ELSEVIER Journal of Hazardous Materials 54 (1997) 201-226

JOURNAL OF HAZARDOUS MATERIALS

Practical modelling of gas dispersion in low wind speed conditions, for application in risk assessment

I.G. Lines, D.M. Deaves *, W.S. Atkins

W.S. Atkins House, Birchwood Boulevard, Birchwood, Warrington, Cheshire, WA3 7WA, UK

Received 24 April 1996; accepted 3 November 1996

Abstract

Risk assessments for hazardous installations, in which loss of inventory could result in offsite risk, will generally require the modelling of the dispersion of toxic or flammable gases for several realistic scenarios in a range of representative wind conditions. Hazard ranges — the distances affected by hazardous gas clouds — are usually greater for low wind speeds, but these are frequently omitted from the assessment. It is therefore useful to be able to model such conditions in an appropriate manner, and also to understand the nature and frequency of these low wind speed conditions.

This paper presents the results of part of a study which considered the whole problem of using low wind speed conditions in risk assessments. A brief review is given of the current status of the modelling of gas dispersion in low wind speeds, with particular reference to releases of dense gas from low level, and the problems associated with using dispersion models beyond their range of validation or stated application are discussed. Different types of models are reviewed, and the potential for using models specifically developed for low wind speed conditions is assessed. A brief discussion is then given of the likely effects of using such models on the results of risk assessments and safety cases. © 1997 Elsevier Science B.V.

1. Introduction

When undertaking an assessment of the consequences of an accidental release of a hazardous substance, one of the most important parameters which may affect the results is the magnitude of the wind speed. The wind speed is particularly important when one is considering the dispersion of toxic or flammable substances in the atmosphere and can have a significant effect on the hazard ranges associated with the scenario, which in turn

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* Corresponding author.

PII S0304-3894(96)01873-0

can affect the calculated risk significantly. The majority of dispersion models use the wind speed as one of the key inputs, and safety cases and quantified risk assessments (QRAs) are generally based on an evaluation of the potential consequences over a range of wind speeds and atmospheric stabilities. However, the lowest wind speeds generally used for such assessments are in the range of 2 to $2.4\,\mathrm{m\,s^{-1}}$, with typical wind speeds, representing normal conditions, being about $5\,\mathrm{m\,s^{-1}}$.

There appear to be two reasons why lower wind speeds and calm conditions are generally neglected. One reason is that the data on the frequency of such conditions in the UK are not always readily available or sufficiently detailed or accurate. More significantly, however, the majority of dispersion models are not capable of dealing with low wind speeds or calms. It should be noted that a wind speed will be 'low' when certain assumptions on which the dispersion model used is based become untenable. It is therefore not possible to set a single value of wind speed below which it is considered 'low', since this will depend upon the specific modelling conditions. This will be discussed in more detail throughout this paper, but, for most of the general discussion, a value of $2\,\mathrm{m\,s^{-1}}$ will be used, since this is typical of the lowest value currently in regular use in QRA studies.

The justification that is sometimes used for not considering low wind speeds (i.e. $< 2\,\mathrm{m\,s^{-1}}$) or calm conditions is that they are a rare occurrence, although this assumption is not borne out by the currently available data. For example, the mean wind speed at Manchester Ringway (1983–1992) was recorded as less than 3 knots ($1.5\,\mathrm{m\,s^{-1}}$) for 20% of the time, although there is some doubt over the accuracy of the low wind speed data. The frequency of Beaufort Scale Force 0 (1 knot or $0.5\,\mathrm{m\,s^{-1}}$) is somewhat lower, but may reach up to 3 or 4% of the time in some parts of the country. Furthermore, although the frequency of such calm conditions may be low, the dispersion during such conditions may dominate the risk as they represent some of the worst cases. It is therefore important that the potential effect of low wind speed conditions is considered in any QRA involving the dispersion of hazardous material in the atmosphere; this has been discussed by Lines and Deaves [1].

It is generally recognised that the hazard ranges and risks associated with many types of accidental release, for example those materials where a dose-based criterion is used, tend to increase with decreasing wind speed. In these cases, wind speeds of around $2\,\mathrm{m\,s^{-1}}$ in stable atmospheric conditions are often taken as the worst case weather conditions. It is by no means clear whether lower wind speeds or calm conditions represent an even worse case, in terms of either hazard range or risk implications. This may be particularly important when considering the worst case conditions for the purposes of emergency planning. The problem is compounded by the generally poor performance of gas dispersion models at low wind speed. This problem was identified by Nussey [2], who concluded that there are significant differences in predictions of dense gas dispersion models in low wind speed stable conditions.

This paper assesses the development and use of gas dispersion models, with particular reference to the modelling of low wind speeds within risk assessment studies. This includes a consideration of the accuracy of 'standard' models at low wind speeds, as well as a review of the potential for using specifically developed low wind speed dispersion models.

2. Atmospheric structure

2.1. Wind speed

The wind, and in particular its turbulent nature, is a significant agent in dispersing any gas released to the atmosphere. It is therefore useful to understand the structure of the atmosphere and the characteristics of atmospheric turbulence.

Winds are generated by coriolis forces and by large-scale pressure differences which, in turn, are caused by the rotation of the earth and by differential solar heating of land and sea masses. The structure of the wind at any location is then determined by the underlying terrain, a rougher terrain causing more turbulence and resulting in lower mean wind speeds, but with higher turbulence and hence greater gustiness. Lighter winds are generated in a similar way, but on a smaller scale. Examples of these are sea breezes, downslope winds in mountainous areas and valley drainage winds. In these cases, gravity may play an important part in driving the flow.

The mean wind speed ($\bar{u}$) will adopt a boundary-layer type profile, the lower part of which can be plotted as a straight line of speed against height (z) on a log-linear plot, since

$$\bar{u} = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

where k = von Karman's constant (= 0.4), u_* = friction velocity and z_0 = roughness length.

Values of z_0 over land range typically from 0.001 m at exposed airfield sites to around 1 m in city centres. In this latter case, since the logarithmic profile cannot describe the detailed flow within the roughness elements (i.e. between buildings), models using this approach cannot describe dispersion in this region.

Meteorological Office data have almost always been collected at the standard height of 10 m, or, where the exposure requires it, at greater heights, and the values can then be corrected to the standard height. Within risk assessments for major hazard sites, those releases which are of greatest concern are effectively at ground level. Wind speed estimates are therefore required for the lowest few metres, which is well below the level at which measurements have generally been made, in order to be able to determine the dispersion characteristics of gas clouds whose heights may remain less than 10 m for some considerable distance. This was observed by Mercer and Nussey [3] in relation to the continuous release trials 45 and 47 from the Thorney Island datasets, where the effective plume velocities were 45% or less of the measured 10 m wind speeds.

2.2. Atmospheric stability

A further important property of the atmosphere is stability. This is primarily a function of the temperature variation in the lower part of the atmosphere, and gives an indication of the tendency of vertically displaced parcels of air to move within the atmosphere. In neutral conditions, which generally occur for moderate to high wind speeds, the temperature lapse rate is adiabatic, which means that a vertically displaced parcel of air will neither rise nor fall any further. Such conditions thus result in strong mechanical mixing with negligible convective effects.

In very stable conditions, the temperature may actually increase with height. This results in a tendency for any displaced parcel of air to be returned to its original position. Turbulence is thus suppressed and reduced mixing occurs. In very unstable conditions, the lapse rate is superadiabatic, causing any vertically displaced air to continue its movement, thus setting up large convective cells and enhancing both turbulence and the consequent mixing.

The wind speed reduction at heights less than 10 m is even greater for stable conditions than for neutral conditions. This was also demonstrated by Mercer and Nussey [3], who showed that the plume speed of the continuous release trial 47, in F stability, was 40% of the 10 m value compared with 43% for trial 45 (E/F stability).

