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

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

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Several earlier studies have identified that, although they are not normally considered in risk assessments or safety cases, low wind speed conditions are likely to produce most of the worst case dispersion conditions. A validation study was also undertaken, which demonstrated reasonable confidence in the application of current dense gas dispersion models at low wind speeds down to around 1 m/s.

The study presented here has therefore drawn together the results of all the previous studies, and provided guidelines on 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 LOX, 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. Most importantly, it also showed that, when low wind speeds are included, it is not only their dispersion effects, but also their effects on release rate and impact on the population which need to be considered to ensure that the calculated risks are neither overly conservative nor optimistic.

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1. INTRODUCTION

1.1 Definition of low wind speed

A 'low wind speed' in the context of dense gas dispersion can be defined in a number of ways. Various possible criteria are discussed in Appendix A (based upon Webber(1998)), where it is shown that they are essentially equivalent to those which are used to determine the onset of density effects. Effectively, a low wind speed can therefore be considered as one in which the source effects dominate over the atmospheric turbulence over a significant part of the near field dispersion.

Clearly, where there are strong source effects, they may dominate for some distance even where the mean wind speed is relatively high. Many current dense gas dispersion models would be valid for such cases, and could be considered to be reasonably accurate, having in most cases been validated by full scale data at a representative range of wind speeds. The more interesting cases are those for which these effects occur at lower wind speeds, for which there is little available validation data, partly because of the difficulties of obtaining good data in these particular types of atmospheric conditions, which can be extremely variable.

For the purposes of this study, a low wind speed is defined by reference to current usage in risk assessment studies. Thus, for practical application in QRA, wind speeds of 2.4 m/s or less are considered 'low', although it is recognised that this definition is not universally applicable.

1.2 Previous studies

A preliminary study into the effects of low wind speed on gas dispersion was reported by Lines & Deaves(1998). This focused on three areas:

- the prevalence of low wind speed conditions
- methods for calculating dispersion in low wind speeds
- implications to the risks calculated in safety cases.

A literature review was undertaken to ensure that all relevant information was used. In addition, the Meteorological Office was consulted, and good quality data were obtained for four sites so that the frequency of low wind speed conditions could be estimated. Finally, the implications for safety cases and risk assessments were determined by specific reference to results from the HSE risk model RISKAT.

A further study was then undertaken to assess the implications for risk assessments of dispersion in low wind speeds (Lines & Deaves(1998)). The specific objectives for the second study were:

i) To undertake a realistic QRA to determine the significance of using a more representative set of weather categories;

ii) To identify relevant data for validation of dispersion models at low/zero wind speeds;

iii) To consider the feasibility of developing a simple methodology to assess dispersion in low/zero wind speeds.

The preliminary study found that there was no generally applicable model that could be used for the range of risk assessment type applications in low/zero wind speeds. The later study therefore explored several possible approaches in order to determine possible ways forward and to consider whether it was worthwhile developing such models further; it did not,
however, include any detailed model development. Nevertheless it did include consideration
of a realistic QRA which helped to determine those types of event where improved modelling
of low wind speeds could have the greatest impact.

Some of the results from these first two studies have been published more widely by Lines &
Deaves(1997a, 1997b), where the focus has been on practical applications in QRA studies.

A further follow-on study has been undertaken, (Lines, et al(2000)) which provided an
independent validation of three currently used dense gas dispersion models against low wind
speed data. This has allowed improved levels of confidence in the use of such models, and
identified that there is no immediate need for further specific model development to cover low
wind speed conditions.

1.3 Objectives

Quantified Risk assessment 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 HSE to advise local planning authorities on planning applications in their
vicinity. Although HSE gives advice on all types of development, the advice is based on risk
to a hypothetical householder, present all of the time and indoors most of the time. Where
large outdoor populations are likely to be present, for example at sports grounds, different
assumptions may be necessary. 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.

The earlier studies alluded to above have demonstrated the sensitivity of far field risk
calculations to low wind speed conditions. The Phase 2 study (Lines & Deaves(1996))
considered a particular base case chlorine risk assessment and demonstrated ways in which
low wind speed effects could be included, even using current dense gas dispersion models. It
showed that risk results were sensitive to the number of additional low wind speed categories
considered, and also depended on whether finite duration releases were treated as either
continuous or transient. Wind speed persistence effects were also considered, and some
tentative suggestions provided regarding how to incorporate them.

It was therefore the objective of this study to extend the work which was commenced in the
Phase 2 study to provide detailed guidelines for the inclusion of low wind speed effects into
quantified risk assessments. 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.

1.4 Scope of work

1) Identify typical risk assessments. This was undertaken by considering the sites which
now fall under COMAH, and identifying common types of installation which would
be considered. It has been agreed that this would include the following generic types
of installation:
   - Chlorine storage site (toxic gas)
   - Bromine storage site (toxic liquid)
   - LPG storage site (flammable/explosive liquefied gas)
   - Liquid Oxygen (LOX) or LNG storage site (flammable liquefied gas)
2) Ascertain scenarios contributing most to risk. For each risk assessment considered, a range of scenarios which have the most significant contribution to risk in the near, medium and far fields were used.

3) Consider transient and persistence effects. Some exploration of these effects has been undertaken in the Phase 2 study. This work is extended to consider the implications of using transient wind data i.e. with the wind speed increasing after maybe a few minutes of a low wind speed episode.

4) Consider accuracy and capabilities of current models. This subject is covered in the parallel model validation study (Lines et al(2000)). Conclusions are therefore drawn from that study which are relevant to the risk assessments identified in Task 1, and the scenarios identified in Task 2.

5) Ascertain optimum use of dispersion modelling. This task focuses upon the scenarios identified in Task 2. It considers both the transient/persistence effects as noted in Task 3 and also the number and definition of additional low wind speed classes which should be considered.

6) Draw up guidelines specific to the various risk assessment types identified in Task 1. This draws upon the work done in Tasks 3-5, and also provides comments on how the guidelines should be modified for other materials or conditions likely to be encountered in risk assessments.

7) Produce a report for the guidance of HSE risk assessors. It may also be considered appropriate to produce this for wider dissemination, for example as an IChemE monograph. The aim of such a document would be to help raise the awareness of the potential significance of low wind speed conditions, and to demonstrate the practical approaches that are currently available.
2. USE OF DISPERSION MODELS

2.1 Models considered

As noted in Section 1.2, a parallel study has been undertaken to provide validation of current dense gas dispersion models at low wind speed. The three models which were examined within that study were:

- HGSYSTEM Version 3.1 (Shell Research)
- GASTAR Version 3.05 (Cambridge Environmental Research Consultants)
- DRIFT Version 2.23 (AEA Technology)

These are currently considered to be three of the most appropriate dense gas dispersion models for practical use in safety case and risk assessment applications. It is noted that other studies (CCPS 1996) have identified over 100 different dispersion models, but, since it was not feasible to conduct a detailed examination for such a large number, the above selection of just three was agreed with HSE as part of the scope for the validation study. GASTAR and DRIFT are of particular interest to the HSE, who were involved in their development, and HGSYSTEM is a widely used and widely applicable model that is publicly available.

2.2 Considerations of model assessment

2.2.1 Previous validation studies

All three of the models considered in the validation study have been subject to varying degrees of validation over recent years. However, it is worth noting that all of the published independent validation studies and evaluations relate to earlier versions of the models. For example, Hanna et al. (1993) used the following versions:

HGSYSTEM Version 1.0 (Nov 90)
GASTAR Version 2.22 (1990)
(DRIFT was not included in Hanna’s review)

None of these studies refer specifically to low wind speeds, although they did include some low wind speed data.

Chapter 10 of the HGSYSTEM Technical Reference Manual (Post 1994) describes the validation of the more recent HGSYSTEM Version 3.0 against the same set of data that was used by Hanna (i.e. the Modellers’ Data Archive). HGSYSTEM Version 3.0 has also been included as one of the models in a recent review by the US Department of Energy (Lazaro et al. 1997). There is no published validation or model evaluation that relates specifically to the current version of HGSYSTEM, although it is emphasised that some (but not all) of the changes would have little impact on the validation studies conducted for earlier versions.

Since Hanna’s study, there do not appear to have been any more recent published validation studies for GASTAR.

The initial verification and validation studies for DRIFT (Jones et al. 1993) related to DRIFT Version 2.03. Jones et al describe the validation of this earlier version of DRIFT against test data from:

- Thorney Island
- Heinrich et al. (1991)
- Lyme Bay
Predicted results are compared with observations in a number of graphs, but no quantitative evaluation statistics are given. It is also noted that some of the data (e.g. from Thorney Island) were used to help define some of the empirical constants within the models, and so cannot be regarded as independent validation data.

2.2.2 Methods of comparing modelling results

In most datasets used for comparison, concentrations are given at various distances downwind of the source. For continuous releases these would be time averages, whereas for instantaneous releases they may be peak values. In some cases, the dataset indicates the averaging time which was used. Although for some datasets it would be possible to obtain more detailed information on the time variation of the concentration, in most cases use of such detail would go beyond the scope of a normal model evaluation, and was therefore beyond the scope of the validation study.

Further comparison measures could be used, such as cloud area, hazard range or dose. Cloud widths, cloud passage times and doses would be particularly valuable comparisons because of the influence of those parameters on risk calculations. In most cases, however, there is insufficient information available to allow the confident use of any of these other measures as a comparison.

2.3 Model performance at low wind speed

2.3.1 Limitations of validation study

The focus of the validation study was on using low wind speed data to validate current dispersion models. Since experiments to collect such data are relatively rare, and also present more measurement problems than those in higher wind speeds, there are relatively few datasets which satisfy the required criteria for low wind speed. When useful datasets were collated it was found that the data for several of the cases were not readily available in a form in which they could be used for validation. This resulted in a relatively limited subset of the data being used, although it was chosen, as far as possible, to cover the expected ranges of both wind speed and Richardson number.

For many of the trials considered, measurements were available only at relatively few measurement points. These would generally have been chosen to be as close to the downwind centre-line as possible, and would therefore not necessarily enable plume parameters such as width or height to be determined. In practice, the comparison method chosen, as described in Section 2.2.2, was sensitive to the use of data from the edge of the plume, where variability in concentration measurements could result in large contributions to the calculated statistical parameters. For these two reasons, most of the comparisons related to downwind concentrations on or near the centre-line, and gave no information on whether the integral plume parameters, such as width and height, were correctly modelled.

Another potential problem for toxics is the long distance effect. Most trials report near field concentrations but toxic effects are predicted over very long distances, for which there may be no validation at all.

The other significant limitation, which has already been alluded to above, is in the range of wind speeds considered. Thus, availability of data resulted in only 2 wind speeds less than 1.5m/s, one of which was an extremely low wind speed (0.2m/s) jet case. Most of the validation is therefore given in the range 1.5-2.5m/s. Attempts to fill gaps in the data using wind tunnel modelling ran into practical problems of running the tunnel at low speeds and of

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applying appropriate scaling. In the event, by using the very dense gas krypton, the lowest scaled wind speed which was obtained was 1.7m/s. (The results were presented in Appendix C of Lines et al(2000)).

2.3.2 Comparison with other model validation and model evaluation studies

The guidelines produced by CCPS (CCPS (1996)) include a useful section giving details of commonly used vapour cloud models. This includes all three of the models used in the validation study, and is followed by a section giving a useful summary of recent studies which evaluated some of these models against full scale data. The database used included trials from Burro, Maplin Sands and Thorney Island, together with others which had either passive releases or were at a higher wind speed. The data used covered a wide range of source conditions, and wind speeds which ranged from around 1m/s to 10m/s, but with most in the range 4-8m/s.

