THE SENSITIVITY OF QRA RESULTS TO THE INCLUSION OF LOW WIND SPEED CONDITIONS

I.G. Lines, D.M. Deaves,
WS Atkins Safety & Reliability, Woodcote Grove, Ashley Road, Epsom, Surrey.

Risk assessments for hazardous installations will generally require the modelling of toxic or flammable gas dispersion for several potential accident scenarios in a range of representative wind conditions. Since hazard ranges are usually greater for low wind speeds, it is necessary to model dispersion in such conditions in an appropriate manner, and also to understand their nature and frequency. This paper presents part of a study which considered the whole problem of using low wind speed conditions in risk assessments. The current status of dispersion modelling within such assessments is reviewed, and it is shown that risk estimates can be sensitive both to the representative range of wind conditions considered, and also to the type of dispersion models. Examples are presented showing the sensitivity of risk calculations for chlorine, and outline recommendations are given for improving the robustness of quantified risk assessments to account for low wind speeds.

Keywords: Dispersion, low wind speeds, risk assessment.

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. This can have a significant effect on the hazard ranges associated with scenarios involving the dispersion of toxic or flammable substances, which in turn can affect the calculated risk significantly. Most dispersion models use the wind speed as one of the key inputs, and safety cases and Quantified Risk Assessments (QRAs) are generally based on the potential consequences of selected scenarios in 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 m/s, with typical wind speeds, representing normal conditions, being about 5 m/s.

There appear to be two reasons why lower wind speeds and calm conditions are generally neglected. Firstly, the majority of dispersion models are not capable of dealing with low wind speeds or calms, and secondly, the data on the frequency of such conditions in the UK is not always readily available or sufficiently detailed or accurate. The justification that is sometimes used for not considering low wind speed or calm conditions is that they are a rare occurrence, although this assumption is not borne out by the currently available data. Furthermore, although the frequency of such calm conditions may be low, they 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.

Current usage of both dispersion models and wind categories within QRAs is reviewed. Examples are then given of chlorine risk calculations using various models and wind conditions, and it is shown that there may be significant increases in calculated risk by using a more realistic set of representative weather conditions. On the basis of these results, some tentative conclusions are drawn as to the potential for improving the robustness of risk assessment calculations in relation to low wind speeds.

ATMOSPHERIC CONDITIONS

Wind structure

The structure of the wind at any location is determined by pressure differences, and is modified by the underlying terrain; a rougher terrain causes more turbulence and results 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 will adopt a boundary layer type profile, increasing with height in the region of interest. Meteorological Office data has almost always been collected at the standard height of 10 m, or, where the exposure requires it, at greater heights, with the values then being 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 at around 1.5 to 2 m (typical breathing height), which is well below the level at which measurements have generally been made. The ratio of 2 m to 10 m wind speed will decrease as the roughness length increases, since a rougher surface will extract more energy from the mean flow; for typical roughness, z_0, in the range 0.1 m - 0.01 m, the value of this ratio for neutral conditions is 65-77%.

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 super-adiabatic, causing any vertically displaced air to continue its movement, thus setting up large convective cells and enhancing both turbulence and the consequent mixing. The ratio of the 2 m wind speed to the 10 m wind speed is also dependent on stability, dropping to only 52% for F stability with $z_0 = 0.1$ m.

Topographical and building effects

Low wind speeds 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, and may penetrate significant distances inland. 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.

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 levels of interest. 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 need to be considered in a safety case.

Definition of low wind speed and calm conditions

There is no generally accepted definition of what constitutes a *low wind speed.* However, the particular interest here is in wind speeds of less than about 5 knots (2.57 m/s), as this corresponds to the area where standard meteorological data may become misleading and the applicability of dispersion models may need to be considered more carefully.

Smith(1) 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, $\sigma_u \simeq 0.187\ H^{1/3}$. For stable conditions, Smith describes various experimental results which suggest that σ_u lies in the range 0.35 to 0.5 m/s. Table 1 provides a simple summary of the wind speed at which $\sigma_u = u$ for each of the Pasquill stability categories, derived from (1).

