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The implications of dispersion in low wind speed conditions for quantified risk assessment

Prepared by **WS Atkins Consultants Ltd**
for the Health and Safety Executive

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The implications of dispersion in low wind speed conditions for quantified risk assessment

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Quantified risk assessment is now an important technique which is widely used both in safety cases and to assist in land-use planning decisions. The assessment of the level of risk associated with major hazard sites often involves a calculation of the dispersion of toxic or flammable releases, and the dispersion of material in the atmosphere depends on the ambient conditions, particularly the wind speed. In general, low wind speeds lead to higher toxic concentrations and larger flammable gas clouds, and therefore it is important that dispersion in low wind speeds is adequately modelled in order to quantify the risks accurately. However, at low wind speeds, risk assessments are subject to two areas of uncertainty. Firstly, the likelihood of low wind speeds is not well understood, and secondly, the majority of dispersion models are not applicable in low wind speed situations. In recognition of these issues, HSE requested that WS Atkins undertake a study to determine their significance, and to assess the implications that dispersion in low wind speeds might have on quantified risk assessment.

Liaison with the Meteorological Office at an early stage in the project led to the acquisition of wind data which were obtained with sonic anemometry from two UK sites. Such data are accurate down to much lower wind speeds than the standard cup anemometers, enabling an investigation of low wind speed conditions to be carried out. This showed the considerable over-estimates of 'calm' conditions which are induced by the standard instrumentation. It also enabled studies to be undertaken of wind speed and direction persistence, effects of averaging time (from 10 minutes upwards) and frequency estimation for low wind speeds in general, and during stable conditions in particular.

A number of low wind speed dispersion models were identified and their features compared. Some of these models were then used, alongside standard Gaussian and dense gas dispersion models, to assess the effects of using lower wind speed weather categories within risk assessments. The comparisons demonstrated the significant effect which inclusion of these lower wind speeds has on risk results, particularly for toxic releases. The implications of the results of the study are discussed, and recommendations provided for further work in those areas significant to risk assessments.

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ABBREVIATIONS AND ACRONYMS

ach	Air changes per hour
ADMWG	Atmospheric Dispersion Modelling Working Group
AIChE	American Institute of Chemical Engineers
BLEVE	Boiling Liquid Expanding Vapour Explosion
CEGB	Central Electricity Generating Board
CHEMET	Chemical Meteorology scheme
CIMAH	Control of Industrial Major Accident Hazards
CPU	Central Processor Unit
DTL	Dangerous Toxic Load
ETSU	Energy Technology Support Unit
GPM	Gaussian Plume Model
HSE	Health and Safety Executive
LFL	Lower Flammable Limit
LNG	Liquefied Natural Gas
LPB	Loss Prevention Bulletin
LPG	Liquefied Petroleum Gas
MHAU	Major Hazards Assessment Unit
mph	Miles per hour
NRPB	National Radiological Protection Board
NWP	National Wind Power
PDF	Probability Density Function
ppm	Parts per million
QRA	Quantified Risk Assessment
RAE	Royal Aircraft Establishment
rms	Root-mean-square
UFL	Upper Flammable Limit
UK	United Kingdom

UNITS

In general, metric units will be used throughout this report, although it is noted that much of the literature and data relating to wind speeds is measured in knots or mph, and so these alternative units may be referred to occasionally. The following conversions apply:

1 knot = 0.5148 m/s
= 1.1515 mph

1 mph = 0.8684 knots
= 0.4470 m/s

1 m/s = 1.9426 knots
= 2.2369 mph

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the help and assistance of a number of individuals and organisations who have provided information for this project. Particular thanks must go to the Meteorological Office, who provided helpful discussion at the outset of this study, and useful comments on the final report. The provision of unpublished Met. Office reports is also acknowledged, as is the input to the discussion presented in Appendix 1. The assistance of Eurotunnel, who supplied some of their wind data recorded at the Folkestone and Calais terminals, is also gratefully acknowledged.

1. INTRODUCTION

1.1 Background

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 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 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 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. One reason is that the data on the frequency of such conditions in the UK is 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 report, but, for most of the general discussion, a value of 2 m/s 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 speed 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 m/s) for 20% of the time, although there is some doubt over the accuracy of the low wind speed data, as discussed in Section 4.2. The frequency of Beaufort Scale Force 0 (1 knot or 0.5 m/s) 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, 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.

It is generally recognised that the hazard ranges and risks associated with many types of accidental release, for example toxic materials when a dose based criterion is used, tend to increase with decreasing wind speed. In these cases, wind speeds of around 2 m/s 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, either in terms of hazard range or risk implications. This may be particularly important when considering the worst case conditions for emergency planning. The problem is compounded by the generally poor performance of gas dispersion models at low wind speed. This problem was identified by

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Nussey(1992), who concluded that there are significant differences in predictions of dense gas dispersion models in low wind speed stable conditions.

As noted in the next section, the emphasis of this study is on the use of low wind speed conditions within risk assessments. Although there is little work which has addressed this problem, a recent review by Jones(1996) has considered the implications of low wind speeds to the application of Gaussian plume models for elevated releases. There is therefore little overlap between this study and that of Jones, although some reference to his work is included in specific areas.

1.2 Scope of study

In recognition of the above issues, the HSE requested that WS Atkins carry out this research project to assess the implications of dispersion in low wind speed conditions for quantified risk assessment. The two principal objectives of the project are:

a) To provide a better understanding of the risks posed to people in calms and low wind speed conditions. This will help to improve the quality of risk assessments and associated decision making for land-use planning.

As noted in the next section, the emphasis of this study is on the use of low wind speed conditions within risk assessments. Although there is little work which has addressed this problem, a recent review by Jones(1996) has considered the implications of low wind speeds to the application of Gaussian plume models for elevated releases. There is therefore little overlap between this study and that of Jones, although some reference to his work is included in specific areas.

b) To use this improved understanding to provide better emergency planning advice and hence to mitigate the consequences of accidents more effectively.

Section 2 of this report provides an initial introduction and background to some of the topics which are relevant when considering dispersion in low wind speeds, and defines what is meant by low wind speed and calm conditions.

Section 3 comprises a review of published information relating to the issues associated with low wind speed conditions, covering both the likelihood of such conditions and the dispersion models which can be applied.

Section 4 presents various analyses of meteorological data and attempts to draw some conclusions on the implications that the results might have when conducting a QRA. The data used for the analyses includes both standard meteorological data, and some data obtained using more sensitive anemometry, much of which was supplied by the Meteorological Office.

Section 5 reviews the main types of dispersion model currently used for safety cases and QRA applications, highlighting the limitations that these models may have when considering low wind speeds. The review also includes some dispersion models that have been specifically developed to provide a better description of dispersion under low

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wind speed conditions, and summarises the extent to which the various types of model are currently used.

Section 6 concentrates on an assessment of the significance of low wind speed conditions when producing a safety report, QRA or when identifying the worst case scenario for the purposes of emergency planning. This requires consideration of both the frequency of such conditions and of the adequacy of the dispersion models used. Several simple case studies are presented to demonstrate the sensitivity of hazard ranges and risk calculations to the assumptions made concerning the frequency of, and dispersion in, low wind speeds. These case studies cover both a range of materials, and a range of types of release which are generally considered in safety reports.

Section 7 summarises the main findings of this project, and makes recommendations for the areas in which further research would improve the methodologies which are currently in use in QRAs.

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2. ATMOSPHERIC DISPERSION

The dispersion of material in the atmosphere is a complex topic, and it is therefore worthwhile to review some of the areas which may be significant in relation to the low wind speed conditions considered in this project. The remainder of this section therefore addresses the following topics:

i) Structure of atmospheric turbulence
ii) Atmospheric stability
iii) Relevant small scale effects
iv) Definition of low wind speed and calm conditions

2.1 Structure of atmospheric turbulence

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 large scale pressure differences which, in turn, are caused 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 turbulent fluctuations which give natural wind its characteristic unsteadiness make it quite unlike the steady flow obtained in a conventional aeronautical wind tunnel. In particular, it is evident that the fluctuations are not regular, like a sine wave, but are highly complex and irregular. This fundamental randomness in the variations in wind speed has several important implications. The most obvious is that the occurrence, (or not), of a particular value of wind speed can only be discussed in terms of a probability. Thus, at any instant, a complete description of the flow field is never likely to be available, nor is it possible to predict, from a knowledge of the flow field at one instant, exactly what its state will be in the future. Instead, any useful description of the flow has to be confined to a few simple average properties.

It is also evident that the random fluctuations in wind speed (and also in wind direction) have a very wide range of timescales ranging from several days down to fractions of a second. Any treatment of wind structure must therefore start by separating the wind speed as recorded by an anemometer at one point into the sum of a mean value taken over a suitable averaging period, and a random 'gust' component superimposed on that mean. It is generally accepted that there is a clear advantage in choosing an averaging period of about one hour, so that the wind fluctuations can be separated into the macro- and micro-meteorological ranges. Fortunately, one hour is the period on which are based the averaged wind data collected by the majority of the national meteorological services, including that of the UK. It is also possible to use shorter averaging periods,

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down to about 10 minutes; some 10 minute data is analysed in Section 4.4, where it is compared with hourly mean data.

The mean wind speed ($\overline{U}$) 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:

$$\overline{U} = \frac{u_*}{k} \ln\left(\frac{z}{z_o}\right) \tag{2.1}$$

where:

k = von Karman's constant (= 0.4)
u_* = friction velocity
z_o = roughness length

Values of z_o 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. Such flows are clearly of significance for many dispersion problems, including pollution from vehicle emissions. However, relatively little is understood of the details of such flows, although there is currently considerable interest in applying research effort to this problem, under the title of 'Urban Meteorology'.

Equation 2.1 provides a description of the variation of the wind speed over the lower part of the atmospheric boundary layer. Typically, this would cover at least the lowest 50-100m, and should therefore be adequate for all short- to medium-range dispersion applications. At the top of the boundary layer, typically a few hundred metres, the wind speed no longer follows the boundary layer profile, but reaches a value, known as the geostrophic or gradient wind, which can be determined directly from pressure gradients.

The variation of wind speed with height indicated in Equation (2.1) is appropriate to neutral stability conditions, with modifications for non-neutral stability conditions, as discussed in Section 2.2. Most measurements which have been used to fit such profiles would have been in the moderate to high wind speed range, since atmospheric boundary layer structure is of greatest interest in the wind-loading context where high wind speeds are of concern. At low wind speeds, anemometer accuracy (see Section 4.2) and variability of the wind make the collection of wind profile data more difficult.

Meteorological Office data (see Section 4.1) 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 often 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

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Nussey(1987), in relation to the continuous release Trials 45 and 47 from the Thorney Island datasets, whose 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 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.

Pasquill has defined a range of stability categories from A to F to characterise these effects, the most significant of which are:

A Unstable - highly turbulent but relatively low wind speed
D Neutral - moderate turbulence; generally moderate to strong winds
F Stable - very little turbulence, with low wind speed.

The magnitude of the turbulent fluctuations is often represented as a turbulence intensity, which is the ratio of the rms of the wind fluctuations to the hourly mean wind speed. Typical values of this ratio, at 10 m height, are around 10% for neutral conditions. For stable conditions, turbulence, and hence mixing, is much lower, resulting in plumes with a reduced vertical spread, and hence generally with higher concentrations. Unstable conditions produce a higher turbulence intensity, a greater spread and hence a more dilute plume.

Although local conditions are obviously important in determining the stability characteristics of a given site, certain general observations can be made. Unstable conditions tend to occur when there is strong solar heating, and convection currents are set up. Neutral conditions occur during moderate to strong winds, when there is cloud cover, and hence minimal solar heating. Stable or very stable conditions usually occur at night under clear skies and in light winds. In this case, rapid ground cooling results in a temperature inversion and an almost complete suppression of turbulence. Further data on the prevalence of various stability classes has been presented and discussed in Section 4.1.

The atmospheric stability not only affects the turbulence as noted above, but also modifies the profile of mean wind speed. Thus, Equation 2.1 is replaced by the more general form (Post(1994a)):

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$$u = \frac{u_*}{k}\left(\ln\frac{z}{z_0} - \psi\left(\frac{z}{L}\right)\right) \tag{2.2}$$

where L = Monin-Obukhov length = $-\dfrac{T}{kg}\dfrac{u_*^3}{\overline{w'\theta'}}$ (2.3)

The Monin-Obukhov length is defined by the ratio of the surface shear stress to the surface heat flux, where k is the von Karman constant (0.4), g is the gravitational acceleration, T is the absolute temperature, u_* is the surface friction velocity and $\overline{w'\theta'}$ is the surface heat flux. L gives the relative importance of mechanical and buoyancy forces in the production of turbulence. A negative value implies instability where buoyancy forces are contributing to the production of turbulence, a positive value implies stratification where the buoyancy forces are attempting to suppress turbulence and a value of 1/L close to zero implies little contribution to the production of turbulence by buoyancy forces.

For stable atmospheres ($L \geq 0$):

$$\psi\left(\frac{z}{L}\right) = -\beta\frac{z}{L} \tag{2.4}$$

For unstable atmospheres ($L \leq 0$):

$$\psi\left(\frac{z}{L}\right) = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1}(x) + \frac{\pi}{2} \tag{2.5}$$

$$x = \left(1 - \gamma\frac{z}{L}\right)^{1/4}$$

$$\beta = 6.9,\ \gamma = 22$$

Hunt et al (1990) give a much more complete discussion of stability effects on dispersion, and include useful information on typical values for u_* and L appropriate to each stability class.

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(1987), 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 Relevant small scale 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, and these are discussed below.

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2.3.1 Topographical effects

Local winds can be set up by temperature differences. Sea breezes, for example, occur during the summer months in the UK. They can occur during periods of settled weather, start at about 10 am, 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 either of Equations (2.1) or (2.2), 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, or drainage flows, whose characteristics are discussed further in Section 3.3.4. 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 speed-up 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.

2.3.2 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 may be important, and it may be appropriate to consider them when drawing up the off-site emergency plan.

Little work seems to have been undertaken to quantify the effects noted above. Some studies have been performed in which real plant areas were modelled in wind tunnels (e.g. Guldemond(1988) and Robins(1994a)), but the emphasis has been on the actual dispersion rather than the quantification of local wind speeds.

2.4 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

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conditions. Jones(1996) includes a brief discussion of the definition of low wind speeds in which he distinguishes between unstable conditions, where the mean windspeed may be zero but turbulent fluctuations remain, and stable conditions, where mean and fluctuating components could both tend to zero, and gravity current flows begin to dominate. In this section, a brief summary of the various definitions of these terms is given, and the use of these terms in this report is clarified.

Low Wind Speeds

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 project, the particular interest is in wind speeds of less than about 2 m/s. 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(1992) 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, $\sigma_u \approx. 0.187 H^{1/3}$, where H is in W/m^2 and σ_u in m/s. 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 2.4.1 below 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 Section 4.4.3.

Pasquill category	Heat flux (W/m^2)	Wind speed where $\sigma_u = u$ (m/s)
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

Table 2.4.1
Approximate Wind Speeds at Which rms Turbulent Horizontal Velocity is Equal to the Mean Wind Speed

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This table clearly indicates that, based on 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) should not necessarily be classed as a low wind speed in stable F conditions. This important point is considered further in Section 5.2 when considering the applicability and limitations of current dispersion models .

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 Section 4.2. This instrument-based definition is at best useful in deciding how accurate measurements may be for validation purposes, or for use 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.

Calm Conditions

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). For standard data provided by the Meteorological Office, the frequency of calms corresponds 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 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), whilst others may continue to provide a reading at speeds as low as 0.01 m/s (in the case of sonic anemometers). The Meteorological Office has undertaken some comparisons of the performance of various types of anemometer, and some of their data has been made available for this study. Analysis of selected data sets is therefore given in Sections 4.2 and 4.4.

