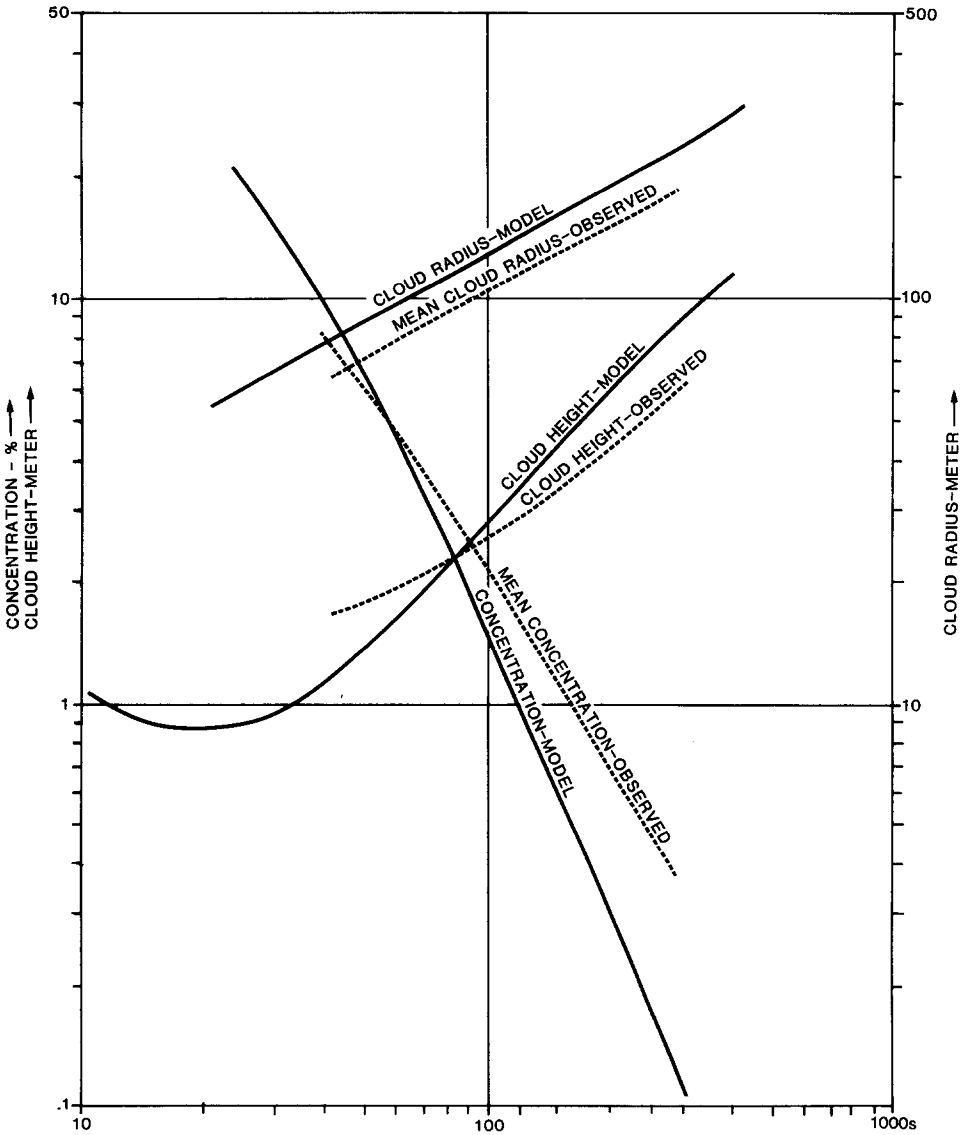

Fig. 4. Model predictions and observed mean concentrations, cloud radius and cloud heights — Trial 8.

tribution or mass conservation and cloud radius. The radius may be estimated from the equivalent cloud area, or from cloud height and mass conservation. Both methods have been applied. Considering the uncertainties final results can only be tentative. Figure 4 shows values from Trial 8. The following features are quite representative for all trials:

(1) predicted cloud radii are too high, but increases, proportional to the square root of time, are fairly well established;

TABLE 3

Predicted and observed critical distances and times

Trial No.	Distances to concentration levels (m)									Times to 1% (s)		
	5%			1%			0.5					
	Model	Observed	Model / Observed	Model	Observed	Model / Observed	Model	Observed	Model / Observed	Model	Observed	Model / Observed
7	239	150	1.5	430	400	1.1	565	520	1.1	130	270	0.5
8	220	150	1.5	410	385	1.1	545	500	1.1	160	350	0.5
9	220	125	1.8	410	360	1.1	495	475	1.0	190	800	0.2
10	185	110	1.7	327	–	–	435	–	–	155	–	–
11	240	160	1.5	450	280	1.6	620	340	1.8	95	190	0.5
12	235	130	1.8	410	350	1.2	511	525	1.0	130	750	0.2
13	250	140	1.8	515	400	1.3	645	550	1.2	70	130	0.5
14	330	125	1.9	510	425	1.2	700	500	1.4	85	120	0.7
15	255	190	1.3	520	450	1.2	685	550	1.2	105	140	0.8
16	225	150	1.5	455	400	1.1	635	550	1.2	105	190	0.6
17*	(237)	(80)	(3.0)	(440)	(220)	(2)	535	320	(1.7)	(75)	(150)	0.5
18	251	100	2.5	300	300	1.7	675	450	1.5	75	60	(1.3)
19	250	120	2.0	480	320	1.5	640	450	1.4	80	130	0.6
Mean			1.7			1.3			1.3			0.6
Standard deviation			0.3			0.2			0.2			0.3
Maximum			2.5			1.7			1.8			1.3
Minimum			1.3			1.1			1.0			0.2

*Trial 17 data omitted in calculations.

(2) predicted cloud heights are also too great, resulting in too low concentrations, but again, variations with time are quite good.

These general statements do not apply to Trial 12, where the cloud height stayed exceptionally low and concentrations very high.

Maximum values were about twice the mean values and are not plotted.

Of great importance in practical applications is the prediction of maximum distances to hazard concentrations. For explosive gases these are of order 1%. The model predicts the distance, D, to concentration $C = A\%$, to be:

$$D = U_{10} * t(C{=}A\%) + R(C{=}A\%)$$

where U_{10} is the 10 m wind speed, t time, and R cloud radius.

Table 3 shows maximum distances to the 5%, 1% and 0.5% concentration levels. Here maximum observed values were considered, not mean values as in Fig. 3. Also shown is time, in seconds, to concentration 1%. Predicted distances are on the "safe" side, in the mean by a factor of 1.3 for 1% and 0.5%, and 1.7 for 5%. Most importantly, variations in this factor are small, and Trial 12 no longer is an exception. Predicted time to concentration 1% is about half of observed time. Here the variations are relatively much greater.

5. Conclusions

After the initial slumping, and a more or less pronounced formation of a vortex ring, redistribution of mass took place. At later stages the highest concentrations were found to be well inside the cloud. Wind speed increment with height and surface drag sheared the cloud in the direction of the wind. They also created a high front and a low trailing edge. Some trial measurements suggest high gas concentrations below 0.4 metres, which could be due to gas withheld in the grass at low wind speeds.

The field data verified the model assumption and prediction that maximum distances to critical concentrations are independent of wind speed and air stability. Predicted distances were on the safe side and remarkably accurate, considering that all experimental coefficients were kept unaltered, since the model was compared with the Porton experimental data. This suggested that a simple box model is well suited for prediction of hazard distances. The too high decrease in concentration with time could be offset by applying the wind speed at 10 m level and disregarding the wind profile.

References

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