Plots of geometric variance (VG) against geometric mean bias (MG) were provided for various models for instantaneous and continuous releases. Although these included HGSYSTEM and GASTAR, they did not cover results from DRIFT. They showed that, for all models, MG was generally in the range 0.5 < MG < 2.0, and 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. In general, the values obtained were consistent with the limits noted above. Full details are given in Lines et al(2000), and brief discussion of the exceptions is given below. A summary of the results in the same VG vs MG format, but excluding jet releases, is shown in Figure 2.1.

![Figure 2.1 Summary results for validation study of Lines et al(2000)](image-url)
Jet releases

The GASTAR results were outside the ranges of MG and VG indicated above, but this is not surprising as jets tend to have relatively small dimensions and so the results at any particular sensor can be very sensitive to the plume trajectory and local turbulence effects. One feature of these tests is the elevated plume trajectories, which gives the potential for large modelling errors caused by a slightly incorrect prediction of the plume centre-line.

Instantaneous releases

All the results in this category were very good, which was probably a reflection of the development routes of the models used; i.e. they would all have been well tested against the original Thorney Island data.

Evaporating pool release

The DRIFT results were outside the ranges of MG and VG. The other results were generally good, although they show a slight deterioration as the wind speed is reduced.

Low velocity vapour releases

Just one set of GASTAR results was outside the MG and VG ranges. Although the other results were reasonable, there was possibly a slight tendency towards deterioration at lower wind speeds.

An alternative presentation is given by CCPS\textsuperscript{(1999)} in which the ratio of predicted to observed concentrations, \(C_p/C_o\), is plotted in bands of wind speed. The result (their Figure 8-5) suggests a deterioration in model accuracy at the lowest wind speed band. Summaries of the results from this validation study (94 data points) are presented in a similar form in Figures 2.2 - 2.4, from which clearly outlying results, with \(|\log(C_p/C_o)| \geq 2\) were omitted. Whilst there are clearly some trials which are not well modelled, these results do not imply a significant deterioration in model performance as the wind speed is reduced.

Figure 2.2 Scatter of results from HGSYSTEM
2.4 Areas identified for improvement

The following areas for improvement in the use of dispersion models were identified by the validation report.

Use of Models

One of the key results from the study was that existing models can be used with reasonable confidence at low wind speeds, provided that care is taken and especially that the source can be accurately characterised within the model. Therefore, in terms of the use of dispersion...
models at low wind speeds, the area which requires most attention is the need for guidance on how to model the source terms, and hence provide appropriate inputs; this may often mean that some external models or rules of thumb are required to handle the very early stages of a release. This could, for example, involve the specification of initial cloud dimensions, concentrations and temperatures. The problem is that, in most cases, actual scenarios in safety cases, risk assessments or field trials do not correspond exactly with the theoretical source characteristics in the model. In practice, there is a need for consistency of approach when applying QRA to similar types of installation, and this has to be balanced against the desire for greatest modelling accuracy.

Furthermore, some dispersion models (such as the HEGADAS module of HGSYSTEM, and GASTAR) allow the user to specify complex source characteristics (such as time varying releases) but these features are rarely used, due both to the additional modelling effort involved, and also to the additional uncertainties which their use may introduce. The provision of guidance, including that for the use of such features, is the subject of the remainder of this report.

**Better provision of data from trials**

The study showed not only that there is a limited amount of relevant data from trials at low wind speeds, but also that many of the trials that have been conducted cannot be accurately characterised in terms of the source definition for use in typical dispersion models. Furthermore, the presentation of information from trials needs to be improved, for example to remove uncertainties and ambiguities, before it can be used for any kind of model validation.

**Development of better dispersion models for low wind speeds**

There did not appear to be any obvious areas for major scientific improvement of models, based on the limited validation study. There are some developments that are taking place, such as Shell's HEGLOW model (Roberts(1999), which is a low wind speed model based on HEGABOX. However, the greatest scope for improvement in the short term is the better use of the existing models.

**Validation**

The study highlighted the fact that there is no published validation for the current versions of any of the dispersion models considered. Whilst some limited validation at low wind speeds was undertaken, it was shown that there is a need for a more wide ranging and independent validation project to cover all those models likely to be used in safety cases and risk assessments in the UK, particularly those used by regulators such as the HSE. Previous validation exercises provide some useful approaches, but the quoted statistics must be questioned in view of some of the uncertainties identified in the course of the validation exercise.

It should be noted that methods of evaluating dispersion models have been developed within the SMEDIS (Scientific Model Evaluation of DIspersion models) project (Daish et al(1998)). This has included protocol on the validation of such models, but has not yet been widely disseminated.

### 2.5 Importance of wind speed persistence time

It has been previously shown by Lines and Deaves(1997) that very low wind speeds are unlikely to persist for long periods. Lines & Deaves(1998) refined this analysis, and showed that the maximum downwind travel distance for a release in a low wind speed $u(<1.5)$ m/s is approximately $3000u^2$ m. It was also suggested that continuous plume models should not be
used when $s > 1.5 \mu T$, 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 minute release durations in the schematic diagram of Figure 2.5, which can be used to draw practical conclusions which are pertinent to quantified risk assessments.

![Figure 2.5 Choice of dispersion model as a function of wind speed and distance of interest](image)

For example, if one were interested in the risks at 1000 m from a major hazard site, then Figure 2.5 indicates that:

a) any wind speeds of less than 0.7 m/s are unlikely to persist long enough for the release to travel 1000 m at this speed, 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;

b) wind speeds from 0.7 to 2.2 m/s (i.e. in Region B) should be modelled using a transient dispersion model;

c) wind speeds above 2.2 m/s may be modelled using a continuous plume model.

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

a) it should not be used to predict any risks beyond 3000 m;

b) a transient dispersion model should be used to calculate risks from 450 to 3000 m;

c) 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 Figure 2.5 depends on the release duration. The figure shows the transition line for a 5 minute release, and this has been used in the examples described above. Furthermore, the boundaries of the regions on Figure 2.5 are not very clearly defined and so should only be regarded as being indicative. For example, it is possible that a wind speed of 1 m/s could
persist for longer or shorter than 3000 seconds, as shown in Lines & Deaves\textsuperscript{[1998]}, so that probabilities could be associated with a range of persistence times.

In QRA studies which use very low wind speeds ($<0.4\text{m/s}$) then Figure 2.5 indicates that 5 minute duration releases should only be modelled using such low speeds up to at most 200m. 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.
3. RISK ASSESSMENT STUDIES

3.1 Background

3.1.1 Selection of types of site

It has been shown in previous studies that the significance of low wind speed conditions depends on the type of release being considered. Therefore, in order to be able to draw up some widely applicable guidelines, it is necessary to consider a range of types of major hazard installation.

The four main types of installation which have been chosen for analysis are:

a) Chlorine storage site (toxic gas)
b) Bromine storage site (toxic liquid)
c) LPG storage site (flammable/explosive liquefied gas)
d) LOX or LNG storage site (flammable liquefied gas)

This choice was based on the fact that these types of installation are representative of many major hazard sites, and the substances involved represent a range of hazard types, including some concentration and dose based harm criteria:

For each type of installation, the following stages of analysis were undertaken:

- Identification of relevant scenarios;
- Base case modelling (with no explicit consideration of low wind speeds);
- Consideration of significance of low wind speeds to specific scenarios;
- Results of including low wind considerations on the overall risk results;
- Discussion of significant low wind speed effects, by consideration of individual scenarios.

It is emphasised that the analyses in the remainder of this report relate to hypothetical installations, and that the release rates and frequencies quoted here should not be used for any specific installation. However, the scenarios and frequencies chosen are considered to be sufficiently representative of typical installations to allow conclusions to be drawn regarding the inclusion of low wind speeds in risk assessments.

It should also be noted that the chlorine storage site, as identified by Carter et al. (1993), has been the subject of a number of studies involving both mitigation effects (Lines et al. (1998)) and low wind speed effects. Thus, much of the background risk assessment was available in some detail, and this detail has been retained in this study. For the other materials, representative scenarios only have been used for the purposes of determining the low wind speed effects.

3.1.2 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.

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 & Nussey\textsuperscript{1985}), where the letters correspond to the Pasquill stability category (D for neutral and F for stable), and the numbers correspond to the wind speed in m/s. The percentage frequencies of these four 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 low wind speed 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. Directionality has not been considered, although it is recognised that wind direction during the 30 minutes or so of a typical incident could be extremely variable when the wind speed is low.

**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, where outdoor exposure occurs for 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 2 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 minutes after the cloud has passed before evacuating to fresh air, but in no case does evacuation take place until at least 30 minutes 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.

**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 (Lines\textsuperscript{2000}). This code has been used because it is possible to incorporate the effects of various improvements in terms of the modelling of low wind speeds, which will be required in the sensitivity studies aimed at assessing the significance of low wind speeds.

The risk assessment calculation methodology and assumptions described above are also typical both of the assumptions made when giving Land Use Planning advice, and of those used in the HSE’s code RISKAT for toxic gas releases. The principal difference lies in the fact that RISKAT uses the older CRUNCH and DENZ codes for the gas dispersion modelling.

**3.2 Base case risk assessments**

**3.2.1 Chlorine storage site (Toxic Gas)**

In order to quantify the risks associated with potential chlorine release events, it is first necessary to define a set of representative events which covers all possible significant accidents that could occur. The release rate of chlorine and the frequency of each of these events then needs to be determined. This definition of the scenarios is in many ways the most
difficult part of any risk assessment, often requiring considerable expertise and detailed calculations of release rates and frequencies. Once selected, they form a representative set for all assessments of that type of installation. This is important, otherwise comparisons become impossible and inconsistency creeps in. One such set of representative scenarios (from Carter, Deaves and Porter1999), corresponding to a typical small chlorine installation, has been used in this study.

The set of representative events which is used for the base case analysis is summarised in Table 3.1, in which a 'full' aperture represents a guillotine failure. It should be noted that a slight adjustment to the event frequencies has been made in taking the scenarios from the Carter et al example. It was noted that the original frequency of the road tanker coupling event resulted in this event dominating the risk. The latest evidence suggests that this frequency is too high, and it would in any event be reduced on sites which had a lower frequency of road tanker deliveries. By reducing this frequency by a factor of 10, this event ceases to dominate the risk, and the resulting risk assessment is still considered to be representative of a typical chlorine storage site.

The dispersion of chlorine vapour clouds has been assessed using the models in the latest version of HGSYSTEM (Version 3.1, Post1994). Continuous releases have been modelled using the HEGADAS-S code, and instantaneous releases have been modelled using HEGABOX followed by HEGADAS-T. The continuous releases are assumed to have an initial aspect ratio (height/half-width) of 2.0, and the instantaneous releases are assumed to have an initial aspect ratio (height/radius) of 1.0. The initial air entrainment is defined in terms of the mass dilution ratio (air/chlorine) which is assumed to be 2.5 for continuous releases, and between 4.2 and 9.7 for the instantaneous releases (depending on the mass of chlorine involved).