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3. LITERATURE REVIEW

There is a considerable quantity of literature which relates to the dispersion of hazardous materials in the atmosphere, and it is not the intention of this report to review all of this information. This literature review concentrates solely on identifying those references which deal specifically with dispersion in low wind speed or calm conditions, or with the likelihood of such conditions occurring. Many standard texts on dispersion, such as **Pasquill and Smith** (1983), do not address the particular problems which may arise when assessing dispersion in low wind speeds, and so it is worth highlighting the information that does currently exist.

The literature review has concentrated on the following areas:

- General discussion of turbulence and the atmospheric boundary layer, in relation to the calculation of gas dispersion
- Meteorological information
- Dispersion
- Application to risk assessment

The following sections are based on the topics identified above, but it should be noted that many papers address more than one of these topics. More detailed information on specific dispersion models and their limitations in low wind speeds is presented in Section 5.

3.1 Turbulence and the atmospheric boundary layer

Several authors provide descriptions of the atmospheric boundary layer, and of the parameters which are important when assessing turbulence and dispersion. Although some of these are not directly relevant to this study on low wind speeds, they are mentioned below because they provide an up-to-date background to the subject.

Van Ulden and Holtslag(1985) provide an excellent introduction to the various atmospheric boundary layer parameters, including a description of the main existing similarity theories which are used for diffusion applications.

Gryning, Holtslag, Irwin and Sivertsen(1987) also summarise the principle characteristics of the atmospheric boundary layer, and provide a clear description of the various scaling regions in unstable and stable conditions. For each scaling region, models are suggested for dispersion in the horizontal and vertical directions. In general, the vertical concentration profile is non-Gaussian in convective conditions, whilst the lateral concentration profile is always Gaussian.

Weil (1983, 1985), **Nieuwstadt**(1984), **Wyngaard**(1985) and **Briggs**(1985) all describe improvements in the understanding of the planetary boundary layer. It is noted that much of the work reported by these authors concentrates on elevated releases from stacks in convective conditions, largely because the highest ground level concentrations from stack releases occur in these unstable conditions.

Šinik and Lončar (1990) estimate the diffusion during calm wind situations by means of general similarity laws in the surface layer, and show that the diffusion intensity is much less than in windy conditions, but is still about two orders of magnitude stronger than molecular diffusion. The methodology requires the introduction of a "critical velocity" which marks the dying stage of dynamically generated turbulence, coinciding with the onset of a calm. Šinik and Lončar consider that this critical velocity is in the range 0.15 to 0.3 m/s.

Kristensen, Jensen and Petersen(1981), **Hanna**(1983) and **Van der Hoven**(1976) all emphasise the important point that the low level of small scale turbulence in a stable atmosphere results in an instantaneous plume which looks like a thin tube. However, large scale horizontal wind fluctuations will give rise to meandering which will make σ_y dependent on the averaging time. Kristensen, Jensen and Petersen present a fairly complex method for estimating the appropriate value of σ_y, but it should be remembered that, for the purposes of a QRA, it is the peak concentration and cloud width of the narrow instantaneous plume which are the important factors in determining the risk from an accidental release.

Gifford(1961) summarises some of the conclusions from **Meade**(1959). These include the observation that in very light winds (< 2 m/s) on a clear night, the vertical spread will be even less than the values generally used for category F, and no estimates are given for such a case because, in practice, 'the plume from a ground level source is unlikely to have any definable travel'. This assertion may be appropriate for accidents at nuclear sites, where the concern relates largely to releases that could travel considerable distances (e.g. tens or hundreds of km) but it is not considered to be satisfactory for chemical releases where even short travel distances in very light winds could lead to significant consequences. It is also noted that a further extremely stable category, G, has subsequently been introduced by some authors to account for the light wind (<2 m/s) night time conditions (see Section 3.2.3).

Turner (1967) notes that quantitative estimates of concentrations are nearly impossible for class F stability with very light winds on a clear night. Under such conditions, ground level releases free of topographic influences are subject to frequent shifts in wind direction which serve to spread the plume horizontally. For elevated passive or buoyant sources under these conditions, significant concentrations do not reach ground level until the stability changes.

Hunt, Holroyd, Carruthers, Robins, Apsley, Smith and Thomson(1990) discuss many of the recent developments in modelling air pollution for regulatory uses. This is chiefly concerned with modelling dispersion when the mean wind speed is large compared with σ_u (i.e. it ignores the case of low wind speeds). However, it is noted that, for air flow over flat uniform terrain, the main improvements required are for modelling extreme conditions of strongly stable or strongly unstable flows.

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3.2 Meteorological information

3.2.1 Importance of good meteorological data and turbulent typing schemes

In order to model dispersion in the atmosphere it is necessary to be able to measure the parameters which characterise the atmospheric boundary layer, such as wind speed, direction, temperature gradients, roughness lengths, insolation, etc, which may all play a part in determining the level of turbulence. It is impossible to undertake a risk assessment which covers all possible combinations of these parameters, and so, for the purposes of analysis, it is necessary to group together similar sets of conditions. The results of any risk assessment will therefore depend on ensuring that the original meteorological data is accurately recorded, so that the frequency of each representative category can be accurately determined, and furthermore that the turbulent typing scheme itself provides a good representation of all possible conditions, and that its use does not bias the resulting risk calculations. Further consideration of this latter point is given in Section 3.4.2 and in the examples presented in Section 6.4.

Pasquill(1961) provides a scheme to determine the stability category for various conditions, and provides estimates of the vertical and lateral spread of plumes for weather categories A to F. However, for wind speed conditions of less than 2 m/s at night, Pasquill does not attempt to assign a category and simply states that the vertical spread may be even less than the values given for category F. During the day, wind speeds of less than 2 m/s are taken to correspond to A or B stability, depending on the level of insolation.

Vanderborght, Mertens and Kretzschmar (1983) compare the calculated and measured aerosol concentrations and deposition around a metallurgical plant. They emphasize the importance of on-site measurements, at least for wind speed and direction, as data from a meteorological station at a similar site just 22 km away led to systematic errors in the concentration ranging from 5 to 60%. The use of on-site meteorological data resulted in considerable improvement to the concentration predictions.

This is an important point from the view point of risk assessments, as the majority of QRAs rely on using data from the nearest weather station, which may be some distance from the site. This is considered further in Section 4.3.2.

Kretzschmar and Mertens(1984) describe an assessment of the influence of the turbulent typing scheme on concentration results. Experimental meteorological data obtained over a three year period was used to determine the frequency of hourly stability classes according to ten commonly used schemes, such as those of Pasquill, Turner, Smith etc. It was found that there was little correlation of the results in terms of the stability at any particular moment or in the overall frequency of a particular category. A simple Gaussian plume model was used to predict concentrations using dispersion parameter sets appropriate to each typing scheme, and it was found that there were major differences in the extreme and mean values between the various schemes. This was largely attributed to the differences in the numerical values (as a function of distance) of the various sets of dispersion parameters actually in use. The general conclusion was that the appropriate choice of a specific turbulent typing scheme, and the corresponding set of dispersion parameters, is critical when undertaking dispersion assessments.

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Dilger and Thomas (1975) describe a device for testing the performance of propeller anemometers in low wind speeds. The importance of accurate wind speed measurements at low wind speeds is emphasised by observing that, under unstable weather conditions, an error of a few tenths of a metre per second may give rise to errors in the determination of the stability category by up to two steps. However, Dilger and Thomas do not provide any more detailed evidence for this assertion.

Kaganov and Yaglom(1976) describe the errors that may occur in wind speed measurements obtained from rotation anemometers (either cup or propeller), but they tend to concentrate on the well known overspeeding of these types of anemometer in a gusty wind, both in the horizontal and vertical directions. This phenomenon is essentially due to the non-linearity of the response of rotation anemometers, which tend to respond more quickly to the increase of wind speed than to its decrease after a short duration gust.

Hu, Katagiri and Kobayashi (1991, 1995) describe how improved wind speed data from a sonic anemometer can affect the results of dispersion estimates in low wind speeds and calms for continuous releases of radionuclides. The Meteorological Guide for Safety Analysis of Nuclear Power Reactors by the **Japan Atomic Energy Safety Commission**(1977) recommends that hourly meteorological data are statistically processed to yield the sum of the inverse of wind speed for every wind direction and stability. The contribution from calm conditions (< 0.5 m/s) is included, but with the wind speed set to a nominal value of 0.5 m/s. The wind direction distribution for calm (< 0.5 m/s) conditions is estimated from the distribution for wind speeds in the range $0.5 < u \leq 2$ m/s. Hu et al. examine whether lowering the threshold definition for calm conditions from 0.5 to 0.1 m/s has a significant effect on the risks from a potential release, and they conclude that the change is not significant when determining the adult thyroid dose following a postulated accident.

This kind of approach may have some application in risk assessments, although it is noted that there are obvious complications in that the concentrations are not generally inversely proportional to wind speed (e.g. in dense gas dispersion box models), and also the risk is generally not simply proportional to concentration. These drawbacks are less important for radiological releases where simple Gaussian models and dose-response relationships can generally be used.

Hu et al. also analyse the data for a particular site where low wind speeds are relatively common. Using a definition for calm conditions of 0.5 m/s, a propeller anemometer gives the frequency of calms as about six times higher than that obtained using a sonic anemometer. This is clearly due to the finite starting speed of the propeller anemometer, whereas the sonic anemometer can measure accurately down to 0.01 m/s. It is also interesting to note that the frequency of calms (< 0.1 m/s) as measured by the sonic anemometer is virtually zero. This may be due to averages being taken over a one hour period, but this is not discussed by Hu et al. Further discussion of this point is given in Section 4.4.4.

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Schacher, Fairall and Zannetti(1982) compare a number of the standard stability classification schemes for use in describing coastal overwater dispersion. None of the schemes were found to be ideal and a modified Pasquill scheme was developed.

3.2.2 Frequency of wind speeds and weather categories

The majority of QRAs use a number of representative weather categories, each of whose frequency is determined by meteorological observations over a suitable period such as ten years. One of the objectives of this project is to examine the frequency of calms and low wind speeds, and to determine whether such conditions are adequately covered by current assessments. Clearly, if the frequency of calms were found to be negligible then there would be little point developing sophisticated dispersion models for calm conditions as these situations would not contribute significantly to the risk (although they may still be of interest for emergency planning purposes). Alternatively, it may turn out that the frequency of low winds is quite high and that this is not reflected in current QRAs, which generally assume a significant minimum wind speed (e.g. 2.4 m/s).

Cox, Lees and Ang(1990) discuss the applicability of dispersion models in low wind speeds in the context of the production of safety cases. They state that 'Dispersion under calm or low wind conditions is ill defined' and they go on to make the following points:

- Pasquill category F applies for about 20% of the time in the UK
- Calm conditions apply for 5 to 8% of the time
- Dispersion in these calm conditions is very uncertain, but use of F stability to represent them is probably conservative

They also discuss the problem of modelling dispersion indoors. In this context, they observe that, at very low wind speeds, around 0.5 m/s, experimental work outdoors has shown that dispersion is highly variable. Sometimes this variability is expressed as the fit obtained to the theoretical models in terms of the Pasquill stability categories, in which case dispersion parameters in calm conditions have been found to correspond to those applicable to the whole range of stability categories from Pasquill A to F. At higher air speeds, say above 2 m/s, Gaussian models such as that of Sutton could be used for indoor dispersion, perhaps with neutral stability parameters.

It appears that indoor dispersion of hazardous materials is an area of significant and growing interest, and air flow speeds in such situations are usually rather lower than atmospheric wind speeds. For example, it is important when undertaking a hazardous area classification to be able to determine the area over which the vapours from a spillage of flammable liquid, such as acetone or petrol, would remain above the flammability limit. In such situations, forced ventilation may be the predominant cause of mixing/advection. Although this area is clearly related to the subject of this report, it is not part of the scope of this particular project and so will not be considered further.

Luna and Church(1974) describe an approach for the estimation of long term average concentrations in which an analytical distribution of wind speeds is combined with a simple dispersion model (eg. concentration proportional to 1/u). The frequency

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distribution of wind speeds is assumed to be log-normal and the probability density function is taken as:

$$P(u) = \frac{1}{\sqrt{2\pi}u\sigma} \exp\left[- \left(\frac{\ln(\frac{u}{u_g})}{\sqrt{2}\sigma} \right)^2 \right] \qquad (3.1)$$

where:

u_g is the geometric mean speed
σ is the standard deviation of ln u

It is concluded that the concentration based on a log-normal distribution is higher than that predicted using the mean wind speed. The ratio is typically found to be around 1.5, although the value may depend significantly on the wind speed distribution and dispersion model used.

One particularly relevant point made by Luna and Church, based on the above approach, is that the effect of failure of the diffusion formulae at low wind speeds is of little importance, particularly when concentrations at speeds below the threshold are 'filled in' by a constant concentration below the velocity at which the l/u formulation begins to fail.

Takle and Brown(1978) describe how a Weibull distribution may be fitted to the cumulative distribution of wind speed frequency, i.e.

$$F(x) = 1 - \exp\left[- \left(\frac{x}{c} \right)^k \right] \qquad (3.2)$$

where:

F(x) is the cumulative distribution function
c is the scale parameter (same units as x)
k is the dimensionless shape parameter

The corresponding probability distribution function is:

$$P = \frac{k}{c} \left(\frac{x}{c} \right)^{k-1} \exp\left[- \left(\frac{x}{c} \right)^k \right] \qquad (3.3)$$

Takle and Brown noted that this distribution predicts a zero frequency for calms, and so they develop a hybrid density function which includes a non-zero frequency of calms. It is claimed that this slight variation improves the fit to observed data. However, as noted in Section 4.4.4, recent sonic anemometer data appears to indicate that the frequency of absolute calms (u=0 m/s) is extremely low, and so it may not be necessary to use such hybrid functions.

Stewart and Essenwanger(1978) review a number of the models for wind speed frequency distributions. These include the elliptical bivariate distribution of two vector components and the special case of the bivariate Gaussian distribution. However, they concentrate on the three parameter Weibull distribution:

$$F(x) = 1 - \exp\left[- \left(\frac{x - \gamma}{c} \right)^{k} \right] \tag{3.4}$$

where γ is the location parameter, with the same dimensions as x.

If $\gamma=0$, this reduces to the simple two parameter Weibull distribution. Various methods can be used to fit data to these distributions, such as least squares, maximum likelihood, or the method of moments.

Stewart and Essenwanger present the Weibull parameters derived from data for 45 weather stations in the Northern Hemisphere, calculated using a variety of methods, and they conclude that the three parameter Weibull distribution provides a significantly better fit to the data than the two parameter Weibull distribution. However, a detailed review of the data and the fitting undertaken indicates that the 3 parameter fits depend upon the frequency class grouping, and that the difference between the goodness of fit for 2 parameter and 3 parameter distributions was only statistically significant in around a third of the cases. This, coupled with the fact that the data was probably unreliable at the low wind speeds, suggests that the case for using a 3 parameter Weibull distribution is not conclusive. Further discussion of this point is given in Section 4.4.4.

Mage$^{(1980)}$ describes several statistical models for the distribution of wind speeds. He concentrates on the development of three and four parameter log normal distributions, which introduce parameters u_{max} and u_{min} which are representative of the maximum and minimum wind speeds. These parameters are used to define a variate X, which is bounded by $-\infty<X<\infty$, where:

$$X = \ln\left(\frac{u - u_{min}}{u_{max} - u} \right) \tag{3.5}$$

X is assumed to be normally distributed with mean μ and variance σ, so that the probability density function (PDF) of X may be written as:

$$P(X;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{X - \mu}{\sigma} \right)^{2} \right] \tag{3.6}$$

Mage shows that this four parameter distribution (termed the Johnson S_L distribution) can be fitted to experimental data to give the frequency distribution over the whole range of wind speeds. For low wind speed data (≤ 2.5 m/s), the (u_{max} - u) term becomes relatively constant, and so a simplified three parameter distribution (termed the Johnson S_B distribution) can be used in which ln(u $-u_{min}$) is taken to be normally distributed; i.e.(u_{max} -u) is taken to be constant. Mage examines various data sets, and shows how they may be fitted to these distributions, although it is clear that the fits are dependent both upon the poor quality of data at the low wind speed end, and also on the particular way in which data is grouped into wind speed classes. It is concluded that these lognormal distributions provide good engineering approximations to the data, although it is noted that chi-squared statistical tests show that both models are rejected at the 0.001 level of significance.

