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Project Report

The CEC Major Technological Project BA: Research on Continuous and Instantaneous Heavy Gas Clouds

J.K.W. Davies

Safety Engineering Laboratory, Health and Safety Executive, Broad Lane, Sheffield S3 7HQ (Great Britain)

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Abstract

A summary is presented of the datasets produced by participants in the Commission of the European Communities (CEC) Major Technological Hazards Project BA: Research on Continuous and Instantaneous Heavy Gas Clouds, and of the data analysis and modelling which have been carried out on these datasets. In particular, a brief account is given of the statistical analysis conducted by the UK Health and Safety Executive (HSE) on replicated wind tunnel experiments on dispersion over flat terrain and in the presence of a fence and a parallel-wall longitudinal channel; and on field trials on the lower flammability distance of propane dispersing over flat terrain in stable atmospheric conditions. All the HSE analyses showed that so far as these datasets are concerned the log-normal distribution is an adequate representation of between-release variation in cloud parameters. Further analysis of fence effects are planned by HSE under the CEC Science and Technology for Environmental Protection Project FLADIS: Research on the Dispersion of Two-phase Flashing Releases.

Introduction

This report is a summary of the final report [1] on work carried out by the Safety Engineering Laboratory of the UK Health and Safety Executive (HSE) under Phases 2 and 3 of the joint CEC Major Technological Hazards Project BA: Research on Continuous and Instantaneous Heavy Gas Clouds, and should be read in conjunction with the brief accounts of other research under this heading which have already appeared in this journal [2,3]. The work was concerned with the creation of a database of wind tunnel and field experiments on variability effects and obstacle effects in dense gas dispersion in Phase 2 of the project, and with the analysis of this information in Phase 3 of the project.

Correspondence to: Dr. J.K.W. Davies, Safety Engineering Laboratory, Health and Safety Executive, Broad Lane, Sheffield S3 7HQ (Great Britain)

TABLE 1

Overview of the Project BA Database and Analyses. For detailed accounts please refer to the relevant final reports. Dispersion experiments were conducted at wind tunnel (W/t) scale and at field scale

Project BA participant	Experimental scale	Release mode	Replicated?	obstacles?	Analysed by	Comments	See reference
TNO	W/t	Instant.	Yes	No	BU	W/t comparison	[9]
	W/t	Continuous	No	No	BU	W/t comparison	[9]
	W/t	Continuous	No	No		Ground roughness	
	W/t	Continuous	No	No	BU	Velocity measurements	[9]
	W/t	Continuous	Yes	Yes	BU	Remodelling of TÜV/Risø trial EEC57	[9]
WSL	W/t	Instant.	Yes	No		W/t comparison	
	W/t	Continuous	No	No		W/t comparison	
	W/t	Instant.	Yes	No	HSE, BU	Flat terrain dataset	[1,9]
				No	HSE, SRD	Fence dataset	[1,10]
	W/t	Instant.	Yes				
UH	W/t	Instant.	Yes	No		W/t comparison	
	W/t	Continuous	No	No		W/t comparison	
	W/t	Instant.	Yes	Yes	HSE	UH dataset	[1]
	W/t	Continuous	No	No	HSE	UH dataset	[1]
	W/t	Instant.	No	Yes		For TÜV/Risø	
	W/t	Instant.	Yes	Yes	SRD	For modellers	[10]
	W/t	Continuous	Yes	Yes	SRD	For modellers	[10]
	W/t	Continuous	No	Yes		Remodelling of TÜV/Risø trial EEC57	
TÜV	Field	Continuous	No	No	HSE	TÜV dataset	[1]
TÜV/Risø	Field	Continuous	No	Yes	BU, SRD	EEC-series	[10,9]

Data of this kind is needed to increase the scope of the consequence models used in quantitative risk assessment.

More specifically, the role of HSE in Phase 2 of the joint project consisted in the handling and dissemination to other project participants of the extensive volume of data produced in the Warren Spring Laboratory (WSL) replicated wind tunnel simulations of Thorney Island-type instantaneous releases [4,5]. The wind tunnel runs were performed initially over flat terrain with no obstacle present and later with fence-type obstacles in position at right-angles to the wind direction. A range of fence heights and source conditions was covered.

HSE activity in Phase 3 was mainly centred round the analysis of the two WSL datasets mentioned above, though a considerable amount of effort was also devoted to the analysis of data from some University of Hamburg (UH) wind tunnel measurements on instantaneous and continuous releases [6], and from the initial full-scale liquid propane flat terrain spills conducted by the Technischer Überwachungs-Verein Norddeutschland e.V., Hamburg (TÜV) [7,8].