2.3. *Topographical effects*

The low wind speeds which are being considered within this review will generally occur when the large scale wind-forcing mechanisms, in the form of pressure gradients, are rather weak. In such cases, local effects become significant; sea breezes, for example, occur during the summer months in the UK. They can occur during periods of settled weather, start at about 10 a.m., and may penetrate inland by as much as 90 km by sunset. Such extensive penetration requires a moderate depth of convection, such as may occur on a fine summer's day. If the air is very stable, with little convection, the sea breeze will remain localised at the coast.

Local wind systems may also be set up within valleys. Anabatic winds occur where the air flows up slopes which have been warmed by solar heating. The vertical profile of wind speed will not follow the normal boundary layer equations, but maximum speeds will occur within a few metres of the surface of the slope. The situation is reversed during nocturnal cooling, giving katabatic winds. When there is no strong external forcing, the valley wind system will be complex, with significant diurnal variation in both flow speed and direction.

Isolated hills may affect the wind speed by causing a speedup of flow at the brow, with corresponding speed reductions upwind and downwind. In strong stable stratification, air is likely to flow around rather than over an isolated 3D hill, and would tend to be channelled along the axis of 2D obstructions. Whilst these flow features may cause some effects on wind speed, with possible slight increases, the greatest effect would be on wind direction.

2.4. *Site and building effects*

Most industrial sites from which gas dispersion would be considered will contain a number of buildings, vessels, bunds, pipework runs etc. Buildings will vary in height, typically between 3 m and 10 m, and will significantly affect the air flow at the 2 m level. Channelling and sheltering effects may therefore be present which, in light winds, would suggest that 2 m winds may have very little correlation with those recorded at 10 m.

In addition, there are likely to be heat sources which would set up local convective flows. Even differences in ground cover such as tarmac/gravel/grass/trees will ensure significant temperature differences which may drive local convection when there is strong insolation. In such conditions, diurnal variation of these locally induced flows will be important and may affect safety cases or emergency planning advice. Little work seems to have been undertaken to quantify these effects. Some studies have been performed in which real plant areas were modelled in wind tunnels (e.g. Guldemond [4] and Robins [5]), but the emphasis has been on the actual dispersion rather than on the quantification of local wind speeds.

2.5. *Definition of low wind speed and calm conditions*

Terms such as 'low wind speeds' and 'calm conditions' are not defined precisely, and it should be noted that different authors may use such terms to imply different ranges of conditions. In this section, a brief summary of the various definitions of these terms is given, and the use of these terms in this paper is clarified.

There is no generally accepted definition of what constitutes a *low wind speed.* Indeed, the point at which the wind speed may be considered 'low' will be dependent upon the details of the application such as gas density and concentration, ambient turbulence etc. However, for the purposes of this paper, the particular interest is in wind speeds of less than about $2\,\mathrm{m\,s^{-1}}$. This corresponds to the area where standard meteorological data almost certainly become misleading and the applicability of dispersion models may need to be considered more carefully. It is also typical of the lowest values currently in regular use in performing QRA and safety case studies.

Smith [6] defines low wind speeds as being when the mean wind speed (u) is comparable to or less than the root-mean-square (rms) turbulent horizontal velocity (σ_u). In convective conditions, σ_u depends largely on the heat flux (H), and Smith suggests that when u is small, $\sigma_u \approx 0.187 H^{1/3}$. For stable conditions, Smith describes various experimental results which suggest that σ_u lies in the range 0.35–$0.5\,\mathrm{m\,s^{-1}}$.

Table 1 provides a simple summary of the wind speed at which $\sigma_u = u$ for each of the Pasquill stability categories, derived from data given by Smith. Although no indication is given of the averaging times used, it is assumed that standard hourly averages, as used for meteorological data, have been taken. The implications of taking shorter averaging times, as would be appropriate for short duration accidental releases, are discussed further in Lines and Deaves [1].

Table 1
Approximate wind speeds at which rms turbulent horizontal velocity is equal to the mean wind speed

Pasquill category	Heat flux H ($\mathrm{W\,m^{-2}}$)	Wind speed where $\sigma_u = u$ ($\mathrm{m\,s^{-1}}$)
A	250	1.2
B	150	1.0
C	90	0.8
D	0	0.35–0.5
E	–	0.35–0.5
F	–	0.35–0.5
G	–	0.35–0.5

This table clearly indicates that, on the basis of Smith's definition, it is not appropriate to define 'low wind speeds' by a single threshold wind speed value, and that a low wind speed in A stability conditions (e.g. 1 m s^{-1}) should not necessarily be classed as a low wind speed in stable F conditions. This important point is considered further in Section 5 where the applicability and limitations of current dispersion models are considered.

Smith also suggests that low wind speeds could be defined as being when the wind measuring instruments begin to perform inadequately, or else when the influence of the geostrophic wind becomes small when compared with topographic influences. The first of these definitions is dependent on the instrument, and is discussed in greater detail in Deaves and Lines [7]. This instrument-based definition is at best useful in deciding how accurate measurements may be for validation purposes, or in ascertaining the frequency of low wind conditions, but is clearly unrelated to the physics of gas dispersion. The second is also difficult to generalise since it is determined by the particular site, although it does relate more closely to the physics. Hence neither of these definitions would be generally applicable.

The Beaufort Scale describes Force 0 as '*Calm*', and defines the equivalent wind speed at 10 m above ground for these conditions as < 1 knot (i.e. < 0.515 m s^{-1}). The standard data provided by the Meteorological Office gives the frequency of calms as corresponding to periods where the wind is insufficiently strong to cause the wind vane to change direction, which typically also corresponds to about 1 knot.

It should be noted that calms do not necessarily correspond to periods during which an anemometer reads zero, as anemometers vary considerably in design so that some may read zero in all wind speeds below 5 knots (2.57 m s^{-1}) whilst others may continue to provide a reading at speeds as low as 0.01 m s^{-1} (in the case of sonic anemometers). The Meteorological Office has undertaken some comparisons of the performance of various types of anemometer, and analyses of some of their data have been presented in Deaves and Lines [7].

3. Review of dispersion modelling for low wind speeds

A brief review is presented here of approaches to the practical modelling of gas dispersion in low wind speed conditions. The emphasis is therefore upon models which are currently readily available and in use for risk assessment or similar applications; more detail on the limitations of the various types of model is presented in Section 4.

3.1. Gaussian models

Carruthers et al. [8] describe UK-ADMS, which is discussed further in Section 3.2. One important point which they note is that, for calm meteorological conditions (defined as when the mean wind speed is less than 0.5 m s^{-1}), the speed of upwind diffusion can exceed the wind speed, so that a well-defined plume may not actually form. This should be recognised when considering the low wind speed application of any of the following models, which are based on Gaussian plumes.

Jones [9] provides a summary of an international conference on atmospheric dispersion in low wind speeds, which was organised by the European Association for the Science of Air Pollution. Several papers considered ways of modelling the variability of wind direction found in low wind speed conditions. One methodology which may be particularly applicable when considering short period releases and QRAs was presented by Anfossi et al. [10]. This involved splitting the hourly average wind direction into separate contributions from the atmospheric turbulence and from that due to meandering. This is very similar to the fluctuating plume model originally developed by Gifford. This approach appeared to be a considerable improvement over assuming a broad plume around the hourly average wind direction. The alternative is to use the statistics (wind speed, direction, standard deviation of the wind etc.) evaluated every 2 or 3 minutes, which are rarely available in practice.

Hanna and Paine [11] describe the development and evaluation of the hybrid plume dispersion model (HPDM). This model, in which a non-Gaussian vertical concentration distribution is used, was found to be an improvement over previous regulatory models during light wind convective conditions.

Jones [12] describes the estimation of long-range dispersion and deposition of continuous releases. Again, low wind speeds are not considered in any detail, although some data are given on the persistence of stability categories before a change towards neutral stability occurs. This data shows that A and G stabilities are least likely to persist for long periods, as one would expect.