Mage also emphasises that the starting and stopping thresholds of anemometers can influence measured wind statistics, and that several techniques are used to distribute calm observations to the various compass directions. For example, the stability array (STAR) program adds calm observations to those intervals less than 3 knots for each direction in proportion to the measured values less than 6 knots for that given direction.

Smith(1992) explores the meteorological nature of low wind speeds, and thereby emphasises many of the difficulties associated with dispersion under these conditions, although dispersion is not addressed explicitly. A number of important points are made by Smith:

- Low wind speeds can be defined as being when the mean wind speed is comparable to or less than the root-mean-square turbulent horizontal velocity (see Section 2.4 of this report).
- Standard Munro Mark IV cup anemometers can only be trusted when the wind speed is greater than 6 knots, or 3 m/s (see Section 4.2 of this report).
- In light winds, geostrophic control becomes weak and topography becomes relatively more important in determining the wind field.
- The majority of light winds occur at night, and during the summer months.
- Data from Ringway implies an almost uniform probability of the speed lying in any fixed speed band out to about 4 knots, although it should be noted that this conclusion was based upon extrapolation from poor quality data above 2kt. Further discussion of the quality of this data is given in Section 4.1.1
- The frequency of light winds varies quite markedly between sites.

Table 3.2.1 gives the percentage frequencies of hours when the wind speed at 10 metres (recorded by standard cup anemometers) was less than 4 knots, divided according to month, based on data from 1981 to 1990 from a selection of UK inland sites. The annual average frequency of these conditions varies significantly between different sites, ranging from 9.2 to 29.7% of the year. This variation may be due, in part, to local topographic effects. The table also shows the average frequency of calms for each site over the same period.

The large variation in the frequencies of calm conditions, as shown in the table, could also be due to differences in the recording systems and instruments, since it is known that even nominally identical Munro anemometers may have significantly different start-up characteristics.

Clarke(1979) describes the standard Gaussian plume model which has been widely used in the UK for a number of years. This includes stability category G conditions for dispersion in very stable night time conditions. The plume centreline concentrations resulting from ground level releases in typical category G conditions are shown to be about a factor of three higher than those in typical category F conditions.

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Month	Watnall	Ringway	Squires Gate	Finningley	Eskdalemuir	Wyton
January	11.2	15.5	7.6	13.1	25.9	8.9
February	11.6	16.8	6.7	17.1	27.1	10.1
March	12.1	15.3	7.5	13.0	22.8	7.8
April	15.0	21.8	11.2	18.7	30.5	12.0
May	15.2	22.0	9.8	18.7	29.2	14.3
June	18.4	23.5	9.6	20.8	30.8	15.3
July	19.1	24.0	8.8	21.8	32.2	15.0
August	19.2	24.4	9.6	21.9	28.3	15.2
September	19.0	23.0	10.1	20.8	32.5	15.8
October	18.2	20.0	9.4	21.5	30.4	14.7
November	17.4	25.3	11.0	19.8	33.6	15.2
December	14.1	21.5	9.7	16.8	32.5	11.1
Average	15.8	21.1	9.2	18.7	29.7	13.0
Calms	1.4	2.3	0.6	2.7	6.6	2.0

Table 3.2.1
Percentage of Hours when the Wind Speed at 10 m was less than 4 Knots, by Month, Based on Data From 1981 to 1990 (From Smith, 1992)

No detailed consideration is given to the problems associated with low wind speeds, although the typical meteorological parameters are given as a function of stability category, as summarised in Table 3.2.2.

Category	% Frequency	Mean Wind Speed U_{10} (m/s)
A	0.125	0.625
A - B	1.25	1.25
B	3.8	2.0
B - C	2.6	3.37
C	15.0	4.12
D	62.4	4.12
E	6.7	3.4
F - G	8.4	1.2

Table 3.2.2
Typical Frequencies and Wind Speeds for Atmospheric Stability Classes (From Clarke, 1979)

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Figure 11 in Clarke(1979) shows how the frequency of occurrence of the Pasquill stability categories varies over Great Britain. Table 2 in Clarke(1979) also gives a tabulation of typical values of the wind speed to be used for each weather category when measured values are not available, and these are reproduced in Table 3.2.3.

Category	Mean Wind Speed U_{10} (m/s)
A	1
B	2
C	5
D	5
E	3
F	2
G	1

Table 3.2.3
Typical Wind Speeds for Atmospheric Stability Classes
(From Clarke, 1979)

The **HSE Handbook of Radiological Protection**(1978) states that the frequency of occurrence of Pasquill categories is reasonably unaffected by location, and gives the following distribution of weather conditions as being typical for the UK. (See Table 3.2.4.)

Category	Wind Speed (m/s)	Frequency of Occurrence in Britain (%)	Description
A	1	2	Very sunny, summer weather
B	2	8	Sunny and warm
C	5	17	Partial cloud during day
D	5	41	Overcast day or night
E	3	12	Partial cloud during night
F	2	20	Clear night; fog

Table 3.2.4
Typical Descriptions of Atmospheric Stability Classes
(From HSE Handbook of Radiological Protection, 1978)

However, it is now generally recognised that the frequency of occurrence of Pasquill categories can vary significantly with location, and so the statements made in the above reference should be treated with caution, especially since Clarke's (NRPB R91) Figure 11 gives a much more detailed version of Table 3.2.4 in which the frequencies vary across the UK. It is also noted that NRPB R91 is slightly inconsistent with Table 3.2.4, in that the frequency of D stability varies between 50 and 75% on the map presented in Figure 11, compared with only 41% in Table 3.2.4.

3.2.3 Information from meteorological office reports

The Meteorological Office has produced a document '**Guidance Notes on the Spread of Pollution**(1990)', which discusses how to assess the dispersion of an accidental radioactive or toxic release in an emergency situation. This guidance note includes a number of simple nomograms and a set of 15 templates which can be used to identify the 'area-at-risk' in different meteorological conditions. The choice of template depends on the wind speed and stability. The guidance note makes several specific points in relation to low wind speeds:

- In situations with wind speeds less than 1 knot the area-at-risk is a circle centred on the point of release and expanding at 2 km/h (1.08 knots).
- In conditions of low wind speed combined with high stability, or if there are sea breezes or complex orography near the site, the low level wind will be particularly variable, and the reliability of the calculated area-at-risk is likely to be low.
- In stable, light wind conditions the plume will tend to flow into valleys and hollows not indicated by the templates.

The wind speeds specifically considered in the templates are 2, 4, 7, 10, 14 and 19 knots, and it is recommended that, for wind speeds between the given values, the lower value should be chosen, so as not to underestimate the risk.

In general, a release which has travelled sufficiently far that it has a significant vertical spread is advected by the wind at a velocity equal to the geostrophic wind speed (or slightly less) in a direction slightly off-set from the geostrophic wind. However, under stable conditions the release will remain within a circle of radius uT whose centre moves at a speed u/2, where u is the 10 m wind speed, and T is the time since the release.

Jenkins(1983) highlights some aspects of measurement techniques which need to be considered when planning to use meteorological data for dispersion calculations. He makes the important point that the Pasquill category determined by most schemes is very dependent on the wind speed, especially in conditions of light wind. He quotes the example that a change of wind speed from 0.5 to 2 m/s with 3/8 cloud cover at night in the **Smith**(1972) scheme (adopted by NRPB) would correspond to a change in Pasquill number from 6.5 to 5.5 (i.e. one whole stability category). This in turn would change calculated concentrations at short range by at least an order of magnitude, due to the combined effects of lower wind speed and greater stability.

Jenkins also notes that the standard Munro Mk IV large cup anemometer has a starting speed of about 2 m/s (it varies considerably even between individual instruments of the same pattern). Furthermore, the chart on which speed is generally recorded is largely compressed at the low wind speed end, with only 1.5 mm separating the zero line from the 5 kt line, making wind speed estimates below about 2 - 3 m/s somewhat suspect. It is possible to draw some inferences on winds below this speed using the behaviour of the companion wind vane, but 'care must be taken if standard synoptic data are used for dispersion in light winds.'

Jenkins makes a number of other relevant points:

- Anemometers of a lighter construction are available which have lower starting speeds (0.2 m/s), such as the Porton-type cup anemometer.
- When determining wind speed profiles, particularly in very low wind speeds, the unequal starting and stopping speeds of even identical anemometers can generate meaningless profiles.
- The performance of the standard direction wind vane in light winds is better than that of the anemometer; it is generally thought to start responding to direction between 0.5 and 1 m/s. Nevertheless, the use of a smaller vane with lower starting speed (e.g. the Porton-type with a threshold of 0.3 m/s) is to be recommended if specific measurements for dispersion estimates are contemplated.

Smith (1984) reviews a number of the aspects which can lead to uncertainty in dispersion modelling. One of the most important points made by Smith is that data on wind speed and direction should be averaged over a period which is linked to the safety issues involved, and not to some arbitrary standard time like 1 hour. The effects of averaging time on wind speed distributions are discussed in Section 4.4.3, with reference to the more accurate wind data which has been obtained from the Meteorological Office.

Smith also notes that meteorological observing stations, whilst maintaining good quality instruments, may be too far away to give an adequate picture of local flow conditions, even in flat countryside. **Vanderborght et al** (1983) have given results which emphasise this from a study of wind speed and direction differences between sites at Beerse and Mol separated by some 22 km on the very flat northern Belgian plain. The standard rms differences were about 15°and 2 m/s. This is an average over the whole wind speed range, thus suggesting that low wind speeds may not be well represented by data from nearby sites (see also Section 4.3.2).

Smith also makes the point that it is often assumed that the <u>mean</u> values of the various parameters appearing in a model are the most appropriate, and that these will give the best estimate of the mean concentration. This is clearly not so. Smith considers an example involving the application of the standard Gaussian plume model to the dispersion of a ground level source where the wind speed fluctuates slowly between 3 and 7 m/s, with a uniform probability distribution over the range. Since the concentration is inversely proportional to the wind speed, using an average wind speed of 5 m/s leads to an underestimate of the true average concentration by some 6%. This is fairly small, but the difference would obviously increase at lower wind speeds.

The potential for using averages of 1/u has also been considered by **Hu et al**$^{(1995)}$, as discussed in Section 3.2.1.

Parrett $^{(1980)}$ provides a comparison of the response characteristics of four light-weight cup-anemometers. Measurements were made in a wind tunnel and comparisons of the following characteristics were made:

a) Angular response - how the measured wind speed varies with the angle between the wind direction and the plane through the anemometer's cups.

b) Cup-ripple and revolution-ripple - caused by the increased torque acting on the anemometer when each cup 'catches' the wind, and by some asymmetry in the anemometer's construction, respectively.

c) Length constant - the distance ut, where t is the time constant for the anemometer for a step change in wind speed from zero to u. For the standard Munro cup anemometer this is of order 10 m.

The response of the anemometers at low wind speeds was not explicitly considered, although some of the measurements were made at 1 m/s.

Smith$^{(1979)}$ discusses the factors which may affect the lateral spread of a plume and reviews the available models. However, no specific consideration is given to calm or low wind speed conditions.

Derbyshire$^{(1994)}$ describes the Cardington stable boundary layer experiment of 1993. Low wind speeds are not considered in the report, although the point is made that evidence from operational anemometers, typically at a height of 10 m, should be treated with caution because their starting speeds are typically 5 knots. Derbyshire also states that turbulence in stable boundary layers is often said to be 'intermittent', but the nature of such intermittency is not well understood. It should be noted that some sample data for Cardington has been obtained from the Meteorological Office, and the analysis is presented in Section 4.4.

Thomson and Tonkinson$^{(1992)}$ describe two distinct methods which are used by the Meteorological Office to estimate the Pasquill Stability parameter P for use in dispersion applications. These schemes are summarised below:

Scheme 1

This determines P from the surface heat flux F_{P0} (W/m^2) and the wind speed u(m/s) during the day, and from the 'modified' cloud amount N_m (in oktas) at night (see **Nielsen, Prahm, Berkowicz and Conradsen,**$^{(1981)}$). The equations used are:

$$P = 7 - [2.26 + 0.019(\hat{u} - 5.6)^2][0.1\hat{F}_{\theta 0} + 2 + 0.4\hat{u}^{3/2}]^{[0.28 - 0.004(\hat{u}-2)^2]} \qquad (3.7)$$

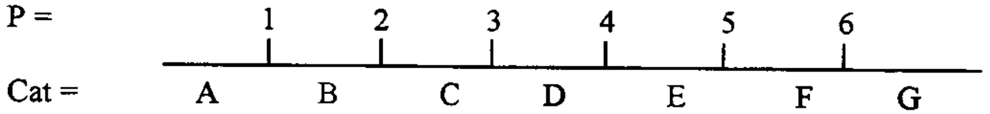
during the day

$$P = 3.6 + \frac{120 - 13.3N_m}{27 - 2N_m}\exp\left(-\frac{3}{8}\hat{u}\right) \qquad \text{at night} \qquad (3.8)$$

$$\hat{u} = \min(u,8)$$

$$\hat{F}_{\theta 0} = \max(F_{\theta 0},0)$$

The stability parameter P can be converted to a letter as follows:



Scheme 2

a) Daytime. If the solar elevation is less than 6.5°, then the Pasquill stability category is taken to be D. Otherwise, the stability category is estimated from the mean wind speed u and the level of incoming solar radiation K (W/m^2) using the following table (where N is cloud cover in oktas).

Wind Speed (knots)	N = 8	N < 8		
		K < 300	300 ≤ K < 600	600 ≤ K
u ≤ 3	C	B	A - B	A
3 < u ≤ 5	C	C	B	A - B
5 < u ≤ 9	C	C	B - C	B
9 < u ≤ 12	D	D	C - D	C
12 < u	D	D	D	C

Table 3.2.5
Daytime Atmospheric Stability Classification Scheme

b) Night time. The following table should be used:

Wind Speed (knots)	N = 0, 1	N = 2, 3	N = 4, 5, 6, 7	N = 8
u ≤ 1	G	F	F	D
1 < u ≤ 3	F	F	F	D
3 < u ≤ 5	F	F	E	D
5 < u ≤ 9	E	E	D	D
9 < u	D	D	D	D

Table 3.2.6
Night time Atmospheric Stability Classification Scheme

Callander and Whitlock(1986) describe the results of dispersion experiments in the Sirhowy Valley in South Wales in June 1983. Experiment B was conducted in calm, convective conditions, with a wind speed at the source of only 0.37 m/s. The 8 m wind speeds (averaged over 10 minutes) measured over an array of 13 masts varied between 0.5 and 1.8 m/s. It was concluded that the airflow affecting the tracer was strongly influenced by an area of dry, black, pit waste to the south of the source. Under strong insolation this became an area of convergence, the wind flow at times being strong enough to reverse the wind direction at the source. Consequently, the observed distribution of tracer was a result of particular features of the Sirhowy Valley, and no attempt was made to interpret the results in any general way, except to point out that in such calm convective conditions tracer could be found at almost any point in the valley.

