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Guidelines for the inclusion of low wind speed conditions into risk assessments

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Abstract

Although they are not often considered in risk assessments or safety cases, low wind speed conditions are likely to produce many of the worst case dispersion scenarios, especially for situations where dense vapour clouds would form close to the ground. The results of previous review and validation studies, undertaken by the authors for the UK Health and Safety Executive, have been drawn together in this paper to provide guidelines for the practical application of appropriate modelling of scenarios involving low wind speeds within quantified risk assessments. The production of these guidelines has been achieved by using example risk assessments covering the storage of chlorine, bromine, LPG and Liquid Oxygen, for each of which sensitivity studies were also undertaken. These demonstrated that the inclusion of low wind speeds has varying effects, depending on the material considered, which could be as much as 1–2 orders of magnitude. Most importantly, it also showed that, when low wind speeds are included, it is not only their dispersion effects but also their effects on source term and impact on the population, which need to be considered to ensure that the calculated risks are neither overly conservative nor optimistic. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Quantified risk assessment (QRA) is now widely used as a tool to allow the risks from major hazard sites on their surroundings to be evaluated. This usually results in the prediction of individual risk contours around a site within which certain planning restrictions may be applied. In the UK, for toxic gas major hazard installations, the individual risk contours are used as decision boundaries by the UK Health and Safety Executive (HSE) to advise local planning authorities on planning applications in their vicinity [1]. Although HSE gives advice on all types of development, the advice is based on risk to a hypothetical householder, present

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all of the time and indoors most of the time. Current risk methodologies tend to be conservative, and any reductions in the conservatisms or uncertainties would generally enable better and more confident decisions to be made regarding the use of land around such sites.

In addition to the offsite risk effects, there is also a need to determine risks to on site personnel. This is an area in which there has been recent interest, which has resulted in guidance on occupied buildings [2]. Whilst much of the concern relates to blast effects on buildings, there are also issues relating to infiltration of toxic gases, which will clearly be dependent on wind speed.

One significant area of uncertainty relates to the performance of dispersion models in low wind speeds, where the assumption that a continuous cloud advects with the ambient wind speed begins to break down (although it is difficult to specify a single value which defines a 'low wind speed', it is taken, within this paper, as any value less than 2.4 m/s). These effects were discussed by Nussey [3] and Smith [4], and were considered worthy of further investigation in relation to the calculation of risk. A preliminary study into the effects of low wind speed on gas dispersion modelling was therefore undertaken by Lines and Deaves [5]; this focused primarily on the prevalence of low wind speed conditions and methods for calculating dispersion in low wind speeds. Further studies were then undertaken to assess in detail the implications for risk assessments of dispersion in low wind [6–8]; these included a realistic QRA, which allowed the significance of using a more representative set of weather categories to be determined. They also identified relevant data for validation of dispersion models at low wind speeds and considered the feasibility of developing a simple methodology to assess dispersion in such conditions.

Independent validation of three currently used dense gas dispersion models against low wind speed data was provided by Lines et al. [9]. This allowed improved levels of confidence in the use of such models and identified that there was no immediate need for specific model development to cover low wind speed conditions. The extent of the validation data used was relatively limited, although further datasets are now becoming available from the PERF tests [10]. Several relatively low wind speed runs (2–3 m/s at 2 m height) were undertaken, and some validation of dense gas dispersion models was undertaken for DEGADIS by Spicer and Havens [11] and for HEGADAS by Hanna and Chang [12]. Although this latter paper suggested some minor improvements to HEGADAS, it is unlikely that this would modify the conclusions of the Lines et al. [9] study.

This paper therefore extends our earlier studies in order to provide guidelines on certain features relating to the inclusion of low wind speed effects into quantified risk assessments, whilst recognising the distinction between model validity or accuracy and risk sensitivity. In order to make such guidelines as widely applicable as possible, the study was extended beyond just the base case chlorine risk assessment to include other common representative cases.

2. Model performance at low wind speed

The 14 datasets selected for the validation study of Lines et al. [9] are identified in Table 1. Many of these are taken from the Rediphem database (Nielsen and Ott [13]). The GRADE data are taken from Roberts [14], whilst the ENFLO data were obtained specifically for the

Table 1
Low wind speed validation database

Category	Test	U_{ref} (m/s)	Ri	Mass flow rate (kg/s)	Release conditions
Continuous momentum release	Lathen 72	0.2	3×10^6	3.0	Horizontal obstructed jet
	Lathen 60	1.5	2×10^4	3.0	Horizontal jet between fences
	Lathen 64	2.0	9×10^3	3.0	Horizontal jet across fence
	Fladis 12	2.1	2×10^2	0.21	Vertical jet
Instantaneous vapour release	Thorney 9	1.7	6×10^3	3800[a]	Large quiescent cloud (I)
	Lathen 74	0.9	3×10^3	40[a]	'Puff' (I)
	Thorney 10	2.4	4×10^3	4300[a]	Large quiescent cloud (I)
Evaporating pool	Burro 8	1.8	1×10^4	117	Evaporating pool
	Maplin 12	2.0	3×10^3	7	Evaporating pool
	GRADE 20	2.1	3×10^2	101[a]	Array of vapour sources (I)
Low velocity vapour release	Thorney 47	1.5	1×10^4	4.1	Continuous vapour source
	Lathen 57	2.4	2×10^3	3.0	Obstructed cyclone
	ENFLO 2	3.1	1×10^3	18.7	Vertical area source
	ENFLO 4	1.7	3×10^3	7.8	Vertical area source

[a] 'Release rate' for instantaneous releases (I) is given as total quantity released (kg); see comments below on the difficulties of achieving low wind tunnel speeds.

validation study. Within this table, U_{ref} is as given in the database, and is usually the wind speed at 10 m. For some datasets, however, the reference height is 2 m. Wind speeds quoted in the remainder of this paper are generally taken to apply at 10 m unless otherwise stated.

The most significant limitation of this validation study is in the range of wind speeds considered. For example, availability of data resulted in only two wind speeds less than 1.5 m/s, one of which was an extremely low wind speed (0.2 m/s) jet case. Most of the validation is therefore given in the range 1.5–2.5 m/s. Attempts to fill gaps in the data using wind tunnel modelling (in the ENFLO facility at Surrey University) ran into practical problems of running the tunnel at low speeds and of applying appropriate scaling. In the event, by using the very dense gas krypton, the lowest scaled wind speed which was obtained was 1.7 m/s.

The guidelines produced by CCPS [15] include a useful section giving details of commonly used vapour cloud models. This includes all three of the models used in the validation study (HGSYSTEM, GASTAR and DRIFT), and is followed by a section giving a summary of recent studies which evaluated some of these models against full scale data with wind speeds ranging from around 1 to 10 m/s, but with most in the range 4–8 m/s. The results showed that, for all models, geometric mean bias (MG) was generally in the range $0.5 < \text{MG} < 2.0$, and the geometric variance, VG, ≤ 4, although VG was generally less than 2 for both HGSYSTEM and GASTAR.

The results from the low wind speed validation study were compared with these typical values and were generally consistent with the limits noted above. Full details are given in Lines et al. [9], and a summary of the results, excluding jet releases, is shown in Table 2.

An alternative presentation is given by CCPS [15] in which the ratio of predicted to observed concentrations, $C_{\text{p}}/C_{\text{o}}$, is plotted in bands of wind speed. The results (their Figs. 8–5)

Table 2
Summary of validation results

Model	MG	VG
HGSYSTEM	1.09	1.61
GASTAR	1.47	2.26
DRIFT	0.73	1.61

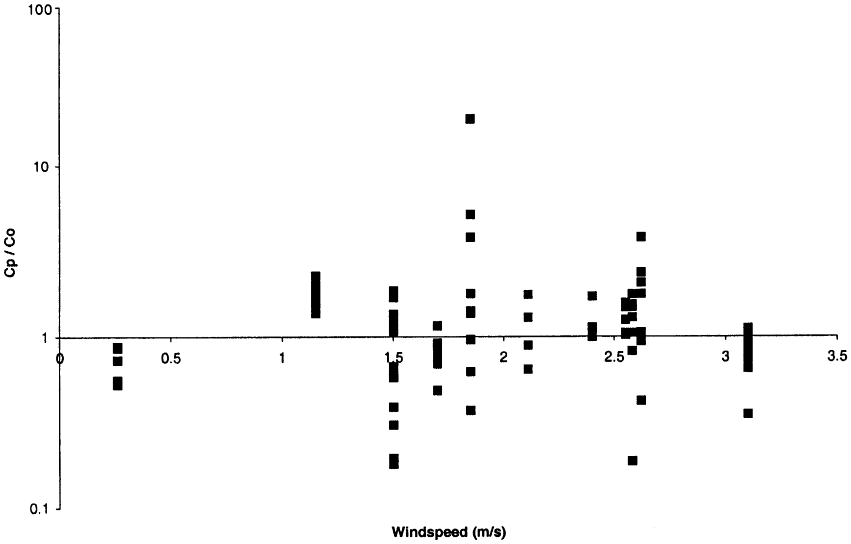

Fig. 1. Scatter of results from HGSYSTEM.

suggest a slight deterioration in model accuracy at the lowest wind speed band. A summary of typical results from this validation study (94 data points) is presented in a similar form in Fig. 1 (for HGSYSTEM only), from which clearly outlying results, with $|\log(C_p/C_o)| \geq 2$, were omitted. Whilst there are some trials which are not well modelled, these results, and those for GASTAR and DRIFT (not shown), do not imply a significant deterioration in model performance as the wind speed is reduced for any of the release types considered.