Jones [13] considers the long range dispersion of short releases and gives the following equation for the time-integrated concentration (C) at a distance x (m):

$$C(x) = \frac{Q}{u\Theta xA} \tag{2}$$

where Q is the total activity released, u is the wind speed ($\mathrm{m\,s^{-1}}$), Θ is the total width of the plume in radians and A is the depth of the mixing layer (m).

The point is made that there is a correlation between wind speed and wind direction persistence, strong winds having a greater tendency to maintain their direction than light winds. This means that the product of wind speed and plume width ($U\Theta$) in Eq. (2) is largely independent of wind speed, and so a single value of $8\,\mathrm{m\,s^{-1}}$ was used to represent this quantity. This suggests that $\Theta = 8/u$, which exceeds the value π when u drops below $2.54\,\mathrm{m\,s^{-1}}$, indicating that this particular long-range plume model breaks down at wind speeds of this order.

Hanna [14] makes the same point on the basis of wind direction measurements made at a site in the United States. The hourly average variation in wind direction σ_Θ was found to increase in low wind speeds, so that the product $\sigma_\Theta u$ remains constant at about $1\,\mathrm{m\,s^{-1}}$ (σ_Θ is in radians). In this case, σ_Θ will exceed π only for wind speeds less than $0.3\,\mathrm{m\,s^{-1}}$, suggesting that this model was probably based on shorter timescales than that of Jones. Models of this type imply that the standard Gaussian plume model will overestimate hourly average concentrations, as the increased plume width with decreasing wind speed is not predicted in the models. However, these results may not be applicable in the majority of risk assessments as releases are generally of short duration and plume meander over a period of an hour is not relevant.

Jones [15] describes the uncertainty in dispersion estimates obtained from the standard models produced by the UK Atmospheric Dispersion Modelling Group, such as the widely used R-91 Gaussian plume model. He noted that the Gaussian plume model is clearly not applicable in conditions with zero wind speed, since the formula, which contains the reciprocal of the wind speed, diverges as the wind speed approaches zero. Its use in conditions of low wind speed is therefore questionable because the wind speed and direction are very variable in these conditions; a well-defined plume is unlikely to exist and the assumption that along-wind dispersion can be neglected is no longer valid. The Working Group, for which Jones was reporting, therefore suggested that the model should not be used for a wind speed below $1\,\mathrm{m\,s^{-1}}$.

Jones also gives a table showing the probability that a stability category will persist for a given time, from which it is seen that most categories persist, on average, for only a few hours, with a low probability of any category other than D persisting for six or more hours.

Jones discusses the uncertainty in parameter values for dispersion models, such as wind speed, direction, stability category and its distribution. It is noted that there are complications at low wind speeds arising from instrumental error if a standard anemometer is used, as its starting speed may be comparable to the wind speed (see further discussion in Deaves and Lines [7]). This can lead to difficulties in specifying extremes of stability and the frequencies with which they occur.

Jones reviews many of the model validation studies that are described in the literature. In particular, Draxler [16] is noted as having produced an improved Gaussian plume model which includes an improved treatment of calm conditions.

In his latest review, Jones [17] considers low wind speed models separately from those for calms. In the first category, he refers to the Hanna observation that $\sigma_\Theta u$ is constant, but suggests that the value is $0.5\,\mathrm{m\,s^{-1}}$ rather than 1 (Hanna [14]). He also refers to unpublished work by Hunt (discussed further in Section 5), which he includes as an appendix to his review. In the second category, he refers to a model developed by Smith for application to elevated plumes in unstable conditions. He also suggests that this situation could be modelled as an expanding disc of radius $\sigma_u t$, with σ_u approximately equal to $0.5\,w_*$, where w_* is the convective velocity scale.

Hanna et al. [18] provide an introduction to the use of the Gaussian plume model, which is quoted as

$$\frac{C}{Q}=\frac{1}{2\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right] \tag{3}$$

where C = concentration, Q = source strength, σ_y = standard deviation in the horizontal direction, σ_z = standard deviation in the vertical direction, u = wind speed, h = height of release, and z = height above ground.

Hanna et al. [18] go on to say:

> *Newcomers to this field often ask, "What happens in the Gaussian equation when the wind speed (*u*) goes to zero?" The standard reply is "Calm winds are defined as* u *equal to 0.5 m/s." The truth is that anemometers near the surface may*

register u = 0, *but the winds in the planetary boundary layer very seldom stop entirely. There is always a slight drift, and the seemingly facetious answer to the above question is based on considerable experience.*

3.2. Quoted wind speed limits for various models

Various models are relatively readily available for use in performing dispersion studies. In many cases they include quoted lower limits of validity which may be advisory or, in the case of some computer codes, mandatory in the sense that it is not possible to input wind speeds below the stated threshold. The limits quoted for several such models are discussed in this section, although there is often little information available on the reasons for the choice of threshold values.

The Health and Safety Factbook [19] states that the worst condition for dispersion of material occurs on still days, and for a source close to the ground this is approximated by the formula of Katan [20], which gives the distance travelled, d_s (m), to achieve satisfactory dilution of a flammable vapour release as

$$d_s = [36.8Q/(uC_L)]^{0.552} \tag{4}$$

where Q is the release rate ($m^3 s^{-1}$), u is the wind speed ($m s^{-1}$), and C_L is the lower flammable limit (m^3 of vapour/m^3 of air).

The lowest wind speed for which this correlation applies is quoted as $2.24 m s^{-1}$, which is not a particularly low wind speed. It should also be noted that this formula is based upon empirical data, contains a dimensional constant (if the exponent were 0.5, then the constant would be dimensionless) and is applicable only to flammable vapours (i.e. down to around 2% concentration). It should therefore be treated with caution.

Witlox et al. [21] and Post [22,23] provide a description of the HGSYSTEM suite of codes, which includes models for both dense gas and passive dispersion. No explicit consideration is given to the case of low wind speeds, but the report does give the validity range for the dense gas dispersion model (HEGADAS) as:

U_0	Wind speed at reference height	1.5 to $20 m s^{-1}$
z_0	Reference height for U_0	0.1 to $50 m$
z_r	Roughness length	10^{-5} to $1 m$

The range of validity of the HEGABOX dense gas box model (for the initial slumping of an instantaneous release) is the same, except that the lower limit on U_0 is $1.0 m s^{-1}$. For the passive dispersion model (PGPLUME) it is stated that data validation requires that the ambient wind speed at the plume centroid height should lie in the range 1.0–$20 m s^{-1}$.

The TNO Yellow Book [24] describes the simple Gaussian plume model used in the EFFECTS computer program for dispersion modelling. It is stated that, at a wind speed lower than $1 m s^{-1}$, the wind direction is very uncertain and, since the dispersion experiments on which the recommended dispersion parameters are based were carried out mainly at higher wind speeds, a calculation for wind speeds lower than $1 m s^{-1}$ must be regarded as very unreliable. Nomograms are given which suggest that F stability should be used for all low wind speeds at night.

Bennett [25] describes the CEGB's ALMANAC plume dispersion model, which was based on the earlier work of Moore. Bennett discusses the problem encountered with the use of Meteorological Office wind measurements owing to a starting speed of several knots for the standard anemometer. The lowest two wind speed categories, < 1 knot and 1–3 knots, thus have little physical reality and were replaced in his analysis by a single category with a wind speed of 2 knots. Although this seemed to work well in predicting the peak annual hourly concentrations in light winds, there may be problems in predicting higher, less frequent peaks associated with convective conditions with near-zero mean wind speeds.