Caton(1976) provides a number of maps of hourly mean wind speed over the United Kingdom for the period 1965-73. These maps show wind speed threshold contours which were exceeded for 75%, 50%, 25%, 10%, 5%, 1% and 0.1% of the time. From the point of view of this project, the contours for 75% are the most interesting, in that they correspond to areas where the wind speed is below the thresholds for 25% of the time. For example, most of the coast of England lies between the 3.0 and 3.5 m/s contours, indicating that on the coast the wind speed is less than about 3.25 m/s for 25% of the time. A number of inland areas lie close to the 2.5 m/s contour, indicating that in these areas the wind speed is less than 2.5 m/s for 25% of the time. The regions of lowest wind speed are the low lying, sheltered, inland areas of the UK.

3.3 Dispersion in low wind speeds

3.3.1 Gaussian dispersion models

This section describes some of the approaches that have been reported in the literature for dealing with dispersion in low wind speeds. Some specific models and their limitations are discussed further in Section 5 of this report.

Carruthers et al(1992) describe UK ADMS, which is discussed further in Section 3.3.2. 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), 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(1990) 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, Brusasca and Timarelli**(1990). This involved splitting the hourly average wind direction into separate contributions from the atmospheric turbulence and from that due to the 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(1989) describe the development and evaluation of the Hybrid Plume Dispersion Model (HPDM). This HPDM 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(1981a) 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 is 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. A brief persistence study, using the Cardington sonic anemometer data, has been presented in Sections 4.4.5 and 4.4.6.

Jones(1981b) considers the long range dispersion of short releases and gives the following equation for the time integrated concentration (C) at a distance x (m):

$$C(x) = \frac{Q}{u\Theta x A} \tag{3.9}$$

where:

Q is the total activity released
u is the wind speed (m/s)
Θ is the total width of the plume in radians
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 the equation above is largely independent of wind speed, and so a single value of 8 m/s was used to represent this quantity. This suggests that $\Theta = 8/u$, which exceeds the value π when u drops below 2.54m/s, indicating that this particular long range plume model breaks down at wind speeds of this order.

Hanna(1981) makes the same point based on 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 1m/s (σ_Θ in radians). In this case, σ_Θ will only exceed π for wind speeds less than 0.3 m/s, 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 over-estimate 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(1986) 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 m/s.

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 their distributions. It is noted that there are complications at low wind speeds arising from instrument error if a standard anemometer is used, as its starting speed may be comparable to the wind speed. (See Section 4.2). 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**(1980) is noted as having produced an improved Gaussian plume model which includes an improved treatment of calm conditions.

In his latest review, **Jones**(1996) 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 m/s rather than 1 (**Hanna**(1981)). He also refers to unpublished work by Hunt (discussed further in Section 5.2.1), 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 $0.5w_*$, where w_* is the convective velocity scale.

Hanna, Briggs and Hosker(1982) provide an introduction to the use of the Gaussian plume model, which is quoted as:

$$\frac{C}{Q} = \frac{1}{2\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right] \qquad (3.10)$$

where:

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

Hanna, Briggs and Hosker 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.'*

This is a very important point, and will be considered further in Section 5.1 of this Report.

3.3.2 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**(1990) states that the worst condition for dispersion of material occurs on still days, and for a source close to the ground is approximated by the formula of **Katan**(1951), which gives the distance travelled, d_s(m), to achieve satisfactory dilution of a flammable vapour release as:

$$d_s = [36.8\ Q\ /\ (u\ C_L)]^{0.552} \qquad (3.11)$$

where:

Q is the release rate (m^3/s)
u is the wind speed (m/s)
C_L is the lower flammable limit (m^3 vapour/m^3 of air)

The lowest wind speed for which this correlation applies is quoted as 2.24 m/s, 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 (ie. down to around 2% concentration). It should therefore be treated with caution.

Witlox, McFarlane, Rees and Puttock(1990) and **Post**(1994a & b) provide a description of the HGSYSTEM (Version 3.0) 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
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_o is 1.0 m/s. For the passive dispersion model (PGPLUME) it is stated that data validation requires that the ambient wind speed at the plume centroid height lies in the range 1.0 to 20 m/s.

The **TNO Yellow Book**(1979) 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, 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 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(1989) describes the CEGB's ALMANAC plume dispersion model, which was based on the earlier work of Moore. Bennett discusses the problem with the use of Meteorological Office wind measurements due 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(1994) 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 m/s or greater than 50 m/s, although wind speeds lower than 1 m/s may be entered via a file.

As noted above, **Carruthers et al**(1992) 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

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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 m/s.

It is concluded that a wide range of lower wind speed limits are quoted for current dispersion models, and that these 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.

3.3.3 Dense gas dispersion models

The majority of the early 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 effort was invested in improving the modelling of dense gas dispersion during the 1980's. This commenced with the Maplin Sands experiments (Colenbrander & Puttock(1984)) and was significantly enhanced by the Thorney Island experiments (McQuaid(1985)). Results from these trials were widely disseminated and led to significant advances in understanding and modelling.

In terms of the significance of low wind speeds, the important 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(1985) on the basis of some of the Thorney Island results.

Britter(1979) presents the results of a laboratory experiment to study the spread of a negatively buoyant gas release into a calm environment, and gives a formula for the position of the leading edge of the plume as:

$$r_m = (0.84 \pm 0.06)\,(Q_1 g')^{1/4}\, t^{3/4} \qquad (3.12)$$

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

For example, a 3 kg/s chlorine release has $Q_1 \approx 1$ m^3/s, $g' \approx 15$ 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 3.3.1:

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)	1.24	0.94	0.70	0.53	0.39	0.30

Table 3.3.1
Radius and velocity of slumping dense gas cloud

Hence, after only about 1 minute, the cloud velocity is less than 0.5 m/s, 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(1987) 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 over 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 which determines 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 for validation, was that air entrainment into the top of the cloud need not be considered in calm conditions.

Van Ulden(1987) 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**(1990). The model incorporates the processes of top and side entrainment, the occurrence of a leading torus and a trailing disk, and uses Gaussian distributions in the entrainment

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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(1992) 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.

3.3.4 Physical modelling in low wind speed conditions

Physical modelling is often recommended as an alternative to theoretical modelling in order to address complex dispersion problems. Physical modelling may include experiments in wind tunnels, towing tanks and field trials. However, due to the difficulty in meeting the scaling requirements at low wind speeds, very few model scale experiments have been undertaken. For example, complete scaling generally requires that the wind speed scales as the square root of the linear scale, and so simulation of a 1 m/s wind at a model scale of 1/400 would require a wind tunnel velocity of 0.05 m/s, which is impractically low. Furthermore, wind tunnels and towing tanks are not capable of simulating the meandering nature of plumes in low wind speeds. Some facilities, such as those at Surrey University's Environmental Flow Research Centre, are capable of simulating stable flows (see **Robins**(1994a&b)) but these studies generally relate to the effects of buildings and topography, rather than the fundamental problems associated with low wind speeds. A large wind tunnel facility has been developed at the University of Arkansas (**Havens, Spicer and Walker**(1995)). Preliminary results of a dense gas dispersion simulation in a tunnel speed of 0.2 m/s have been presented, and have highlighted the difficulties both of scaling, and also of maintaining a turbulent boundary layer over the length of the working section at such low speeds.

There have also been relatively few field measurements of dispersion in low wind conditions, largely due to the fact that they are significantly more difficult to conduct for the following reasons:

- Sampling locations may need to cover all wind directions
- Local topographic features may become important (drainage winds, channelling, etc.)
- Good quality meteorological data is required, including accurate low wind speed measurements
- The results may be very variable, and so a greater time may be required to obtain statistically significant results

However, some such studies have been undertaken, and in most cases the results are compared with dispersion models of varying complexity.

The Thorney Island trials (**McQuaid**(1985)) covered the release of dense gases, mostly from instantaneous sources, in a wide range of wind speed and stability conditions. At least one (Trial 9) had a wind speed less than 2 m/s, and one trial (34) was intended to have zero wind speed, but actually had a mean wind speed of 1.1 m/s. Results from this trial were compared by **Havens et al**(1987) with those from wind tunnel tests and also with the CFD model MARIAH II. A more general analysis of the Thorney Island data was undertaken by **Puttock and Colenbrander**(1985), who observed that there were greater discrepancies between measurements and model predictions at low wind speed than at moderate or high wind speeds.

Dickson and Sagendorf(1975) describe a series of tests under stable conditions with light winds, the results of which were compared with various models. The standard Gaussian plume model over-predicted concentrations by a factor of eight (due to horizontal plume meander), whereas a 'split sigma' approach, in which the long time-scale meander component is separated out from the short time-scale turbulence component, reduced the over-prediction to a factor of 1.5. However, such approaches cannot be used when the meander is so great that pollutant is spread over a 360° arc, and so it was concluded that the best approach was to use a segmented plume model, in which the release was divided into a number of 2 minute segments or puffs. Each segment is treated separately and the concentrations at each location are summed to give the overall concentration.

Wilson, Start, Dickson and Ricks(1976) describe a series of tracer releases to study terrain effects under low wind speed conditions near Oak Ridge, Tennessee. The main reason for conducting these trials was that it was recognised that low wind speeds (less than 2 m/s) are extremely significant to the estimation of pollutant concentration, and that the Gaussian diffusion equation leads to concentrations that tend to infinity as the wind speed approaches zero. The general conclusion of the research was that, for these low wind speeds, the lateral plume spread was on average 6 times greater than the values predicted by the Pasquill-Gifford curves for the appropriate stability classes, leading to significantly lower ground level concentrations. The increase in lateral spread was attributed mainly to wind meander. The vertical spread was also enhanced, but this was attributed to roughness of the surface caused by vegetation and topography.

It is important to remember that, although these trials seem to indicate that the standard Gaussian model leads to over-prediction, this is due to averaging effects and meandering of the plume. In a QRA, plume meander may not be so important, since releases tend to be of relatively short duration. It is vital therefore that risk calculations take into account the peak concentrations that could be reached, and are not based on an hourly average figure.

Van der Hoven(1976) provides a review of a number of similar studies, and concludes that experimental concentration results are significantly lower than those predicted by the standard Gaussian plume model, particularly in hilly or forested terrain. However, this may be partly due to the fact that most of the measurements relate to relatively long averaging times (such as an hour) so that meandering of the plume leads to significantly lower average concentrations at any specified receptor. Van der Hoven also notes that the wind instruments used in studies generally had a starting speed of 1 mph, and so meaningful wind statistics are not available for the near-calm conditions.

Hanna$^{(1983)}$ describes much of the available data relating to lateral turbulence intensity and plume meandering during stable conditions. This includes a review of field experiments to determine the value of the horizontal turbulent velocity (σ_v) in stable conditions, which is summarised in Table 3.2.2:

Study by:	Site	Results
Smith and Abbott (1961)	Porton (England)	σ_v = 0.3 m/s for all wind speeds during stable conditions
Hanna (1981)	Complex terrain site in California	σ_v = 1 m/s for all wind speeds during nighttime conditions
Schacher et al. (1982)	Overwater diffusion experiment off the California coast	σ_v = 0.5 m/s

Table 3.3.2
Reported Values of Horizontal Turbulent Velocity

Hanna$^{(1990)}$ describes the estimation of lateral dispersion in light wind stable conditions, based on the results of several field trials. The general conclusion reached was that the lateral distribution of pollutant concentration over any given period was equal to the standard deviation of the wind direction fluctuations during that period. Hanna also presented further data which suggested that σ_v (= $\sigma_\theta u$) = 0.5 m/s rather than the value of 1m/s noted above in Table 3.3.2.

Graziani and Maineri $^{(1990)}$ compare calculated and measured concentrations from a tracer release at ground level in low wind conditions. The models used were a segmented (puff) Gaussian model (AVACTA II) and a Monte Carlo model (MCLAGPAR). Both models can accept wind data that varies in time and space within the domain, which allowed the experimentally determined time-dependent wind speed and direction to be applied in each model. It was shown that both models could be used to predict concentration distributions, although the Monte Carlo model required a large amount of CPU time.

Such models are unlikely to be a viable option for most practical situations, in view of the lack of availability of time-dependent wind speed and direction data at the required resolution and level of detail.

3.3.5 Topographic and building effects in low wind speeds

There are two aspects to consider when assessing topographic and building effects in low wind speeds. Firstly, the normal influence of topographic features or a large building on a dispersing plume may be more or less significant when the mean wind speed is low, and secondly, additional features (such as building heat losses, drainage flows, etc) may begin to play an important part in actually determining the nature of the mean and turbulent flow field. For example, in low wind speeds building wake entrainment is likely to be less important whilst drainage flows might dominate the flow field.

Robins(1994a) discusses the flow and dispersion around buildings in light wind conditions, and emphasises that the role of emission conditions (buoyancy and momentum) becomes more significant as wind speeds fall. Additional factors which become more important at low wind speeds include heat losses from buildings, flows induced by plant operations and local flows generated by solar heating of building surfaces, or on a larger scale, whole industrial sites. Robins summarises some of the results from a number of dispersion experiments under light wind conditions undertaken at the Rancho Seco nuclear power plant site, and his Figure 12 shows the variation in wind speed and direction during a one hour experimental period. Wind speeds vary from about 0.5 to 1m/s and wind direction changes by over 100° during this period. Robins also refers to an algorithm developed by Bouwmeester et al(1980) for combining short term dispersion estimates with two minute averaged meteorological data to simulate concentration distributions over a full one hour period.

Hanna and Drivas(1987) provide useful guidelines on the use of vapour cloud dispersion models, but no specific consideration is given to the limitations of such models in low wind speed conditions. However, they do discuss drainage flow models which are concerned with the nocturnal cooling of slopes and the subsequent formation of shallow gravity-driven density flows. These flows are typically only a few metres deep for downslope distances of about 100 m from the hilltop, but can reach depths of about 100 m for downslope distances from the hilltop of several kilometres.

Hanna, Briggs and Hosker (1982) give a summary of the results produced by **Briggs**(1979) in relation to drainage flows. The thickness (h) of the drainage layer on a simple slope is given as:

$$\begin{aligned} h &= 0.05\, x \sin\beta && \text{for } \beta > 0.35 \text{ radians } (20°) \\ h &= 0.037\, x\, \beta^{2/3} && \text{for } \beta < 0.35 \text{ radians } (20°) \end{aligned} \qquad (3.13)$$

where x is the distance along the slope from the top of the slope and β is the slope angle in radians. The characteristic wind speed in the drainage layer is given by:

$$u = 2.15\, (\sin\beta)^{2/9}\, (Hx)^{1/3} \qquad (3.14)$$

where H is the downward sensible heat flux (in units of m^2/s^3), which is given by:

$$H = -g\, \frac{\overline{w'T'}}{T} \qquad (3.15)$$

On a typical clear night, H can be of order 0.001 m^2/s^3. Thus, if $\beta = 27°$ and $x = 1$ km, then $u = 1.8$ m/s, which is a typical value of the wind speed observed in drainage layers.

Britter and McQuaid(1988) emphasise that, under light wind conditions, dense gas flows are very sensitive to variations in height of the underlying surface, and that, given the diversity of the problems that could be met, it is unlikely that simple correlations could be used for flow over topography in light winds. It is suggested that physical modelling might be more appropriate, but it should be noted that scaling problems may be difficult to overcome for physical modelling at low wind speeds.

Picknett(1981) found that, in very low wind speed conditions, instantaneous releases on slopes of 1 in 13 were influenced by the slope. For example, a release with a relative density of 2.5 in a wind speed of 0.4 m/s resulted in a long period of gravity flow downhill against the wind. Dense gas releases are therefore susceptible to slope effects in low wind speeds, and this should be considered within risk assessments.

In his recent review, **Jones**(1996) considers the effects of non-uniform terrain and buildings on low wind speed plume dispersion. Whilst the emphasis on elevated plumes renders little of the discussion directly applicable to this study, he does make the interesting observation that building effects are unlikely to be very important in strongly convective flows. It should be noted, however, that buildings and topography are likely to affect low level releases to a greater extent than elevated plumes.