3. The importance of wind speed persistence time

Low wind speeds are unlikely to persist for periods which are long compared with typical release durations of 5–30 min. Based on a limited analysis of good quality wind data, Lines and Deaves [8] showed that the maximum downwind travel distance for a release in a low wind speed u (<1.5) m/s is approximately $3000u^3$ m (note that, while the appropriate wind speed, u, could be considered to be a value averaged over the cloud depth, in practice it is expedient to use the value at 10 m height). It was also suggested that continuous plume

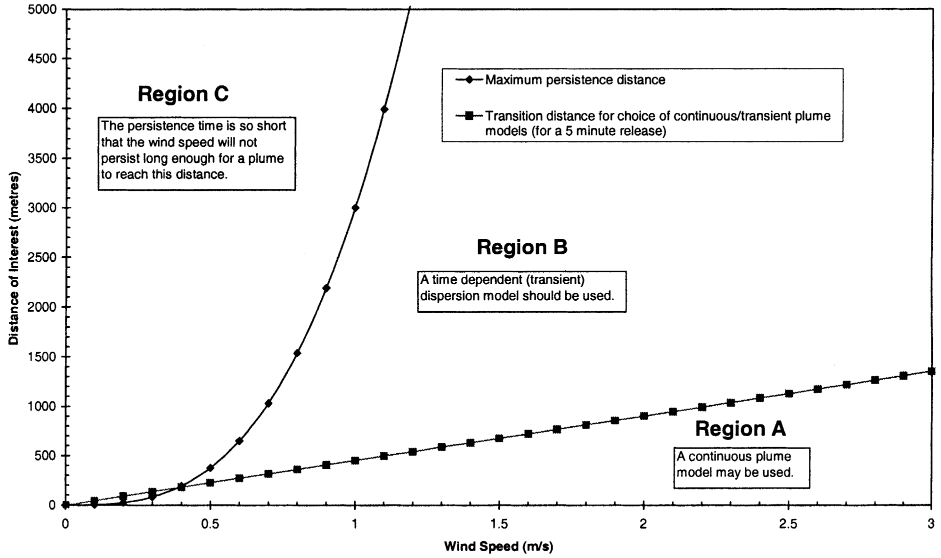

Fig. 2. Choice of dispersion model as a function of wind speed and distance of interest.

models should not be used when $x > 1.5uT$, where T is the release duration (the value of 1.5 applies to 'standard' roughness of $z_0 = 0.1$ m, although it is not expected to vary significantly for other roughness categories). These conditions are illustrated for 5 min release durations in the schematic diagram of Fig. 2, in which $x = 450u$ ($1.5uT$) gives the boundary between regions A and B, and $x = 3000u^3$ gives the boundary between regions B and C. This figure can then be used to draw practical conclusions which are pertinent to quantified risk assessments.

For example, for the risk at 1000 m from a major hazard site, Fig. 2 indicates that

1. any wind speeds of less than 0.7 m/s are unlikely to persist long enough for the release to travel 1000 m, unless the cloud travel speed is significantly enhanced by jet or gravity spreading effects; this implies that using such low wind speeds would not be realistic, and would, at least in some cases, result in over-estimation of risk;
2. wind speeds from 0.7 to 2.2 m/s (i.e. in region B) should be modelled using a transient dispersion model;
3. wind speeds above 2.2 m/s may be modelled using a continuous plume model.

Similarly, if one had chosen to use a 1m/s weather category, then

1. it should not be used to predict any risks beyond 3000 m;
2. a transient dispersion model should be used to calculate risks from 450 to 3000 m;
3. a continuous plume model should be used to predict risks at less than 450 m.

It should be noted that the position of the dividing line between regions A and B on Fig. 2 depends on the release duration. Furthermore, the boundaries of the regions on Fig. 2 are not very clearly defined and so should only be regarded as being indicative. For example,

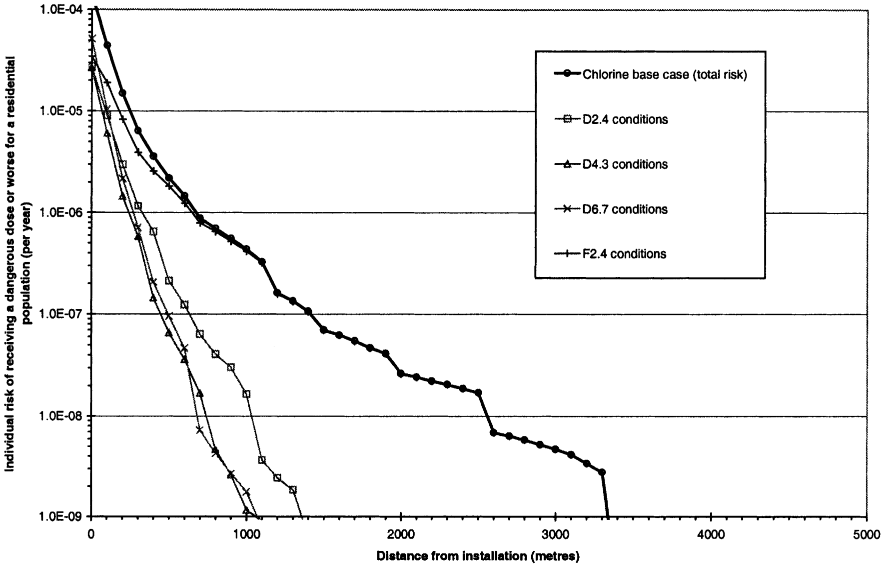

Fig. 3. Base case risk for chlorine, showing contributions from each weather category.

it is possible that a wind speed of 1 m/s could persist for longer or shorter than 3000 s, as shown in Lines and Deaves [8], so that probabilities could be associated with a range of persistence times.

In QRA studies which use very low wind speeds (<0.4 m/s) then Fig. 3 indicates that 5 min duration releases should only be modelled using such low speeds up to at most 200 m. It also indicates that there is not a clear preference for either instantaneous or continuous modelling; for ease of application, it is suggested that continuous modelling should be used.

4. Base case risk assessments

4.1. Common features of base case assessments

The features used in this study have been chosen to correspond as closely as possible to current practice in HSE land-use planning risk assessments.

4.1.1. Weather conditions

For each of the risk assessments considered, there is a range of possible weather conditions which may occur. For all except the LOX assessments, each of the events has been considered in 4 representative weather conditions, namely D2.4, D4.3, D6.7 and F2.4 (as used by Pape and Nussey [16]), where the letters correspond to the Pasquill stability category (D for neutral and F for stable), and the numbers correspond to the wind speed at 10 m height in meters per second. The percentage frequencies of these 4 weather conditions are taken to be 17, 20, 45 and 18%, respectively, based on typical UK meteorological data. For the LOX assessment, D5 and F2 categories have been used, in line with current practice. The frequencies have been taken as 82 and 18%, respectively, to give consistency of the stable frequencies with the fuller set of weather conditions. For ease of application, a uniform wind rose has been assumed, and the risk results presented are therefore a function only of distance. Thus, directionality has not been considered, although it is recognised that wind direction during the 30 min or so of a typical incident could be extremely variable when the wind speed is low.

4.1.2. Population exposure

The risk calculations involve a summation of the risks from each event in each of the representative weather conditions. The risks have been calculated for a typical residential population, which is assumed to be present for 100% of the time, and which is outdoors for 10% of the time, except in stable (F2.4) weather conditions (which occur predominantly at night), where outdoor exposure occurs for only 1% of the time. The population is assumed to be indoors for the remainder of the time.

The risks from toxic releases to persons indoors are based on a calculation of the time varying concentration inside the building, using an air exchange rate of two air changes per hour (ach) for all conditions except D6.7, for which the higher wind speed implies a higher air exchange rate of 3 ach. The persons indoors are assumed to remain indoors for 10 min after the cloud has passed before evacuating to fresh air, but in no case does evacuation take place until at least 30 min has elapsed from the start of the release.

For flammable risks from LPG, no allowance is made for any mitigating effect of the building. For risks from LOX, infiltration calculations are performed to ascertain whether the internal concentration of oxygen reaches the hazardous level.