CERC [26] describe the model features incorporated within UK–ADMS, and it is specifically noted that calm meteorological conditions are excluded. It is stated that:

> *'Calculations cannot be carried out during calm conditions; the situation is flagged and execution continues for the next period in the meteorological data base. For standard UK Meteorological Office Station instrumentation, calm conditions are equivalent to a wind speed of less than 0.5 m / s (1 knot).'*

When entering a wind speed as an input to the UK–ADMS model, the user is prevented from entering a value of less than $1\,\mathrm{m\,s^{-1}}$ or greater than $50\,\mathrm{m\,s^{-1}}$, although wind speeds lower than $1\,\mathrm{m\,s^{-1}}$ may be entered via a file.

As noted above, Carruthers et al. [8] also describe UK–ADMS and make the point that correct modelling of the extreme conditions (highly unstable and highly stable) is very important, and that, while such conditions may occur only rarely, they can give rise to the highest concentrations. They also define calm meteorological conditions for the purposes of ADMS modelling as those when the wind speed is less than $0.5\,\mathrm{m\,s^{-1}}$.

It is concluded that a wide range of lower wind speed limits is quoted for current dispersion models, and that these limits are frequently given without sufficient justification. It is also noted that many computer models will allow input of unrealistically low wind speeds, often without warning. It is therefore important that such models are used by those who have some understanding of the physics of gas dispersion, and also of the model limitations.

3.3. Dense gas dispersion models

The majority of the published work on gas dispersion relates to the passive or buoyant dispersion of stack discharges. However, many of the potential major hazards considered in QRAs for sites handling hazardous substances involve ground-level releases of heavier-than-air gases, such as chlorine, and the resulting gas cloud formed tends to remain close to the ground. In recognition of this, much efffort was invested in improving the modelling of dense gas dispersion during the 1980s. This commenced with the Maplin Sands experiments (Colenbrander and Puttock [27]) and was significantly enhanced by the Thorney Island experiments (McQuaid [28]). Results from these trials were widely disseminated and led to significant advances in understanding and modelling.

In terms of the importance of low wind speeds, the point to emphasise is that, in the initial stages of dispersion, the gas cloud tends to slump downwards since it is denser than the surrounding air. The initial dispersion is therefore governed by processes which do not depend critically on the wind speed. It is therefore expected that dense gas dispersion models may be quite adequate in the very near field, but at greater distances, when the influence of cloud density is less significant, the dense gas dispersion models will begin to suffer from all the low wind speed uncertainties which apply to the majority of dispersion models. This feature is evident from the assessment of the transition from gravity-driven slumping to passive dispersion which has been undertaken by Brighton [29] on the basis of some of the Thorney Island results.

Britter [30] presents the results of a laboratory experiment to study the spread of a negatively buoyant release into a calm environment, and gives a formula for the position of the leading edge of the plume:

$$r_m = (0.84 \pm 0.06)(Q_1 g')^{1/4} t^{3/4} \tag{5}$$

where $Q_1 g'$ is the negative buoyancy flux.

For example, a 3 kg s^{-1} chlorine release has $Q_1 \approx 1\,\mathrm{m^3\,s^{-1}}$, $g' \approx 15\,\mathrm{m\,s^{-2}}$, giving $r_m = 1.65\,t^{3/4}$. The local velocity is obtained by differentiating this, and is $v_m = 1.24\,t^{-1/4}$. This gives the cloud development, as shown in Table 2.

Hence, after only about 1 minute, the cloud velocity is less than 0.5 m s^{-1}, and the cloud may begin to be influenced by atmospheric motions. The results from a model such as this may, however, be useful in defining a virtual source for a plume model.

As noted above, the Thorney Island trials provided a significant stimulus to the development of dense gas dispersion models. Whilst most models were developed to cover the full range of wind speeds, some were specifically developed for calm or very light wind conditions. A review of *all* dense gas dispersion models developed on the basis of this data is therefore inappropriate at this point, but details of two still air models are discussed below.

Webber and Wheatley [31] present a model for the behaviour of an instantaneously released heavy gas cloud in calm conditions, or sufficiently close to the source that gravity effects dominate ambient turbulence effects. The object of this model is to clarify how turbulence generated from the initial potential energy of the cloud may affect the subsequent dilution. The model is an integral one which treats the turbulent energy in the cloud as a dynamic variable determining the entrainment rate, such that overall dissipation of mechanical energy is guaranteed. The turbulent energy of the cloud released from rest is thus generated explicitly from the initial potential energy, and the entrainment rate may depend on the initial aspect (height to radius) ratio, and the initial density, of the cloud. An investigation of the properties of the model indicates that these effects, whilst present, are small.

An important conclusion from this theoretical study, which used Thorney Island data

Table 2
Radius and velocity of slumping dense gas cloud

t (secs)	1	3	10	30	100	300
r_m (m)	1.65	3.8	9.3	21.2	52.2	119
v_m (m s^{-1})	1.24	0.94	0.70	0.53	0.39	0.30

for validation, was that air entrainment into the top of the cloud need not be considered in calm conditions.

Van Ulden [32] considers mixing processes in still air, and describes a dynamic integral model which includes a time-dependent radial momentum budget and a turbulent kinetic energy budget. These budgets are used to predict radial gravity spreading and cloud-generated turbulent entrainment. In a comparison with measurements from two of the Thorney Island trials with low atmospheric turbulence, it appears that the model accurately describes radial gravity spreading. It is also observed, from the trials considered, that there were strong vertical gradients of concentration. An appropriate similarity profile has been developed and incorporated into the model.

A further semi-empirical model, which predicts the concentration field resulting from the collapse of a cylindrical gas cloud in calm air, is described by Matthias [33]. The model incorporates the processes of top and side entrainment, the occurrence of a leading torus and a trailing disc, and uses Gaussian distributions in the entrainment zones. Matthias acknowledges that, in its present form, the model is of limited application since atmospheric turbulence is assumed to be zero. The model may, however, be applicable in the early stages of cloud growth in the atmosphere during which self-induced turbulence is dominant. The model appears to give reasonable results over a range of scales, although it should be treated with caution since, for practical applications, its use is limited to near-field dispersion.

Nussey [2] describes work sponsored by the HSE concerning the objective assessment of complex dense gas dispersion models by rigorous benchmark testing. He states that the conclusion from one such study was that "the major differences occur for releases at low wind speed, in Pasquill F stability". It is clear, therefore, that most of the currently available models should be treated with considerable caution at low wind speeds.

4. Types of model and their limitations in low wind speeds

In this section, a brief review of the main types of dispersion model currently used for safety case and QRA applications is given. For each type of model, an assessment is made of the model limitations in low wind speed conditions.

4.1. Gaussian models

4.1.1. Plume models

Gaussian plume models have been used for a wide variety of purposes for many years, and are described extensively in the literature (e.g. Gifford [34,35]). The crosswind concentration in the plume is assumed to have a Gaussian profile, and the standard deviation of the distribution is determined as a function of the downwind distance, the atmospheric stability, the roughness length, etc. These models can be used for continuous or instantaneous releases, and are relatively easy to use. The most commonly used Gaussian plume model in the UK is the R-91 model (Clarke [36]).

Gaussian plume models generally predict that the concentration at any fixed downwind location varies in inverse proportion to the mean wind speed. This leads to the models predicting concentrations which tend to infinity as the wind speed approaches zero, and so a limit is usually quoted for the lowest wind speed which may be used in the model. For example, the R-91 model recommends a lower limit of $1\,\mathrm{m\,s^{-1}}$, as noted in Section 3.3. The more sophisticated model used in UK–ADMS is restricted to the range $1 \leq u \leq 50\,\mathrm{m\,s^{-1}}$, thus retaining the same lower limit.

Some progress can be made towards determining a lower limit on the wind speed for a plume model. This can be done by considering the centreline concentration, C_0, and observing that this can never exceed unity:

$$C_0 = \frac{Q}{\pi u \sigma_y \sigma_z} \leqslant 1 \tag{6}$$

where Q = volumetric release rate, σ_y, σ_z = lateral and vertical plume spread, and u = wind speed.