Category	A	B	C	D	E	F	G
Wind speed	1.2	1.0	0.8	0.35 - 0.5			

Table 1. Approximate limit of 'low' wind speeds

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, as discussed below. The second is also difficult to generalise, since it is determined by the particular site; 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). The standard data provided by the Meteorological Office gives the frequency of calms as corresponding to periods where the wind is not strong enough to cause the wind vane to change direction, which typically also corresponds to about 1 knot. It is noted that calms do not necessarily correspond to periods during which an anemometer reads zero, since some types may read zero in all wind speeds below 5 knots (2.57 m/s), whilst others may continue to provide a reading at speeds as low as 0.01 m/s (in the case of sonic anemometers).

CURRENT USE OF LOW WIND SPEEDS

Historical experience of hazardous events in low wind speed conditions

AIChE(2) describe several vapour cloud explosions which have occurred in light wind conditions. In 1970, a propane pipeline ruptured near Port Hudson in a wind speed of approximately 2.5m/s. Witnesses observed that the propane formed a large white cloud settling into the valley around a complex of buildings prior to ignition and explosion.

Lewis(3) presents a number of case studies involving liquid fuel fires, vapour cloud fires and explosions. One of the general conclusions reached was that very light wind conditions were a common factor in a considerable number of the incidents. Furthermore, there are no records of aerial explosion type incidents (VCEs) under conditions of high wind, presumably because high winds will more effectively disperse the material and make the ignition of the fuel-air cloud by accidentally occurring ignition sources less likely.

Lees(4) also describes some of the most well known incidents which have occurred in low wind speeds. On 16 November 1970, 160 t of ammonia were released from a refrigerated anhydrous ammonia storage tank at the Gulf Oil Company's installation at Blair, Nebraska. As there was almost no wind, a low lying visible 'pancake' shaped cloud was formed, covering approximately 2.6 km^2 and extending over 2.7 km from the tank.

Risk assessments using low wind speeds

Nussey and Pape(5) describe the classical approach to risk assessment which is adopted in the HSE's code RISKAT. One of the areas of uncertainty is identified as the choice of a representative subset of weather conditions and probabilities which result in similar risk levels to those which would have been calculated if a complete set of weather probability data had been used. The HSE generally uses four weather categories, namely 2.4, 4.3 and 6.7 m/s in D stability and 2.4 m/s in F stability. The F stability category is generally taken to represent all stable weather conditions (i.e. E, F and G stability).

Nussey and Pape describe a sensitivity study involving chlorine releases to demonstrate the sensitivity of risk estimates to the choice of weather types, using two, four or twelve combinations of wind speed and stability. The main refinement for the latter case was the inclusion of 1.2 m/s in B, C, D and F stability classes. The results of the sensitivity study showed that current procedures may underestimate the risk levels by up to a factor of four, and that this is largely due to the neglect of lower wind speed categories (particularly the 17% frequency of occurrence for F 1.2) where it is recognised that the predictions from dispersion models may be less reliable.

Current usage of dispersion models

Most of the basic types of dispersion model currently in use for safety case and QRA applications 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. These have been reviewed by Lines & Deaves(6), and four of the main types of model are listed here for completeness:

- Simple Modifications to Gaussian Plume Models
- Puff Models
- Analytic Solutions of the Diffusion Equation
- CFD Models

In general, none of these types of low wind speed model 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. Also, very few safety cases or QRAs explicitly consider wind speeds of less than 2 m/s, which means that the standard dispersion models used in these assessments are applied to cases for which they are reasonably well validated.

However, it has been shown in Deaves & Lines(7) that the mean wind speed may be less than the lower threshold used by most QRAs (e.g. 2 or 2.4 m/s) for a substantial fraction of the time. A straightforward attempt to quantify the effect of low wind speeds could be made by simply applying the standard models down to a lower threshold, such as 0.5 or 1 m/s. It is accepted that the standard dispersion models may not be so well validated in this region, but the errors that this introduces are likely to be at worst comparable with the other uncertainties involved in a QRA.

Alternatively, the types of low wind speed model noted above 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 Apsley(8) or Hunt (in an Appendix to Jones(9)). It is also emphasised that there is a lack of good validation data for such low wind speed models.

USE OF LOW WIND SPEEDS IN QRA

In order to investigate the potential effect of low wind speeds on risk assessments, the risk has been calculated for various cases using a simple methodology which does not take account of low wind speeds, and this has been compared with the results of using various schemes for refinement. The term 'risk' has been taken to be the risk to an individual, assuming that the accident has just occurred. This is sometimes termed the 'conditional risk', and does not include the likelihood of the actual event. For simplicity, a uniform wind rose has been assumed for all calculations.