4.1.3. Dispersion and risk modelling

For the purposes of this project, all the dispersion calculations have been undertaken using models in the HGSYSTEM suite, and the risk assessment calculations have been undertaken using the WS Atkins code RiskTool [17]. This code has been used because it is possible to incorporate the effects of various improvements, related to the modelling of low wind speeds, which are required in the sensitivity studies.

4.2. Chlorine storage site (toxic gas)

The set of representative release scenarios corresponding to a typical small chlorine installation, as described by Carter et al. [18] has been used in this study. This covers 40 scenarios ranging from catastrophic vessel failures (18te) to flange leaks (<1 kg/s). The dispersion of chlorine vapour clouds has been assessed using the models in Version 3.1 of HGSYSTEM [19]. Continuous releases have been modelled using the HEGADAS-S code, and instantaneous releases have been modelled using HEGABOX followed by HEGADAS-T.

The risk calculated in this study is the risk of people receiving a dangerous dose (or worse) of chlorine, where the dangerous dose for chlorine is defined as 108,000 ppm^2 min. The possibility of escape from the cloud is modelled by assuming that, at concentrations above 500 ppm, there is no chance of escape for persons outdoors; between 300 and 500 ppm, there is a 20% chance of escape; and below 300 ppm there is an 80% chance of successful escape. Escape will be to an indoor location, where there will still be exposure, but to a lower concentration. The base case results are shown in Fig. 3, in which the contributions to risk from each weather category have been indicated. This shows, as expected, that the low wind speed stable conditions dominate the risk in the far field.

4.3. Bromine storage site (toxic liquid)

Bromine is a dense liquid, from which dense brown fumes are evolved when it is released. The events that are most significant for risk assessment purposes at a bromine storage site can be summarised as

1. catastrophic or partial failure of bulk tank;
2. failure of liquid or vapour pipework (including leaks at pipework fittings);
3. pipework or connection failure during loading/offloading of ISO tanks.

In all events involving the spillage of bromine, the most significant parameter is the rate at which bromine vapour evaporates from the spillage. This depends principally on the area of the spill, the temperature of the liquid, the vapour pressure of bromine (and its other physical properties), and the wind speed over the spill. Only the first of these parameters (spill area) is likely to vary significantly between different events. This generic risk assessment therefore considers just a small number of representative bromine releases, characterised by the spill area: small (4 m^2), bunded (40 m^2) and unbunded (400 m^2).

It is noted that HSE's guidance is that bulk bromine tanks should be bunded with a layer of water at the bottom of the bund, so that any bromine sinks beneath the water to reduce its evaporation rate. The 'bunded' scenario therefore represents events where, for example, the water may have drained away, frozen or evaporated. The 400 m^2 'unbunded' scenario is considered representative of the maximum probable size of spillage at a typical bulk storage site. If the storage volume is large, or if the ground is particularly flat, with no drains, then much larger pools could be formed.

The evaporation rates from liquid bromine pools have been calculated using the method of MacKay and Matsugu [20], as described by IChemE [21]. These evaporation rates have been used as the input to HEGADAS-S, which has then been used to calculate the extent of the bromine vapour cloud. In all cases, the release duration from the pool is taken to be 30 min. It is noted that, since the evaporation source term depends on the wind speed, there is a different source term for each weather type in the risk assessment.

The risks in Fig. 4 (calculated by RiskTool), are the base case risks of an individual member of a typical residential population receiving a dangerous toxic load of bromine (i.e. 250,000 ppm^2 min). As in Fig. 3, the risk is shown broken down into the contributions from each of the 4 basic weather categories.

4.4. LPG storage site (flammable/explosive liquefied gas)

The events chosen to be representative of a typical LPG tank installation, involving a single 50 tonne propane tank, are

1. Boiling liquid expanding vapour explosion (BLEVE). This occurs as a result of fire impingement on a vessel. It would result in a major fireball.

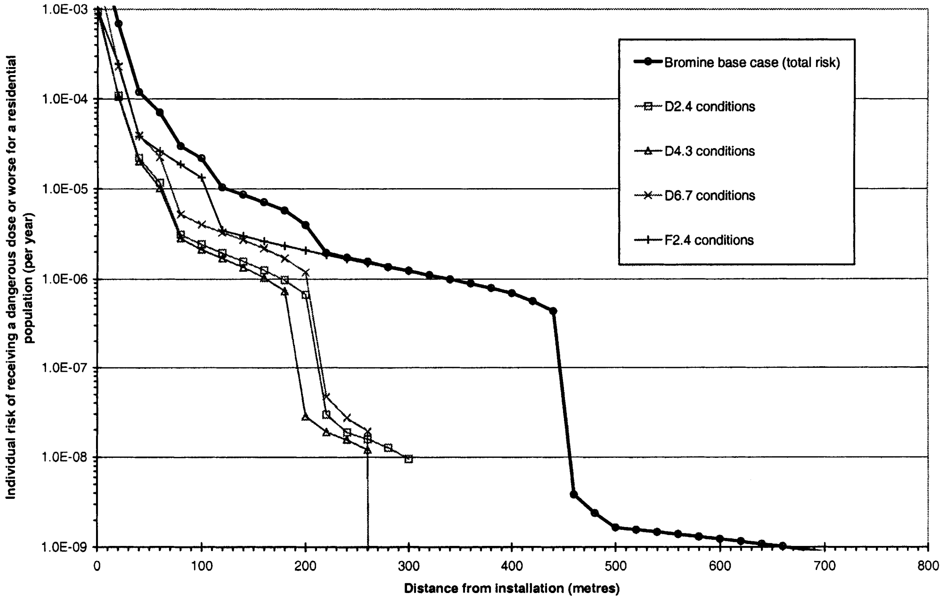

Fig. 4. Base case risk for bromine, showing contributions from each weather category. Note that confined regions are assumed to be located at 80 m and at 220 m.

2. Catastrophic tank failure. This may be as a result of a BLEVE, or of a cold failure. It could result in a vapour cloud explosion (VCE) or flash fire, depending upon the time of ignition and the degree of confinement of the vapour cloud.
3. Tank or liquid line rupture. Immediate ignition would result in a jet fire or a pool fire. If ignition were delayed, the release would result in rapid flashing to vapour, and the resulting vapour cloud would form either a VCE or a flash fire.
4. Rupture of gas supply line. Immediate ignition would result in a jet fire, and delayed ignition would cause a VCE or a flash fire.

Only delayed ignition effects have therefore been considered for scenario types (3) and (4), as the consequences of immediate ignition have relatively short hazard ranges which are not sensitive to the wind speed.

The risks have been calculated based on the risk of an individual:

- receiving a dangerous thermal load of 1000 $kW^{4/3}$ s for BLEVEs;
- being within the 1/2LFL contour for flash fires;
- receiving a dangerous level of overpressure of 140 mbar for VCEs.

It is assumed that being indoors offers no protection against these risks, which simplifies the analysis compared with that for a toxic material.

Blast overpressures have been calculated using the TNT equivalence model [21] for the inventory of LPG within the lower flammable limit. For the purposes of this assessment, it is assumed that there are congested regions at 80 and 220 m downwind from the source. These are such that a VCE based upon a stoichiometric cloud of propane (covering a volume

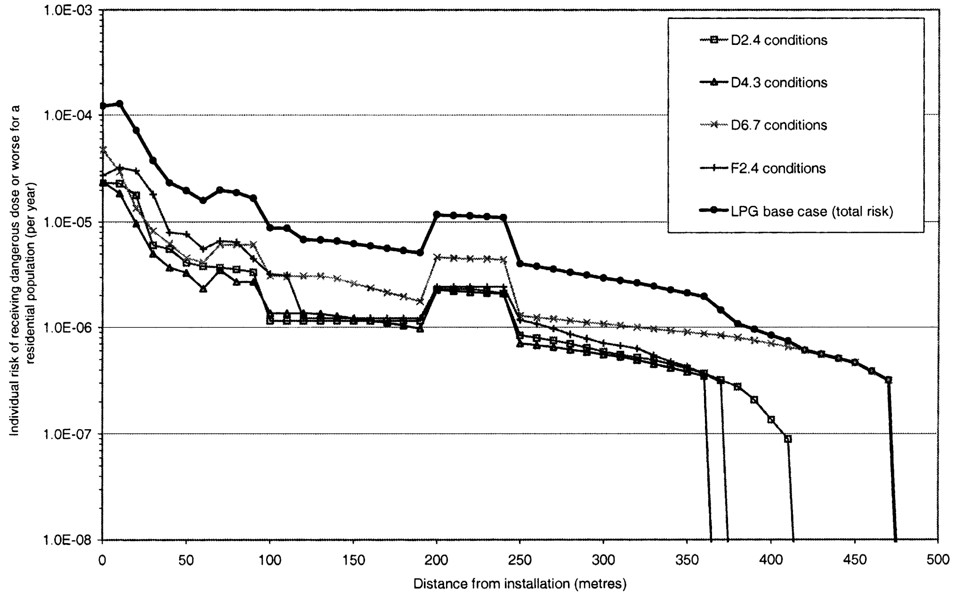

Fig. 5. Base case risk for LPG, shows contributions from each weather category (excluding BLEVE event).

of 300 or 1000 m^3, respectively) is assumed to occur if the centre of the congested area is within the LFL contour.