Hence

$$u \geq \frac{Q}{\pi \sigma_y \sigma_z} \tag{7}$$

It should be noted that σ_y and σ_z are both empirical functions which are derived from measurements in moderate winds and increase with distance from the source. Eq. (7) should therefore be treated with caution, since it is not clear that the same σ_y and σ_z functions will be appropriate for low wind speeds. However, it does indicate that the lower limit for u *increases* with release rate and *decreases* with distance from the source.

Doury [37] presents an assessment of the limits to the use of 'Plume' models for short distances and light wind conditions. The horizontal turbulent velocity is quoted as being of the order of $0.5\,\mathrm{m\,s^{-1}}$ and it is therefore concluded that the results of plume models are less reliable for wind speeds of less than about $2\,\mathrm{m\,s^{-1}}$, where longitudinal dispersion may become an important factor.

4.1.2. *Puff models*

Puff models are in many ways similar to Gaussian plume models, in that the release is usually considered to have a Gaussian profile. The principal difference is that the release is divided into a number of separate 'puffs', each of which is modelled independently, although the final concentration at any point is found by a superposition of all the puffs. Hanna et al. [18] identify a number of such 'puff' models. The main advantage of these models is that it is relatively easy to model a time-varying release with a wind velocity which varies in direction and magnitude. The spread of each puff is generally determined either as a function of the downwind distance, as for a Gaussian plume model, or, more commonly, as an empirically determined function of time.

Such puff models would appear to be well suited for modelling dispersion in low wind speeds in that they can characterise the inherently variable nature of the wind field, provided appropriate input data are available. Ideally, this would take the form of raw wind data at each time step considered. They also have the advantage that, if the spread is taken as a function of time, the concentration is no longer proportional to $1/u$, thus avoiding the non-physical singularity inherent in standard models. This is discussed further in Section 5.

4.2. Box models

4.2.1. Integral plume models

Integral plume models are generally used for the assessment of the near-field dispersion of a continuous, elevated jet release into a crossflow. A set of differential equations for the conservation of momentum, energy, mass etc. is solved along the plume, together with various assumptions concerning the rate of air entrainment. The solution of the differential equations gives the plume path and the variation in the centreline plume parameters such as velocity, temperature, concentration etc. The profiles of these parameters across the plume are generally assumed to follow Gaussian forms.

In principle, these models may be applied in low or even zero wind speed conditions. In such calm conditions there would be no momentum transfer to the plume, whose path would then be determined entirely by its own momentum and buoyancy. However, the models can be applied only to the near field, so, although they may be useful for predicting the range to the lower flammable limit, they are not appropriate for calculating the hazard ranges for accidental releases of most toxic substances.

4.2.2. Heavy gas dispersion models

Box models for heavy gas dispersion are similar to integral plume models, except that they generally apply to ground-level releases and incorporate additional spreading of the plume due to the initial density-induced slumping behaviour. In the near field, the dispersion is often dominated by this gravity-induced slumping and, as the wind speed has relatively little effect, it is considered that this phase of the modelling would still be appropriate for low wind speeds or calm conditions. However, as the cloud disperses and begins to be affected by the wind, this type of dispersion model assumes that the spread of the cloud is determined by atmospheric turbulence, as for a standard Gaussian plume model. Eventually, the cloud is sufficiently dispersed that it behaves as a passive release, so most models incorporate a transition to a simple Gaussian plume model of the type described above. Therefore, in the medium and far field, these box models must be treated with the same caution as Gaussian plume models when used for low wind speeds.

4.3. CFD modelling

In theory, there is no reason why computational fluid dynamics (CFD) models could not be used in low wind speed situations, although it should be noted that the current status of CFD modelling is such that the results would effectively be 'means' over long periods, unless large eddy simulations are undertaken. However, care would need to be taken that the boundary conditions were adequately specified and that the turbulence model was satisfactory. As the mean wind speed is reduced, so there will be two particular problems in the specification of a turbulence model. The first relates to the fact that, even if the mean wind speed drops to zero, the effective viscosity will tend to a constant, the laminar viscosity. The second is that there is almost always residual turbulence in the atmosphere, even at zero mean wind speed. This is more difficult to incorporate, since it requires the specification of a turbulence generation mechanism which is not related to mean wind gradients.

In view of the difficulty and expense associated with such CFD modelling, it is unlikely to be of practical use for the majority of safety case and risk assessment applications. However, it is noted that CFD modelling may be specially valuable when considering dispersion around buildings and complex terrain; some preliminary results from research by the Health and Safety Executive (HSE) are presented by Gilham et al. [38], and Havens [39] has also presented preliminary results of CFD modelling of large-scale dense gas releases in low wind speed conditions. In addition, preliminary results on the uncertainties associated with the use of CFD modelling for dispersion applications have been presented by Hall et al. [40].

Havens et al. [41] analysed one of the Thorney Island low wind speed trials (Trial 34) using the CFD code MARIAH II. This code uses a local turbulence model which simulates Fickian diffusion. The predictions were generally good, although peak concentrations were slightly overestimated.

4.4. Physical modelling

One often neglected method for assessing dispersion is to undertake physical modelling in a wind tunnel or water tank. This clearly has advantages and disadvantages, but in terms of undertaking a practical risk assessment such physical modelling of all the combinations of releases and weather conditions required in a QRA is generally impractical; hence the need for models which can be rapidly applied to a range of situations. In spite of this, physical modelling will still be useful for validating models and might be useful when carrying out assessments of major sites where low wind speeds are a concern and terrain or building effects are claimed to be significant. However, it should be noted that physical modelling may involve some scaling problems, particularly when considering non-neutral conditions and non-passive releases.

In any wind tunnel simulation, it is necessary to consider some of the Reynolds number limitations on scaling. These limitations are summarised by Meroney et al. [42].

1. When the wall roughness Reynolds number ($\mathrm{Re}_* = u_* z_0/v$) falls below 2.5, the near-wall region will not behave in a fully turbulent manner. This imposes a, possibly unrealistically high, lower limit on z_0 for low wind speeds.
2. When the characteristic obstacle Reynolds number ($\mathrm{Re} = uL_c/v$) falls below 3300, wake turbulence no longer remains similar to field conditions. This implies a lower limit on the size of obstacle which can be modelled adequately and this may be a limitation in complex terrain.

These results suggest that wind tunnel simulations of the type described by Havens et al. [43] (1:150 scale of LNG releases into bunded areas) cannot exactly simulate full-scale releases, and can only be considered as partial simulations.

Petersen and Diener [44] and Meroney et al. [42] identify a number of the other operational limitations associated with wind tunnel experiments. These include:

1. Most large wind tunnels cannot operate satisfactorily at very low wind speeds ($< 0.1\,\mathrm{m\,s^{-1}}$) as the flow becomes sensitive to small disturbances, both external and internal.

2. The minimum spatial resolution for concentration measurement in the laboratory is about 2.0 mm. At a model scale of 1:150 this would correspond to 0.3 m, which may be significant in comparison with a shallow dense gas cloud.
3. The mixing rate associated with molecular diffusion exaggerates dilution at low wind speeds. The ratio of the Peclet/Richardson number provides a measure of the importance of turbulence vs molecular diffusion.
4. The walls of the wind tunnel may cause lateral interference with a spreading dense gas plume. This constraint is normally less significant than the Reynolds number limitations.
5. The turbulent eddies produced by meteorological wind tunnels are typically no larger than the simulated boundary layer thickness. This results in model turbulent integral scales near 1–3 m, but atmospheric turbulence which dominates mixing in the far-field region supports ground-level integral scales near 100 m. Therefore, models with length scale ratios smaller than about 33 should not be used in most meteorological wind tunnels.