3.4 Application to risk assessment

3.4.1 Historical experience of hazardous events in low wind speed conditions

In this section, a few brief examples are given of incidents which are known to have occurred in low wind speed conditions.

The AIChE(1994) 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. A large vapour cloud was formed and was ignited after about 24 minutes, resulting in a blast equivalent to 50000kg of TNT. Witnesses observed that the propane formed a white cloud settling into the valley around a complex of buildings prior to the explosion.

In 1966, an explosion occurred at Raunheim in Germany after liquefied methane was discharged from a vent. The methane was discharged at a height of 25m, but, because of the low wind conditions, a white cloud formed on the ground which expanded slowly and drifted towards the control room, where it was ignited.

Caufield and Kossup (in LPB No. 057) describe a tank farm fire and explosion at Texaco's Newark storage facility in 1983. A petrol storage tank was overfilled and heavier than air vapours from the spill travelled to an adjacent facility where they were ignited. An eyewitness stated that an initial blue flame seemed to travel back to the tanks prior to the explosion. At the time of the incident, which occurred around midnight, the winds were listed as negligible.

Lewis (1982) 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.

Lewis (in LPB No. 100) describes an incident at Puebla, Mexico on 19 June 1977 in which there was a massive spill of vinyl chloride. A large white cloud was formed and continued to increase in size. There was no wind at the time, so the cloud slowly drifted forwards and backwards in different directions, reaching a size of about 330 m by 240 m. One hour and twenty five minutes after the initial release, the cloud found a source of ignition leading to a major fire and several BLEVEs.

Lees(1980) also describes some of the most well known incidents which have occurred in low wind speeds. On 16 November 1970, 160 tonnes 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 square kilometres and extending over 2.7km from the tank. Other incidents in low wind speeds described by Lees include:

- Potchefstroom, South Africa, 1973 - ammonia storage tank failure
- Pensacola, Florida, 1971 - cyclohexane vapour
- Southwest Freeway, Houston, Texas, 1976 - ammonia road tanker crash
- Youngstown, Florida, 1978 - chlorine release

There are many other incidents for which the available documentation does not record the wind speed, but where low wind may still have been an influencing factor.

3.4.2 Influence of low wind speeds on the likelihood of major accidents

High wind speeds can cause structural damage which may escalate to a release of hazardous material, whereas low wind speeds are unlikely to be the direct initial cause of any major accident. However, once an accident has occurred, then the wind speed may have a significant effect on the likelihood and extent of the accident progression or escalation. For example, low wind speeds may increase the likelihood of a vapour cloud explosion, but may reduce the rate of spread of a fire.

Purdy, Pitblado and Bagster(1992) describe a methodology to model tank fire escalation by considering the heat flux received by a tank adjacent to a tank fire. The effect of wind speed on the time taken for the fire to spread from one tank to the next is calculated, and it is concluded that, for any particular tank separation distance, the escalation time is greatest in low wind speeds. For the case considered by Purdy, Pitblado and Bagster, the escalation time in low wind speeds (< 1 m/s) exceeded 4 hours for all tank separations down to 0.3D (where D is the tank diameter), whereas in a 4 m/s wind the escalation time was reduced to 1.4 hours for a separation of 0.3D.

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3.4.3 Risk assessments using low wind speeds

Risk assessments where specific consideration is given to low wind speeds are of particular interest in this project, and the literature search has shown that there is a very significant lack of information in this area.

Nussey and Pape(1987) 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 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, as shown below:

(1)

Weather categories	D 2.4	D 4.3	D 6.7	F 2.4
Occurrence probability	0.22	0.22	0.31	0.23

(2)

Weather categories	D 5	F 2
Occurrence probability	0.77	0.23

(3)

Weather categories	B 1.2	C 1.2	C 2.4	C 4.3	D 1.2	D 2.4	D 4.3	D6.7	E 2.4	E 4.3	F 1.2	F 2.4
Occurrence probability	0.04	0.03	0.06	0.1	0.08	0.05	0.11	0.29	0.02	0.02	0.17	0.02

The probabilities were based on the data from a typical inland UK weather station.

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. Nussey and Pape concluded that 'the need for model improvements is clear'.

This under-prediction of risk appears to be a very important conclusion, and is one of the major reasons for conducting the more detailed research presented in this report. In particular, further studies considering the sensitivity of RISKAT results to the incorporation of very low wind speeds are presented in Section 6.4.

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4. ANALYSIS OF METEOROLOGICAL DATA

This section presents various analyses of meteorological data from sites in the UK. It begins by looking at some of the standard data available from the Meteorological Office and attempts to draw some conclusions in terms of the significance of low windspeeds. The results of measurements using more sensitive anemometry are then examined, and it is shown how useful information may be obtained on the nature and frequency of low wind speed conditions.

4.1 Standard data

4.1.1 Background to data acquisition

The standard anemometer data provided by the Meteorological Office for sites in the UK is generally obtained from Munro Mk IV cup anemometers, which have the advantage of being reliable and rugged. However, due to their heavy construction, their starting speed is typically about 5 knots, and so an accurate frequency distribution of wind speeds below this level is not readily obtainable.

Standard wind data has historically been recorded as hourly mean of wind speed and direction. Where these are taken from anemograph traces, there is some subjectivity in the values ascribed, although an increasing number of sites now have the data recorded electronically (**Ashcroft**(1994)). Although these raw data can be manipulated in a variety of ways, the standard presentation of data is within wind speed and direction categories. The wind speed categories correspond to the Beaufort scale, for which the lowest two categories are 'calm' and 1-3 knots. Thus, both the quality and resolution of standard wind data are inadequate to assess the frequency of low wind speeds with any confidence.

It would appear, from discussion with the Meteorological Office, that the data from automatic measurement stations display different characteristics to those from the older manual records, even where nominally identical instrumentation is used. The reason is that the manual recording method allows for some subjective correction at low wind speeds. For example, if the anemometer is stationary but the vane is turning, manual recording would give a 2 kt reading whereas an automatic weather station would give zero. Hence at least part of the peak at zero for automatic stations is displaced to 2 kt for manual stations. However, it should be noted that in neither case is an accurate record of low wind speeds provided if the instrumentation is inadequate. Some further discussion, using additional data supplied by the Meteorological Office, is given in Appendix 1.

In spite of these reservations, since there is a considerable quantity of standard data currently available and in use for safety reports and QRAs, it is worth examining some typical examples in order to determine how much useful information can be extracted. The major advantage of this data is that it is readily available for many sites in the UK and covers a large number of years.

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4.1.2 Analysis of standard data

The standard format in which data is reported provides a distribution of frequencies between 9 stability categories, 6 wind speed ranges and 12 directions. Some of the data for Ringway, averaged over a 20 year period from 1971 to 1990, has been presented in Table 4.1.1. This gives total frequency for all directions, but otherwise divided into wind speed and stability classes.

Stability	**Wind Speed (knots)**						
	Calm	**1 - 3**	**4 - 6**	**7 - 10**	**11 - 16**	**17 - 98**	**Total**
A	0.003	0.116	-	-	-	-	0.119
A/B	0.093	1.212	0.092	-	-	-	1.397
B	0.454	3.030	0.996	0.136	-	-	4.616
B/C	-	-	0.547	2.029	-	-	2.576
C	0.179	1.177	5.455	7.389	0.116	0.017	14.333
C/D	-	-	-	0.858	1.434	-	2.292
D	0.871	3.513	6.169	16.253	23.279	6.479	56.564
E	-	-	4.245	2.664	-	-	6.909
F/G	1.953	7.219	2.021	-	-	-	11.194
ALL	3.553	16.267	19.526	29.329	24.829	6.496	100.000
Cumulative	3.553	19.820	39.346	68.675	93.504	100.000	

Table 4.1.1
Distribution of Wind Speeds and Stabilities at Ringway
(1971-1990)

There are some important points to note from Table 4.1.1:

- The total frequency of wind speeds less than or equal to 6 knots (3.09 m/s) is over 39%. This wind speed is not much higher than the 2.4 m/s wind speed used by the HSE in QRAs to represent the lowest wind speeds, i.e. about 30% of the time the consequences of a hazardous event could potentially be worse than those currently used in risk assessments.
- The frequencies for the first two or three wind speed ranges in the table must be treated with caution, as the anemometry may not provide reliable estimates of the wind speed at less than about 5 knots. For example, the frequency of wind speeds less than 1 knot appears to be 3.6%, but this figure cannot be regarded as accurate. (See analyses in Sections 4.2 and 4.4).
- The most common stability category for winds less than 4 knots is category F/G.
- The most common stability category for winds of less than 1 knot (calm) is also category F/G.
- The total frequency of wind speeds less than 4 knots is 9.2% in stable conditions, 6.3% for unstable conditions (A-C) and 4.4% for neutral stability.

Table 4.1.1 does not show the directional frequency distribution of the wind, but examination of the original data shows that the most frequent wind direction is the same for every wind speed range. For Ringway, it also appears that the most frequent wind direction for each of the stability categories is the same, although there are some exceptions for some of the low frequency categories such as A, A/B, B/C and C/D. It is emphasised that these conclusions will not apply to the majority of sites, particular exceptions being coastal sites where land and sea breezes may have some influence.

It is stressed that, for any particular site, the directional frequency distribution for a single atmospheric stability category or wind speed range is rarely the same as the overall directional frequency distribution averaged over all weather conditions. For example, the most common wind direction for a particular weather category (such as F stability) may not correspond to the overall 'prevailing' wind direction. Risks in the far field are often dominated by a single representative weather condition (such as F2.4), whose most common wind direction may even oppose the overall prevailing wind at the site. This means that risk contours may extend furthest from the site in a direction which is not the same as that of the overall prevailing wind. It is therefore important that companies, local planning authorities and emergency planners realise that the worst case scenarios with the greatest hazard ranges may be more likely to affect sectors other than those corresponding to the overall prevailing wind direction.

Similar analyses to that described above have been carried out for other sites including:

Ringway (1981-1990)
Church Fenton (1981-1985)
Finningley (1977-1986)
Elmdon (1980-1989)
Watnall (1980-1989)

The key points from these data sets, shown in Table 4.1.2, indicate that results from Ringway (1971-1990) given in Table 4.1.1 appear to be reasonably representative of inland sites in the UK, although analysis of further sites would be required to confirm this. The table also demonstrates a large variation in the frequency of wind speeds less than 1 knot (more than a factor of three), but this is almost certainly due, in part, to differences or changes in the instrumentation and recording systems, and probably also due to differences in local topography.

The Meteorological Office has published meteorological data for a number of sites around the UK. Although this data is based upon old measurements (see below), it does provide a good overview of how the wind speed distribution varies at different locations. Table 4.1.3 summarises some of this data for 35 anemograph stations (from Met.O. 792, 1968). There are some important points which should be noted when considering this data:

- In most cases, the period covered is the 10 years from 1950-59.
- The wind speeds are hourly means.
- For most sites the data is incomplete, so that the frequencies sum to less than 100%.

Parameter		Ringway 1971-90	Ringway 1981-90	Church Fenton 1981-85	Finningley 1977-86	Elmdon 1980-89	1980-89
Frequency of wind speeds ≤ 1 knot (calm)		3.6	2.3	2.9	2.6	5.5	1.5
Frequency of wind speeds ≤ 3 knots (Force 0 & 1)		19.8	21.1	22.7	18.1	19.0	16.0
Frequency of wind speeds ≤ 6 knots (Force 0, 1 & 2)		39.3	41.4	44.1	38.4	44.0	40.5
Most common stability category for winds of < than 1 knot (calm)		F/G	F/G	F/G	F/G	F/G	F/G
Most common stability category for wind speeds of 0 to 3 knots		F/G	F/G	F/G	F/G	F/G	F/G
Total frequency of wind speeds of 0 to 3 knots for various stabilities	Stable	9.2	10.2	9.4	7.9	9.6	6.7
	Unstable	6.2	6.6	7.6	5.3	5.6	5.0
	Neutral	4.4	4.3	5.7	4.9	3.8	4.3

Table 4.1.2
Summary of Low Wind Speed Data for Various Sites (percentage frequencies)

- The anemometers are located at various heights, and the speeds have not been corrected to the standard height of 10m.
- The siting and exposure varies between different sites.
- The mean values quoted here should not be regarded as average values for the UK, as the anemograph stations are not evenly distributed.

Examination of Table 4.1.3 reveals the following main conclusions:

- The frequency of calms (< 1 knot) varies from 0.8% at Birmingham (Edgbaston) to 16.4% at Eskdalemuir, with a mean for all sites of around 5.1%. Even sites that are relatively close together (e.g. Hampton and Kew) show considerable variation, which suggests that this low wind speed data would not be suitable as a direct input to any form of QRA, as the uncertainties would be unacceptable. The uncertainties may be due to instrument and recording system errors/variations or due to local siting effects. It is considered that these frequencies are unlikely to be a true representation of the frequency with which the mean hourly wind speed is less than 1 knot, and so it must be concluded that the true frequency of calms around the UK is not known.

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Anemograph Station	Percentage Frequency of Specified Ranges of Mean Hourly Wind Speed (knots)										
	Calm	1-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	> 40	Total
Lerwick	3.5	6.4	10.0	17.6	22.2	18.6	12.8	6.5	2.1	0.4	100.1
Stornoway	5.8	7.5	7.7	15.2	26.3	16.4	12.0	5.9	2.6	0.5	99.9
Dyce	13.6	20.1	15.9	21.2	20.6	6.3	1.9	0.4			100.0
Bell Rock	1.9	7.6	7.9	14.7	25.6	18.4	13.3	6.1	2.7	0.8	99.0
Leuchars	2.7	24.6	20.8	23.7	19.2	6.3	2.1	0.4			99.8
Tiree	3.3	7.7	9.8	18.1	28.5	15.9	10.8	3.7	1.4		99.2
Renfrew	11.9	14.3	18.5	24.9	22.6	5.4	1.9	0.4			99.9
Prestwick	6.1	17.2	19.2	25.1	21.6	6.0	2.3	0.2			97.7
Eskdalemuir	16.4	18.7	19.7	20.7	15.8	5.0	2.2	0.4			98.9
South Shields	2.0	13.7	20.1	26.5	24.8	8.7	3.4	0.7	0.1		100.0
Cranwell	4.6	13.5	16.6	25.6	25.0	8.4	2.6	0.4			96.7
Mildenhall	2.7	19.7	24.5	27.4	20.3	4.1	1.0	0.1			99.8
Felixstowe	3.3	15.4	15.1	24.1	28.6	9.9	2.8	0.5			99.7
Dunstable	2.3	17.5	26.4	28.0	18.5	2.9	0.3				95.9
Cardington	5.3	16.5	14.4	23.5	25.3	8.7	3.3	0.8	0.1		97.9
Shoeburyness	2.7	6.5	13.6	25.9	32.5	11.7	4.9	1.1	0.2		99.1
B ham (Edgbaston)	0.8	9.1	27.5	36.0	21.6	4.1	0.6				99.7
Keele	4.0	29.4	22.5	25.3	14.9	2.3	0.4				98.8
London (Kingsway)	2.1	15.3	25.3	35.1	18.5	2.0	0.2				98.5
Hampton	3.3	22.9	25.1	27.0	17.5	2.9	0.4				99.1
Kew	2.7	16.8	28.3	29.4	18.7	3.7	0.3				99.9
Croydon	10.2	18.2	19.2	25.6	20.8	4.6	1.2				99.8
Thorney Island	5.1	24.8	20.1	25.1	19.3	4.0	0.9	0.1			99.4
South Farnborough	8.9	28.8	22.3	22.5	14.4	2.3	0.5				99.7
Abingdon	10.0	20.3	19.7	24.2	18.6	4.3	0.8				97.9
Boscombe Down	3.2	18.3	19.2	26.4	24.3	6.1	2.0	0.2			99.7
Sellafield	7.1	12.4	17.4	22.8	24.6	9.3	3.3	0.5			97.4
Fleetwood	1.9	10.4	16.2	25.1	27.7	10.6	4.7	1.3	0.3		98.2
Speke	4.8	11.6	14.4	23.4	29.3	10.8	4.4	1.0	0.2		99.9
Manchester (Ringway)	3.3	9.3	17.8	28.4	29.8	8.5	2.5	0.3			99.9
Holyhead/Valley	5.1	12.8	13.0	18.6	26.3	13.8	7.5	2.3	0.7		100.1
Aberporth	5.6	10.5	13.7	21.9	27.0	13.0	6.2	1.5	0.4		99.8
Lizard	5.4	10.8	10.1	17.7	26.6	13.6	8.9	4.1	1.5	0.3	99.0
Scilly	1.8	6.4	9.1	18.9	30.2	17.3	10.9	3.5	1.3	0.2	99.6
Aldergrove	3.7	12.9	16.8	26.3	28.0	8.4	3.0	0.6			99.7
Mean	5.1	15.1	17.7	24.1	23.3	8.4	3.9	1.2	0.4	0.1	99.1
Cumulative Mean	5.1	20.1	37.8	61.9	85.2	93.6	97.5	98.7	99.1	99.1	

Table 4.1.3
Summary of Data from Various Meteorological Stations
(Extracted from Met. O. 792, 1968)

- The frequency of wind speeds less than or equal to 6 knots varies from 17.3% at Scilly to 60.0% at South Farnborough, with a mean of 37.8%. There is clearly some correlation between nearby sites, and the most exposed sites tend to have low frequencies whilst inland sites tend to have the highest frequency of winds within this range. This result tends to imply that the frequency of wind speeds ≤ 6 knots is not determined significantly by the instrument/recording system, although local siting effects may still have some influence.