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 108,000ppm/min. The possibility of escape from the cloud is modelled by assuming that, at concentrations between 300 and 500 ppm, there is a 20% chance of escape for persons outdoors, and that below 300 ppm there is an 80% chance of successful escape. In both cases, 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 Figure 3.1, in which the contributions to risk from each weather category have been indicated. This shows, as expected, that the lower wind speed conditions dominate the risk in the far field.
<table>
<thead>
<tr>
<th>Event</th>
<th>Aperture (mm)</th>
<th>Rate (kg/s)</th>
<th>Duration (minutes)</th>
<th>Frequency (cpm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Storage vessels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catastrophic failure</td>
<td>-</td>
<td>18 te</td>
<td>Inst.</td>
<td>1</td>
<td>Two vessels</td>
</tr>
<tr>
<td></td>
<td>3 te</td>
<td>Inst.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 te</td>
<td>Inst.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 te</td>
<td>Inst.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid space</td>
<td>50</td>
<td>44</td>
<td>6.8</td>
<td>2</td>
<td>Vessel &amp; nozzle failures</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>11</td>
<td>27.2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>2.8</td>
<td>30</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.69</td>
<td>30</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Vapour space</td>
<td>50</td>
<td>2.63</td>
<td>30</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1.3</td>
<td>30</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.42</td>
<td>30</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.1</td>
<td>30</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Pipework 25 mm diameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road tanker delivering liquid</td>
<td>Full</td>
<td>7.4</td>
<td>20</td>
<td>0.25</td>
<td>1st section</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>5.9</td>
<td>20</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.15</td>
<td>20</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flanges</td>
<td>1.5</td>
<td>20</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>To vessel</td>
<td>Full</td>
<td>4.6</td>
<td>20</td>
<td>9</td>
<td>2nd section</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3.6</td>
<td>20</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.15</td>
<td>20</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flanges</td>
<td>1.4</td>
<td>20</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Vessel outlet</td>
<td>Full</td>
<td>4.2</td>
<td>20</td>
<td>1</td>
<td>Pre-ROSOV</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3.2</td>
<td>20</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.17</td>
<td>20</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flanges</td>
<td>1.1</td>
<td>20</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>ROSOV to plant</td>
<td>Full</td>
<td>2.7</td>
<td>5</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2.1</td>
<td>5</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.11</td>
<td>5</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flanges</td>
<td>0.73</td>
<td>5</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>In plant</td>
<td>Full</td>
<td>0.23</td>
<td>5</td>
<td>2</td>
<td>CV+ROSOV available</td>
</tr>
<tr>
<td>Road tanker coupling</td>
<td>Full</td>
<td>7.4</td>
<td>20</td>
<td>6</td>
<td>20 deliveries per year</td>
</tr>
</tbody>
</table>

Note: Taken from Carter, Deaves and Porter (1998), but frequency of road tanker coupling event reduced by a factor of 10.

Table 3.1 Representative events for Chlorine QRA
3.2.2 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:

a) catastrophic failure of bulk tank
b) partial failure or hole in bulk tank
c) failure of liquid pipework (including leaks at pipework fittings)
d) pipework or connection failure during loading/offloading of ISO tanks
e) bromine vapour release due to failure of vapour pipework

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:

- area of the spill
- temperature of the liquid
- vapour pressure of bromine (and its other physical properties)
- wind speed over the spill

Only the first of these parameters (spill area) is likely to vary significantly between different events. Therefore, for the purposes of this generic risk assessment, it is possible to consider just a small number of representative bromine releases, characterised by the spill area, i.e.

- small local spill (4 m²) Frequency of 10² per year
- bunded spillages (40 m²) Frequency of 10³ per year
- unbunded spillages (400 m²) Frequency of 10⁴ per year
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, there was overtopping/leakage from a bund, or where the water may have drained away, frozen or evaporated. The 40m² release may also be representative of moderately sized unbunded releases. The 400m² '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.

Each of the frequencies is representative of the total frequency of a number of slightly different events, each of which would have similar consequences. The frequencies quoted are only intended to be indicative, illustrating that larger releases tend to be less frequent.

The evaporation rates from liquid bromine pools have been calculated using the method of MacKay and Matsugui (1973), as described by IChemE (1995). 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 minutes. It is noted that the evaporation source term depends on the wind speed, and so there is a different source term for each weather type in the risk assessment.

The risks that are shown in Figure 3.2, 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 min). As in Figure 3.1, they show the risk broken down into the contributions from each of the four basic weather categories.

Figure 3.2 Base case risk for bromine, showing contributions from each weather category
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) **BLEVE (Boiling Liquid Expanding Vapour Explosion)**

   This occurs as a result of fire impingement on a vessel. It would result in a major fireball.

2) **Catastrophic Tank Failure**

   This 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.

It is emphasised that the above events are only intended to be representative of the range of events that could occur, and that a more detailed plant-specific analysis would require the consideration of a large number of events based on the results of an event tree analysis. In addition, it would be necessary to consider various fill fractions and alternative pipework leak locations/sizes.

As noted, immediate ignition would result in pool or jet fires. These have a relatively limited range and are unlikely to dominate off-site risk, although they have the potential to escalate to a BLEVE event, which is considered. In addition, they are unlikely to be greatly affected by low wind speeds. Only delayed ignition effects have therefore been considered for scenario types 3) & 4). Each of scenario types 2), 3) & 4) are therefore considered using the event tree shown in Figure 3.3. The frequency of the vapour release under consideration is then multiplied by the probabilities relating to immediate ignition ($p_i$), delayed ignition ($p_d$) and flame acceleration ($p_a$) to obtain the frequencies of VCE or flash fire. 'Vapour cloud' at the output from the event tree relates to an unignited vapour cloud; although there is the potential for asphyxiation at high concentrations (>~25%), it is assumed in this study that this event has no hazardous consequences.
The resulting set of scenarios considered is given in Table 3.2. For each scenario, the frequency given covers all possible ways of achieving that release; for example, 'major' releases from liquid space of the vessel or from liquid pipework are combined to give Scenario 2c. The 'event frequency' refers to the likelihood of each release occurring, rather than the frequencies of the consequences, which may be derived from Figure 3.3. In addition to the scenarios given in Table 3.2, the BLEVE event is considered, with a frequency of $10^{-3}$/yr. Its consequences are dependent only upon the quantity of propane released (assumed to be 50t) and not on any dispersion characteristics.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Release location</th>
<th>Release type</th>
<th>Phase</th>
<th>Release rate (kg/s)</th>
<th>Dispersion mode</th>
<th>Event Frequency (/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>2&quot; vapour line or vessel vapour space</td>
<td>full bore 'major'</td>
<td>vapour</td>
<td>4.25</td>
<td>jet/plume</td>
<td>$2\times10^{-4}$</td>
</tr>
<tr>
<td>1b</td>
<td>2&quot; vapour line or vessel vapour space</td>
<td>full bore 'major'</td>
<td>vapour</td>
<td>0.43</td>
<td>jet/plume</td>
<td>$2\times10^{-3}$</td>
</tr>
<tr>
<td>2a</td>
<td>Liquid, vessel or pipe</td>
<td>1&quot; full bore (vessel)</td>
<td>liquid</td>
<td>7.80</td>
<td>slumping</td>
<td>$2\times10^{-4}$</td>
</tr>
<tr>
<td>2b</td>
<td>Liquid, vessel or pipe</td>
<td>1&quot; full bore (pipe)</td>
<td>2-phase</td>
<td>2.12</td>
<td>slumping</td>
<td>$2\times10^{-4}$</td>
</tr>
<tr>
<td>2c</td>
<td>Liquid, vessel or pipe</td>
<td>'major'</td>
<td>liquid</td>
<td>0.78</td>
<td>slumping</td>
<td>$2\times10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>Vessel failure</td>
<td>catastrophic</td>
<td>2-phase</td>
<td>50 tonnes</td>
<td>slumping</td>
<td>$1\times10^{-4}$</td>
</tr>
</tbody>
</table>

Table 3.2  Release rates from propane plant

For the purposes of this base case assessment, the likelihood of a jet fire/VCE/flash fire is assumed to be equally distributed in all weather conditions.

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

- receiving a dangerous thermal load of 1000 kW/Ks for BLEVEs,
- being within the $\frac{1}{4}$LFL 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 of Kingery & Pannill[1994] 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 80m and 220m downwind from the source. These are such that a VCE based upon a stoichiometric cloud of propane (covering a volume of 300 or 1000m³ respectively) is assumed to occur if the centre of the congested area is within the LFL contour.

The risk from 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 for the cases given in Table 3.2 has been modelled using HEGABOX and HEGADAS-T for the catastrophic failure case (Scenario 3), and HEGADAS-S for Scenarios 1a to 2c.

The risks from all events have been summed and the results, excluding the risks from the dominating BLEVE event, are shown in Figure 3.4, 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 (50t) release, which, being effectively instantaneous, travels further before being diluted below ½LFL.

![Figure 3.4 Base case risk for LPG, shows contributions from each weather category (excluding BLEVE event)](image)
3.2.4 LOX or LNG storage site (Flammable Liquefied Gases)

This analysis is based on a typical 1000 tonne 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 effects are primarily due to ignition and subsequent fire, there is also the potential for cold stress in regions close to the source.

The scenarios which will be considered are:

1. Failure of tank resulting in a major release contained within the bund.
2. 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 Scenario 1 the pool area is based on a 35m diameter bund and the vapour release is assumed to continue for a period of 30 minutes. In the second scenario, the release is assumed to form an unconfined spreading pool. The frequencies for Scenarios 1 and 2 are taken as $10^{-7}$ and $10^{-9}$/year respectively.

It is noted that, in addition to the fairly catastrophic events considered above, there is a wide range of lesser events that could occur, such as pipework failures etc. However, analysis shows that the hazard ranges and risks associated with these lesser events are not significant, because of the relatively high concentration harm criterion; they are therefore not considered as part of this analysis.

The major failure is assumed to result in the entire contents of the tank being released over a short time (approximately 30 seconds). 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 the hazardous level of 30% (11.4% excess). The indoor concentration is calculated on a transient basis for each scenario as the cloud passes, and the conditional risk is assumed to be 0 unless the oxygen concentration reaches 30%, in which case it is 1.

The results of the base case risk assessment are shown in Figure 3.5, 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 400m 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 3 reasons for this:

a) For the large instantaneous scenarios considered, hazard ranges are similar in both D5 and F2 conditions

b) D conditions occur 4 times as frequently as F conditions

c) 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 will shortly be moving to a higher enrichment factor of 35%, as recommended in BCGA\textsuperscript{(1999)}. This will reduce hazard ranges and lessen the significance of small events in terms of off-site risk.

![Graph showing risk vs distance from intake]

**Figure 3.5** Base case risk for LOX, shows contributions from each weather category

### 3.3 Qualitative assessment of low wind speed effects

#### 3.3.1 General frequency considerations

Explicit consideration of low wind speeds will not affect the fundamental likelihood of any of the scenarios for any of the assessments considered. The principal frequency consideration is that the dispersion of vapour can be very different in low wind speeds, and it is obviously important that the frequency with which such conditions occur should be accurately incorporated. Some frequencies considerations do, however, apply to the LPG case, and these are discussed in Section 3.3.4

#### 3.3.2 Chlorine storage site (Toxic Gas)

**Source terms**

For a chlorine storage site, wind speed is unlikely to have a major effect on the source terms used in the risk assessment. Possible ways in which low wind speeds could be significant are:

- for those releases which occur inside a building, a reduced rate of leakage of chlorine due to the reduced external pressure driving forces. Many of the significant scenarios tend to result in pressurisation of the building, and external wind pressure forces would then be less significant in determining the leak rate to atmosphere. However, there will be some lower release rate conditions where the leak rate from the building may be affected by wind speed. This has been assessed in more detail in the GRAB (Spencer & Deaves\textsuperscript{(1997)}) and GRAB-T (Shepherd & Deaves\textsuperscript{(1999)}) model developments.
although most risk assessments for chlorine tend to assume that 100% of the release rapidly forms vapour, it is likely that some releases in confined areas could lead to pools of liquid chlorine. The evaporation rates from such pools would depend significantly on the wind speed (as will be discussed later in the case of bromine).

Gas Dispersion

As noted above, the principal effect of low wind speeds is to cause a major impact on the concentration-time history of the plume at all downwind locations. In addition, at low wind speeds there is an increased probability of some significant upwind and crosswind spreading of the cloud. (Thus risks may extend upwind of the source and the increased cloud widths increase the risks calculated.) However, the likelihood that the wind persists in the same direction for the duration of the release tends to be lower at reduced wind speeds.