Although wind tunnel modelling has been used for dispersion studies for a number of years, it has generally been applied to problems of complex terrain rather than low wind speeds. For example, Robins [5] presented results of the modelling of dispersion affected by groups of buildings. Meroney [45] gave a review of bluff body effects on dispersion, which is substantially based on previous wind tunnel studies. Recently, Havens et al. [39,43] have presented comparisons between wind tunnel and CFD modelling of dense gas dispersion affected by the presence of tanks and bunds. In this case, the physical modelling was undertaken in a specially built facility which was designed to give good simulation of very low wind speeds.

Several empirical models of dispersion exist, based upon full-scale or model-scale dispersion data. However, such models are not widely used and generally do not deal with low wind speed situations. For example, Katan [20] gives several formulae for the concentration and hazard ranges associated with petrol vapour.

5. Use of low wind speed models

The previous section has identified the basic types of dispersion model currently in use for safety case and QRA applications. It has been shown that some of these models have limitations when applied to low wind speed conditions. There are, however, a few models which have been developed specifically to cope with low wind speed conditions, and these are summarised below.

5.1. Simple modifications to Gaussian plume models

Hanna [46] and Van der Hoven [47] emphasise how the horizontal meander in low wind speeds can lead to significant increases in the hourly average value of the horizontal plume spread σ_y. Hanna goes on to describe how the results of a number of field experiments were condensed into a set of tentative empirical correction factors for σ_y, for use in the NRC Regulatory Guide. The procedure involves determining σ_y by the use of standard Pasquill–Gifford–Turner techniques, and then multiplying by an empirical factor M which is a simple function of the wind speed and the stability. For wind speeds of less than $2\,\mathrm{m\,s^{-1}}$, M takes values of 2, 3 and 6 for stabilities D, E and F/G respectively. For wind speeds of between 2 and $6\,\mathrm{m\,s^{-1}}$, the value of M is given by assuming that M falls to 1 at $6\,\mathrm{m\,s^{-1}}$ and using log–log interpolation for intermediate wind speeds.

It is noted that, although this approach may be appropriate to determine the average concentration at a point over a period of an hour, the majority of accidental release scenarios for toxic or flammable substances are generally considered to have shorter durations, typically not exceeding 20 to 30 minutes. Therefore, meander of the plume becomes less important, as the safety assessment generally requires the peak concentration and toxic dose over a relatively short duration, rather than the average concentration over a long period such as an hour.

Hunt has considered modifications to Gaussian plume models in unpublished work which is included as an appendix to Jones [17]. In this note, he makes the point that current Gaussian plume models are based on the assumption that the mean wind speed is greater than the turbulence velocities, which is not a good assumption in strongly convective conditions when there is a low wind speed. Hunt provides a simple modification to the Gaussian plume model to allow for low wind speeds in these conditions, but it is emphasised that it is not suitable for very stable low wind speed situations. In the near field, the concentration for a point source is given by

$$C=\frac{2Q\exp\left[-\beta^2\left(1-\frac{x^2/2\sigma_u^2}{x^2/2\sigma_u^2+y^2/2\sigma_v^2+z^2/2\sigma_w^2}\right)\right]\left(\exp(-p^2)+\frac{\sqrt{\pi}}{2}p(1+\operatorname{erf}(p))\right)}{(2\pi)^{3/2}\sigma_u\sigma_v\sigma_w(x^2/2\sigma_u^2+y^2/2\sigma_v^2+z^2/2\sigma_w^2)}$$

$$\text{where } p=\frac{x\beta^2/u}{(x^2/2\sigma_u^2+y^2/2\sigma_v^2+z^2/2\sigma_w^2)^{1/2}}$$

$$\text{and } \beta=u/(\sqrt{2}\,\sigma_u) \tag{8}$$

The mean wind speed u and the three turbulence velocities σ_u, σ_v and σ_w are therefore the only parameters required to determine the concentration.

When $x \gg z$, taking $\exp(-p^2) \ll p$ and $\sigma_u = u\sigma_x/x$, etc., the downwind concentration becomes

$$C=\frac{Q\exp\left[-\left(\frac{y^2}{2\sigma_y^2}+\frac{z^2}{2\sigma_z^2}\right)\right](1+\operatorname{erf}(\beta))}{2\pi\sigma_y\sigma_z u} \tag{9}$$

This formula is very similar to the standard Gaussian plume model and, in the limit as $\sigma_u/u \to 0$, it is identical to that for a ground level source. As σ_u/U increases, the

Table 3
Ratio between concentrations calculated using Hunt's model and those calculated using the standard Gaussian plume model puff models

Turbulence σ_u U	β	erf(β)	Ratio of concentrations $C_{\mathrm{Hunt}}/C_{\mathrm{GPM}}$ for $x/z \gg 1$
0	∞	1	1
0.1	7.07	1	1
0.2	3.54	1	1
0.5	1.41	0.95	0.975
1	0.71	0.68	0.84
2	0.35	0.38	0.69
5	0.14	0.16	0.58
10	0.07	0.08	0.54

concentration becomes a fraction of that predicted by the standard Gaussian plume model, as shown in Table 3.

As the mean wind speed becomes very small compared with the turbulence velocity, the concentrations predicted by Hunt's model fall to half of those predicted by the standard Gaussian plume model. If low wind speed conditions are defined by $U \leq \sigma_u$ (see Section 2.5), then $\sigma_u/u \approx 1$, and the Gaussian model will only overpredict by a factor of 1/0.84, i.e. around 20% high.

Crabol and Deville-Cavelin [48] describe a Gaussian puff model for use in light wind conditions. The release is divided up into a series of puffs, and a time varying wind field can be applied. The concentration at any particular point is simply derived from the summation of all the puffs. The dispersion model for each puff takes the form

$$\frac{C}{Q} = \frac{1}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{(x-x_0-ut)^2}{\sigma_x^2}+\frac{(y-y_0)^2}{\sigma_y^2}+\frac{(z-z_0)^2}{\sigma_z^2}\right)\right] \tag{10}$$

where C = concentration of the pollutant, Q = total quantity of the released pollutant, σ_x, σ_y = standard deviations in the horizontal direction, σ_z = standard deviation in the vertical direction, u = mean wind speed, and x_0, y_0, z_0 = coordinates of the release point.

Unlike the standard Gaussian plume model, the standard deviations are determined by the elapsed time rather than the distance downwind, so

$$\sigma_x = \sigma_y = \sigma_h = (A_h t)^{B_h}, \quad \sigma_z = (A_z t)^{B_z} \tag{11}$$

where A_h, A_z, B_h, B_z are constants which depend on both t and the atmospheric stability.

The values of these constants are given by Crabol and Deville-Cavelin [48] on the basis of experimental results. The horizontal dispersion parameters are stated as being independent of the stability. Although this formulation avoids the dependence of concentration on $1/u$, it does involve the summation of individual puff concentrations over a potentially long series of time steps. Each puff will depend on $t^{-(2B_h+B_z)}$, and, since B_h and B_z are both of order 1, it is expected that $2B_h + B_z \geq 2$. Hence, even the summation of an infinite series will give a finite concentration, ensuring that solutions remain well-behaved at low wind speeds.

The important point is made that the horizontal standard deviation depends on the averaging time period used for the meteorological measurements, and that it is therefore necessary to calculate the values of σ_h $(= \sigma_x = \sigma_y)$ for the appropriate time period. For example, hourly meteorological data may conceal considerable variations in the mean wind speed and direction, and so an assessment of the concentration at a point must either use suitably increased values of σ_h, or else the analysis could be conducted using meteorological data obtained at much shorter intervals. In essence, there is a choice as to whether the variations in wind speed and direction are modelled deterministically or probabilistically.