The discussion so far has only considered the overall frequency distribution of wind speeds. However, it is obvious that this frequency distribution will vary considerably from one stability category to another. For example, high wind speeds are very unlikely in strongly stable or unstable conditions. Indeed, the scheme used for the assignment of particular weather conditions to a stability category generally imposes limits on the wind speeds that may be assigned to particular categories. For example, the ranges of wind speeds that may be assigned to the standard 9 categories used by the Meteorological Office are shown in Table 4.1.4.

Stability Wind Speed (knots)	**Calm**	**1 - 3**	**4 - 6**	**7 - 10**	**11 - 16**	**17-98**
A	▨	▨				
A/B	▨	▨	▨			
B	▨	▨	▨	▨		
B/C			▨	▨		
C	▨	▨	▨	▨	▨	▨
C/D				▨	▨	
D	▨	▨	▨	▨	▨	▨
E			▨	▨		
F/G	▨	▨	▨			

Table 4.1.4
Ranges of Wind Speeds for Various Stability Classes

4.1.3 Analysis of data for risk assessment purposes

Corlett(1995) presents a summary of the meteorological data for 36 weather stations, selected for their proximity to major hazard sites, and describes the way in which this data is used to provide the probability of representative weather conditions for use in QRAs using RISKAT. For many of the weather categories, the frequency is greater than zero for only two or three wind speed ranges, and so it is impossible to draw any conclusions about the precise nature of the frequency distribution within a single weather category. It is, however, possible to group categories together, such as all the stable categories, to investigate whether it is possible to estimate the frequency distribution for various ranges of stability. Table 4.1.5 provides a summary of wind speed distributions, derived from information presented by Corlett, and shows the total frequency of wind speeds in categories A to D and E to G, as reported in standard

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Meteorological Office data. Examination of Corlett's data and Table 4.1.5 reveals the following main points:

- The frequency of calms (< 1 knot) varies from 0.9% at Squires Gate to 18.1% at Renfrew, with a mean for all sites of around 4.6%. The points made for Table 4.1.3 concerning variability and uncertainty also apply here.

- The frequency of wind speeds less than or equal to 6 knots varies from 16.6% at Lerwick to 45.9% at South Farnborough, with a mean of 32%.

- Once again, the mean values quoted here should not be regarded as average values for the UK, as the anemograph stations are not evenly distributed.

- Corlett's analysis showed that the distribution of wind speeds in category D appeared, in general, to follow a standard Weibull distribution (see Sections 3.2.2 and 4.4.4).

- The distribution of wind speeds in combined categories A - D also appears to follow a standard Weibull distribution, but with slightly higher frequency in the low wind speed range.

- The distribution of wind speeds in combined categories E - G is not readily apparent from the data. The sensitivity of the raw anemometer data is probably not sufficient to provide a good description of the wind speed distribution in the 0 to 10 knot range. Although, using most current data, it can only be surmised that the frequency distribution in stable conditions may approximate to a Weibull distribution, the results of using improved data, presented in Section 4.4.4, do suggest that the Weibull distribution can be applied in stable conditions down to very low wind speeds.

- Some of the sites for which data is presented in Table 4.1.5 also appeared on Table 4.1.3, although the data is given in a slightly different format. However, sample comparisons (e.g. Stornoway, Shoeburyness) indicate significant differences. These may be due to inter-annual (and inter-decade) statistical variability, but may also reflect long term climatic changes, either of which would affect the frequency throughout the complete wind speed range. It is noted, in particular, that for each of these two sites there is a factor of 2 difference in the frequency of calms, when comparing data from these two tables.

Anemograph Station	Percentage Frequency of Specified Ranges of Mean Hourly Wind Speed (knots)										Total
	A - D Stabilities						E - G Stabilities				
	Calm	1 - 3	4 - 6	7 - 10	11-16	17-98	Calm	1 - 3	4 - 6	7 - 10	
Lerwick	1.429	2.517	7.202	17.257	28.968	35.651	1.533	1.592	2.328	1.526	100.003
Stornoway	1.305	3.049	9.411	21.567	29.098	23.287	1.657	3.240	4.669	2.719	100.002
Dalcross	2.572	8.548	12.338	25.508	31.290	13.305	1.083	2.205	2.205	0.948	100.002
Dyce	3.708	7.627	10.958	23.822	26.671	11.575	4.785	5.158	3.447	2.246	99.997
Prestwick	1.803	6.460	10.211	23.176	28.935	14.315	2.658	6.298	4.298	1.844	99.998
Renfrew	10.206	2.861	12.882	23.405	24.076	8.823	7.919	2.125	5.642	2.061	100.000
Turnhouse	3.213	7.319	11.174	23.525	27.074	11.703	3.832	5.613	4.340	2.209	100.002
Carlisle	1.628	10.645	13.836	25.430	23.098	7.209	1.957	8.437	5.808	1.951	99.999
Squires Gate	0.305	3.681	9.719	24.705	33.798	16.591	0.555	3.452	4.377	2.818	100.001
Speke	1.885	6.883	11.934	25.873	27.095	10.236	2.104	5.033	6.009	2.948	100.000
Wilsden	4.162	6.821	12.553	24.513	26.890	11.775	2.428	3.726	4.350	2.785	100.003
Kilnsea	2.912	2.131	8.199	20.572	34.105	24.688	1.112	0.782	3.089	2.409	99.999
Shawbury	1.576	9.681	15.642	28.227	21.104	6.250	2.300	6.847	5.681	2.693	100.001
Elmdon	1.879	6.776	13.872	28.753	24.744	6.412	3.104	5.620	6.148	2.692	100.000
Pershore	3.482	8.264	12.593	25.756	24.591	8.010	3.806	5.621	5.021	2.857	100.001
Waddington	0.640	4.756	12.108	28.688	29.731	10.024	0.695	3.116	5.897	4.344	99.999
Watnall	1.253	7.899	15.258	29.213	24.422	5.036	1.303	5.152	7.046	3.420	100.002
Wyton	1.317	6.000	12.313	28.284	29.228	8.686	1.190	3.198	5.570	4.218	100.004
Coltishall	2.094	5.979	11.730	26.327	27.707	10.053	3.142	4.860	5.212	2.892	99.996
Marham	0.391	7.728	10.813	25.744	29.754	9.992	0.581	6.366	5.073	3.560	100.002
Wattisham	0.481	3.721	10.023	29.519	33.364	10.814	0.502	2.096	4.480	4.998	99.998
Stanstead	1.492	5.149	16.140	29.673	25.106	4.417	2.069	4.633	8.140	3.179	99.998
Shoeburyness	0.908	4.314	12.876	31.804	33.231	10.779	0.368	1.132	2.463	1.954	99.829
London	0.447	5.097	11.050	29.306	32.575	8.274	0.439	3.741	5.022	4.050	100.001
Gatwick	2.718	8.345	13.200	26.398	22.790	5.769	4.624	7.841	5.867	2.449	100.001
Herstmonceux	2.303	10.904	12.598	21.010	19.933	11.291	3.272	11.996	4.831	1.863	100.001
Brize Norton	1.671	8.965	13.394	25.963	25.148	6.067	2.215	7.061	6.258	3.260	100.002
Thorney Island	1.102	6.802	10.884	23.645	27.971	12.198	1.689	6.208	5.924	3.580	100.003
Filton	2.250	6.153	13.997	25.635	24.539	7.633	3.784	5.408	7.496	3.105	100.000
Yeovilton	8.151	5.974	11.012	21.489	22.798	10.457	9.467	3.917	4.603	2.130	99.998
Plymouth	1.111	6.301	10.006	21.680	28.859	16.241	1.838	6.226	5.126	2.612	100.000
Valley	1.106	3.390	7.671	17.791	27.898	31.962	1.435	2.528	3.711	2.508	100.000
Brawdy	0.616	3.287	9.061	21.431	33.809	20.187	0.777	2.812	4.970	3.051	100.001
Mumbles	4.195	3.088	9.059	20.954	25.291	26.140	1.580	1.426	4.119	4.150	100.002
Rhoose	0.727	6.437	10.707	23.729	30.007	12.713	0.914	6.468	5.571	2.727	100.000
Tynemouth	3.352	2.567	10.195	24.599	25.319	23.571	1.638	1.525	4.579	2.656	100.001
Mean	2.233	6.003	11.573	24.860	27.528	13.115	2.343	4.541	4.983	2.817	99.996
Cum. Mean	2.233	8.236	19.809	44.669	72.198	85.313	2.343	6.884	11.866	14.683	

Table 4.1.5
Summary of Data from Various Meteorological Stations for the period 1974-1983 (Extracted from Corlett, 1995)

Further data for four stations in Ireland over the period (1960-1974) have also been assessed (see Table 4.1.6 below). The general conclusions are no different from those already discussed above.

Anemograph	**Percentage Frequency of Specified Ranges of Mean Hourly Wind Speed (knots)**										
Station	**Calm**	**1-3**	**4-6**	**7-10**	**11-16**	**17-21**	**22-27**	**28-33**	**34-40**	**> 40**	**Total**
Valentia 1960-1974	7.9	7.2	11.9	27.2	27.7	12.0	4.8	1.2	0.2	0.0	100.0
Shannon Airport 1960-1974	2.5	7.4	16.8	29.0	27.3	10.8	4.7	1.2	0.2	0.0	100.0
Malin Head 1960-1974	1.8	3.4	10.9	17.0	31.7	16.9	13.0	4.0	1.1	0.2	100.0
Belmullet 1960-1974	2.2	5.0	10.8	21.9	29.6	17.3	9.9	2.4	0.7	0.1	100.0
Mean	3.6	5.7	12.6	23.8	29.1	14.3	8.1	2.2	0.6	0.1	
Cum. Mean	3.6	9.4	22.0	45.8	74.8	89.1	97.2	99.4	99.9	100.0	

Table 4.1.6
Summary of Data from Various Irish Meteorological Stations

One point which is relevant to this project, but which is not emphasised by Corlett, is that the frequency of the D2.4 low wind speed category is determined from the frequency of winds speeds *up to* 2.4 m/s, and the wind speed for this category is therefore an upper bound rather than a representative value. The current method of assignment used by the HSE for allocating weather conditions to 'representative' weather categories is summarised in Table 4.1.7.

Representative Weather Category	**Stability**	**Wind Speed (m/s)**
D 2.4	A - D	0 - 2.4
D 4.3	A - D	2.4 - 4.3
D 6.7	A - D	4.3 - 50.6
F 2.4	E - G	0 - 50.6*

* Although 50.6 is the stated upper limit, in practice, stable wind speeds are unlikely to exceed around 5 m/s (see Table 4.1.4)

Table 4.1.7
Assignment of Weather Conditions to Representative Categories
(From Corlett, 1995)

It appears that the choice of the wind speeds for the representative categories was determined by the mean wind speed for the Beaufort wind forces, as shown in Table 4.1.8.

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Beaufort Scale Force	Quoted Range (knots)	Calculated Mean Wind Speed		Mean Wind Speed (m/s) (from Clay, 1995)
		knots	m/s	
0	< 1	-	-	-
1	1 - 3	2	1.03	0.8
2	4 - 6	5	2.57	2.4
3	7 - 10	8.5	4.38	4.3
4	11 - 16	13.5	6.95	6.7
5 - 12	17 - 98	-	-	-

Table 4.1.8
Wind Speeds Used for Representative Weather Categories

Neither **Clay**(1995) nor **Corlett**(1995) make it clear why the mean wind speeds that they quote for the Beaufort scale values are slightly lower than those calculated in column 4 of Table 4.1.8, but it seems that they are simply based on values given by the Meteorological Office, as shown in Table 4.1.9.

Beaufort Scale Force	Description	Knots		Metres per second	
		Mean	Limits	Mean	Limits
0	Calm	0	<1	0.0	0.0-0.2
1	Light air	2	1-3	0.8	0.3-1.5
2	Light breeze	5	4-6	2.4	1.6-3.3
3	Gentle breeze	9	7-10	4.3	3.4-5.4
4	Moderate breeze	13	11-16	6.7	5.5-7.9
5	Fresh breeze	19	17-21	9.3	8.0-10.7

Table 4.1.9
Specification of Wind Speeds Quoted by Meteorological Office

The conversion between units in Table 4.1.9 appears to be somewhat approximate in some cases (N.B. 1 knot = 0.5148 m/s). The discrepancies are not large (e.g. 5 knots = 2.6 m/s instead of 2.4 m/s), but it is not clear why they should occur.

It is also not immediately obvious how to derive the frequency of each of these categories from the basic meteorological data, which are generally divided up into wind speed ranges of 0, 1-3, 4-6, 7-10, 11-16, 17-98 knots. The method which is described by **Clay**(1995) and which appears to have been used by **Corlett**(1995) is as follows:

D 2.4	Pasquill A - D	Calm + Force 1 + ½ Force 2
D 4.3	Pasquill A - D	½ Force 2 + ½ Force 3

D 6.7	Pasquill A - D	½ Force 3 + higher wind speeds
F 2.4	Pasquill E - G	Calm + All non-zero wind speeds

It should be noted that this method assumes that a definite stability category can be allocated to each hour of 'calm'.

Hence, the frequency assigned to D2.4 only includes half of the wind speeds in Force 2 (3.5 - 6.5 knots, or 1.8 to 3.3 m/s). Therefore, when using this method of frequency assignment, the following points should be remembered:

- It appears to assume that there is an approximately uniform distribution of wind speed frequencies.
- The 'representative' wind speeds in categories D2.4 and D4.3 are in fact the upper bound wind speed of the weather conditions they are intended to represent, and are not the average wind speed for those conditions. Categories F2.4 and D6.7 will include some higher wind speeds, but in general the mean wind speed for category F2.4 will be less than 2.4 m/s.
- The frequency of calms is allocated to the 2.4 m/s weather categories, and it is assumed that the frequency of these calm conditions is uniformly distributed around all the sectors.