It is emphasised that the results of these case studies rely on using specific models with somewhat arbitrarily chosen, but realistic, input data (e.g. for release rate and duration), and so care should be taken when trying to generalise the results. This applies particularly to any quantitative results, and further studies covering a wide range of input parameters would be required in order to draw more definitive conclusions. Nevertheless, the results given here provide a useful indication of the general type of results and highlight some of the areas of greatest importance.

Continuous release of chlorine - using simple Gaussian plume model

This case considers a continuous 20 minute release of 1 kg/s of chlorine in a 2.4 m/s wind speed in F stability conditions, in terrain with a surface roughness length of 0.1 m. This is typical of the sort of representative event which might dominate the individual risks to an off-site population. The dispersion of this release is modelled using a standard Gaussian plume model, which, although not strictly applicable for this type of dense gas release, could be a reasonable approximation in some situations. Three risk calculation schemes are described below: Scheme A corresponds to the way the event might currently be considered, using a single wind speed of 2.4 m/s, whilst Schemes B and C incorporate additional refinements to take account of low wind speeds.

A Using the simple R-91 Gaussian plume model, the centreline concentration at 500 m downwind is 160 ppm with σ_y = 38 m. The probability of exceeding a Dangerous Toxic Load (DTL) at 500 m is then found simply by determining the arc fraction where the toxic load (c^2t) would be greater than 108,000 ppm^2min. For a 20 minute release this corresponds to 73.5 ppm, which is the concentration at a distance of 47 m either side of the plume centreline at 500 m. This implies that the probability of exceeding a DTL at 500 m is given by Arctan(47/500)/180^o = 0.030. The centreline concentration falls below 73.5 ppm at about 800 m (the 'Hazard Range'), which implies that the probability of exceeding the DTL at distances greater than 800 m is zero.

B If the frequency of this event is assumed to be uniformly distributed over all wind speeds from 0.1 to 2.4 m/s, then the risk can be recalculated using the same simple Gaussian dispersion model. This refined methodology increases the probability of exceeding the DTL at 500 m by a factor of 2.08 to 0.062.

C If the same wind speed distribution as for Scheme B is used, but all dispersion in winds less than 0.5 m/s is assumed to be identical to that at 0.5 m/s, then the probability of exceeding the DTL at 500m is increased to 0.053 (1.78 times greater than in Scheme A).

At 1000 m, since the centreline concentration in a wind speed of 2.4 m/s is only 49 ppm, the probability of exceeding the DTL is predicted to be zero (Scheme A). However, the concentration exceeds the critical value of 73.5 ppm for all wind speeds less than 1.3 m/s, whose frequencies will therefore contribute to the overall risk. If the uniform wind frequency distribution is again used, then the overall probability of exceeding the DTL at 1000 m is calculated as 0.023 (Scheme B), reducing to 0.016 (Scheme C) if all winds less than 0.5 m/s are modelled using an effective wind speed of 0.5 m/s.

The important conclusion from this simple example is that, even though the lower wind speeds imply much higher centreline concentrations, the width of the plume over which the DTL is exceeded does not increase very significantly, and so the level of risk does not increase as much as might be expected. This conclusion is generally valid for distances less than the hazard range for the 2.4 m/s wind condition (~800 m in the example above). However, the most significant change that the use of lower wind speeds introduces is that non-zero risks are predicted at distances in excess of this 'hazard range', where formerly the risk was calculated as zero, because of the finite cut-off implied by the use of the DTL.

Figure 1 shows the variation in the risk of receiving a dangerous toxic load for each of the three schemes. It should also be noted that more sophisticated risk assessments would include effects such as the probability of escape from the cloud and the probability of being (or escaping) indoors. The effects of these refinements have not been considered here, but it is likely that the general conclusions would not be significantly affected.

Risk of fatality based on probit equation

Many risk assessments do not use the concept of a DTL, but rather calculate the individual risk of fatality based upon a probit equation. One of the advantages that this gives is that it avoids the 'cliff edge' effect which occurs at the hazard range (i.e. the risk of exceeding the DTL falls to zero over a comparatively short distance). The probability of fatality at any specified distance in a random direction can be found by integrating the risk across the plume, using a probit equation (such as that of AIChE(10))for fatality due to chlorine exposure to convert toxic loads to risk of fatality.