Draxler [16] describes two simple methods to account for calm periods. In the first method, calm winds are assumed to equal $0.5\,\mathrm{m\,s^{-1}}$, but Draxler prefers an improved method in which calm situations are simulated by summing the source term until the wind speed increases, rather than performing the calculation with an arbitrarily low wind speed. The effect of this was to simulate a pollutant collecting at the source until the wind speed increases. However, this assumption should not be applied for calculations near the source, but may be appropriate for radioactive releases which can travel tens of kilometres. The application would therefore be inappropriate for short-duration accidental releases where relatively near-field concentrations are required.

5.2. *Analytic solutions of the diffusion equation*

Apsley [49] describes a model for diffusion in light wind conditions which is based on an analytic solution of the complete diffusion equation:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(k_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial C}{\partial z}\right) \tag{12}$$

It is assumed that u, k_x, k_y and k_z are constants. One may then take the eddy diffusivities $k_x = k_y = k_z = K$, rescaling the crosswind coordinates if necessary. This corresponds to the situation where diffusion is dominated by molecular processes rather than atmospheric turbulence; e.g. if $k_y \neq k_x$, then $y' = (k_x/k_y)^{1/2}y$.

For a continuous point source Q, the solution to the complete diffusion equation becomes

$$C = \frac{Q}{4\pi Kr}\exp\left[-\delta^2\sin^2(\phi/2)\right] \tag{13}$$

where $\delta^2 = ur/K$, $r =$ the distance from the source to the receptor, $R =$ the off-axis distance $= (y^2 + z^2)^{1/2}$, and $\phi =$ the angle made by the source–receptor vector with the mean wind direction $= \sin^{-1}(R/r)$.

By taking $\sigma^2 = 2Kx/u$, Apsley [49] notes that the standard Gaussian plume model arises naturally as an asymptotic approximation to this equation in the limit

$$R/x \ll 1 \text{ and } \delta \gg (R/x)^{-2}$$

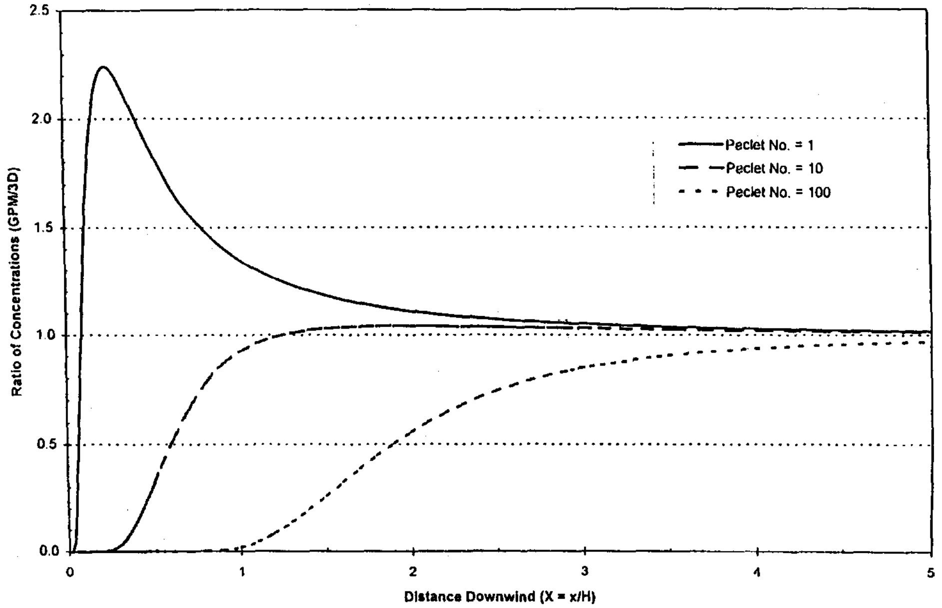

Fig. 1. Ratio of ground-level centreline concentrations from Gaussian plume and 3D diffusion models: source at $z = H$; ratio for $y = z = 0$.

that is, that advection dominates diffusion (for example, near axis, far field or high wind speed).

For an elevated source at height H, an image source is used to ensure a zero flux condition at $z = 0$. The non-dimensional concentration χ can then be written as

$$\chi_{3\mathrm{D}} = \frac{C_{3\mathrm{D}} u H^2}{Q} = \frac{\mathrm{Pe}}{4\pi}\left[\frac{\exp[-(1/2)\mathrm{Pe}(R_1 - X)]}{R_1} + \frac{\exp[-(1/2)\mathrm{Pe}(R_2 - X)]}{R_2}\right] \tag{14}$$

where Pe = Péclet number = uH/K, X = non-dimensional downwind distance = x/H, R_1 = non-dimensional source to receptor distance = r_1/H, and R_2 = non-dimensional image-source to receptor distance = r_2/H.

This can be compared with the concentration calculated using the standard Gaussian plume model for a source at height $z = H$, which is given by

$$\chi_{\mathrm{GPM}} = \frac{C_{\mathrm{GPM}} u H^2}{Q} = \frac{\mathrm{Pe}}{4\pi X}\exp\left(-\frac{\mathrm{Pe}Y^2}{4X}\right)\left[\exp\left(-\frac{\mathrm{Pe}(Z-1)^2}{4X}\right) + \exp\left(-\frac{\mathrm{Pe}(Z+1)^2}{4X}\right)\right] \tag{15}$$

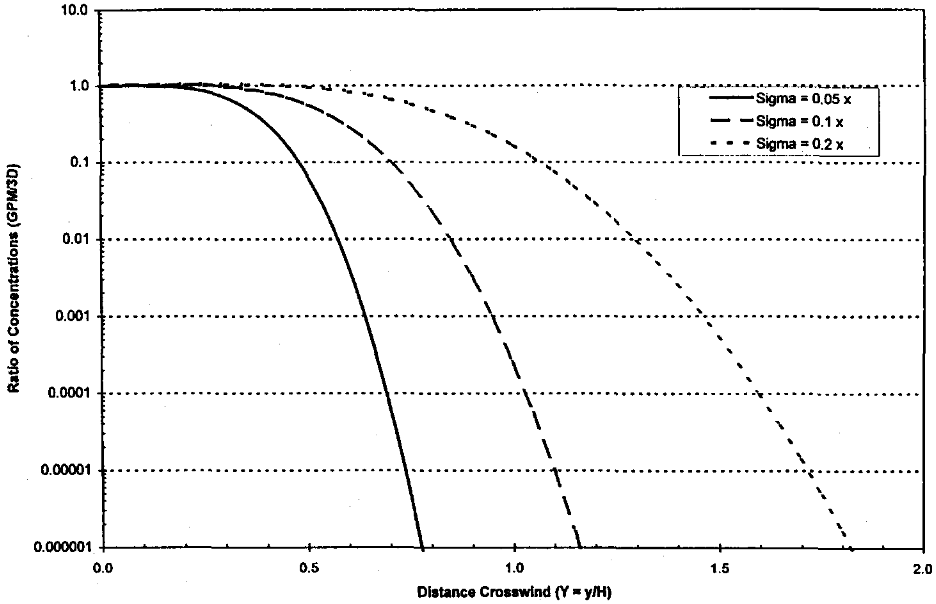

Fig. 2. Ratio of ground-level concentrations from Gaussian plume and 3D diffusion models: source at $z = 0$; ratio for $z = 0$ plane.

where Y is the non-dimensional crosswind distance $= y/H$, and Z is the non-dimensional vertical distance $= z/H$.

The ratio of the concentration calculated using these two methods can be evaluated on the downwind centre-line ($y = 0$, $z = 0$), and is found to be:

$$\frac{C_{\mathrm{GPM}}}{C_{\mathrm{3D}}} = \frac{\left(1+X^2\right)^{1/2}}{X}\exp\left[-1/2\mathrm{Pe}\left(\frac{1}{2X} - \left(1+X^2\right)^{1/2} + X\right)\right] \tag{16}$$

This ratio is plotted in Fig. 1 for various values of Pe. It can be seen that, beyond about $4H$ downwind, the 3D diffusion equation and the Gaussian plume model yield similar results over a wide range of values of Pe. However, closer to the source there may be a considerable difference in the predictions, as shown in the figure.