The above methodology has been used by **Corlett**(1995) and his Table 3 summarises the probability of each of the four weather categories (D2.4, D4.3, D6.7 and F2.4) for 36 weather stations. The probability of F2.4 varies from 6% to 22%, and that of D2.4 from 7% to 19%.

Influence of time of day

Many hazardous operations tend to occur within specific periods of the day, and are never conducted outside these hours. For example, at some sites road tanker off-loading might only occur between the hours of 9 am and 4 pm, and so it would be inappropriate for a risk assessment of these operations to include the frequency of stable conditions and low wind speeds that occur at night. For these reasons, it is sometimes necessary to be able to assess the variation in the likelihood of particular meteorological conditions with the time of day.

The standard stability analysis data provided by the meteorological office include tables which give the average probability of particular stability categories for each of the 24 hours. These data are generally given for each month and as an average over the year. Table 4.1.10 shows how the various stability categories only occur at particular times of the day.

Stability Category	Overall Frequency (%)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A	0.10									▨	▨	▨	▨	▨	▨	▨									
A/B	1.49							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
B	4.96					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨					
B/C	2.81							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
C	14.71					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨					
C/D	2.30							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
D	54.16	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
E	6.98	▨	▨	▨	▨	▨	▨	▨	▨								▨	▨	▨	▨	▨	▨	▨	▨	▨
F	11.84	▨	▨	▨	▨	▨	▨	▨	▨								▨	▨	▨	▨	▨	▨	▨	▨	▨
G	0.63	▨	▨	▨	▨	▨	▨	▨	▨								▨	▨	▨	▨	▨	▨	▨	▨	▨

Table 4.1.10
Hours During Which Particular Stability Categories May Occur
(Based on Ringway 1981-1990)

The standard data give no direct indication of how the probability of low wind speeds varies during the day, but Table 4.1.10 clearly shows that any low wind speeds in stable conditions can only occur between 4 pm and 8 am the following morning. Conversely, low wind speeds in neutral or unstable conditions could occur at any time during the working day, although the most unstable conditions (when wind speeds are low by definition) are most common around midday.

It is noted that there is also a seasonal variation in the time period and frequency of particular stability categories and wind speeds. However, as most QRAs relate to hazards which are present throughout the year, it is generally not necessary to consider the month to month variation in meteorological statistics, and average figures over the year can be used satisfactorily.

Implications for QRA

The majority of standard risk assessments currently conducted by the HSE use representative weather categories where the wind speeds are, in general, greater than most of the actual conditions they are supposed to represent. For categories D2.4 and D4.3, the wind speed is actually the upper bound of all the conditions it is supposed to represent. However, F2.4 does include some higher wind speeds from category F, and D6.7 does include the complete range of high wind speeds in unstable and neutral conditions, but these exceptions only represent a small frequency contribution, and the general conclusion that the representative weather categories use wind speeds which are higher than the conditions they are supposed to represent remains valid. The effects that this might have on the results of a QRA are discussed in Section 6.4.

It may be possible to make some correction for the above problem by simply reallocating the frequency of various weather conditions within the same representative categories. This would tend to increase the frequency of the D2.4 weather conditions, which may not have a significant effect on the overall results.

Alternatively (or in addition), it may be more appropriate to specify additional representative weather categories, which would provide a better description of the frequency of low wind speeds. The use of lower wind speed categories in risk assessment is also discussed, with reference to specific examples, in Section 6.4.

4.2 Use of more sensitive anemometry

4.2.1 Availability of data from the meteorological office

Over recent years, a number of different types of anemometer have become available which are capable of recording wind speeds down to much less than 1 knot. However, because of the proven ruggedness of the standard Munro MkIV anemometers, these improved instruments are not currently in routine use at any of the standard Meteorological Office weather stations. Consequently there is a paucity of good quality anemometer data for wind speeds below 5 knots, as has already been demonstrated by some of the analysis reported in Section 4.1.

There are several hundred of these more sensitive anemometers around the UK, owned by various companies, institutions or individuals, but the data from these instruments are not readily available and are generally not subject to the same quality standards as that available from the Meteorological Office. For example, the anemometers may not be regularly checked and calibrated, they may not be situated in appropriate locations or the data may not be recorded in a suitable format for sufficient periods of time to obtain useful information.

The Meteorological Office has, however, conducted some studies which have included the use of anemometers capable of recording low wind speeds. Two studies are of particular interest, namely:

Camborne	A detailed comparison of the output from a number of anemometers located on a tower at Camborne, near the Cornish coast.
Cardington	Data collected from a sonic anemometer and a cup anemometer on separate masts over a three year period at the Meteorological Office Research Unit field site at Cardington, Bedfordshire.

The detailed descriptions of the sensors and their locations for the Camborne and Cardington studies are given in Appendices 2 and 3 respectively. A sample of this data was obtained from the Meteorological Office for the following months:

Camborne	June, July 1994
Cardington	February, July, November; 1988, 1989, 1990

These data have been analysed in this section in order to ascertain the performance of the various types of anemometer, and hence to consider the reliability of the low wind speed data. Section 4.4 provides a more detailed assessment of the most sensitive data (from sonic anemometers), where such data are considered particularly in relation to the frequency of low wind speeds.

Some standard meteorological data from the Meteorological Office station at Bedford Royal Aircraft Establishment (RAE) were also provided, and are included in Table 4.2.2, for comparison.

4.2.2 Comparison of different anemometers

The data from Camborne and Cardington enable some direct comparisons to be made of the results from different types of anemometer, namely:

At Camborne -	Gill	(Solent 3-axis standard ultrasonic anemometer)
	Munro	(Met. Office Mk IVb)
	Vaisala	(WAA15 rotating cup)
	Vector	(A100 Porton rotating cup anemometer)
	Youngs	(05103 propeller)
At Cardington -	Sonic	(Kaijo-Denki DAT-300 model)
	Vector	(A100 Porton rotating cup anemometer)

The instruments at Camborne were all located on the same tower along a boom at a height of 10 m, but at Cardington the sonic anemometer was located on a 20 m mast and the Vector instrument was located at 16 m on a separate mast.

The data from the various instruments have been compared by plotting the results of an anemometer directly against those of another on a simple scatter graph. Examples of these graphs are shown as Figures 4.2.1 to 4.2.5. In each of these, it has been assumed that the sonic instruments are the most accurate, and these have therefore been used as the baseline. The graphs also show the 'y=x' lines, onto which the data would fall if the instruments were all equally accurate.

It is hard to draw definitive conclusions from these figures about the absolute accuracy of any one particular anemometer, as it is impossible to say which, if any, give an accurate measurement of the actual wind speed. Furthermore, each anemometer has its own characteristics, and therefore different anemometers may perform better for different purposes. However, comparison of the results from a number of anemometers, such as is available with the Camborne data, does clearly show the low wind speed problems associated with the Munro anemometer, which has been widely used by the Meteorological Office for the majority of routine observations. In particular, the data show that the Munro over-estimates the frequency of zero wind speeds. This is clearly seen in the frequency plot presented in Figure 4.2.6, and can be

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interpreted as being due to the Munro anemometer having a start-up speed of 4 to 5 knots.

In general, the comparisons of the various types of anemometer indicate that there is broad agreement in the higher wind speed ranges for the various instruments, although there can be significant discrepancies in individual observations. The 10 minute mean wind speeds recorded over the observation periods provides a simple comparison between instruments; these parameters are tabulated in Table 4.2.1.

For the Camborne results, there were some problems with the Youngs instrument. If these measurements are neglected, it can be seen that the means observed from all the other instruments, with the exception of Munro, are consistent within about 2%. Those observed from the Munro instrumentation are rather lower, by about 5-10%. It is clear, from Figure 4.2.1, that this arises from the under recording of the Munro instrument at low wind speeds.

Instrument	**Mean wind speeds (m/s)**			
	Site	**Cambourne**		**Cardington**
	Date	**Jun 94**	**July 94**	**Feb 88**
Gill/sonic		5.10	4.30	4.55
Munro		4.82	3.90	-
Vaisala		5.05	4.23	-
Vector		5.20	4.27	4.18
Youngs		4.75	3.88	-

Table 4.2.1
Comparison of Mean Wind Speeds for Various Data Sets

This feature of the measurements can be seen more clearly by plotting the ratio of the measured wind speeds for two anemometers against the reference measured wind speed. For both the sites, the sonic anemometer measurements were taken as reference. Figure 4.2.7 shows the ratio, (M/G), of Munro to Gill (sonic) readings for 10 minute averages at Camborne, plotted against the Gill measurements. This shows a clear under-prediction by the Munro instrument for G < 10 knots, with significant effects below 5 knots, as expected. Figure 4.2.8 shows a similar plot, but for hourly rather than 10 minute averages. The reduction of scatter in this plot enables the trend to be seen more clearly.

Similar plots are shown in Figures 4.2.9 and 4.2.10 respectively for comparisons of Vector and Gill measurements at Camborne, and Vector (Porton) and Sonic measurements at Cardington. It should be noted that, for the comparison in Figure 4.2.10, the Vector instrument was located at a height of 16 m, compared with the 20 m height of the sonic anemometer. Assuming an airfield roughness length of about 1 mm, the ratio between these two sets of measurements would be expected to be around 0.98, as indicated on the graph. Although there is some scatter, which increases towards the low wind speed end, there is no clearly discernable trend, as there evidently is for the Munro vs sonic comparison.

In terms of providing good quality data on the frequency of low wind speeds, it is considered that the sonic anemometers at Camborne and Cardington are producing the best data. Therefore, the remainder of the analyses described in this report will concentrate on the results from these sonic anemometers.

4.2.3 Comparison of Cardington and Bedford data

It is interesting to compare the data collected from a standard Meteorological Office weather station with those obtained using a more sensitive anemometer located at a nearby site. This situation is of relevance to QRAs and safety reports for major hazard sites in that many such studies use information from a nearby weather station and assume that it is representative of the conditions at the site. Some further comparisons of wind data from a different pair of sites in close proximity have been presented in Section 4.3.2.

For the purposes of this project, some routine meteorological data from the Royal Aircraft Establishment at Bedford were obtained to provide a comparison with the data obtained using more sensitive sonic anemometry at nearby Cardington. The wind speed distributions from the Bedford and Cardington data for two sets of monthly records are summarised in Table 4.2.2. The July data from Cardington was unfortunately tainted by a large number of spurious zeros, rendering comparison with the Bedford data difficult.

The table shows that there are discrepancies between the results from Bedford and Cardington. This is clearly due to differences in the conditions relating to the measurements, as well as real differences in the weather conditions at the two sites. In particular, the following differences are noted:

a)	instrument	- sonic (Cardington) - cup (Bedford)
b)	location	- both are airfield sites, although separated by about 10 km. Cardington is slightly more exposed, and would have a lower roughness
c)	height	- 20 m (Cardington) - 10 m (Bedford)

It is difficult to draw many more conclusions from such a limited data set, except that there is clearly a significant seasonal variation in the wind speed distribution, with high winds being most common in the winter. The frequency of calm conditions (< 1 knot) appears to be very low for each month, but it is not possible, on the basis of a few months data, to say whether an average over a longer period (e.g. 10 years) would yield similar results.

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Hourly Mean Wind Speed U (knots)	February 1988-1990		November 1988-1990	
	Bedford	Cardington	Bedford	Cardington
0	0.0	0.0	0.1	0.0
$0 < U \leq 1$	0.0	0.1	0.1	1.3
$1 < U \leq 2$	0.9	0.8	6.3	5.9
$2 < U \leq 3$	1.3	1.8	7.9	7.7
$3 < U \leq 4$	2.7	2.7	8.2	9.3
$4 < U \leq 5$	5.1	4.1	12.0	10.8
$5 < U \leq 6$	4.1	3.8	11.8	10.5
7 to 10	22.6	19.2	32.0	31.9
11 to 16	31.0	33.7	16.5	16.8
17 to 21	18.4	15.2	4.1	4.1
22 to 27	10.5	13.0	0.9	1.2
28 to 33	3.0	3.8	0.0	0.0
34 to 40	0.4	1.7	0.0	0.1
Total	100.0	99.9	99.9	99.9

Table 4.2.2
Comparison of Data from Bedford RAE with that from Cardington Sonic Anemometer

4.3 Other sources of information

4.3.1 Data availability

The Meteorological Office has an extensive network of recording stations which have been collecting wind measurements for a number of years. Whilst there are problems with the relatively high start-up speed of the standard cup anemometers, and occasional problems relating to exposure, the data are of sufficient quality that there is generally little need for taking further wind measurements. Some specialist requirements dictate the need for specific local data, and the following types of organisations have been identified for which this would be the case:

- Major hazard chemical sites
- Nuclear sites
- Potential wind farm sites
- Wind-sensitive transport systems operators

A number of operators within each of these areas has been approached, and the results of discussions, and, in some cases, site visits, are presented below.

Major Hazard Chemical Sites

Information was obtained from Shell (Stanlow Refinery), BP (Grangemouth Refinery) and Associated Octel (Ellesmere Port and Amlwch). Because of the numbers of buildings and other obstructions on this type of site, anemometers are frequently mounted on the top of buildings, with non-ideal exposure. Data are normally logged on a regular basis either electronically or manually, and the records kept. Such records are often not used, but may need to be referred to in the event of fugitive emissions (e.g. odours) or releases from the site, so that the conditions at the time of the release could be determined.

In the case of Grangemouth, the exposure is deemed sufficiently good that the data are passed to the Meteorological Office for incorporation into their records. The data from Associated Octel's site at Ellesmere Port are fed into Major Incident Analysis software which can be used in an exercise or emergency to define the sectors at risk. The location of this site, on an estuary, renders this data more useful than that which is available from nearby Meteorological Office recording stations. At Associated Octel's Amlwch site, data are not collected, but instead data from a nearby nuclear installation (see below), for which the anemometer exposure is much better, are used.

At each of these sites, there are wind socks strategically positioned so that at least one can be seen from most locations on the site. These are generally located in accordance with Health & Safety at Work guidance, such as HSG28, (**HSE**(1986)). Clearly, in an emergency, the wind direction will be of much more consequence than the wind speed to on-site personnel seeking refuge, and such a system allows the chances of escape to be maximised.

Nuclear Sites

These sites are required to install anemometry to enable wind speed and direction at the instant of any release to be identified, for emergency response purposes. The Meteorological Office undertook a survey of all the nuclear sites in the UK during 1993, from which the following key points emerged:

a) Whilst frequently not fully meeting the ideal criteria for separation of anemometers from buildings or other obstructions, the locations of the anemometers are (with one or two exceptions) considered to be representative of the nuclear site or the best that can be achieved considering the size and physical limitations of the site.

b) A wide variety of wind recording systems can be found throughout the industry, often on sites owned by the same operating authority. Some systems are not able to report gusts and/or the variation in wind direction with time.

c) Servicing arrangements vary throughout the industry and, again, within a single organisation. At some establishments, instruments are only serviced when faults are noticed, although the usual arrangement is for regular servicing or maintenance to be carried out by on-site maintenance departments or by the Meteorological Office Maintenance Organisation.

d) There is no standard across the industry, or even within a single organisation, on reporting wind and weather for the PACRAM Forecast Information Form. The reported wind ranges from an instantaneous reading to the average speed and direction over an hour. Gusts are unlikely to be taken into account.

Note. PACRAM is the name given to the scheme under which the Meteorological Office can provide information in the event of a nuclear emergency. It is similar to the CHEMET scheme for chemical emergencies, which is described further in Section 6.5.

As a result of the review, the Meteorological Office made a number of recommendations on improving the current position. These related primarily to bringing the instrumentation at Nuclear Sites into line with their current standards, but also included the offer of Meteorological Office expertise in relation to the calibration and maintenance of instruments.