The thermal radiation risk from ignited BLEVEs has been calculated using a simple point source model, but taking transmissivity of the atmosphere into account when assessing radiation effects. As noted above, the contribution to risk from BLEVEs is unaffected by wind speed. The dispersion of vapour has been modelled using HEGABOX and HEGADAS-T for the catastrophic failure case, and HEGADAS-S for the continuous release scenarios.

The risks from all events have been summed and the results, excluding the risks from the dominating BLEVE event, are shown in Fig. 5, which also indicates the contributions to total risk from each of the weather categories. It is interesting to note that, in this case, the risks over most of the range are dominated by the D6.7 weather category, rather than by the lower wind speed conditions. This is due to a combination of the higher frequency of these conditions, and also the greater hazard range of the catastrophic (50te) release, which, being effectively instantaneous, travels further before being diluted below 1/2LFL.

4.5. Liquid oxygen or liquefied natural gas storage site (flammable liquefied gases)

This analysis is based on a typical 1000 tonne liquid oxygen (LOX) storage tank, where the refrigerated LOX is stored at just above atmospheric pressure in a bunded storage tank. It is noted that the hazards and risks associated with refrigerated LNG would be broadly similar to those encountered with LOX. Although the hazardous effects of LOX are primarily due to ignition and subsequent fire, there is also the potential for cold stress in regions close to the source.

The scenarios considered are

- Failure of tank resulting in a major release contained within the bund.
- Failure of tank resulting in a major release which is not contained within the bund (e.g. due to bund overtopping or bund failure).

As for the bromine case, the release rate is very dependent on the pool area. In the first scenario, the pool area is based on a 35 m diameter bund and the vapour release is assumed to continue for a period of 30 min. In the second scenario, the release is assumed to form an unconfined spreading pool. The frequencies for the above scenarios are taken as 10^{-4} and 10^{-5} per year, respectively.

The major failure is assumed to result in the entire contents of the tank being released over a short time (approximately 30 s). The rate of vapour generation from the spill for the bunded and unbunded cases has been modelled using the LPOOL model in HGSYSTEM, which generates a time dependent release rate of vapour. For both scenarios, it is found that the release rate is most significant during the first few minutes. Therefore, for the base case analyses, these scenarios have been modelled as an instantaneous release using HEGABOX.

The risks have been calculated as the risk of an individual being in an area where the vapour concentration reaches 30% by volume (11.4% excess), which is the concentration above which enhanced flammability is deemed to be hazardous. It is assumed that the indoor population will only be at risk if the internal concentration of oxygen exceeds this hazardous level. The indoor concentration is calculated on a transient basis for each scenario as the cloud passes, and the conditional risk is assumed to be zero unless the oxygen concentration reaches 30%, in which case it is one.

The results of the base case risk assessment are shown in Fig. 6, which includes the contributions to total risk from each of the two weather categories (D5 and F2 in this case). The sudden risk reductions evident at 100 and 400 m occur at distances which represent the hazard ranges from bunded and unbunded releases, respectively. The results show that the risk for D5 conditions is dominant, rather than that for the low wind speed (F2) conditions. There are three reasons for this:

1. For the large instantaneous scenarios considered, hazard ranges are similar in both D5 and F2 conditions.
2. D conditions occur four times as frequently as F conditions.
3. There is no risk to the indoor population, and it is assumed that 10% are outdoors in D5 (daytime) whereas only 1% are outdoors at night (F2).

It is noted that HSE has now moved to a higher enrichment factor of 35%, as recommended by BCGA [22]. This will reduce hazard ranges and lessen the significance of small events in terms of off-site risk.

5. Inclusion of low wind speed effects in risk assessments

5.1. Sensitivity studies

To assess the significance of low wind speed effects, a number of sensitivity studies were conducted. The following features were included:

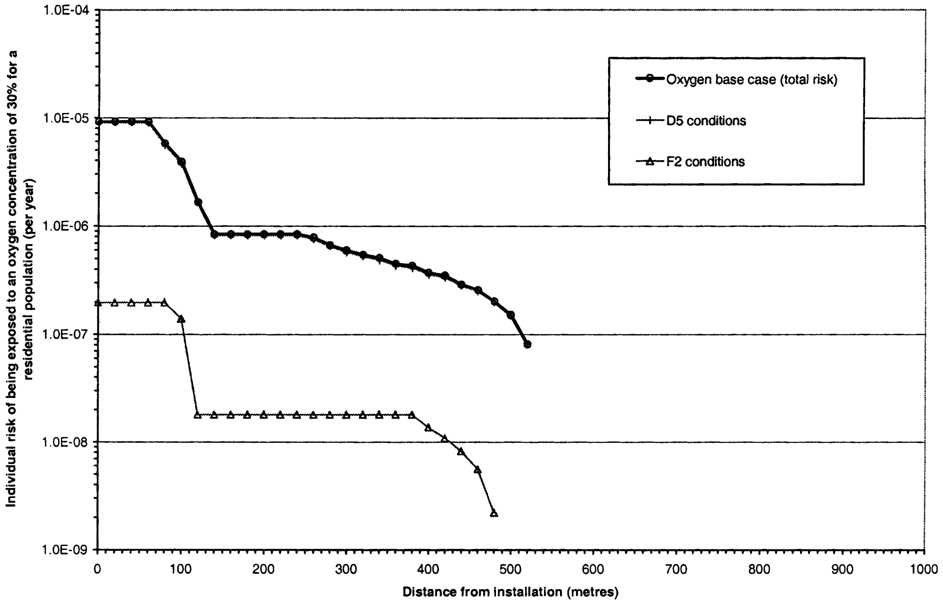

Fig. 6. Base case risk for LOX, shows contributions from each weather category.

a. More low wind speed weather categories

The ideal in this case would be to use a continuum of wind speeds and stability classes, and apply probability density functions. This approach has been assessed by Mitchell [23], although it is recognised that it is not at the stage where it is likely to be applied routinely. In practice, it is therefore necessary to use a representative set of discrete weather classes. Given this constraint, the next best approach would be to use the data with the most refined categories given by the Meteorological Office data. This would involve considerable computational effort, which is generally reduced by using only representative classes; these are currently set so that they combine all E and F stability cases within a single category, generally F2.4.

A more refined partition of the data has been presented by Lines and Deaves [8], in which the F2.4 category was divided into E2.6, E4.4, F1.0 and F2.6 in the following percentages: 12, 8, 70, 9%. It can be seen that the majority of the previous F2.4 class then becomes F1.0, with the potential for greater hazard ranges. A re-consideration of the raw data which were used by Lines and Deaves also suggests that almost half of the D2.4 category (which includes A, B & C2.4) actually relates to D1.0 (or A-C1.0) conditions. For this study, the 18% of the time previously allocated to F2.4, and the 17% allocated to D2.4 have therefore been subdivided as indicated in Table 3.

It should be noted that the frequencies of stability classes A–C are incorporated into those for class D. This is done because, for ground level dense gas releases, dispersion is always more rapid in classes A–C, so that D represents a worst case. If the assessment included many elevated passive releases, it would be appropriate to include the unstable conditions

Table 3
Re-allocation of low wind speed categories (original allocation within parenthesis)

Wind speed (m/s)	Stability class		
	D (%)	E (%)	F (%)
1.0	8.0		12.5
2.4	9.0 (17)	2.4	1.6 (18)
4.3	20 (20)	1.5	
6.7	45 (45)		

Table 4
Ventilation rates for use in risk assessments (ach)

Weather category	D2.4	D4.3	D6.7	F2.4
Closed house	1	1	1.5	1
Normal occupied house	2	2	3	2
Values used by Pape and Nussey [16]	0.7	1	1.5	0.5

(A–C); however, any refinement to include more unstable conditions was not considered significant within study.

It is also noted that it is generally not appropriate to use wind speeds lower than 1 m/s since they do not persist for long enough (as discussed in Section 3) and there is less confidence in the validity of dispersion models at very low wind speeds. However, because hazard ranges for LPG dispersion are rather shorter than for toxic materials, it is useful to consider how using wind speeds as low as 0.5 m/s would affect the results of the LPG assessment. To this end, a more refined breakdown of wind speed categories was used, with the 1 m/s classes split: D1.0–5.6%; D0.5–2.4%; and F1.0–8.7%; F0.5–3.8%.

b. Modified air ingress rates to buildings

Infiltration of gas is important when toxic effects are considered, and it is assumed that the ventilation rate will increase with wind speed. Current usage within risk assessments is given in Table 15.65 of Lees [24], which is reproduced in Table 4.

The following variations of air change rate (λ air changes per hour) with wind speed u (m/s), based upon these values and extrapolated to lower wind speeds, are used:

For D stability class: $\lambda = 0.4 + 0.32u$.