Impact Assessment

At low wind speeds, gas clouds will take longer to reach a particular downwind location, perhaps allowing a greater probability of escape. Conversely, the gas cloud will tend to persist for longer and will be wider than at higher wind speeds, making escape more difficult in some circumstances. The normal assumption that exposure time is equal to release duration is less valid at low wind speeds. Doses would accumulate from lower concentrations, making cross-wind escape more difficult.

At low wind speeds, the rate of gas infiltration into buildings is also likely to be reduced because:

- low wind speeds occur more frequently at night when doors/windows are likely to be closed;
- the lower wind speeds generate lower wind pressure driving forces, thus reducing infiltration.

3.3.3 Bromine storage site (Toxic liquid)

Source terms

The evaporation rate of bromine from a liquid pool is proportional to $u^{0.78}$ in most commonly used evaporation models such as MacKay and Matsugu (1973) or Clancey (1974), which are all based on the original work of Sutton (1953). Lower wind speeds therefore imply lower source terms for the same scenario. However, it is assumed that wind speed has little or no effect on the size of the pool.

Gas Dispersion

As noted above, the principal effect of low wind speeds is to cause a major impact on the concentration-time history of the plume at all downwind locations. In addition, at low wind speeds there is an increased probability of some significant upwind or crosswind spreading of the cloud. However, the likelihood that the wind persists in the same direction for the duration of the release tends to be lower at reduced wind speeds.

Impact Assessment

At low wind speeds, gas clouds will take longer to reach a particular downwind location, perhaps allowing a greater probability of escape. Conversely, the gas cloud will tend to
persist for longer and is likely to be wider than at higher wind speeds, making escape more difficult in some circumstances.

At low wind speeds, the rate of gas infiltration into buildings is also likely to be reduced, as noted in Section 3.3.1.

3.3.4 LPG storage site (Flammable/Explosive Liquefied Gas)

Low wind speeds will have no effect on the consequences of events such as BLEVEs, but may affect the results for the other scenarios.

Source terms

The wind speed has no effect on any of the source terms used in the analysis.

Frequency

A secondary consideration for this particular case is that the likelihood of ignition of a flammable gas cloud could increase in low wind speed conditions. This may be because the area within the LFL is greater, or perhaps because a lower ignition energy is required. This would modify the probabilities in the event tree of Figure 3.3, and hence the partition of event frequency between VCE, flash fire and unignited vapour cloud, and is discussed in greater detail in Section 3.4.6.

Gas Dispersion

The principal effect of low wind speeds is to cause a major impact on the inventory of vapour which would become involved in vapour cloud explosions, and the area affected by flash fires. This would also modify the event tree probabilities, giving, for example, a greater frequency of VCE. The likelihood that the wind persists in the same direction for the duration of the release also tends to be lower at reduced wind speeds.

Impact Assessment

At low wind speeds, gas clouds will take longer to reach a particular downwind location, perhaps allowing a greater probability of escape. Conversely, the gas cloud will tend to persist for longer and is likely to be wider than at higher wind speeds, making ignition more likely and escape more difficult in certain circumstances; escape from flammable clouds is discussed further in Section 3.4.3.

3.3.5 LOX or LNG storage site (Flammable Liquefied Gases)

Source terms

The wind speed has little effect on the initial puff of vapour from the release, the magnitude of which is largely determined by the boiling of the liquid due to conduction of heat from the ground. However, the wind speed is important in determining the subsequent rate of evaporation from a hundled pool (Event 1).

Gas Dispersion

The principal effect of low wind speeds is to affect the dispersion and peak concentration reached at any downwind location. The hazard range and area covered by the 30% contour can therefore be much greater in low wind speeds. In addition, at low wind speeds there is an increased probability of some significant upwind or crosswind spreading of the cloud.
Since the release duration (particularly of the initial large puff) is unlikely to be more than a few minutes, issues such as persistence are unlikely to be important.

**Impact Assessment**

For LOX, which has been considered in this report, the harm criterion is based upon reaching a specified concentration (30% O₂) rather than on any accumulated dose. Since there are no adverse effects from enhanced oxygen concentrations until this level is reached, there is a higher possibility of being able to move out of the cloud before the concentration reaches a dangerous level.

At low wind speeds, the protection afforded by being indoors becomes more significant. Since oxygen is not flammable, but enhances ignition probabilities and burning rates, the cloud itself will not ignite. For indoor populations, reduced infiltration rates (as described in Section 3.3.1) will result in reduced indoor concentrations and hence reduced risk.

### 3.4 Inclusion of low wind effects in risk assessments

#### 3.4.1 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 Mitchell¹, 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 & Deaves¹, 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 & Deaves also suggests that almost half of the D2.4 category actually relates to D1.0 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 3.3.

<table>
<thead>
<tr>
<th>Windspeed (m/s)</th>
<th>Stability class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td>1.0</td>
<td>8.0%</td>
</tr>
<tr>
<td>2.4</td>
<td>9.0% (17%)</td>
</tr>
<tr>
<td>4.3</td>
<td>20% (20%)</td>
</tr>
<tr>
<td>6.7</td>
<td>45% (45%)</td>
</tr>
</tbody>
</table>

Table 3.3 Re-allocation of low wind speed categories
*(original allocation in italics)*
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 (A-C).

It is also noted that it is generally not appropriate to use wind speeds lower than 1 m/s, for the following reasons:

(i) They do not persist for long enough, as discussed in Sections 2.5 and 5.3.2, implying that they cannot be used for prediction of far field concentrations.

(ii) There is less confidence in the validity of dispersion models at very low wind speeds, as discussed in Section 2.3.

However, since 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 is used, as given in Table 3.4.

<table>
<thead>
<tr>
<th>Windspeed (m/s)</th>
<th>Stability class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td>0.5</td>
<td>2.4%</td>
</tr>
<tr>
<td>1.0</td>
<td>5.6%</td>
</tr>
<tr>
<td>2.4</td>
<td>9.0% (17%)</td>
</tr>
<tr>
<td>4.3</td>
<td>20% (20%)</td>
</tr>
<tr>
<td>6.7</td>
<td>45% (45%)</td>
</tr>
</tbody>
</table>

Table 3.4 Re-allocation of low wind speed categories to include 0.5 m/s (original allocation in italics)

3.4.2 Modified air ingress rates to buildings.

This is important when toxic effects are considered, and it is assumed that the ventilation rate will increase with wind speed. Some discussion of typical values of ventilation rate and their variation with wind speed is given in Appendix B. As a result, the following variations of air change rate ($\lambda$ ach) with wind speed $u$ (m/s) are used:

For D stability class:

$$\lambda = 0.4 + 0.32u$$ (3.1)

For E and F stability classes

$$\lambda = 0.25 + 0.2u$$ (3.2)

These are to be compared with the base case of 2 ach for all cases except D6.7; note that Equation (3.1) gives $\lambda = 2$ for D5 conditions and 2.54 for D6.7 conditions.
3.4.3 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 have a simple relationship 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 3.2.1 are replaced by 720/u and 1200/u ppm respectively for wind speeds less than 2.4m/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.

It is recognised that these are fairly crude models, since they assume that people would be able to move away from the positions at which the 300ppm or 500ppm contours would be established in the extra time they would have because of the slower progress of the cloud front. The use of these models in this study is primarily for convenience, and is intended to be indicative of the effects of higher escape probabilities at low wind speeds.

The LPG base case risk assessment, as described in Section 3.2.3, 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\(^{(1997)}\), 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 2m/s, and covers the \(\frac{1}{4}\)LFL contour for higher wind speeds (as assumed in the base case).

3.4.4 Persistence effects and use of time dependent dispersion models

These effects have been discussed in Section 2.5. The methodologies described there and summarised in Figure 2.5 will be applied (separately) to determine sensitivity to these effects.

3.4.5 Releases from buildings

As noted in Section 3.3.1, the effective leak rate from a building will only be modified by wind speed for relatively low release rates. Typical results from GRAB-T (Shepherd and Deaves\(^{(1999)}\)) are presented in Appendix C, where it is shown that, for chlorine release rates in the range 0.3-3kg/s, \(M_u = fM_o\),

\[
\text{where } f = \max(0.15u, 0.09M_o) (\leq 1).
\] (3.3)

3.4.6 Greater ignition probabilities at low wind speed

Some recent work on ignition probabilities (Spencer et al\(^{(1998)}\)) has considered the strengths of ignition sources. Their review suggested that most ignition sources would be sufficiently strong that they would 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 base case, the ignition probabilities in the event tree of Figure 3.3 take the values indicated in Table 3.5. (These values are derived from probabilities used in similar analyses by Crossthwaite et al\(^{(1988)}\) and Clay et al\(^{(1988)}\).)
<table>
<thead>
<tr>
<th>Scenario</th>
<th>$p_i$</th>
<th>$p_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic failure</td>
<td>0.15</td>
<td>0.8</td>
</tr>
<tr>
<td>'Full bore' leak</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>'Major' leak</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 3.5 Ignition probabilities in event tree

The conditional probability of flash fire is then $(1-p_i)p_o$. Given that $p_o$ is set at 0.8 for the catastrophic failure, there is limited scope for increasing this value and remaining realistic. It is therefore suggested, for the purposes of determining sensitivity, that the frequency of the catastrophic failure event is increased by 20%, whilst the other (full bore/major) leak frequencies are increased by 50% (corresponding to 60% increases in the values of $p_i$ & $p_o$).
4. RESULTS OF INCLUDING LOW WIND CONSIDERATIONS IN RISK ASSESSMENTS

4.1 Chlorine Storage

4.1.1 Background

The results shown in Figure 3.1 for the base case chlorine assessment incorporate all of the factors and methods that are currently typically used in QRAs, safety cases and land use planning assessments. The graph shows that the risk falls steadily with increasing distance from the installation, and reaches a value of $3 \times 10^{-7}$/year at approximately 1100m (this would normally correspond to the consultation distance).

Following on from the base case analysis, a number of sensitivity studies were undertaken, to investigate the factors which could be included in order to incorporate consideration of dispersion in low wind speeds. The background to the variations used has been given in Section 3.4. For the particular case of the chlorine risk assessment, the following changes are incorporated, with full details provided in the sub-sections indicated.

a) Increased number of weather categories (3.4.1)
b) Modified air ingress rates (3.4.2)
c) Modified escape parameters (3.4.3)
d) Including allowance for persistence (3.4.4)
e) Use of time-dependent dispersion modelling (3.4.4)
f) Releases from buildings (3.4.5)
g) Combination of a),b),c),d) & e)

The results of these changes are shown on Figure 4.1. They are discussed in Section 4.1.2 and summarised in Section 4.1.3.

![Figure 4.1 Sensitivity results for chlorine risk assessment](image-url)
412 Risk assessment results

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 in the predicted risk at all distances, typically of the order 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) to 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 resulted in a significant reduction in the risk at all distances, amounting to a factor of over ten for distances beyond 1000 m downwind. This is due to the fact that the risk at these distances is largely dominated by the risk to people indoors in low wind speed conditions, and reducing the air change rate therefore provides a significant risk reduction.

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 largely because the risks are dominated by relatively long duration releases (~20 minutes) and hence the risks to people indoors are not much less than those for people outdoors (so that escape indoors does not reduce risks significantly). It is emphasised that the assumptions concerning escape would be more significant for a QRA which involved a greater proportion of short duration releases. Alternatively, there are many other ways in which escape could be incorporated in the modelling, such as considering escape from the plume altogether, which could have a more significant effect on the overall risks. This is an issue which merits further consideration but is beyond the scope of this current study.

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 risk from events in such conditions were based on the next highest windspeed category (e.g. D1.0 represented by D2.4, F1.0 by F2.4, etc.). As would be expected, this results in a step change reduction in the risks beyond 900 m (by about a factor of 3). 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). A step change reduction is not ideal, but a more detailed consideration of the probability of various persistence times would allow a number of threshold distances to be defined, with smaller steps at each one.