Additional data analyses have been carried out by Brunel University (BU) [9] and by the Safety and Reliability Directorate (SRD) [10]. BU has been concerned with the effect of instrumental characteristics on the quantities measured, and have paid particular attention to the comparison of slow response and fast response concentration measurements in the plane fence runs EEC54 to EEC58 of the series of full-scale liquid propane releases carried out jointly by TÜV and Risø National Laboratory, Roskilde, Denmark (Risø) [11,12]. BU has also been concerned with the analysis of three datasets from the Netherlands Institute of Environmental and Energy Technology MT-TNO, Apeldoorn (TNO) [13], viz., the instantaneous and continuous releases of the Project BA Wind tunnel Intercomparison Exercise and a modelling of the TÜV/Risø trial EEC57. SRD are making use of the two WSL datasets referred to above and the TÜV/Risø plane fence runs EEC54 to EEC58.

Table 1 summarises the datasets available and the extent to which they have been analysed.

Analysis of WSL Datasets

The WSL replicated flat terrain dataset was analysed to study the statistical properties of the cloud parameters and to determine their variation with sensor position and initial bulk Richardson number. All the cloud parameters measured were found to follow a log-normal distribution, with the occasional exception of the intermittency, and were ranked according to their overall level of variability. Defining the level of variability of a cloud parameter as the ensemble standard deviation of the natural logarithm of the cloud parameter, a statistic which is approximately equal to the coefficient of variation (or inten-

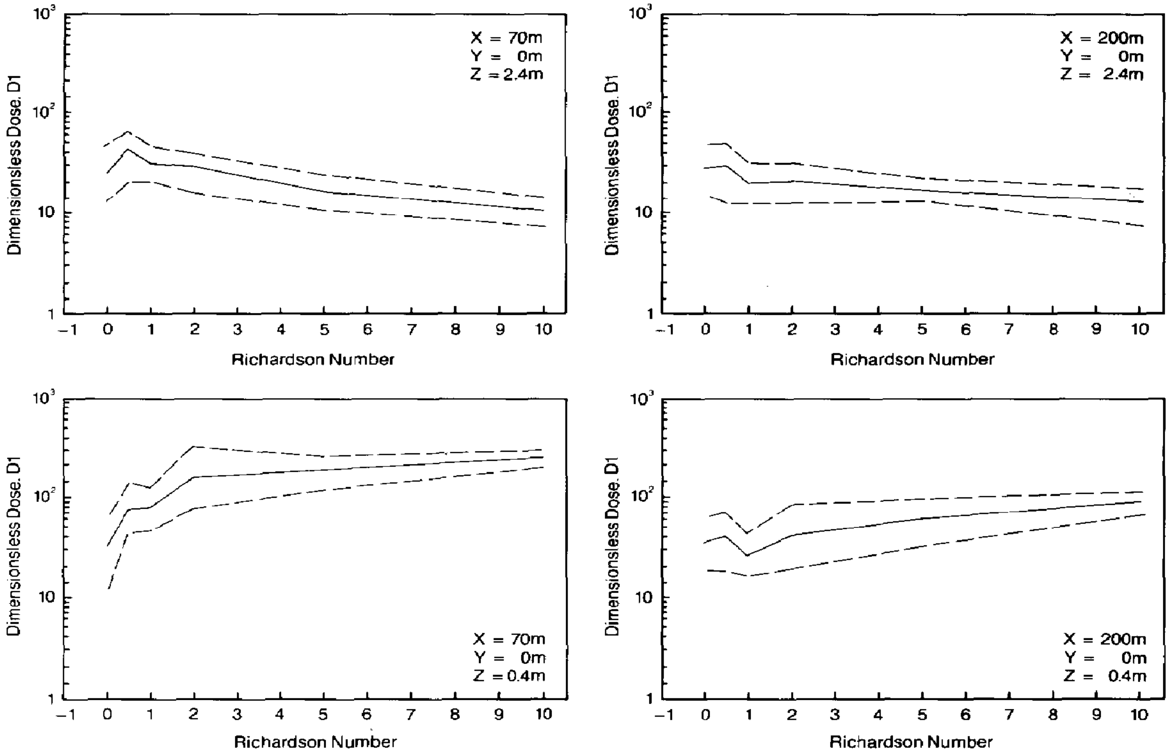

Fig. 1. Variation of dimensionless dose (i.e. concentration integrated over dimensionless time) with position and Richardson number is WSL wind tunnel [4]. *X*, *Y* and *Z* are, respectively, the downwind, transverse and vertical full-scale distances from the source.