For E and F stability classes: $\lambda = 0.25 + 0.2u$.

c. Modified impact/escape probabilities for exposed population

The probability of escape from a toxic cloud depends on a number of unrelated factors, and will not necessarily be simply related to wind speed. In particular, it depends upon detection by the individual, time before correct action is taken, fitness and distance to the nearest refuge. In principle, a low wind speed will give a greater opportunity to respond and escape, and, for the purposes of this relatively simplistic assessment, it is assumed that the threshold concentrations of 300 and 500 ppm for chlorine given in Section 4.2 are replaced by $720/u$ and $1200/u$ ppm, respectively, for wind speeds less than 2.4 m/s. The difference in toxicity between bromine and chlorine suggests that a factor of 1.5 on concentration is appropriate when considering escape from a bromine cloud. Hence, the corresponding criteria for bromine are $1080/u$ and $1800/u$ ppm, respectively.

The LPG base case risk assessment does not allow for either protection within buildings or escape from flammable clouds. However, some discussion of escape probabilities from flash fires was given by Rew et al. [25], which suggested that there may be some (small) probability of escape. Lower wind speeds would allow more time before the extremities of the cloud reach downwind locations, thus potentially allowing escape from a cloud which develops into a flash fire. This will be modelled simplistically by assuming that the flash fire fatality region covers the LFL contour for wind speeds less than 2 m/s, and covers the 1/2LFL contour for higher wind speeds (as assumed in the base case).

d. Persistence effects and

e. Use of time dependent dispersion models

These effects have been discussed in Section 3. The methodologies described there and summarised in Fig. 2 have been applied (separately) to determine sensitivity to these effects.

f. Releases from buildings

The effective leak rate from a building will only be modified by wind speed for relatively low release rates. Typical results from the zone model GRAB-T [26] have been obtained, which show that, for chlorine release rates in the range 0.3–3 kg/s: $\dot{M}_\mathrm{w} = f\dot{M}_\mathrm{o}$ where $f = \min[(\max(0.15u, 0.09\dot{M}_\mathrm{o}), 1]$; $\dot{M}_\mathrm{w}$ = mass release rate from building; $\dot{M}_\mathrm{o}$ = source leak rate into building (u m/s, $\dot{M}$ kg/s).

This reduction in release rate due to building effects has been used for all internal chlorine releases.

g. Greater ignition probabilities at low wind speed

Some recent work on ignition probabilities [27] has considered the strengths of ignition sources. Their review suggested that most ignition sources are sufficiently strong to be unaffected by low wind speed conditions. However, some small changes to these probabilities have been included in the present assessment in order to demonstrate the sensitivity of the results.

For the purposes of determining sensitivity, the frequency of the flash fire due to the catastrophic failure event is increased by 20% at wind speeds less than 2 m/s, whilst the frequencies of flash fire due to full bore or major leaks are increased by 50%.

h. Combinations of certain effects

The sensitivity studies have been undertaken by considering one improved feature at a time. However, since some of the effects work in opposite senses, results have also been calculated using combinations of many of the features to show the overall effects of their inclusion.

5.2. Revised chlorine storage risk assessment

Sensitivity studies were undertaken for the chlorine risk assessment, incorporating some of the changes discussed in Section 5.1. The results are shown in Fig. 7, which should be compared with the base case results in Fig. 3.

Increasing the number of weather categories considered from 4 to 8 (sensitivity study (a)), provided additional refinement of the analysis at low wind speeds, and led to an increase

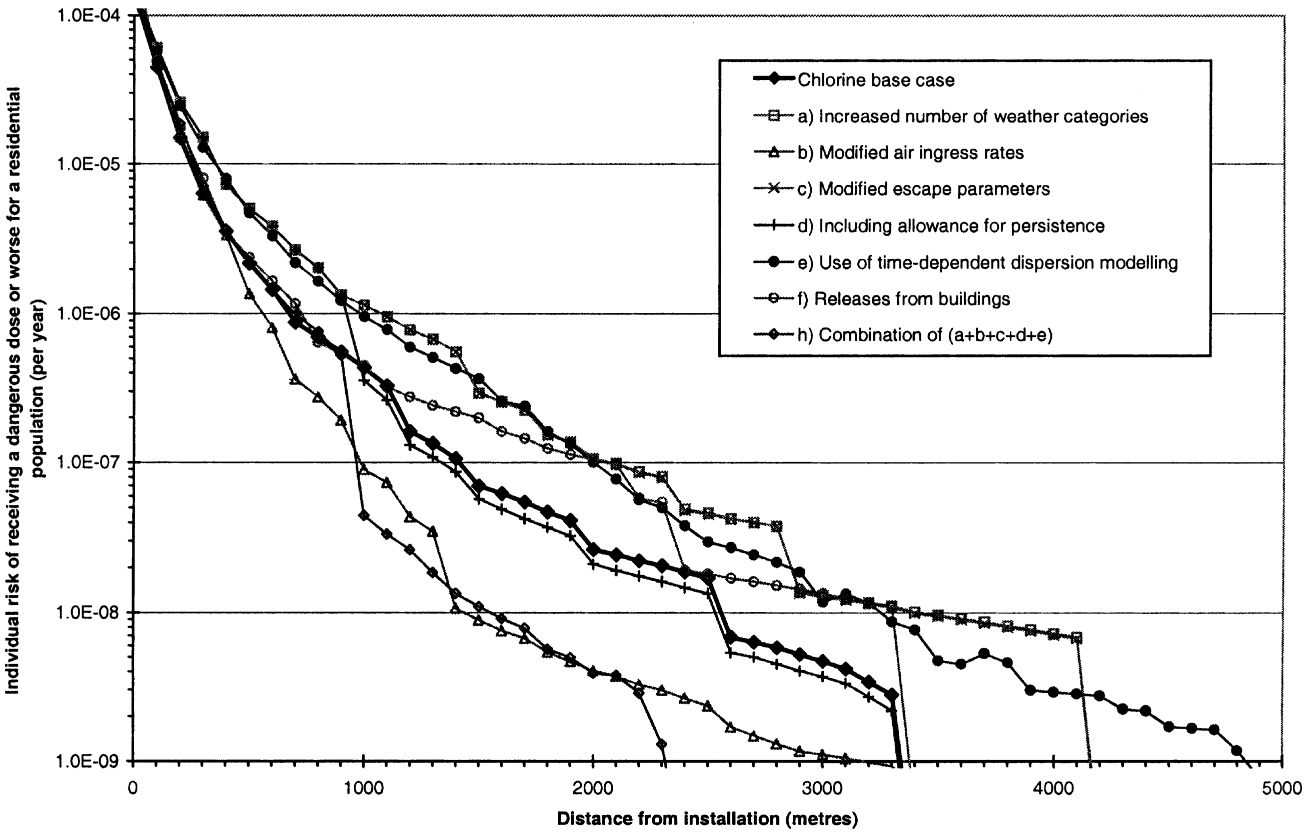

Fig. 7. Sensitivity results for chlorine risk assessment.

in the predicted risk at all distances, typically of a factor of 2 or 3 over a range from 300 m to over 3 km. This is simply due to the higher concentrations and wider gas clouds that are predicted for the low wind speed conditions, such as D1.0 and F1.0. All the subsequent sensitivity studies (b)–(g) also incorporated all 8 weather categories (i.e. they are sensitivity studies based on modifications to sensitivity study (a)).

One of the most important parameters that needs to be considered more carefully at low wind speeds is the infiltration rate of toxic gas into occupied buildings. Sensitivity study (b) showed that modifying the air change rate based on the weather conditions (as described in Section 5.1) resulted in a significant reduction in the risk at all distances, amounting to a factor of over ten for distances beyond 1000 m downwind, where the risk is largely dominated by the risk to people indoors in low wind speed conditions.

Modifying the escape modelling assumptions, so that there is an increased likelihood of escape indoors, was considered in sensitivity study (c). The results demonstrated that these parameters had very little effect on the overall level of risk (less than 1% reduction). This is partly as a result of the base assumption that only 10% of the population is outdoors, but also because the risks are dominated by relatively long duration releases (∼20 min) implying that risks to people indoors are not much less than those for people outdoors (so that escape indoors does not reduce risks significantly).

The effects of allowing for persistence were modelled in sensitivity study (d) by assuming that the results for F1.0 and D1.0 weather conditions were only applicable up to 900 m, and that beyond this distance the risks from events in such conditions were based on the next highest wind speed category (e.g. D1.0 represented by D2.4, F1.0 by F2.4, etc.). Beyond 900 m, the risks correspond closely to those from the original base case (although there is a slight difference due to the fact that E stability category is still being used).

Sensitivity study (e) considered the importance of using transient (time dependent) dispersion modelling for all those events where the outdoor hazard range is greater than $1.5uT$ (T = release duration). Of the $36 \times 8 = 288$ continuous releases, it was determined that 45 (generally those with high release rates and short durations) had to be remodelled using the transient model HEGADAS-T rather than the continuous plume model HEGADAS-S. The overall effect of this change on the risks was relatively small (less than a factor of two at most distances), but this is probably because the risks in this case are dominated by the longer duration releases, which did not need to be remodelled.