A further relevant factor which has not been included is that of wind directional persistence. It was shown by Lines & Deaves (1998) that direction is very variable for low wind speed episodes, and that there may be a preferential shift into certain directions as the speed increases. However, there is currently insufficient information to allow this to be incorporated into a study such as this.

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 36x8=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. If the QRA involved more short
duration releases, then it is clear that this issue would be more important. Sensitivity study g) also showed that, when using the modified infiltration rates, inclusion of transient modelling becomes more important.

Sensitivity study f) illustrates the effect of modifying the release rates, assuming that all the releases occur inside a building. The effective building release rate at low wind speeds (particularly for small releases) is dependent on the windspeed, 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 2 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. Furthermore, in practice, such releases could be significantly mitigated by the effect of building scrubber systems, which have not been considered here. The primary purpose of this sensitivity study was to demonstrate that it was feasible to modify a risk assessment to take account of the variation of building release rate with wind speed, which is most significant for releases at low windspeeds.

The final chlorine sensitivity study incorporates all of the modifications described in the sensitivity studies a) to e). (The building effects are not included in this final case, since its comparison should be against a modified base case). This combines numerous effects, some of which act to increase the risk and some to decrease the risk. 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 900m, but are significantly lower (by about a factor of 10) at greater distances.

4.1.3 Summary

These sensitivity studies have shown that additional consideration of low winds can make a significant difference to the predicted level of risk associated with a typical chlorine bulk storage risk assessment. However, simply including additional weather categories in the analysis may lead to significant overprediction of the risks. The analyses show that, in addition to including extra weather categories, it is also necessary to refine the analysis by suitable specification of infiltration rates, use of transient models for some continuous releases and consideration of persistence effects. Other factors, such as allowing for modification of escape modelling parameters, are less significant for this particular case.

As noted in Section 4.1.1, the consultation distance corresponds to an individual risk value of \(3 \times 10^{-7}\) year, and is at around 1100m for the base case. The combination of most the modifications (i.e. case g)) would reduce this to around 900m. If the effects of release from buildings are also included (not shown on Figure 4.1), there could be a factor of 3-10 reduction on risk, suggesting that the consultation zone would be reduced still further to around 550m, a factor of two below the base case value. It is again stressed that these numbers apply to this particular case, and should not be applied generally.

4.2 Bromine storage site

4.2.1 Background

Figure 3.2 shows the risk associated with the bromine base case. Once again, it is emphasised that the results are based on the generic scenarios, frequencies and assumptions described in Section 3, and are not necessarily representative of any particular installation, where different data and assumptions may be appropriate.
In the base case, which is representative of how a bromine QRA would normally be undertaken, the risks fall with increasing distance, reaching a level of $3 \times 10^{-7}$/year at about 450 m. There is a significant drop in the predicted risk at around this distance, this being due to the fact that beyond this distance it is only the people outdoors who are at significant risk (and 99% of people are assumed to be indoors in stable weather conditions).

Following on from the base case analysis, a number of sensitivity studies were undertaken, to investigate the factors which could be included in order to incorporate consideration of dispersion in low wind speeds. The background to the variations used has been given in Section 3.4. For the particular case of the bromine risk assessment, the following changes are incorporated, with full details provided in the sub-sections indicated.

a) Increased number of weather categories
b) Modified air ingress rates
c) Modified escape parameters
d) Combination of a), b) & c)

The results of these changes are shown in Figure 4.2. They are discussed in Section 4.2.2 and summarised in Section 4.2.3.

![Figure 4.2 Sensitivity results for bromine risk assessment](image)

### 4.2.2 Risk assessment results

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.

It is noted that, unlike the chlorine assessment, the bromine sensitivity studies did not include any cases relating to persistence or transient dispersion modelling. This is simply because these factors would not be important for the types of scenario considered for bromine. All the bromine vapour releases are taken to be of 30 minutes duration, and have outdoor hazard ranges that are less than 1 km, and so persistence and transient modelling considerations are unlikely to have a major influence in this particular case.

The final sensitivity study 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 b), as the escape parameters still have almost no effect on the overall risk.

4.2.3 Summary

There are significant risk reductions between around 150 and 450m, principally as a result of modifications to air infiltration rates. It should be noted that the reduced evaporation source terms at low wind speeds partially compensate for the increased concentration expected for these conditions. In addition, the air ingress rate becomes an increasingly significant parameter at low wind speed.

The consultation zone (distance to 3x10^7/year risk) for this particular case is reduced from 450m in the base case to around 220m when all of the modifications are included.

4.3 LPG storage site

4.3.1 Background

Figure 4.3 shows the total risk, covering each weather category, associated with each of the base case LPG release events discussed in Section 3.2.3. It can be seen that, beyond the first 100 metres, risk is dominated by the BLEVE scenario. Although the same approach to determining the event frequency has been used in all scenarios, it may be argued that the BLEVE frequency of 10^7/year is conservative, particularly if mitigating measures such as intumescent coatings or sloping drainage (to reduce the risk of vessel engulfment) are considered. Also, different methods of calculating the fireball consequences may be used which suggest shorter, i.e. less conservative, hazard ranges arising from the BLEVE. However, since the consequences of a BLEVE are not significantly affected by weather conditions, the BLEVE event has not been included in the subsequent analysis, in order that the sensitivity to dispersion, particularly at low wind speeds, can be illustrated more clearly.
Figure 4.3 Risk associated with each of the base case LPG risk assessment scenarios

The results for the base case LPG assessment are shown in Figure 3.4 and Figure 4.3. These are representative of how a LPG QRA would typically be undertaken, and are broadly consistent with the assumptions made in the LPG RISKAT model (as presented by Crosshwaite, et al.[1988]). The graph shows that the risk falls gradually with increasing distance from the installation, except for increases in risk around the areas that are assumed to be congested, at 80 and 220m, which increase the likelihood of a VCE occurring. A risk value of $3 \times 10^{-7}$/year occurs at approximately 450m (this would normally correspond to the consultation distance).

Following on from the base case analysis, a number of sensitivity studies were undertaken, to investigate the factors which could be included in order to incorporate consideration of dispersion in low wind speeds. The background to the variations used has been given in Section 3.4. For the particular case of the LPG risk assessment, the following changes are incorporated, with full details provided in the sub-sections indicated.

a) Increased number of weather categories (from 4 to 8) (3.4.1)
b) Further increase in weather categories (from 8 to 10) (3.4.1)
c) Modified escape parameters below 2m/s wind speed (3.4.3)
d) Greater ignition probabilities (3.4.6)
e) Combination of a), c) & d)

The results of these changes are shown on Figure 4.4 and values of risk at key distances are summarised in Table 4.1. They are discussed in Section 4.3.2 and summarised in Section 4.3.3. It is noted that the risk at the source (zero downwind distance) varies depending on the sensitivity case, whereas it would be expected to remain fixed. Reasons for these differences are discussed in Section 4.4.2 in relation to the LOX results.
4.3.2 Risk assessment results

![Graph showing sensitivity results for LPG risk assessment (excluding the BLEVE event).](image)

**Figure 4.4** Sensitivity results for LPG risk assessment (excluding the BLEVE event)

<table>
<thead>
<tr>
<th>Case</th>
<th>Base</th>
<th>a)</th>
<th>b)</th>
<th>c)</th>
<th>d)</th>
<th>e)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.79</td>
<td>11.8</td>
<td>13.6</td>
<td>9.01</td>
<td>15.8</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>11.7</td>
<td>10.3</td>
<td>12.2</td>
<td>8.88</td>
<td>12.4</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>2.93</td>
<td>3.40</td>
<td>3.44</td>
<td>2.13</td>
<td>4.10</td>
<td>2.57</td>
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<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 4.1 Summary of individual risk (cpm) from Figure 4.4

(1 cpm = 10⁻⁶ yr⁻¹)

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 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 200m. 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 counter-acted by the reduced range of the cloud when the driving wind is less strong. Hence, beyond 250m the increase due to the lower wind categories is small and, at distances of more than 300m from the point of release, the lower wind speeds actually reduce the risk.
The peaks in risk due to the VCEs are affected in a similar way. The congested areas, described in Section 3.2.3, have been set so as to maximise the sensitivity to wind conditions in this particular case. In the base case, the pipework releases do not quite reach the 'first' congested area, while the minimum range of the LFL of the catastrophic releases is just enough to cover the 'second' area. Thus, in the base case, only the catastrophic release - for all weather categories - produces VCEs. Since the hazard ranges of the pipework releases extend further at lower wind speeds, a VCE occurs in the first congested area in the 7.8kg/s release events for the D1.0 and F1.0 conditions. Conversely, at lower wind speeds instantaneous clouds travel more slowly, while mixing with air, and so the 'second' congested area is not reached by the catastrophic release in the D1.0 and F1.0 conditions. Thus the 'first' VCE peak produces slightly greater risk in sensitivity case a), while the risk at the 'second' peak is slightly lower.

The overall risk is clearly affected by the probability of VCEs occurring, although this can be highly dependent on specific site characteristics. The results shown in Figure 4.4 demonstrate that accurately modelling the wind speed can have some impact on the occurrence of VCEs. However, in a realistic case, the wind direction will be far more important than wind speed in determining whether a vapour cloud reaches areas of congestion that can initiate a VCE.

The same trends are apparent when further increasing, from 8 to 10, the number of weather categories (sensitivity study b)). Although the hazard range to the flash fire ignition limit (\%LFL) of each scenario increases relatively significantly when reducing the wind speed from 1 to 0.5m/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) to e)) 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 is simulated by assuming that the flash fire concentration limit is LFL rather than \( \frac{1}{2} \) LFL, when the wind speed is less than 2m/s. 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 by a relatively small proportion. The reduced risk is evident up to around 350m, beyond which only wind speeds of more than 2m/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 d), 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 with the additional weather categories, and 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 e), which incorporates all of the modifications (combining the effects of studies a), c) and d)), shows a relatively small change from the base case. The most significant factor is the modified escape modelling assumption, and so the curve shown for case e) 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.
4.3.3 Summary

These sensitivity studies demonstrate that the additional consideration of low winds has relatively little impact on the predicted level of risk associated with a typical LPG storage risk assessment. The risk associated with a BLEVE, which is largely independent of weather conditions, is typically the most significant event in any such assessment. VCEs can also have a significant impact on the overall risk, although the variation due to wind speed will be highly dependent on the particular site (i.e. due to the presence and exact position of regions of congestion).

Most of the releases typically considered in LPG risk assessments have relatively short dispersion hazard ranges and, although the wind speed can significantly alter these ranges, the overall impact will be relatively small. The variation in risk for the larger 'catastrophic' release is not significant at lower wind speeds. This is because the higher concentration, and width, of the cloud due to lower wind speeds (which is apparent in the smaller continuous releases) is counter-acted by the lower wind speeds 'carrying' the cloud more slowly. Thus, the extra wind categories considered here were found to have a small impact over the first half of the hazard range, with very little impact on risk further away from the point of release. It should also be noted that there may be particular sites (e.g. those with mounded or coated tanks) for which BLEVEs and catastrophic releases may not be so significant, in which case the relative impact of low wind speeds will be far greater.

If the consultation zone were set by reference to the $3 \times 10^7$/year risk contour, it can be seen that it would not change at all due to the modifications considered here. The current assessment of such sites by HSE is based upon BLEVE consequence ranges, which are also unaffected by the inclusion of low wind speeds. However, the current study has provided confirmation that the use of the BLEVE range is appropriate (for this LPG case with a BLEVE frequency of $10^7$/yr) and is consistent with the risk based approach for sites handling toxic materials.

4.4 LOX storage site

4.4.1 Background

Figure 3.5 shows the base case risks associated with a typical 1000 tonne oxygen installation, calculated using D5 and F2 weather conditions in order to remain consistent with the current HSE methodology. For every scenario, in each weather condition, the total mass of oxygen evaporated in the first 3 minutes of the spill was evaluated (using LPOOL) and used to provide the source term for an instantaneous release model (HEGABOX). This is typical of the approach commonly used in current QRAs and safety cases. The oxygen source terms for each event are summarised in Table 4.2.