Revised calculations using the probit method lead to the probability of fatality at 500 m being 0.0018 in 2.4 m/s wind speeds in F stability, which corresponds to Scheme A above. Application of Schemes A, B and C (as described above) leads to the conditional risks of fatality shown in Figure 2. The results of this example lead to a number of important conclusions. It appears that risks based on probits are much more sensitive to the inclusion of low wind speed conditions than risks based on exceeding a DTL. At 500 m, the risk based on probits is 17 times higher at a wind speed of 0.5 m/s than it is at 2.4 m/s. This ratio increases to a factor of 300 at 1000 m. This sensitivity to low wind speeds means that the average risk predicted by Scheme C (in which all wind speeds of less than 0.5 m/s are taken to be equal to 0.5 m/s) is 7 times higher at 500 m than that predicted by Scheme A, increasing to 86 at 1000 m.

It is possible to conclude that this high sensitivity for risks based on probits means that it is preferable to calculate risks based on exceeding a DTL. However, this could lead to the increased risk of fatality in low wind speeds being neglected in QRAs, safety reports and emergency planning. It is emphasised that there are a number a factors which, for the sake of simplicity, have not been included in the example above (such as the probability and speed of evacuation). Therefore, the results should only be treated as being indicative, and quantitative results should not be regarded as being generally applicable.

Continuous release of chlorine - using a dense gas dispersion model

A 1 kg/s release of chlorine, continuing for 20 minutes in F stability is again considered, but, in this case, a dense gas dispersion model (HEGADAS-S) is used to calculate the ground level concentration distribution. The conditional risks are calculated using the following three schemes:

A Risk simply based on dispersion in 2.4 m/s.

B Risk simply based on dispersion in 1.5 m/s.

C The wind speed probability is assumed to be uniformly distributed over the range 0.1 to 2.4 m/s, but all wind speeds below 1.5 m/s are modelled as 1.5 m/s (the lowest wind speed that can be modelled using HEGADAS-S).

The variations in the conditional risk results with increasing distance are shown in Figure 3, based on the risk of exceeding the DTL. This shows that there is less than a factor of 2 difference in the results for all three schemes up to about 1400 m, but from 1500 m to 2000 m (i.e. beyond the hazard range for Scheme A) Schemes B and C continue to predict a significant risk whilst Scheme A predicts zero risk.

Continuous chlorine release - using RISKAT

The HSE's current risk assessment tool (PC RISKAT v2.0) was used to determine the conditional risks associated with a continuous release of 1 kg/s of chlorine for 20 minutes. The dispersion program used (CRUNCH) was applied in wind speeds of 2.4, 1.2, 0.5 and 0.1 m/s in F stability. Two different population types were used in the risk calculations:

a) Outdoor population - assumed to be outdoors throughout the release.

b) Residential population - 1% assumed to be outdoors initially. Probability of escape indoors dependent on concentration. Indoor ventilation rate of 2 ach. Lag time of 10 minutes (time at which people escape after cloud has passed), provided that this is not sooner than the minimum evacuation time, which was taken as 30 minutes.

The results in Figure 4 show that the risks predicted for 1.2 m/s can be up to factor of 5 greater than those predicted at 2.4 m/s. At 0.5 m/s, the risk is substantially increased, although it still falls to zero at 1000m. At 0.1 m/s, CRUNCH fails to find a solution, due to the plume height falling to less than twice the roughness length. Comparison of Figures 5 and 4 shows that, in this case, the mitigating effects of being indoors is negligible, probably due to the relatively high air change rate (2 ach) and long release duration (20 minutes).

In considering these results, it should be noted that direct comparisons of risk calculations between RISKAT and other models are not straightforward. RISKAT includes the ability of people to escape indoors and, once indoors, to receive a reduced dose of toxic material. Once the gas cloud has passed by, individuals remain indoors for a further 10 minutes. This reflects the emergency situation when it might take some time before the emergency services instruct residential populations to come out of their homes.