Sensitivity study (f) illustrates the effect of modifying the release rates, assuming that all the continuous releases occur inside a building. The effective building release rate at low wind speeds (particularly for small releases) is dependent on the wind speed, and may therefore be a significant consideration in QRA studies involving low wind speeds. In addition to modifying the release rate, the effective release duration has been increased. For this particular chlorine QRA, the risk is dominated by large/moderate releases and so the risk reduction associated with the building buffer effect is relatively small, amounting to about a factor of two at most distances. It is noted that, ideally, the time dependent release rate from the building should be used as the input to a transient dispersion model, rather than simply using an effective mass release rate and duration.

The final chlorine sensitivity study incorporates all of the modifications described in the sensitivity studies (a)–(e); i.e. line (h) in Fig. 7 (the building effects are not included in this final case, since its comparison should be against a modified base case). The overall effect for the particular set of chlorine scenarios considered here is that the risks are broadly similar to those in the base case for distances up to 900 m, but are significantly lower (by about a factor of 10) at greater distances. Since just including lower wind speeds (case (a)) gives an *increase* in risk everywhere, it is clearly important to include the other effects which are expected to change in low wind speeds, and the most important of these other effects is the reduction in air ingress rate.

5.3. Revised bromine storage risk assessment

Sensitivity studies were undertaken for the bromine risk assessment, again incorporating some of the changes discussed in Section 5.1. The results are shown in Fig. 8, which should be compared with the base case results in Fig. 4.

Sensitivity study (a) examined the effect of including additional weather categories, particularly at low wind speeds. This also involved recalculating the bromine evaporation source term, which is proportional to $u^{0.78}$. The overall effect on the total risk was a slight increase in risk at most distances, as would be expected, but a significant reduction between 380 and 450 m. The reason for the reduction is that the indoor hazard range for a 1.2 kg/s release in F1.0 conditions is slightly less than that for a 2.37 kg/s release in F2.4 conditions.

Sensitivity study (b) then considered the effect of modifying the infiltration rate, in addition to using the increased number of weather categories used in sensitivity study (a). The reduction in overall risk associated with this change is very dependent on distance, varying from almost no change up to 130 m or beyond 460 m, to a factor of about 100 at distances around 300 m. These large reductions are principally due to the fact that the risks to a residential population from this type of toxic vapour release are dominated by the risks to people indoors, so that any reduction in air change rate can have significant effects.

The effect of modifying the parameters used in the escape assumptions was investigated in sensitivity study (c). For this particular bromine assessment, this change had very little effect (less than 1% at all distances). As for the chlorine assessment, this is largely because the risks are dominated by the risk to people indoors from long duration releases, and so the precise details for the type of escape modelling algorithms used here have relatively little effect.

The final sensitivity study (h) involved a combination of the increased number of weather categories, modified infiltration rates and modified escape parameters. The results are almost identical to those described above for sensitivity study (2), as the escape parameters still have almost no effect on the overall risk. As was noted for the chlorine risk results, the bromine results show that it is clearly important to model air ingress rates realistically when including more low wind speed categories.

5.4. Revised LPG storage risk assessment

Sensitivity studies were also undertaken for the LPG risk assessment, incorporating some of the changes discussed in Section 5.1. The results are shown in Fig. 9 which should be compared with the base case results in Fig. 5, and values of risk at key distances are summarised in Table 5.

Increasing the number of weather categories considered from 4 to 8 (sensitivity study (a)), provided additional refinement of the analysis at low wind speeds. Slightly higher

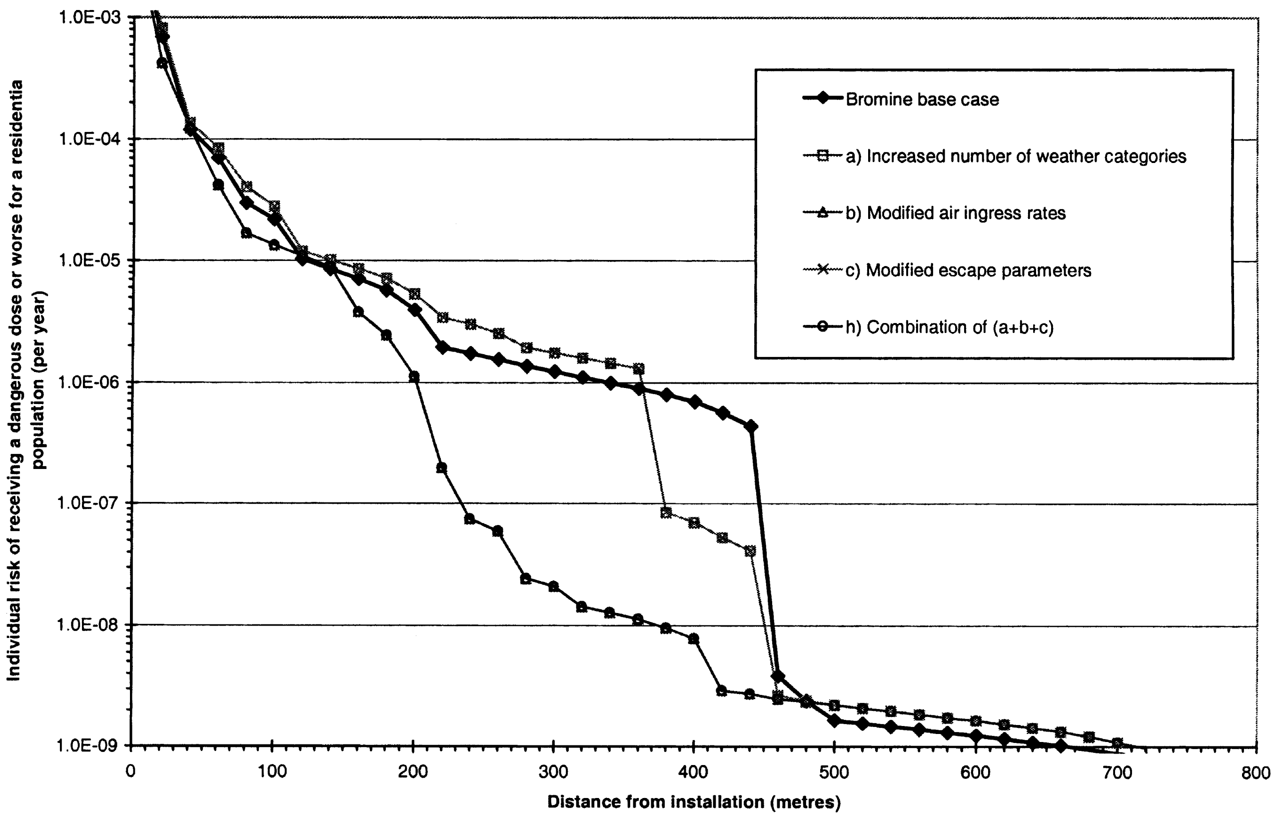

Fig. 8. Sensitivity results for bromine risk assessment.