<table>
<thead>
<tr>
<th></th>
<th>Bunded release (diameter 35m)</th>
<th>Unbunded release</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pool diameter</td>
<td>Mass evaporated</td>
</tr>
<tr>
<td>D5</td>
<td>17349.3 kg</td>
<td>130m</td>
</tr>
<tr>
<td>F2</td>
<td>16071.5 kg</td>
<td>126m</td>
</tr>
</tbody>
</table>

Table 4.2 LOX source terms

The table shows that the source term is relatively insensitive to the windspeed. The maximum pool sizes indicated for the unbunded releases occur 2-3 minutes after the catastrophic failure of the tank. The outdoor population within these pools is 100% affected,
whereas the indoor population may or may not be affected, based on standard infiltration calculations.

Following on from the base case analysis, a number of sensitivity studies were undertaken, to investigate the factors which could be included in order to incorporate consideration of dispersion in low wind speeds. The background to the variations used has been given in Section 3.4. For the particular case of the LOX risk assessment, the following changes are incorporated, with full details provided in the sub-sections indicated.

a) Increased number of weather categories
b) Use of time dependent dispersion modelling (D5 and F2 only)
c) Combination of a) & b)

The results of these changes are shown in Figure 4.5. They are discussed in Section 4.4.2 and summarised in Section 4.4.3.

![Graph showing sensitivity results for LOX risk assessment](image)

**Figure 4.5 Sensitivity results for LOX risk assessment**

### 4.4.2 Risk assessment results

The near field risk results shown in Figure 4.5 for LOX sensitivity studies b) and c) are higher than those for the base case or sensitivity study a) because the full time-dependent transient modelling of the release using LPOOL and HEGADAS-T means that the cloud persists longer at high concentrations and therefore has time to infiltrate into buildings, resulting in an indoor risk. This indoor risk does not arise at all in the base case or sensitivity study a) because modelling the cloud as an instantaneous release results in fairly rapid dilution as the cloud slumps, and so there is insufficient time for indoor concentrations to build up above the threshold level of 11.4% excess.

Care must always be taken in the interpretation of the near field results, since they relate to population in buildings which are surrounded by (or very close to) the large unbunded oxygen pools. Also, in the near field, issues such as cloud height become important factors which are not explicitly included in the building infiltration modelling.
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. Figure 4.5 shows that this modification has very little effect on the predicted risk. There are two principal reasons for this lack of sensitivity:

i) the source terms used as the inputs for the instantaneous model are not significantly dependent on the windspeed;

ii) 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, which is assumed in the base case and in case a) instantaneous modelling, and is not significantly affected by the windspeed.

It is possible to make some adjustments to the instantaneous release modelling used in the base case (or sensitivity study a)) by altering the assumptions relating to the initial cloud temperature, aspect ratio and initial dilution. However, such alterations tend to be very subjective, rather than based on physical arguments, and can never realistically simulate the time dependent release from an evaporating/boiling pool.

There is clearly a major assumption in assuming that the time dependent release of oxygen vapour predicted by LPOOL (or similar models such as GASP) can be modelled as an instantaneous release. Sensitivity study b) 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 Figure 4.5 show that this results in a significant increase in the risk at all distances, and indicate a significant increase in the maximum hazard range. The reasons for the increase over the base case risks are that:

i) most importantly, there is no longer the major lateral spreading (and associated turbulence and dispersion) associated with the gravitational slumping of a large instantaneous release;

ii) the inclusion of the time dependent release means that the total inventory released is slightly greater than the 3 minute source term used in the base case. However, it is thought that this is probably not a very significant factor.

Sensitivity study c) investigated the effect of using this fully time dependent approach with the more refined set of 8 weather conditions. Figure 4.5 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 (see Section 3.2.4).

It is noted that none of the sensitivity studies for oxygen considered the effect of persistence. This is simply because the hazard ranges are generally relatively low, although it is possible that the F1 unbunded release case in sensitivity study c) could be susceptible to persistence considerations as the hazard range extends to over 1 km.

Another factor which has not been investigated is that, particularly in low wind speed conditions, the vapour cloud may persist or linger at greater than the threshold concentration for significant periods of time (e.g. over 15 minutes in F1 conditions in sensitivity study c)).
which is not predicted in the base case for F2 weather conditions. This could have implications for the likelihood of ignition, which could increase the risks still further. In this context, it should be noted that ignition of an LPG vapour cloud would result in a flash fire and fatalities over a wide area, whereas ignition within a LOX cloud is assumed only to affect the individual who provides the ignition source.

A related issue is that of infiltration to buildings, since, as noted in Section 3.2.4, protection of people indoors is taken into account. However, since the base case results demonstrated that indoor concentrations would only rarely exceed dangerous levels, the sensitivity studies did not include the modified air ingress rates as described in Section 3.4.2. Including persistence (longer duration) and infiltration (lower ventilation rate) effects would work in opposite senses (to increase/decrease risk) such that the overall effect would be small.

4.4.3 Summary

It is clear from these results that time-dependent modelling and inclusion of more weather conditions both have the effect of increasing calculated risk. Applying both these improvements would enhance the range to the $10^9/yr$ contour from around 150m to 800m. This suggests that current methods under-estimate risk and should be improved as noted above.

For this case, the consultation zone is increased from 440m in the base case to 800m with the modifications considered. As can be seen, this is only partly due to low wind speed effects, indicating the significant changes obtained by improving other parts of the modelling - transient effects in this case.
5. DISCUSSION OF INCLUSION OF LOW WIND SPEED EFFECTS

5.1 Source term effects

5.1.1 Releases from buildings

Some hazardous materials are normally stored within buildings. Clearly, since the confinement of flammable vapours could lead to the build-up of an explosive mixture, flammables would not normally be stored in this manner. However, toxic materials are frequently stored in buildings to provide some form of partial containment and hence mitigation.

A key example which has been addressed within a number of recent research studies is that of chlorine storage within a building. This was studied using CFD (Lines et al. 1993), and resulted in the production of the computer programs GRAB (Spencer & Deaves 1997) and GRAB-T (Shepherd & Deaves 1999). These have been applied to a number of examples of chlorine releases in buildings which are typical of water chlorination sites.

It was clear from these studies that the presence of a reasonably well-sealed building will provide significant mitigation in reducing the amount of material (chlorine in this case) released to the atmosphere. It was also found that, for cases which are affected by natural ventilation, the mitigation effects are enhanced as the wind speed is reduced, since there is less 'flushing' of the building. Such mitigation will only apply to the lower release rates, since larger releases will be considerably less affected by the beneficial containment effect of the building.

In practice, for any given material and building size, the mitigation effects will be greatest at low release rate and low wind speed. This has been shown in Appendix C, where approximations of the mitigating factor on release rate have been presented for chlorine releases into a typical secondary containment building.

Of the four risk assessments considered, this containment effect has only been applied for the chlorine case. It was shown to be significant in reducing the calculated risk at most distances by up to a factor of around 3.

5.1.2 Evaporation

The evaporation rate of a liquid pool will depend upon a number of factors, one of which is the wind speed. For materials such as LNG, where the boiling point (-160°C) is significantly below ambient temperatures, most vapour will be produced by boiling, and the wind speed has little effect. Where the boiling point is above ambient, such that the material is normally in liquid form, the wind speed does have a significant effect. For the examples considered in this study, this effect will be greatest for bromine. There may be slight effects for chlorine, but the effects are likely to be minimal for LPG or LOX.

For a liquid such as bromine, the evaporation rate will vary as $u^{0.78}$, whereas downwind concentrations typically vary approximately as $u^3$. This implies that the net effect of using a lower wind speed is to increase concentrations only as $u^{0.22}$ rather than as $u^1$. Thus, reducing the wind speed from 2.4 m/s to 1 m/s would give an increase of concentration by a factor of only 1.2 ($2.4^{0.22}$) rather than 2.4. Hence the apparent enhancement of risk as a result of including lower wind speeds would be significantly reduced when correct modelling of evaporation rates is included. This is borne out by the results shown on Figure 4.2 [case a] includes these evaporation effects, whereas the base case does not] and is discussed in Section 4.2.2.
5.2 Frequency

As noted in Section 3.3, the frequencies of the scenarios considered are unlikely to be affected by the low wind speed conditions. One exception to this is the potential for greater ignition probability for a flammable gas cloud in low wind speed. This has been considered by Spencer et al\(^{1998}\), and, although it was concluded that this effect was likely to be secondary, it has been considered in this study. The analysis shown in Figure 4.4 confirmed that the effect on calculated risk was slight when all ignition probabilities are increased, implying that the effect would be minimal if applied to low wind speeds only.

It is therefore suggested that, in all cases, assumptions about event frequency should be used which are independent of wind speed. A possible exception to this is scenarios such as tanker unloading or other delivery, which would only occur during the daytime. In this case the dependence is primarily on stability (stable conditions normally occurring at night), rather than specifically on wind speed.

5.3 Dispersion modelling

5.3.1 Summary of validity

The validation study of Lines et al\(^{2000}\) took 14 datasets in which dense gas dispersion was undertaken in wind speeds ranging from about 0.2 to 3m/s at 10m. The study concluded that the validation at these wind speeds was generally no worse than that at higher wind speeds. However, since only 2 datasets were available at speeds lower than 1.5m/s, some caution should be exercised when using models at very low wind speeds. In general, it was considered that they could be applied at most speeds down to around 1m/s with reasonable confidence.

The validation study also showed the following more specific features of the results (see Section 2.3.2 of this report), relating to the different types of release indicated:

**Jet releases** - The validation was generally not as good for jet releases as for the other categories. This was mainly attributed to the inadequacies in the prediction of jet trajectory in the near field, where most of the measurements were obtained.

**Instantaneous releases** - The validation here was very good at low wind speed. This is not surprising in view of the use by most of the models of this type of data in their development.

**Evaporating pool releases** - The validation was reasonable, although it was noted that there were some uncertainties in the definition of the source.

**Low velocity vapour releases** - The validation was generally good.

5.3.2 Persistence and transient effects

The effects of persistence have been discussed by Lines & Deaves\(^{1998}\), and summarised in Section 2.5 of this report. The main conclusion to emerge is that, since low wind speeds do not persist for as long as higher wind speeds, travel distances at low wind speeds are shorter. This indicates that it is not realistic to use very low wind speeds to calculate far field effects. Hence, for example, 1m/s should be used only out to around 3000m, but 0.5m/s should only be used to 375m. In practice, risks are usually negligible beyond 3000m, indicating that the 1m/s category can be used throughout. However, for risks such as those from LPG sites, hazard ranges of 300-400m are important, and it is therefore appropriate to use lower wind speeds, say down to 0.5m/s, as discussed in Section 5.3.3.
In the present study, persistence effects have only been considered for the chlorine risk assessment. It was shown (see Figure 4.1 lines a) and d)), that this gives a significant reduction in calculated risk when using lower wind speed categories.

In addition, for releases of relatively short duration, but which are not instantaneous, it has been shown both in this study and by Lines et al (1998) that use of transient dispersion modelling gives more realistic results. At low wind speeds, which may not persist for sufficient time to carry the material from the source to the target point, it is particularly important to use transient modelling. This has been demonstrated for the LOX assessment, (Figure 4.5), where significantly higher risks would be calculated. For chlorine (Figure 4.1), the effect is much less marked.