CONCLUSIONS

- Risk calculations for toxic releases based on the risk of exceeding a DTL (such as those undertaken by the HSE) are fairly insensitive to the frequency distribution of low wind speeds for distances within the hazard range corresponding to the DTL. The effect of using a more representative range of wind speeds, rather than a single F2.4 category, is typically to increase the levels of risk by a factor of two to four. However, at greater distances, where current assessments would predict zero risk, detailed consideration of low wind speeds would result in significant levels of risk, since hazard ranges generally increase in lower wind speeds.

- Risk assessments for toxic releases based on the risk of fatality (using a probit approach) are more sensitive to the low wind speed distribution for all distances from the source. The risks predicted using a single F2.4 weather category could be underestimated by a factor of around ten compared with those predicted using a more realistic distribution of low wind speeds, depending on the event and the distance.

- Whilst phenomena such as plume meander in low wind speed conditions may make it very difficult for a dispersion model to reproduce the results of a particular experimental field trial, these difficulties are not so significant when undertaking a probabilistic QRA due to the 'averaging' over many wind directions and weather conditions. Therefore, the uncertainty associated with low wind speeds in a QRA is not necessarily as great as the error in a single prediction of concentration.

POTENTIAL IMPROVEMENTS

Based on the results of this study, and related work ((6) & (7)), the following potential strategies have been identified which could be employed to improve the assessment of risks in a QRA.

a) Continue to use current methods and data

The simplest strategy would be to continue to use current methods and data for assessing the risk. However, it should be noted that such risk assessments could be under-predicting the levels of risk, which might have implications for the size of consultation zones and for land use planning advice.

b) Refine choice of representative weather conditions

The most straightforward way to improve risk assessments is to include more low wind speed conditions as representative weather categories. In view of the insensitivity of standard meteorological data at low wind speeds, it would probably be necessary to determine the frequency of low wind speed conditions by fitting the available data to a Weibull frequency distribution curve. If a greater number of representative weather conditions is to be used to provide better resolution at low wind speeds, then consideration should also be given to the inclusion of stabilities other than D and F. For example, the inclusion of B and E stabilities would probably help to mitigate the increased risk due to the use of lower wind speeds, whilst improving the realism of the results.

The risk assessment methodology would continue to use standard dispersion models, even though it is accepted that they may not be well validated for the low wind speed cases. For the purposes of a QRA, the uncertainty that this introduces may not be too large as the frequency of the lowest wind speed categories will be comparatively low.

c) Refine the dispersion models

The most complex strategy to improve risk assessments would involve using models which are specifically suited to low wind speed situations. It is emphasised that such models are generally theoretically based and are not well validated, or else require substantial meteorological input data. Indeed, for some situations, it is not clear that any model would be applicable. Therefore, it appears that further work is required in this area before the routine use of such models is possible.

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REFERENCES

1 Smith, F.B., 1993 'Low wind speed meteorology', For Cambridge Atmospheric Dispersion Modelling Course, 6/7 July. (Based on the paper presented at Riso in May 1992 and at ECCOMAS, September 1992).

2 AIChE, 1994 'Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVE's', Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York.

3 Lewis, D.J., 1982, 'Case studies of effects of liquid fuel fires and of vapour cloud fires and explosions', in "The Risks of Fuel Transport", Session 1, Paper 1, Oyez International Business Communications, London, 16-17 June.

4 Lees, F.P., 1980 'Loss Prevention in the Process Industries', Butterworths.

5 Nussey, C., and Pape, R.P., 1987 'The significance of vapour cloud modelling in the assessment of major toxic hazards', Proc. Int. Conf. on Vapor Cloud Modelling, Ed. Woodward J., AIChE, Cambridge, MA, pp 889-922, November.

6 Lines, I.G., and Deaves, D.M., 1997 'Modelling Gas Dispersion in Low Wind Speed Conditions', Submitted to Journal of Hazardous Materials.

7 Deaves, D.M., and Lines, I.G., 1996 'The nature and frequency of low wind speed conditions', *Submitted to Journal of Wind Engineering and Industrial Aerodynamics.*

8 Apsley, D.D., 1987 'Diffusion in light wind conditions', CEGB Memorandum, TPRD/L/APM/0328/M87.

9 Jones, J.A., 1996 'Atmospheric dispersion at low wind speed'. ADMLC report, to be published by NRPB.

10 AIChE, 1989 'Guidelines for Chemical Process Quantitative Risk Assessment', Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York.