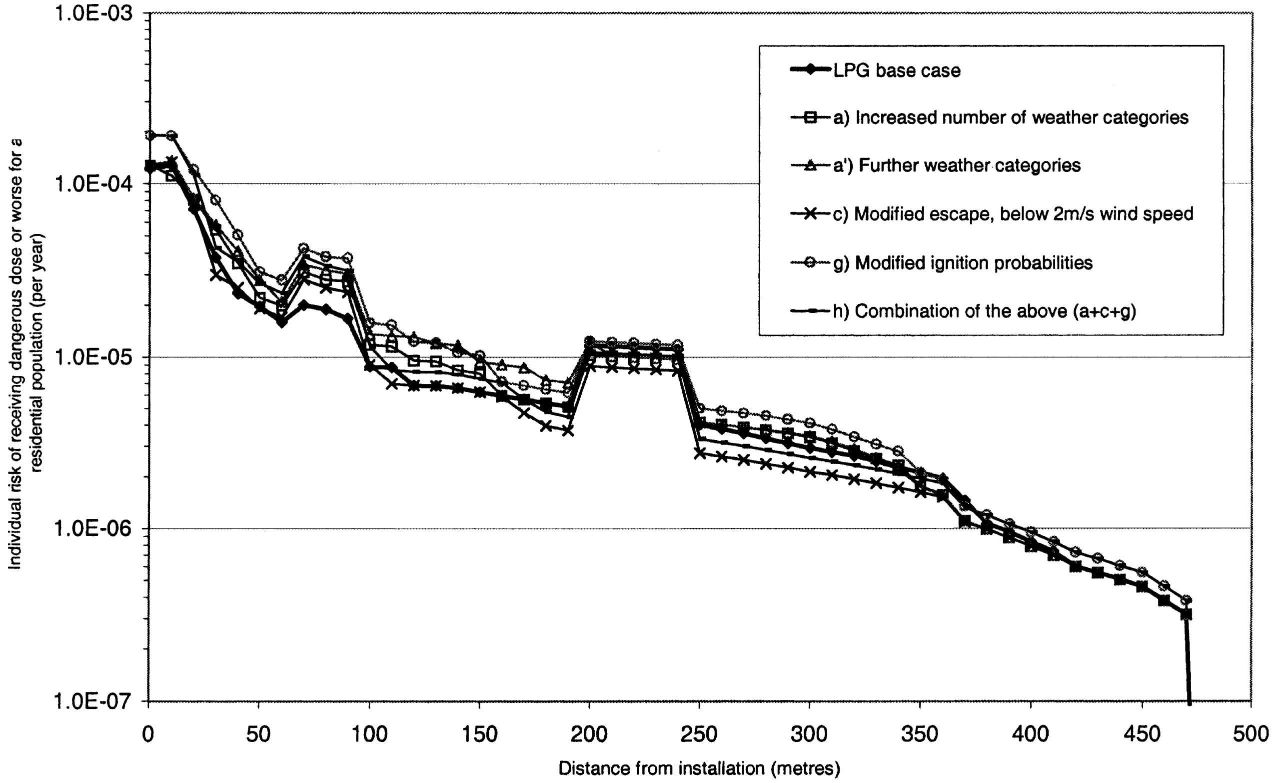

Fig. 9. Sensitivity results for LPG risk assessment (excluding the BLEVE event).

Table 5
Summary of individual risk (cpm) from Fig. 9 (1 cpm (chances per million) = 10^{-6} per year)

Case	Downwind distance from installation (m)		
	100	200	300
Base	8.8	11.7	2.9
(a) 8 weather categories	11.8	10.3	3.4
(a1) 10 weather categories	13.6	12.2	3.4
(c) Modified escape parameters	9.0	8.9	2.1
(g) Greater ignition probabilities	15.8	12.4	4.1
(h) Combination of (a), (c) and (g)	11.5	10.7	2.6

concentrations and wider gas clouds are produced for lower wind speed conditions (i.e. D1.0 and F1.0) for the 'pipework' release cases (i.e. the full bore and major releases), which leads to an increase in the predicted risk at distances up to just over 200 m. Beyond this range, only the dispersion of the catastrophic release can lead to flash fires and the general variation in risk due to the lower wind speeds is minimal. For an instantaneous catastrophic release, the wider clouds and higher concentrations produced by the lower wind speeds are counteracted by the reduced range of the cloud when the driving wind is less strong. Hence, beyond 250 m the increase due to the lower wind categories is small and, at distances of more than 300 m from the point of release, the lower wind speeds actually reduce the risk.

The same trends are apparent when further increasing, from 8 to 10, the number of weather categories (sensitivity study (a1)). Although the hazard range to the flash fire ignition limit (1/2LFL) of each scenario increases relatively significantly when reducing the wind speed from 1 to 0.5 m/s, the frequency of the additional weather categories (D0.5 and F0.5) is relatively low. Thus, although the same patterns can be seen, the increase in overall risk in this case (from 8 to 10 weather categories) is less than the small increase seen in the previous case (from 4 to 8 weather categories). All of the subsequent sensitivity studies ((c), (g) and (h)) incorporated the 8 weather categories considered above (i.e. they are sensitivity studies based on modifications to case (a)).

A simple example of modifying the escape modelling assumptions is demonstrated by sensitivity study (c). The increased likelihood of escape from the cloud plume and the associated flash fire consequences, at low wind speeds, are simulated by assuming that, when the wind speed is less than 2 m/s, the flash fire concentration limit is LFL rather than 1/2LFL. This assumption significantly reduces the hazard ranges of the events at low wind speeds, although it can be seen that the actual risk is only reduced slightly. The reduced risk is evident up to around 350 m, beyond which only wind speeds of more than 2 m/s contribute to the total risk. It should also be noted that the risk associated with VCEs is unchanged, since it is assumed that escape from a VCE is not affected by lower wind speeds.

Greater ignition probabilities are considered in sensitivity study (g), which shows an increase in the overall risk due to the increased risk of flash fires. The increase is greater than that due to the additional weather categories, but is still relatively small.

Because of the relatively small hazard ranges associated with the various LPG release events, the variation in risk associated either with the additional weather categories or with other wind speed related assumptions is small. Since the modified escape parameters tend to reduce the risk, while the increased weather categories and greater ignition probabilities have the opposite effect, sensitivity case (h), which incorporates all of the modifications (combining the effects of studies (a), (c) and (g)), shows a relatively small change from the base case. The most significant factor is the modified escape modelling assumption, so the curve shown for case (h) closely follows that of case (c) (both of which include the increased number of weather categories). The risk in this final sensitivity case is consistently slightly higher than that shown for case (c), because of the increased ignition probability.

5.5. Modified LOX storage risk assessment

The sensitivity studies for the LOX risk assessment incorporated a number of the changes discussed in Section 5.1. The results are shown in Fig. 10, which should be compared with the base case results in Fig. 6.

Sensitivity study (a) used an identical approach to that used in the base case, except that, instead of D5 and F2 weather conditions, the more refined set of 8 weather categories (as used in the chlorine and bromine studies) was applied. Fig. 10 shows that this modification has very little effect on the predicted risk. The principal reasons for this lack of sensitivity are, firstly, that the source terms used as the inputs for the instantaneous model are not significantly dependent on the wind speed, and secondly, that the dispersion of oxygen down to the 11.4% (excess) level is largely dominated by the gravitational slumping of the initial ‘cylinder’ of oxygen vapour, and is not significantly affected by the wind speed.

Modelling the time dependent release of oxygen vapour predicted by LPOOL (or similar models such as GASP) as an instantaneous release is clearly a major assumption. Sensitivity study (e) therefore uses the full time dependent output from LPOOL as the input to the transient dispersion model HEGADAS-T (using D5 and F2 weather conditions as in the base case). This allows a more precise description of the time varying footprint of the vapour cloud, and hence a more accurate prediction of the risks. The results illustrated in Fig. 10 show that this gives a significant increase in the risk at all distances. The main reason for the increase over the base case risks is that there is no longer the major lateral spreading (and associated turbulence and dispersion) associated with the gravitational slumping of a large instantaneous release.

Sensitivity study (h) investigated the effect of using this fully time dependent approach with the more refined set of 8 weather conditions. Fig. 10 shows that this clearly results in a further increase in the level of risk at all distances, principally due to the inclusion of D1 and F1 weather categories (in F1 conditions, the predicted hazard range for the unbunded release is more than twice that predicted for F2 conditions in the base case). This effect is not apparent when modelling the release as an instantaneous cloud (base case and case (a)), in which case cloud advection results in the greatest hazard ranges at moderate wind speeds.

The conclusions from this LOX sensitivity study can therefore be seen to be rather different from those for the other materials. The greatest effect arises from the transient modelling which, when combined with more low wind speed categories gives a significant increase in the calculated risk.