sity) for the levels of variability encountered, and assessing the overall level of variability as the 90th percentile taken over the combinations of sensor position and Richardson number for which data were available, it was found that the overall level of variability increased from 18% for the cloud passage time through 21% for the mean concentration, 26% for the dose or integrated concentration and 30% for the maximum concentration to 78% for the intermittency. Information of this kind may be used to augment the predictions of cloud parameters produced by the heavy gas dispersion codes that are currently employed in quantitative risk assessment studies to provide estimates of, say, the 95th percentile values of the cloud parameters, without the need to modify the codes themselves. Thus, assuming for simplicity that the codes in fact predict ensemble median values and taking as typical the levels of variability quoted above, it may be shown that the 95th percentile of the cloud passage time is 34% greater than its value as predicted by the code. The corresponding increments for the other cloud parameters are, respectively, 41% for the mean concentration, 53% for the dose or integrated concentration and 64% for the maximum concentration.

In addition, a useful scaling law was found relating the level of variability of

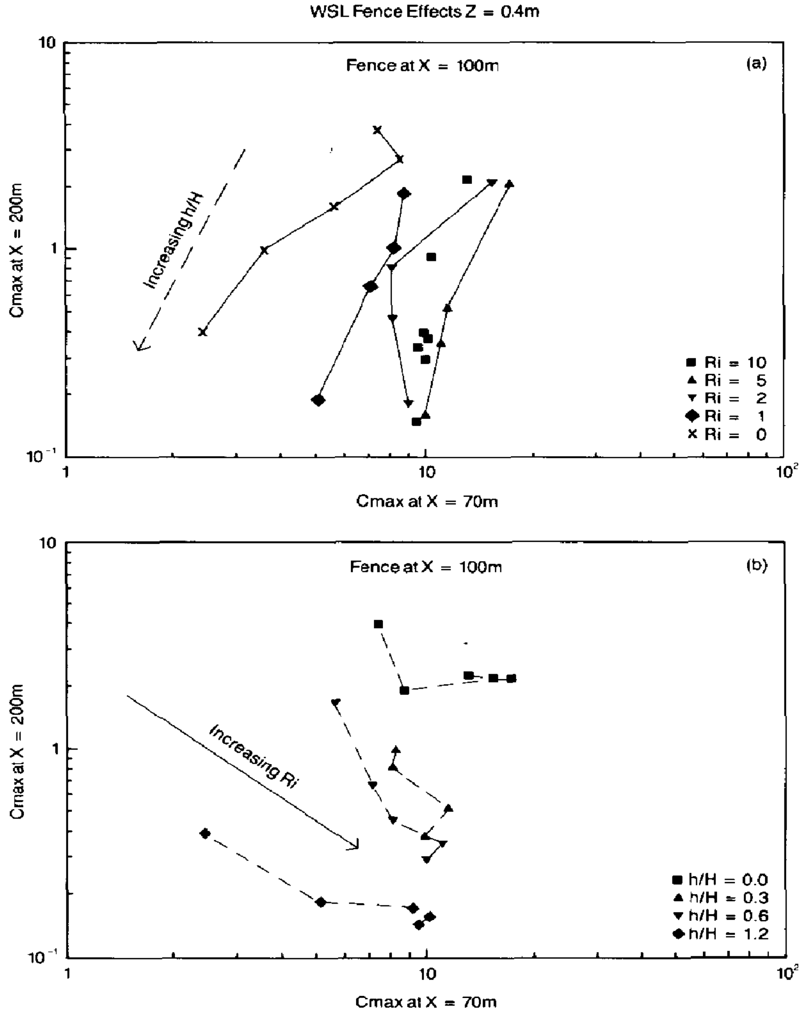

Fig. 2. (a) Variation of ground level ($Z = 0.4$ m) maximum concentration at fixed stations upwind ($X = 70$ m) and downwind ($X = 200$ m) of the fence ($X = 100$ m) showing contours of equal Richardson number Ri. h/H is the fence height h (m) relative to the source height $H = 13$ m at full scale. (b) Same as (a) with the points joined to show contours of equal relative fence height h/H.

the generalised dose $D_n = \int C^n \mathrm{d}t$ and that of the dose or integrated concentration $D_1 = \int C^n \mathrm{d}t$ mentioned above, viz.,:

$$\sigma(\ln D_n) = n\sigma(\ln D_1)$$

This scaling law enables, for example, the 95th percentile of the generalised dose D_n to be calculated from the observed level of variability of the integrated concentration D_1, as exemplified above, and the toxicity exponent n, as derived from toxicological studies. Results were also obtained for the probability of a local ignition conditional on the presence of a suitably energetic source, viz., that the conditional probability reaches its maximum near $Ri = 2$ at ground level near the source, and that the maximum does not in general occur at the same time as the maximum of the ensemble mean concentration. Figure 1 shows the variation of the median and the upper and lower 2.5 percentiles of dose D_1 with Richardson number at the four sensor positions. There was a very rapid rise in dose in the near field at ground level, but in the far field the dose was relatively insensitive to Richardson number. The level of variability of the dose ranged between 20% and 40%, reaching its maximum between $Ri=2$ and $Ri=5$.