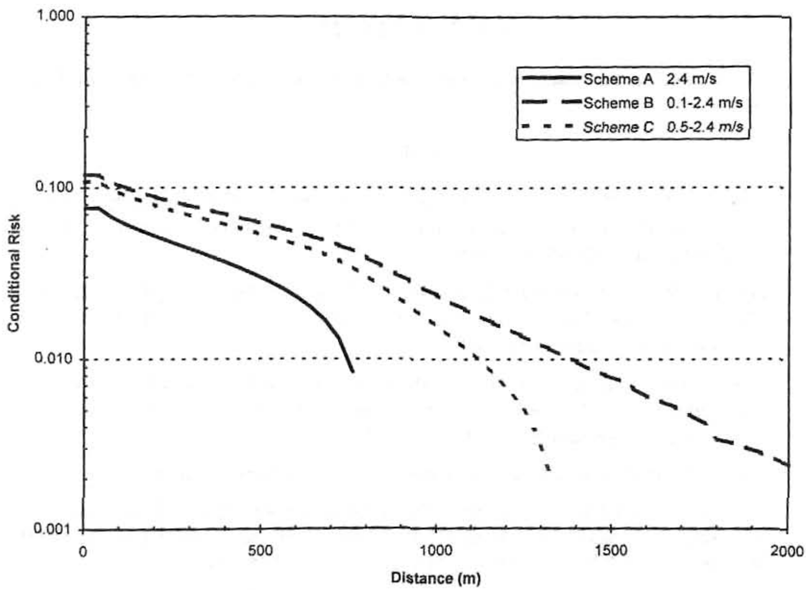

Figure 1 Risk of Exceeding DTL - 1 kg/s of Chlorine Using Gaussian Plume Model

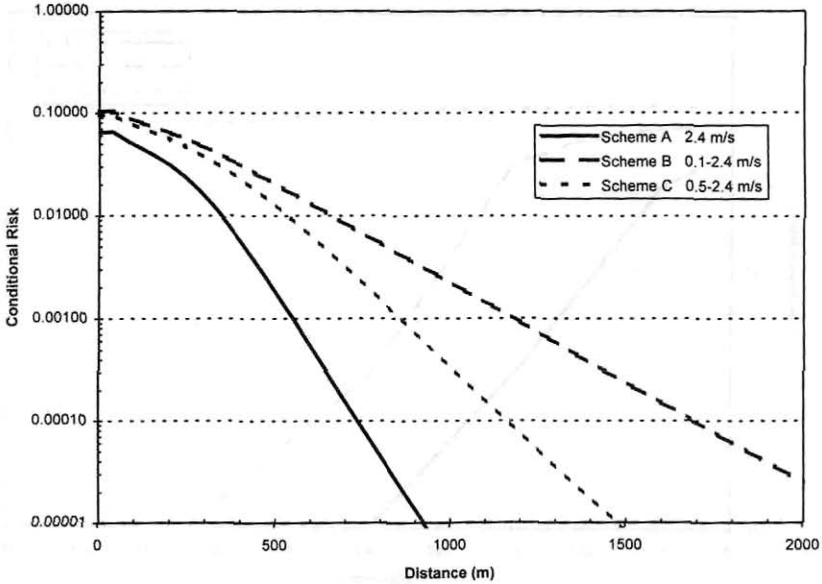

Figure 2 Risk Based on Probit - 1 kg/s of Chlorine Using Gaussian Plume Model

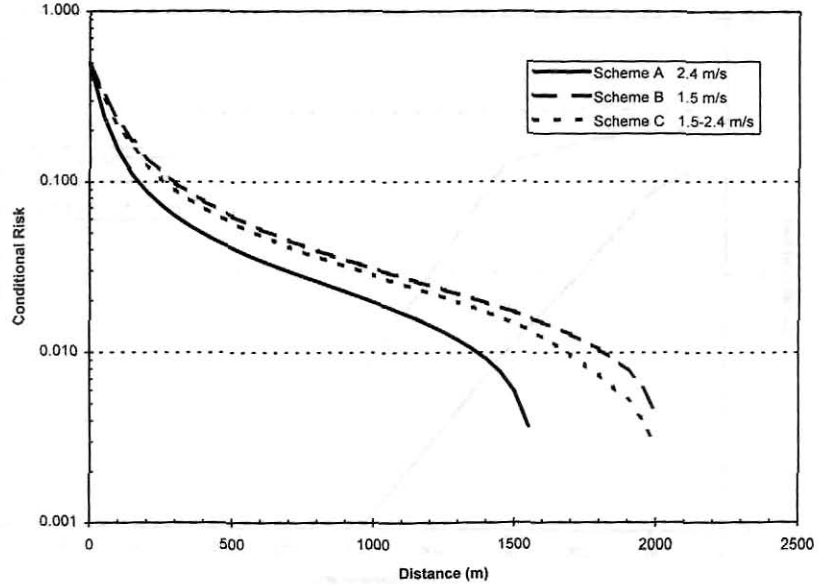