5.3.3 Use of more low wind speed classes

As discussed in Section 3.4, the standard use of F2.4 as the ‘worst’ weather category is a very coarse way of representing the wind data. An improved alternative has been derived, in which D1.0 and F1.0 categories are also included. It can be seen from the sensitivity studies that use of this alternative (with no other changes) generally results in increased calculated risk for all the cases considered. It should also be noted, however, that this is partially mitigated for the bromine and chlorine cases by changes to evaporation rate (also incorporated into variant a)) or release rate from buildings (treated separately for chlorine, as variant f)).

The LPG assessment has also used the lower wind speed of 0.5m/s, with the frequencies allocated as shown in Table 3.4. As discussed in Section 5.3.1, little validation of the use of dispersion models at very low wind speeds has been done, and considerable caution is required in modelling wind speeds below 1.0m/s. The hazard ranges and cloud concentrations in the 0.5m/s cases assessed were found to give results that follow the pattern indicated by the higher wind speeds and are judged to be reasonable, although it would be unwise to derive specific conclusions from these results. However, it can be seen from the results shown in Figure 4.4 that there is a slight increase in calculated risk in the 0.5m/s sensitivity cases, which is less marked than for the inclusion of the 1m/s cases.

The overall effects of including extra low wind speed categories are therefore as summarised below:

- **Chlorine**: Increased risk (factor ~5) at all distances.
- **Bromine**: Marginally increased risk (factor ~1.5) at most distances.
- **LPG**: Little change to risk.
- **LOX**: Little change to risk (unless transient modelling is also included, in which case there could be a factor of at least 4-10 increase in risk, as shown in Figure 4.5).

5.4 Impact effects

5.4.1 Escape

Although some consideration has been given to the potential for increased probability of escape at low wind speeds, it is clearly a complex problem with which it has not been possible to deal in detail within this study. The simplistic approach taken, in which it is assumed that escape would be possible from areas of higher concentration, because personnel would have more opportunity to move away before being engulfed, shows that this has no effect on either the chlorine or the bromine case, because only 10% of the population (1% at night) are assumed to be outside and therefore in need of escape.
It is also noted that the effects are different for toxics and for flammables, since there are rather different considerations between these cases, such as the lack of protection from buildings and the immediate consequences of ignition in flammable assessments. An allowance for increasing escape probability at lower wind speeds has been used in the LPG sensitivity studies in Section 4.3. It could also be argued that the same increase in escape probability applies if wind speed is reduced from, say 6.7 to 4.3 m/s, and modifying the escape assumptions for a broader range of weather categories will clearly have a greater impact on the overall risk. Changing the assumption that buildings offer no protection in the fire events considered in Figure 4.4 would also have a significant impact on the results. However, given that a flash fire or VCE is occurring, any protection that buildings do provide will be independent of the wind speed, unlike for toxic considerations.

5.4.2 Infiltration

The worst case wind conditions (low wind speed, stable conditions) tend to occur at night, when it is assumed that most people would be indoors. It is therefore important to consider the probable reduction in infiltration rate which would occur at these lower wind speeds. The base case modelling assumes discrete ventilation rates which vary slightly with wind speed. The sensitivity modelling has assumed that the ventilation rate is linearly dependent on wind speed, and this shows that the risk would be overpredicted by factors of around 30 if the higher ventilation rates were maintained. (Compare lines a) and b) on Figure 4.1 or Figure 4.2). This indicates that the rather higher risks which would be calculated using lower wind speeds will be mitigated by the realistic inclusion of infiltration effects. It is therefore important that these are understood adequately; some further effort in determining typical ventilation rates would be useful in improving the accuracy of such calculations, and this is discussed further in Section 7.2.

5.4.3 Evacuation

In low wind speed conditions, any toxic cloud would take longer to reach a specific target point. This may provide sufficient time that evacuation could take place, although this is unlikely to be a viable method of mitigation for most cases considered and has not been included in the sensitivity studies. Indeed evacuation is not recommended in most emergency plans, partly because of the large numbers of people who would need to be organised. The cloud could also be present for longer than the 30 (plus 10) minutes that have been assumed (see Section 3.1.2), after which time evacuation would be less effective.
6 DEVELOPMENT OF GUIDELINES

6.1 Use of weather data

All the studies described in this report use meteorological data which is based on the standard type of information provided by the Meteorological Office (e.g. 1 hour 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, comparable with those of the release durations. Analysis of site specific sequential data of this type would also allow the probability of low windspeed persistence to be evaluated. Although data are not readily available in this form, it has been shown by Lines & Deaves(1997) that a Weibull distribution fit to the moderate hourly mean wind speed data could be extrapolated to give frequencies of low wind speeds, and that these frequencies would be representative of 10 minute averaged data.

Another advantage of examining site specific sequential meteorological data would be that a more accurate estimate could be made of the probability of people being indoors or outdoors in each weather category. This would be possible by using the detailed hourly statistics, which include stability class as well as wind speed and direction. At present, typical assumptions (such as 99% of people indoors in stable conditions) have a very significant effect on the overall predicted level of risk for residential populations.

In practice, however, use of wind speed data is likely to be limited to the hourly means available from the Met. Office. The sensitivity studies have shown that wind speeds less than 2.4m/s should be used, but that 1m/s is likely to be the practical minimum. The set of conditions presented in Table 3.3 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 and persistence effects

It has been shown that the incorporation of transient and persistence effects is important in some of the risk assessment cases considered. The practical application of these effects is discussed below.

Transient Modelling

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 would need to be automated for practical application in QRAs involving large numbers of scenarios and weather conditions.

Transient dispersion modelling is not straightforward, and was generally regarded as being impractical in the 1990s for general QRA purposes. Whilst transient modelling can still be time consuming, it has now become practicable to include this level of refinement in routine QRA studies and safety cases.
Persistence

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 the same 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% level, as used in this study), but it would be preferable to use a range of values, e.g. 10, 30, 50, 70 and 90% probability of the low windspeed weather category persisting (for example, F1.0 persists for at least 12 minutes on 30% of occasions). This data should be derived from site specific sequential meteorological data, but if this is unavailable then suitable assumptions may be made using sources such as Lines and Davaes (1997, 1998). 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.

Linking of Models and Automation

The sensitivity studies described here demonstrate that a number of refinements can be incorporated in typical dispersion and QRA studies. For dispersion modelling of a single release it is relatively easy to include these refinements. However, there are a number of issues which QRA practitioners need to consider when undertaking studies involving large numbers of scenarios in an increased number of weather conditions.

1. the choice of appropriate meteorological frequency data may depend on the release duration;

2. some source terms depend significantly on the weather conditions. For example, rather than simply specifying a mass release rate and duration, some time dependent source term models (e.g. GASP, LPOOL, evaporation or building release rate models) need to be incorporated as an integral part of the risk assessment calculation process;

3. a choice needs to be made between continuous and transient modelling for each scenario;

4. inclusion of persistence effects requires reference to results from higher wind speeds.

All of these issues can be addressed, and automated for practical QRA purposes, but this automation is not straightforward with most currently available QRA software packages.

6.3 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:

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 Figure 4.2, where the variant a) includes both low wind speeds and reduced evaporation rates.
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 later some time has elapsed.

Infiltration effects

Infiltration rates will decrease as wind speed decreases, although the effects for practical buildings are not straightforward to estimate. Some cognisance of this variation can currently be taken into account in risk assessments, as discussed in Appendix B. However, it is likely that the effects will be particularly marked at low wind speeds, as shown by comparing lines a) and b) on Figure 4.1 for the chlorine sensitivity study.

6.4 Dependence upon material type

The sensitivity studies presented in Section 4 have demonstrated that the results of risk assessments will be affected to a greater or lesser degree by the inclusion of low wind speed effects. The extent of the change to calculated risk will depend upon the exact scenarios considered, but has also been shown to depend upon the material considered.

The greatest effects 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 Figure 4.4 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

7.1 General Guidelines

The main conclusions from this study relating to the development of guidelines for including low wind speeds in QRAs are:

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 3.3) 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. In particular, any air change rates for low wind speed categories should be lower than those for higher wind speeds (e.g. use the windspeed dependent equations for λ that are presented in this report, Equations (3.1 and 3.2)).

3. If hazard ranges are likely to be greater than 1 km then effects of persistence should be incorporated for any low wind speed weather categories. This should be done by estimating the persistence time τ for a particular windspeed, and then only using the dispersion results for that windspeed up to a distance of ut. At greater distances, the next highest windspeed category should be used. Ideally, a range of values of τ should be used with probabilities assigned to each. (See Lines & Deaves(1988)).

4. Any continuous releases for which the hazard range is predicted to be greater than 1.5uT (where T is the release duration) should be modelled 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 (e.g. see Appendix C), or by using a full time-dependent source term 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.

7.2 Recommendations

Several of the sensitivity studies relating to toxic vapour releases indicated that the predicted risks were relatively insensitive to the assumptions concerning escape. This is partly due to
the types of scenario that were being considered, and also due to the relatively simple formulation of the ‘escape algorithm’. Clearly, there is considerable scope for improving this aspect of the analysis, particularly at low wind speeds where escape is a more significant factor.

The infiltration rate of vapour into occupied buildings has also been shown to be a potentially significant mitigatory factor, which becomes even more important at low wind speeds. At present, risk assessments tend to use a single value for this parameter for any particular weather condition, but the results of the chlorine and bromine sensitivity studies suggest that this parameter is so important that it should be modelled more realistically. The easiest way to improve the modelling would be to consider a range of air change rates for each weather category (e.g. 5% of houses have windows open and so $\lambda = 4$ ach, 45% are moderately sealed and so $\lambda = 2$ ach and 50% are well sealed and so $\lambda = 1$ ach (dependent on windspeed)). Given that this parameter can affect overall total predicted risks by up to two orders of magnitude, it is considered that this type of more detailed modelling would be justified for toxic vapour releases. It is possible that the infiltration assumptions should also be linked to the escape modelling algorithm.

The oxygen sensitivity studies indicated that the risks currently predicted for such installations (including other refrigerated liquefied gases (RLGs) and substances with boiling points below ambient) may be significantly underestimated. This should be considered in more detail. A specific aspect which could be considered is the degree of protection that being indoors can offer for flammable vapour releases such as LOX or LNG; current modelling assumes significant protection against LOX (BCGA(1984)).
REFERENCES


Heinrich, M et al., (1991). 'Work in progress under the Major Technological Hazards Programme of the CEC'.


APPENDIX A
LOW WIND SPEED CRITERIA

Statistical wind data which is used to determine the conditions for which dispersion calculations are undertaken has traditionally been derived from measurements taken by the UK Meteorological office. The instrumentation which is predominantly in use for such measurements is the Munro Mark IV cup anemometer, which has the advantage of being robust and hence able to withstand high wind speeds. The main disadvantage of such instrumentation, however, as far as using the statistics is concerned, is its poor response at low wind speeds. This has been discussed in Lines and Deaves (1997a), and has led to the use of 2-2.4 m/s as the lowest speed which is generally used in risk assessments.

It is recognised that this criterion is based upon pragmatic rather than scientific considerations. If the physical processes at work are considered in more detail, any of the following could be considered as 'low wind speed' criteria:

1. Winds in which the atmosphere is likely to be stable

One of the main problems of dispersion models at low wind speed will be to do with the associated atmospheric stability rather than low wind speed per se. In practice, this will imply windspeeds which are low in absolute terms, and is not related to the conditions of the source.

2. Winds in which the Richardson number $Ri = g' h / u^2$ is large

This is the parameter governing top entrainment and whether the cloud stays heavier longer. (This effect will be strongly modified as the cloud is diluted by atmospheric stability.) It is inextricably related to $Ri_{wind} = g' h / u^2$ where $u$ is the wind speed. This parameter will also govern the extent of upstream flow in a low velocity source.

3. Winds in which $u_{source} >> u_{wind}$

This will apply to jets or other high momentum releases. It should be noted that this is the opposite to the condition needed for investigation of upwind gravity spreading which would be $u_{source} << u_{wind} << \sqrt{g' h}$.