A preliminary analysis of the WSL replicated fence dataset was carried out and further analysis is planned under the STEP Programme. As for the flat terrain dataset, all the cloud parameters were found to follow a log-normal type of distribution, with the occasional exception of the intermittency. A satisfactory graphical form was devised to show the complex interaction between the Richardson number and the fence height. Variability effects in the presence of a fence may be handled in quantified risk assessment in the same way as variability effects over flat terrain. Broadly speaking, the fence acted as a turbulence generator causing the concentration to decrease significantly in the lee of the obstacle. Shifts in the mean value of cloud parameters as the result of the presence of the fence, however, are most probably best dealt with by making appropriate changes in the underlying heavy gas dispersion code, though an empirical solution to this problem leaving the dispersion code untouched is also a possibility by introducing a power law distortion of the distance from the source. Figures 2(a) and (b), respectively, show contours of equal Richardson number and fence height derived from a scatter plot of maximum concentration (vol.%) in the near field ($X=70$ m) and far field ($X=200$ m). Note that in this figure the fence height h is quoted relative to the source height H. At full scale $H=13$ m. Increasing fence height causes very rapid dilution of concentration (vol.%) in the far field, but comparatively little dilution in the near field.

The UH dataset

Analysis of the instantaneous releases in the UH dataset showed that the presence of a parallel-wall longitudinal channel increased the dose by an order of magnitude and the maximum concentration by a factor of two, and at the same time halved the variability levels. The dose and maximum concentration effects may be seen in Figs. 3(a) and (b), respectively, in which downwind distance has been scaled by the characteristic length appropriate for instantaneous releases, $L_{\mathrm{CI}}=V_0^{1/3}$, where V_0 is the initial source volume. The two-fold increase in maximum concentration was consistent with the near field measurements in the WSL fence dataset. The constancy of the variability level of the maximum concentration both with and without the channel confirmed the log-normal nature of the cloud parameters. In the continuous release in which no channel was present an averaging time corresponding to the normal human breathing rate reduced the level of variability by 50%. The log-normal