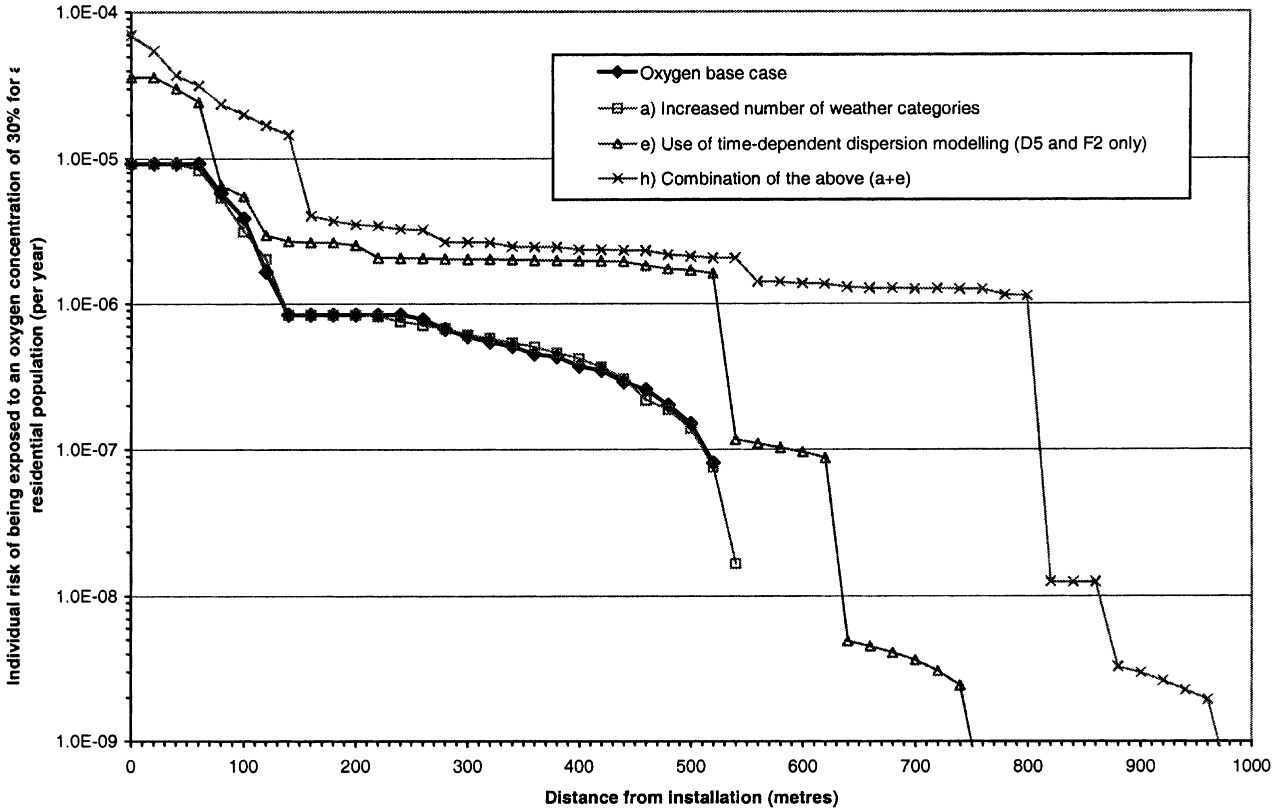

Fig. 10. Sensitivity results for LOX risk assessment.

6. Development of guidelines

It is recognised that the range of risk assessments discussed in this paper is not exhaustive. However, it covers many typical cases, and allows some general principles to be drawn out. These are discussed in this section, and some of the key points are summarised in the conclusions.

6.1. Use of meteorological data

All the studies described here use meteorological data which is based on the standard type of information provided by the Meteorological Office (e.g. 1 h averages). Ideally, for the purposes of major hazard risk assessments involving short duration releases, it would be preferable to use data based on shorter averaging times which are comparable with those of the release durations. Although data are not readily available in this form, it has been shown by Lines and Deaves [5] that a Weibull distribution fit to the moderate hourly mean wind speed (3–10 m/s) data could be extrapolated to give frequencies of low wind speeds, and that these frequencies would be representative of 10 min averaged data.

In practice, however, use of wind speed data is likely to be limited to the hourly means available from the Meteorological Office. The sensitivity studies have shown that wind speeds less than 2.4 m/s should be used, but that 1 m/s is likely to be the practical minimum below which confidence in the dispersion models is reduced. The set of 8 conditions presented in Table 3 is therefore recommended for most cases as a workable compromise between coverage of all the conditions and optimisation of computational effort.

6.2. Treatment of transient releases

One of the major difficulties with transient modelling is that it is not obvious in advance which particular combinations of scenario and weather category require transient modelling, and which can satisfactorily be modelled using a simple continuous plume model. In general, using instantaneous release models for short duration releases is fraught with problems, primarily in defining suitable initial source terms. The approach adopted here was to model all scenarios using a simple continuous plume, and then repeat with a transient model all those scenarios where the outdoor hazard range was greater than $1.5uT$. This approach represents an additional step in the risk assessment process, and could usefully be automated for practical application in QRAs involving large numbers of scenarios and weather conditions.

6.3. Persistence of wind conditions

The best way to allow for the fact that low wind speeds are unlikely to persist for long time periods (particularly with the wind blowing in a constant direction), is to evaluate the persistence time for each low wind speed weather category. In practice, a QRA could use a single persistence time (corresponding to the 50% probability level, as used in this study), but, if this effect was likely to be significant for the scenarios considered, it would be preferable to use a range of values, e.g. 10, 30, 50, 70 and 90% probability of the low wind speed weather category persisting. This data could be derived from site specific sequential meteorological data, but if this is unavailable then suitable assumptions may be made, as in Lines and Deaves [8]. Each persistence time can then be converted to a cloud travel distance, and the dispersion results should only be applied up to that distance. The risks at greater distances should be based on the dispersion modelling results for the next higher wind speed (which is likely to have a significantly longer persistence time). In principle, this process could be automated within a computerised risk assessment methodology.

6.4. Treatment of source and impact effects

Whilst the inclusion of extra weather categories is the most significant improvement which can be made to ensure that QRAs include the effects of low wind speeds, it is important to realise that there are knock-on implications which should also be considered. In particular, failure to include the following effects could lead to over-estimation of risk.

6.4.1. Evaporation rate

Where the material involved has a boiling point above normal ambient temperatures, the evaporation rate from a liquid pool will be strongly affected by the wind speed. Thus, any potential increase in hazard range due to the lower wind speeds will be partially offset by a reduction in the evaporation rate. This can be seen for the bromine QRA in Fig. 8, where the variant (a) includes both low wind speeds and reduced evaporation rates.

6.4.2. Release rate from buildings

For toxic materials which are stored within buildings, the release rate from the building will depend upon both the leak size and the wind speed. Small release rates in low wind speeds may be effectively ‘contained’ within the building, only emerging at a relatively low rate after some time has elapsed. Of the four risk assessments considered, this containment effect has only been applied for the chlorine case, where it was shown to be significant in reducing the calculated risk at most distances by up to a factor of around 3.

6.4.3. Infiltration effects

Infiltration rates will decrease as wind speed decreases, although the effects for practical buildings are not straightforward to estimate. Although some cognisance of this variation can currently be taken into account in risk assessments, it is likely that the effects will be particularly marked at low wind speeds, as shown by comparing lines (a) and (b) on Fig. 7 for the chlorine sensitivity study.

6.5. Dependence upon material type

The greatest effects of the inclusion of low wind speeds have been shown to occur for releases of toxic materials, such as chlorine and bromine. This occurs because toxic risks are strongly dependent upon far field hazard ranges, and infiltration rates, whereas for the particular flammables case taken (LPG), the hazard ranges are relatively short, and the overall risk is dominated by the BLEVE event, which is unaffected by wind speed. It is also interesting to note that, when *all* the suggested improvements are taken into account, the calculated risks for chlorine and bromine are actually *reduced* over much of the range of interest.

The LOX case provides an interesting example which does not fit neatly into the toxic/flammable divide indicated above. It differs from a typical flammables assessment because the risk is taken to be related purely to a threshold (relatively high) concentration, rather than requiring the modelling of fire events such as BLEVE, VCE or flash fire. It differs from a typical toxic assessment in that the threshold concentration is several orders of magnitude higher, and the risk is not related to an accumulated dose. It can be seen, however, that the LOX calculated risk is most sensitive to the variants considered, although it is clear from Fig. 10 that this is due to the inclusion of time-dependent modelling at least as much as it is due to the inclusion of low wind speed categories.

7. Conclusions

The following are tentative guidelines for including low wind speeds in QRAs, based upon the limited studies undertaken:

1. Use a greater number of *weather categories*, with specific emphasis on including low wind speeds. The 8 categories used in this study (see Table 3) are a reasonable assumption, but could easily be refined further by adding additional weather categories. Standard Meteorological Office data may be used to define frequencies, but shorter averaging times and site specific sequential data are preferable.
2. Detailed consideration should be given to specifying appropriate *air change rates* for occupied buildings. In particular, any air change rates for low wind speed categories should be lower than those for higher wind speeds. Specific recommendations are given in Section 5.1(2).
3. If hazard ranges are likely to be greater than 1 km then the effects of *persistence* should be incorporated for any low wind speed weather categories. This should be done by estimating a suitable persistence time τ for a particular wind speed, and then only using the dispersion results for that wind speed up to a distance of $u\tau$. At greater distances, the next highest wind speed category should be used. Ideally, a range of values of τ should be used with probabilities assigned to each [8].
4. Any continuous releases for which the hazard range is predicted to be greater than around $1.5uT$ (where T is the release duration) should be remodelled using a *transient* time-dependent dispersion model. This will tend to involve short duration releases with long hazard ranges (e.g. rapidly isolated chlorine releases).
5. Releases of vapour due to rapid evaporation or boiling from large spillages of refrigerated liquefied gases, such as oxygen, LNG or AHF, should not be modelled using simple instantaneous dispersion models. Ideally, a more refined set of weather categories should be used, together with the *full time-dependent vapour release* rate being used as the input to a transient dispersion model.
6. For toxic vapour *releases inside buildings*, the effect of the building should be incorporated, either by specifying a modified effective release rate and duration, or by using a full time-dependent source term, representing the efflux from the building, as input to a transient dispersion model.

It is emphasised that it is not appropriate to include only a few of the above recommendations. For example, merely including extra low wind speed categories could lead to a significant overestimate or underestimate of risks unless other issues such as persistence, time dependence and modified air change rates are also considered. Each type of QRA will need to be considered individually to determine the relative importance of the above factors. However, in general, the guidelines given above represent a reasonably sound and practical approach for the inclusion of low wind speeds in typical risk assessments.

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