4. Clouds for which the buoyancy parameter $B = g' Q / Du^3$ is large

$B$ is essentially the product of $Ri$ and $u_{source} / u_*$ (and perhaps some source aspect ratio) and so may correspond to a combination of parameters 2 and 3 above: a sort of buoyancy-adjusted source velocity. Since $B$ can be made large either by making the cloud dense at moderate source velocity or by giving it a high velocity at moderate densities, it may be that criteria 2 and 3 separately are more important for gas dispersion.

5. Clouds for which $h - z_0$ or smaller

The wind is clearly low (locally) if the cloud is down among the roughness elements. However, the structure of turbulence is completely different here from what it is in the constant $u_*$ layer, and no heavy gas model has been designed to work here.

In practice, this condition would apply to dispersion among groups of buildings, and would tend to be treated as such rather than using standard dispersion models. At large distances from the source, it may be possible to use standard models with an enhanced roughness, but it is likely that $h$ will have exceeded $z_0$ by this stage, and hence that this criterion is no longer met.
Guidelines have been produced for the use of dispersion models (CCPS(1996)) and these include criteria for the application of dense gas dispersion models. These are given, separately for continuous or instantaneous releases, in terms of a critical Richardson number and are reproduced here:

\[ Ri = g' \frac{Q_0}{D_o u_*^2} \]  \hspace{1cm} \text{(continuous release)} \hspace{1cm} \text{(A.1)}

\[ Ri = g' \frac{V_o}{D_o u_*^2} \]  \hspace{1cm} \text{(instantaneous release)} \hspace{1cm} \text{(A.2)}

where

\[ g' = g \frac{\left( \rho_g - \rho_a \right)}{\rho_a} \]  \hspace{1cm} \text{(m/s}^2) \hspace{1cm} \text{(A.3)}

\[ \rho_g, \rho_a = \text{densities of gas and air (kg/m}^3) \]

\[ Q_0 = \text{volume release rate (m}^3\text{/s)} \]

\[ V_o = \text{volume released (m}^3) \]

\[ D_o = \text{source dimensions (m)} \]

\[ u_* = \text{friction velocity (m/s)} \]

It can be seen that these are equivalent, for continuous releases at any rate, to criterion 4 indicated above.

It is therefore evident that, in practice, the criteria 1-5 listed above are equivalent to the criteria which may be applied to determine whether or not density effects dominate. Since many dense gas dispersion models have been developed to cover these conditions, it is not considered appropriate to rely purely on such criteria to identify low wind speeds. The main problem being addressed in this study is the lack of validation of such models at 'low wind speeds', which in practice means those lower than currently used in risk assessments and lower than have been used in code validation.

For the purposes of this study, the following criteria are therefore applied:

\[ u_{10} \leq 2.4 \text{ m/s} \]

AND

\[ Ri \geq 50 \] \hspace{1cm} Ri defined by Equations A1 and A2.
APPENDIX B

CONSIDERATION OF AIR INFILTRATION RATES TO BUILDINGS

Infiltration to buildings is caused by wind pressure and by differences between internal and external temperature. Thus, although the inflow rate will decrease as the wind speed is decreased, there is a realistic minimum below which it will not fall because of the thermally induced effects. This has been discussed by Lees (1960) in relation to the infiltration of toxic clouds, and a summary of his discussion is reproduced here.

Lees' Figure 15.155 shows some data from a 1951 paper implying a relationship for the form $\lambda = \max (0.7, 0.35u)$. His Table 15.64 gives data for individual room ventilation rates from a 1980 paper, suggesting minimum values of $\lambda$ of around 0.25-0.4. Later work, specifically focused upon infiltration rates for toxic gas clouds, suggests $\lambda=0.87+0.13u$ for an exposed site. Current usage within risk assessments is given in Lees' Table 15.65, which is reproduced here:

<table>
<thead>
<tr>
<th>Weather category</th>
<th>D2.4</th>
<th>D4.3</th>
<th>D6.7</th>
<th>F2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed house</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Normal occupied house</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Values used by Pape &amp; Nussey (1965)</td>
<td>0.7</td>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table B.1 Ventilation rates for use in risk assessments (ach)

For use in this study, the following assumptions, based on the above discussion, have been used:

(a) Lower limit for D stability is 0.4 ach
(b) Lower limit for F stability is 0.25 ach
(c) For D stability, 2ach will be retained at 5m/s
(d) For F stability, slope of variation with $u$ is around 2/3 of that for D stability

This results in the following formulae:

D stability: $\lambda = 0.4 + 0.32u$ \hspace{1cm} (B1)
E/F stability: $\lambda = 0.25 + 0.2u$ \hspace{1cm} (B2)
APPENDIX C

EFFECTS OF LOW WINDSPEED ON RELEASE RATE FROM BUILDINGS: RESULTS OF APPLICATION OF GRAB-T

C1. INTRODUCTION

The current version of GRAB-T allows the user to input any desired windspeed and release (leak) rate for modelling purposes. One of the outputs available is the ventilation flow rate through the chosen openings; an example of which is illustrated below in Figure C.1. This shows the flow out from a room through two openings (A in the windward face and B in the leeward face) for a 3kg/s release of chlorine into a full-scale test room, with an external windspeed of 1m/s acting on face A.

![Graph showing flow rate over time](image)

Figure C.1  Mixture flow rate from test room (via two openings)

It should be observed that there is a negative scale on the flow rate axis, which indicates a flow rate into the room through both openings during the early stages of the transient. For such a flow into the room the medium will be air at the defined ambient temperature, whereas for the flow out from the room the medium will be the gas/air mixture at the calculated room temperature.

The driving force behind the flow rates through an opening is the pressure difference between the room contents and that applied to the external wall (with an opening). The pressure inside the room is governed mainly by the release (leak) rate of the pollutant whilst the external pressure is influenced by the ambient windspeed. For the particular case illustrated in Figure C.1, the leak rate is sufficient to overcome the wind pressure; for rather lower leak rates, there would only be outflow (of gas/air mixture) from opening B, with inflow (of fresh air) through opening A.
C2 METHODOLOGY

Overview:

By performing GRAB-T runs for various windspeeds and pollutant release rates, flow rates out from the building may be obtained and used to calculate a ratio of pollutant outflow to inflow, i.e.

\[
\text{Release Ratio} = \frac{\text{average rate of pollutant leaving room}}{\text{rate of pollutant entering room}}
\] (C1)

Obtaining the average rate:

The ventilation output from GRAB-T gives the total flow rate (kg/s) through all openings as in Figure C.1; however, another model output is the gas mass fraction of the room contents. As the flow out from the room consists of a gas/air mixture, the rate of pollutant leaving the room can be calculated as the product of the gas mass fraction and the flow rate.

For certain scenarios, it is possible for the pollutant to exit the room via more than one opening. In these cases the total rate (as in one effective opening) will be considered via a summation. A plot may then be made of the total release rate against time, the area under which represents the total mass of pollutant released over the simulation period. Division of this total mass by the simulation time will then provide the average rate of pollutant leaving the room. This is converted to a ‘Release Ratio’ value via the corresponding leak rate when applied to Equation C1.

C3. TEST CASE

Room Dimensions

GRAB-T runs were performed on room geometry modelling a chlorination room at a water treatment works. The actual room was 21.93m long by 14.61m wide by 7.32m high and had a free air volume (excluding the tanks and other obstructions) of 1424m³. However, the room itself does not have a simple geometry as required by GRAB-T, so a surface area calculation was performed from a scaled diagram, and a pseudo room geometry constructed to give the same volume and surface area for heat transfer purposes. This calculation also considered the heat transfer from the storage vessel in accordance with the assumptions made in the GRAB-T model. Hence the following ‘effective’ room dimensions were employed:

- Height = 7.32m
- Width = 4.14m
- Length = 46.99m

Room Configuration

Two opposite openings (A and B) were modelled with wind incident upon face A, thus allowing flow through the room. Both openings were given a fixed area of 0.5m² and the bund option was not used. Thermal conductivity was taken as 1.72W/mK and the thicknesses of the wall, ceiling and floor were all set to 0.05m, with the isothermal option not activated.

Ambient Conditions

Air parameters were retained at their default density and pressure values of 1.22 kg/m³ and 101325 N/m², and the temperature was set to 288K (15°C).
Variables

The release substance was set to chlorine with a constant release rate. Three release rate values and four windspeeds per release rate were used to obtain twelve ratio values. These release rates were 3kg/s, 1kg/s and 0.3kg/s, with windspeeds of 1m/s, 2.4m/s, 4.3m/s and 6.7m/s. For each case, a total release time of 20 minutes was assumed.

C4. RESULTS

The Release Ratios were calculated for these twelve runs. They are tabulated in Table C.1; and plotted in Figure C.2.

<table>
<thead>
<tr>
<th>Windspeed [m/s]</th>
<th>Release Rate [kg/s]</th>
<th>Release Ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0.267</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.155</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>2.4</td>
<td>3</td>
<td>0.301</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.306</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.281</td>
</tr>
<tr>
<td>4.3</td>
<td>3</td>
<td>0.437</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.444</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.436</td>
</tr>
<tr>
<td>6.7</td>
<td>3</td>
<td>0.556</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.567</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.569</td>
</tr>
</tbody>
</table>

Table C.1 Release Ratio values for varying windspeed and release rate

C5. DISCUSSION

It may be observed from Figure C.2 that there is a strong positive correlation for windspeeds higher than approximately 2.5m/s. This is because, in all but one scenario evaluated, pollutant escaped through one opening only (B) whilst there was an ingress of air through the other (A). The one event that resulted in an egress of pollutant from both openings was that depicted in Figure C.1 (i.e. 3kg/s release rate and 1m/s windspeed), which caused the ‘rogue’ data point in Figure C.2. However, when the ratio is taken for the outflow from opening B only, a value of 0.167 is obtained which would then be consistent with the three curves depicted in Figure C.2.

It is this ‘rogue’ data point that is of interest to this study, as it represents the case where the internal pressure results in a flow that overpowers the wind-driven flow. So, although the ratio decreases as the windspeed decreases, there is a lower limit on the Release Ratio which is determined by the leak rate.
Figure C.2  Variation of Release Ratio with wind speed

Assuming a linear variation between the Release Ratio and windspeed, and a cut off value dependent upon a leak rate of 3kg/s, the results of Figure C.2 can be approximated for low windspeed, as shown in Figure C.3.

Figure C.3  Approximation of Release Ratio against windspeed

These two additional lines give an indication of the maximum Release Ratio value (although the assumption of a linear relation between ratio and windspeed is somewhat crude). It can then be assumed (conservatively) that, for low windspeeds the Release ratio may be given by:

\[ r = \max(0.15u, 0.09\text{m/s}) \]  \hspace{1cm} (C2)
where \( u \) is the windspeed and \( \dot{m} \) is the leak rate, and the coefficients (0.15 and 0.09) are estimated from the curve. Clearly, this can only sensibly be applied to \( u \leq 6.7 \text{ m/s} \) and \( \dot{m} \leq 11 \text{ kg/s} \), since the Release Ratio cannot exceed 1.

C6. CONCLUSION

Although for higher windspeeds the average rate at which pollutant escapes from the room may be calculated via the Release Ratio approach, the clear correlation is modelled to break down at lower windspeeds, at which there is a possibility of gas escaping from both leeward and windward openings. In these instances however, the Release ratio may be conservatively estimated by the maximum of 15% of the windspeed or 9% of the leak rate.

It should be noted that the calculations in this Appendix relate to a particular building volume and particular opening areas. Thus, whilst it gives a general indication of the Release Rates variation, it should be used with caution. Any specific building could be analysed in a similar way in order to determine the most appropriate parameters to be used. GRAB-T could also be used to determine the time-varying release rate, which could then be applied directly in the dispersion modelling in place of the Release Rates approach.