Figure 3 Risk of Exceeding DTL - 1 kg/s of Chlorine Using HEGADAS-S

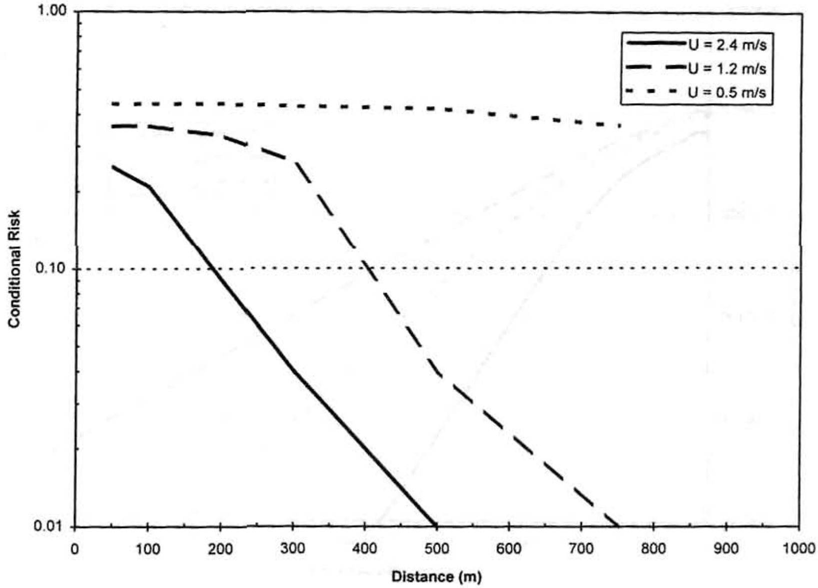

Figure 4 Risk of Exceeding DTL for Outdoor Population - 1 kg/s of Chlorine Using RISKAT

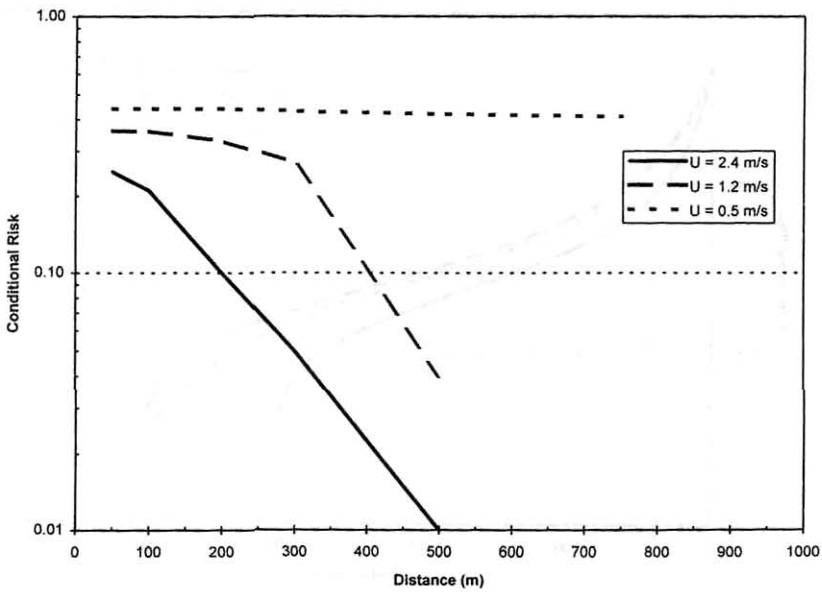

Figure 5 Risk of Exceeding DTL for Residential Population- 1 kg/s of Chlorine Using RISKAT