Typical values of the Péclet number, Pe, will depend upon values used for K. Taking $K = u_* kH$ and $u_* = 0.1u$, Pe $= 25$ ($k =$ von Karman's constant $= 0.4$). Hence, Fig. 1 indicates that the standard Gaussian model breaks down only for $x/H < 3$. Taking 100 m as a typical minimum value of interest suggests that the Apsley model would give significantly improved predictions only if the release height $H > 30$ m.

From the point of view of safety cases and risk assessments, the greatest interest is in sources close to the ground. It can be shown that, if $H = 0$, $z = 0$ and $y = 0$, then the equations above reduce to

$$C_{\mathrm{GPM}} = C_{\mathrm{3D}} = Q/(2\pi K x) \tag{17}$$

However, at any off-axis position (i.e. $y \neq 0$), the 3D diffusion equation may lead to higher or lower concentrations than those predicted using the Gaussian plume model; in particular it leads to non-zero upwind concentrations at locations close to the source.

The ratio of the ground-level concentrations predicted using the Gaussian plume model and Apsley's 3D model for a ground-level source is given by

$$\frac{C_{\mathrm{GPM}}}{C_{\mathrm{3D}}} = \left(1 + \frac{y^2}{x^2}\right)^{1/2} \exp\left[-\frac{x^2}{\sigma^2}\left(\frac{y^2}{2x^2} - \left(1 + \frac{y^2}{x^2}\right)^{1/2} + 1 \right)\right] \tag{18}$$

Fig. 2 illustrates how this ratio varies with increasing crosswind distance (y/x) for three different values of σ. The concentrations predicted by the two models are equal on the centreline and do not differ significantly for low values of the crosswind distance, although it is noted that, for small y/x, the ratio $C_{\mathrm{GPM}}/C_{\mathrm{3D}}$ is very slightly greater than 1. As the crosswind distance increases further, the ratio begins to fall exponentially, implying that the simple Gaussian plume model seriously underpredicts the concentrations. This could be important in terms of a risk assessment in that the area at risk might be increased significantly, even though the hazard range on the plume centreline is not affected.

Pasquill and Smith [50] also describe various approaches which can be adopted to solve the diffusion equation. Some results are quoted for 2D solutions for line sources, and it is emphasised that there are several ways of specifying the eddy diffusivity. Pasquill and Smith note that, in general, analytic solutions are not available, particularly in three dimensions, which indicates that numerical modelling would be required in order to investigate the various turbulence models.

6. Discussion

In general, none of the low wind speed models described above in Section 5 is routinely used for safety case or QRA applications in the UK, although puff-type models may occasionally be employed. Most dispersion modelling for these purposes is undertaken using standard Gaussian plume models or box-type heavy gas dispersion codes. In general, very few safety cases or QRAs explicitly consider wind speeds of less than $2\,\mathrm{m\,s^{-1}}$, which means that the standard dispersion models used in these assessments are applied to cases for which they are reasonably well validated, although, as noted in Sections 1 and 2 and Section 5, there may be conditions for which even $2\,\mathrm{m\,s^{-1}}$ could be considered too low for a sensible use of such models.

However, it has been shown in a related study (Deaves and Lines [7]) that the mean wind speed may be less than the lower threshold used by most QRAs (e.g. 2 or $2.4\,\mathrm{m\,s^{-1}}$) for a substantial fraction of the time. In general, risk assessments do not include any consideration of the significance of this fact.

At present, the best that can usually be done to quantify the effect of low wind speeds is simply to apply the standard models down to a lower threshold, such as 0.5 or $1\,\mathrm{m\,s^{-1}}$. It is accepted that the standard dispersion models may not be so well validated in this region, but the errors that this introduces are usually likely to be small compared with the other uncertainties involved in a QRA, such as the event frequency, frequency of various weather categories, mitigation probability or toxicity data. In the longer term, it would be necessary to improve the models, and hence confidence in their use, for low wind speed conditions.

Alternatively, the low wind speed models described in the previous section could be used to assess the dispersion at low wind speeds, but it is noted that this may not be straightforward as it is not yet clear which models are best suited to particular applications. In most cases, puff models should give improved estimates, and there may also be scope for using one of the analytical models, such as that of Hunt.

It is also emphasised that there is a lack of good validation data for such low wind speed models. This has been confirmed by a brief review of the recently published REDIPHEM database of full-scale dense gas dispersion experiments (Nielsen and Ott [51]). Three tables of summary information are provided. In the first, 35 data sets from Burro, Coyote, Desert Tortoise, Eagle and Fladis are presented, of which only one has a wind speed less than $2\,\mathrm{m\,s^{-1}}$. In the second table, 28 data sets from Lathen are presented, of which two have $u \leq 2\,\mathrm{m\,s^{-1}}$. In the third, however, a further 21 data sets from Lathen are presented, of whch 15 have $u \leq 2\,\mathrm{m\,s^{-1}}$. Of these 15, seven have fence obstacles, six were vertical jet releases and two were described as jet/puffs. It appears that little of the data from these experiments, which were conducted in 1989, has been widely disseminated, so it has not yet been used for model validation outside the project of which it formed a part.

Either of these approaches would give risk assessment results which have a sounder foundation than those based on the current methodologies. The related sensitivity studies of Lines and Deaves [1] indicate that such improvements would generally result in increased estimates of risk, and hence greater areas covered by particular risk contours, although it is emphasised that any increased risk may be overestimated if existing models which predict concentrations varying as $1/u$ are used for wind speeds lower than those which can be justified. However, a review of the magnitude of other uncertainties in current methodologies would be appropriate before committing to a new approach with respect to low wind speeds.

7. Conclusions

- A number of publicly available computer models for dispersion allow the user to specify very low wind speeds, which are well below the range of validity for that type of model and which can lead to erroneously high concentration predictions. Hence, as noted above, any use of these models at low wind speeds to enhance risk estimates may overestimate the actual increase in risk.
- The hazard ranges for ‘worst case’ weather conditions may be very dependent on the actual wind speed used. For example, the hazard range in 0.5 G conditions may be much greater than that in 2.4 F conditions. Particular care will therefore need to be taken to ensure that the low wind speed conditions used can be considered to be representative.
- Many standard texts state that particular types of model should not be used for wind

speeds less than a specific threshold. For example, $1\,\mathrm{m\,s^{-1}}$ is commonly quoted as the lower threshold for the Gaussian plume model to be applicable, as below this wind speed the mean wind is smaller than the rms turbulence velocity. However, it is well known that the rms turbulence velocity depends on the atmospheric stability; hence, for the purposes of carrying out a risk assessment, it may be possible to use wind speeds as low as $0.5\,\mathrm{m\,s^{-1}}$ in stable conditions, although in convective conditions the lower limit should be at least $1\,\mathrm{m\,s^{-1}}$. It is noted that these are indicative values; actual lower limits will also depend on other factors such as release size.

- Some modified models do exist for dealing with dispersion in low wind speed conditions. However, the results from such models are not significantly different from those obtained using current methodologies, provided that the wind speed is not too close to zero (say $> 1\,\mathrm{m\,s^{-1}}$) and that the risks are not calculated too close to the source. Therefore, it is considered that the potential improvements to a QRA which could be obtained by using these modified models are not as great as those which would be obtained from using a wider range of low wind speed representative weather categories with the current methods. These effects will be quantified further in the second phase of this study.
- At very low wind speeds, plume meandering and hence concentration intermittency become increasingly important. These effects should be considered carefully when interpreting output from current models which do not include them.

Acknowledgements

The work reported in this paper was undertaken under contract to the UK Health and Safety Executive. The authors wish to acknowledge the helpful comments provided by a reviewer on an early draft of the paper.

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