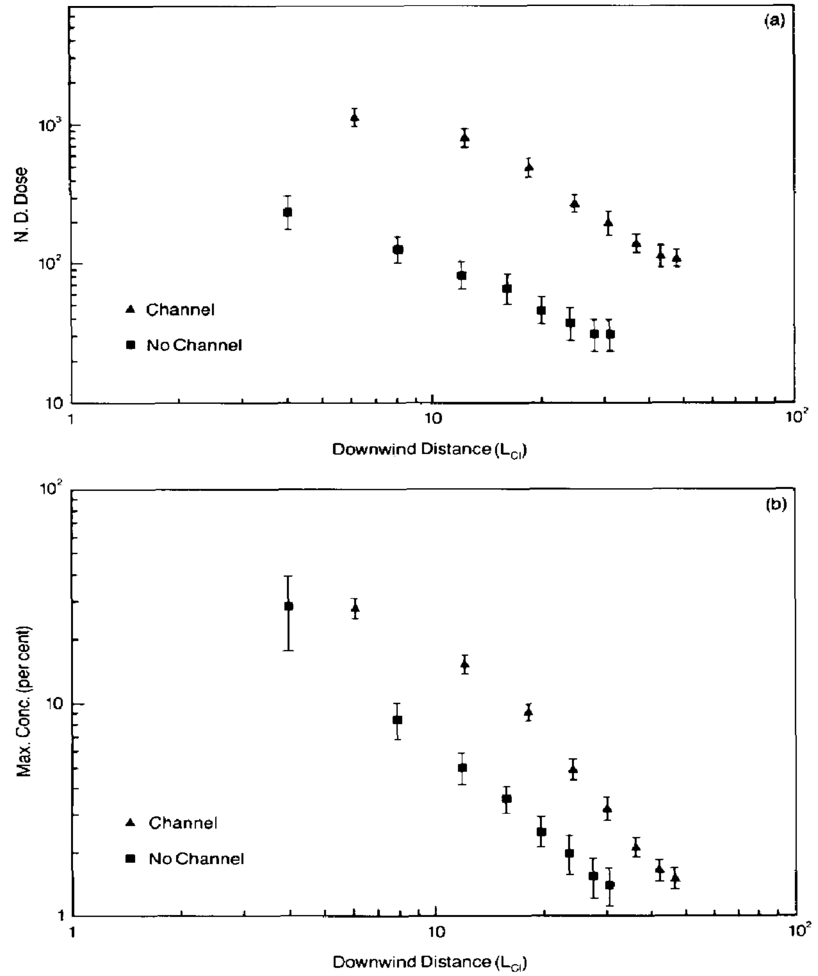

Fig. 3. Variation of non-dimensional dose and maximum concentration with scaled downwind distance with and without a longitudinal channel in University of Hamburg wind tunnel [6].

assumption (but not the normal assumption) when used in conjunction with the 'mean plus two standard deviations' rule to produce estimates of the 97.7 percentile of the concentration gave conservative results.

The TÜV propane dataset

This dataset was analysed to determine the influence of different parameters (e.g. windspeed, source type and strength, weather stability, etc.) on the lower flammability distance (LFD), i.e. the distance from the release point to the downwind location at which the volume concentration falls to 2.1%, the lower flammability limit for propane. Two methods of statistical model selection were employed. The first method began with the full log–linear model of LFD (including spill duration) and proceeded by deleting terms until a significant in-

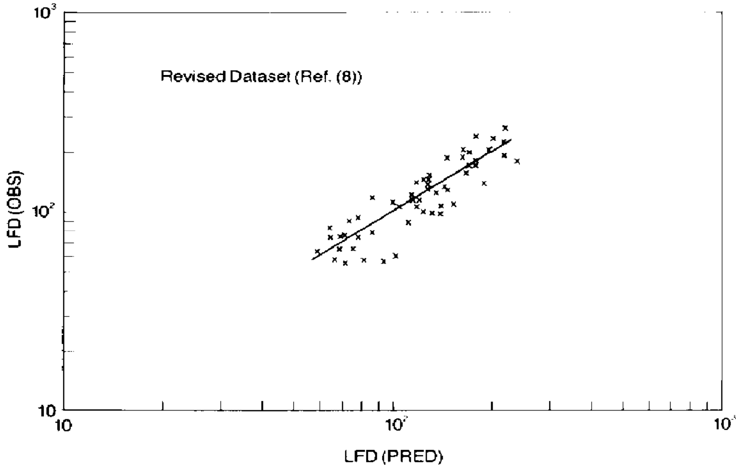

Fig. 4. Scatter plot of observed and predicted lower flammability distances for liquid propane in TÜV field trials [7,8].

crease of RMS error was obtained. The second method used two log–linear models of LFD (excluding spill duration as being irrelevant) based on dimensional analysis and, beginning with the constant term, added further terms until no significant decrease in RMS error was obtained. Figure 4 shows the observed LFD plotted against the predicted LFD using the result of the first model selection method. The model included terms for spill rate and duration, orifice type and diameter and gradient Richardson number. Terms in wind velocity and atmospheric stability were omitted. As expected, the second method of model selection produced a much simpler result: LFD is proportional to (spill rate)$^{0.4}$. The absence in both cases of a term in the wind velocity suggests that in the conditions prevailing during the TÜV field tests the dilution at a given downwind position caused by the increased turbulence accompanying higher windspeeds is cancelled out by the increase in concentration resulting from the increased cloud advection speed.

In both methods of model selection the log-normal nature of the LFD was confirmed, the RMS error about the regression lines lying between 20% and 30%. The log-normal variation of LFD is consistent with the log-normal variation of other bulk cloud parameters remarked on above, as is the range of variability. It also follows that dense gas dispersion codes will have reached the limit of their useful development when they can predict LFDs to within 20% of their true value. This limit is unlikely to have been attained if the discrepancy between the predictions of different dispersion codes is much in excess of 20%.

Conclusions

The four analyses discussed here all point to the log-normal distribution as an adequate representation of the between-release variation in cloud parameters to be expected in nominally identical releases. Extensive information is now available, particularly from the WSL datasets, on the behaviour of the variability under different source conditions both with and without a simple obstacle. Knowledge of the between-spill distributional form of the bulk cloud parameters and their respective levels of variability as determined by the analyses described here are required in risk assessment tools such as HSE's RISKAT [14] to put confidence bounds on the extent of hazard zones, at least in the case of dispersion over flat terrain. The treatment of between-spill variability in the presence of obstacles is more complex and awaits the results of further analysis of the WSL fence dataset described in the second section. As mentioned earlier, this work will be carried out under the STEP Programme.

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