Detailed information was obtained for one nuclear site - Wylfa, on the Anglesey coast. The main reason for choosing this site was its proximity to Amlwch, and the fact that Octel used data from Wylfa to support their Safety Case. This coastal site has a 50 m mast, with anemometers at heights of 10 m and 50 m, set around 1km from the cliff edge, and hence at least 500 m from any building. The instrumentation is not regularly serviced or calibrated, as observed by the Meteorological Office in point c) above. Site personnel are, however, aware of the limitations of the output at low wind speeds, but consider the direction information to be sufficiently reliable for their purposes.

Signals from this instrumentation are fed to a chart recorder in the control room, and recorded in case of future need. They are also recorded electronically, but not processed at the site, although some of this data has been passed to Octel at Amlwch for analysis and subsequent use; an example from this analysis is presented in Figure 4.3.1. The direction signal is also passed to Wylfa's emergency response software, where the instantaneous direction vector is displayed on an on-screen site map.

Potential Wind Farm Sites

In view of the generally windy nature of much of the UK, particularly the coastal and upland regions, it is becoming economic to consider the siting of wind farms in suitable areas. The economics of such an operation are generally determined by the local wind climate, which in turn is affected by small scale topographic features. Thus, it is common for interested parties to set up anemometry which records wind speed and direction at suitable sites over a period of 1-2 years.

National Wind Power has obtained data from a number of sites over the last few years. One such site was identified as Anglesey, about 4 km inland (S) from Amlwch and 10 km ESE from Wylfa. Although it would have been possible to purchase such data, it was felt that it would add little to the study reported in Section 4.3.2. There is also a wind farm about 5 km E of Wylfa, managed by Windfarm Management Services, although it was not possible to purchase the data for this site.

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Much of the data from such sites has been collected and analysed by ETSU (Energy Technology Support Unit). The sites tend to be located on hill tops, where topographic effects are important. However, data are correlated with Meteorological Office data from nearby sites, and, in order to obtain a reasonable correlation in the moderate to high wind speed range, some of the low wind speed data is discarded. This source of data has therefore not been considered further in this study.

Wind-sensitive transport system operators

Certain parts of transport systems may be susceptible to strong winds. This evidently applies to airports, which routinely measure wind speeds to ensure that their operations can be carried out successfully; measurements from many of these sites are currently fed into the Meteorological Office data base. Road and rail transport may also be susceptible to strong winds, where exposed sections of road or track, or particularly high sided vehicles, may be vulnerable to high gusts. Many exposed road bridges operate speed limits based upon wind speeds recorded by anemometers mounted on the bridge itself. Since such systems are implemented in real time, there is generally no incentive to record data. For this reason, and because of their abnormal exposure, such sources of data were not pursued further.

The Eurotunnel shuttle system operates in relatively exposed locations (at each terminal) and also consists of very high sided wagons. Significant analysis of nearby Meteorological Office data has been undertaken by **Deaves and Bradbury**(1995) in order to understand the risks of overturning in high gusts. This preliminary analysis is being periodically updated by the use of locally recorded data from lightweight cup anemometers (Vaisala WAA15). These have been recorded at 1 Hz, but analysed as hourly means. Some of this data has been made available by Eurotunnel, and is included within the analysis presented in Section 4.4.4.

4.3.2 Comparison of meteorological data from nearby sites

It has already been noted in Section 4.1 that there may be significant differences in the meteorological data for a particular location due to inter-annual (and inter-decade) variability. This may be partially due to climatic changes and may also be influenced by instrumentation changes over the years. However, it is worth noting that there may also be a significant variation in meteorological data between a site of interest, and the nearest weather station. In order to investigate the validity of using non-local meteorological data for risk analysis, **Brown**(1995) made a comparison of one year's data from two sites in Anglesey. The sites chosen were RAF Valley, situated near the west coast of the island, and the nuclear power station at Wylfa, which is approximately 10 miles away on the north coast.

Figures 4.3.2 to 4.3.4 show a comparison of the wind direction at the two sites, each graph corresponding to a particular range of wind speed measurements at Valley, i.e.

Figure 4.3.2	< 2 m/s Low wind speed
Figure 4.3.3	2-5 m/s Medium wind speed
Figure 4.3.4	> 5 m/s High wind speed

These scatter graphs show that the correlation in the wind direction measured at the two sites is best in high wind speeds and worst at low wind speeds, where there is a considerable scatter.

Figure 4.3.5 shows how the wind direction frequencies are discretised into the 12 sectors appropriate for use in RISKAT. At high wind speeds, both sites clearly show a prevailing wind from the south-west (Sectors 1 and 2). At low wind speeds, the Valley station shows a peak frequency in Sector 9, with the wind from the east. However, at Wylfa, the most common winds are from the south. In both cases, this indicates that the low wind speeds are dominated by off-coast winds.

Implications for QRA

Risk assessments very rarely use meteorological data collected at the site being considered. Therefore, it is important that an assessment is made of whether the data used are likely to be representative of the site. It has been shown here that the wind direction distribution at low wind speeds can be influenced significantly by factors such as local topography and sea breezes. If it is considered that such factors might be important, then care should be taken in interpreting the results of the QRA, and it may be necessary to conduct sensitivity studies or obtain more site-specific data. In some cases where topography or other local features are important, it may be appropriate to use data from a site which is not the nearest to the hazardous installation, but the reasons for any such choice should be clearly explained.

4.4 Assessment of low wind speed conditions using more sensitive anemometry

One of the major objectives of the first phase of this project was to determine, if possible, the typical distribution of wind speeds, particularly at low wind speeds. Although this seems a relatively straightforward task, almost all of the routine meteorological data available for the UK is not capable of yielding this information, largely due to the starting speed of the standard Munro Mk IV cup anemometers being about 5 knots, and the systematic under-reading of these instruments for wind speeds up to around 10 knots, as shown in Section 4.2, in particular in Figure 4.2.8.

However, newer designs of anemometer are capable of recording much lower wind speeds. Propeller anemometers can now record as low as 0.1 m/s, with an accuracy of about ± 0.3 m/s or better, whilst sonic anemometers are typically used down to 0.01 m/s. There is, unfortunately, very little data available from such sensitive instruments for significant time periods (i.e. a month or more). Several data sets have recently been collected by the Meteorological Office as part of a project to compare various types of anemometer, and a few of these data sets have been analysed as part of this study (see Section 4.2). It is emphasised that these data are only available for relatively limited time periods (e.g. 1 month) and are specific to certain sites, and so care should be taken in applying any of the results generally. Some data from Eurotunnel, as described above, have also been included for comparison.

The meteorological data that have been obtained for this project can be analysed in a number of ways. These are described in the following sections. The principal types of analysis that have been undertaken are:

- Variation of wind speed with time of day
- Dependence of wind speed on stability
- Dependence of wind speed on averaging time
- Frequency distribution of wind speeds
- Persistence of low wind speed conditions
- Persistence of wind direction

These analyses are described in the following sections. Following each analysis, a brief summary is given of the implications that the results might have on the results of a QRA, although it should be remembered that these conclusions are based on limited data and that more detailed analysis of more extensive data might lead to slightly different results.

4.4.1 Variation of wind speed with time of day

The importance of the variation in the probability of different weather conditions with different times of day has already been discussed in Section 4.1.2. The sonic anemometers from Camborne and Cardington provide more accurate data on the variation of the likelihood of low wind speeds during the day. Table 4.4.1 summarises how the frequency of wind speeds below various thresholds varies during the day, based on 10 minute average data from Cardington for the month of February (1988-1990). The same information is also presented in diagrammatic form in Figure 4.4.1.

It is clear, from the data presented in Figure 4.4.1 and Table 4.4.1, that light winds are more likely during certain hours than during others. If the probability for each wind speed range for each hour is compared with the average over the whole day for that wind speed range, it can be seen that, for $u < 4$, 5 or 6, there is a higher probability of low wind speeds approximately during the hours 1700-0900, with a corresponding lower probability during 0900-1700. This is almost certainly due to the prevalence of stable conditions during the night time, when the absence of surface heating tends to reduce near surface wind speeds.

Examination of similar data for the months of July and November (1988-1990) gives similar general results. Although it is noted that low wind speeds are more common in summer than in winter, November shows a greater probability of low wind speeds than either of the other months considered, which is consistent with the observations of **Smith**(1992). This seasonal variation from month to month is probably less important for QRA purposes than the diurnal variations, as the majority of hazardous activities (such as road tanker off-loading) continue throughout the year. The exception may be when the consequences of accidents are very dependent on temperature as well as wind speed, in which case the correlation between these parameters may become significant. However, it should be noted that temperature will generally have a rather greater effect on the source term calculation than it will on the dispersion phase of the consequence analysis.

Time (24 hour)	Probability of Wind Speed Being in Range (Knots)					
	< 1	< 2	< 3	< 4	< 5	< 6
00-01	0.004	0.021	0.056	0.094	0.142	0.192
01-02	0.010	0.021	0.042	0.082	0.134	0.169
02-03	0.000	0.000	0.019	0.065	0.113	0.163
03-04	0.000	0.017	0.061	0.091	0.133	0.175
04-05	0.000	0.015	0.059	0.113	0.176	0.216
05-06	0.002	0.008	0.023	0.073	0.134	0.180
06-07	0.000	0.002	0.025	0.075	0.113	0.159
07-08	0.000	0.004	0.042	0.078	0.109	0.145
08-09	0.006	0.034	0.066	0.086	0.124	0.176
09-10	0.017	0.048	0.076	0.091	0.117	0.143
10-11	0.008	0.023	0.040	0.071	0.112	0.131
11-12	0.013	0.015	0.015	0.031	0.071	0.105
12-13	0.002	0.004	0.015	0.029	0.067	0.090
13-14	0.000	0.000	0.002	0.013	0.036	0.061
14-15	0.000	0.002	0.004	0.006	0.025	0.067
15-16	0.000	0.000	0.002	0.018	0.045	0.084
16-17	0.000	0.002	0.010	0.037	0.075	0.114
17-18	0.000	0.000	0.017	0.065	0.123	0.171
18-19	0.002	0.012	0.035	0.072	0.142	0.212
19-20	0.000	0.006	0.033	0.064	0.120	0.193
20-21	0.002	0.027	0.060	0.098	0.127	0.180
21-22	0.012	0.025	0.048	0.079	0.128	0.184
22-23	0.008	0.027	0.048	0.079	0.112	0.156
23-00	0.000	0.014	0.035	0.089	0.130	0.167
Average	0.004	0.014	0.035	0.067	0.109	0.151

Table 4.4.1
Variation in Frequency of Low Wind Speeds during the Day, based on 10 Minute Average Data from Cardington for the Month of February (1988-1990)

<u>Implications for QRA</u>

There appears to be a significant diurnal variation in the probability of low wind speeds. Therefore, when undertaking a QRA where the likelihood of hazardous events is not the same for each hour of the day, it may be necessary to take these variations into account, or at least to assess their potential significance.

4.4.2 Dependence of wind speed on stability

For the purposes of carrying out any dispersion analyses, it is generally necessary to specify the stability of the atmosphere, as well as the wind speed. The relationship between wind speed and stability is therefore required. For example, it might turn out that low wind speed conditions occur predominantly in stable conditions, and it would be important to reflect this fact in any practical assessment.

The meteorological data obtained from Cardington includes data on the atmospheric stability in terms of a non-dimensional stability parameter M which is defined as:

$$M = \frac{z}{L} = -kz\frac{g}{T}\frac{\overline{w\theta}}{u_*^3} \qquad (4.1)$$

It should be remembered that:

$$L = -\frac{\rho c_p T u_*^3}{kgH} \qquad H = \rho\, c_p \overline{w\theta} \qquad (4.2)$$

where:

L is the Monin-Obukhov length
z_o is the surface roughness length (~ 0.01 m for Cardington)
k is the von Karman constant (~ 0.4)
g is the acceleration due to gravity (~ 9.81 m/s^2)
H is vertical heat flux due to turbulence (W/m^2)
ρ is the air density (~ 1.2 kg/m^3)
c_p is the heat capacity of air (~ 1004 J/kg/K)
T is the air temperature (K)
u_* is the friction velocity (m/s)

Figures 4.4.2 - 4.4.4 show scatter graphs of wind speed against stability parameter M for all the data collected at Cardington, plotted by month. These show, as expected, that the data are grouped around M=0 ($L= \infty$), with all the high wind speed data appearing close to the M=0 axis. It can also be seen that wind speeds in excess of around 12kt are extremely unlikely outside the near neutral stability range ($-0.1<M<0.01$).

The conditional probability of various stabilities within each wind speed range, for all the months considered, is shown in Table 4.4.2.

These data show that there is at least an 80% probability that the stability class is close to neutral for all wind speeds of 7kt and above, and that, even at the 2kt level, 37% of the occurences are neutral. It is also clear that stable conditions ($M > 0.01$) are more common for very low wind speeds than are the unstable conditions ($M < -0.1$).

Implications for QRA

Non-neutral atmospheric stability conditions are clearly associated with low wind speeds. The effects of stability on the turbulence will therefore need to be considered very carefully when assessing dispersion in low wind speed conditions. Some tentative conclusions regarding the frequency distribution for stable conditions have been given in Section 4.4.4.

Wind Speed (Knots)	Probability of Various Stability Ranges in Terms of M			
	M	-1 to -0.1	-0.1 to 0.01	> .01
	Pasquill	A/B	C/D	E/F
0 - 0.99		0.2219	0.3205	0.4576
1.00 - 1.99		0.1705	0.3699	0.4596
2.00 - 2.99		0.1319	0.4251	0.4430
3.00 - 3.99		0.0745	0.5515	0.3740
4.00 - 4.99		0.0551	0.6341	0.3108
5.00 - 5.99		0.0383	0.6929	0.2688
6.00 - 6.99		0.0370	0.7415	0.2215
≥ 7.00		0.0191	0.8920	0.0889

Table 4.4.2
Probability of Stability Ranges for Increasing Wind Speed Bands

4.4.3 Dependence of wind speed on averaging time

Meteorological data are often reported as hourly means. This may not provide an adequate description of the probability of various wind speeds for purposes such as safety cases, risk assessments or emergency planning, where the release being considered may take place over a matter of minutes. For example, it is conceivable that the hourly mean data might suggest that very low wind speed conditions are very rare, whereas in fact they might occur quite regularly but only last for a fraction of an hour.

In order to investigate the variation of the wind speed frequency distribution with various averaging times, the 10 minute data obtained for Camborne and Cardington were also averaged over 20, 30, 40, 50, 60, 120 and 180 minute periods. The frequency distributions for specific wind speed ranges are summarised in Tables 4.4.3 and 4.4.4 for the Camborne and Cardington sonic data. It is noted that the longest duration considered in safety cases and QRAs for toxic or flammable releases is generally about 30 minutes, although in the nuclear industry it is not uncommon to consider releases continuing for several days.

Examination of the limited data presented in Tables 4.4.3 and 4.4.4 reveals that the wind speed distribution is, as expected, dependent on the averaging time used. In general, lower averaging times lead to higher frequencies in the very low wind speed ranges (up to 3 knots). A similar effect is observed at high wind speeds, where longer averaging times smear out the extremes, and thus tend to reduce the frequency of very high winds.

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Wind Speed Range (knots)	Probability for Various Averaging Time Periods (Minutes)							
	10	20	30	40	50	60	120	180
0 - 0.99	0.0066	0.0047	0.0026	0.0023	0.0029	0.0000	0.0000	0.0000
1.00 - 1.99	0.0173	0.0177	0.0193	0.0208	0.0229	0.0240	0.0213	0.0136
2.00 - 2.99	0.0188	0.0177	0.0201	0.0196	0.0157	0.0189	0.0182	0.0317
3.00 - 3.99	0.0348	0.0348	0.0333	0.0323	0.0314	0.0343	0.0395	0.0362
4.00 - 4.99	0.0599	0.0560	0.0665	0.0647	0.0743	0.0669	0.0638	0.0452
5.00 - 5.99	0.0664	0.0726	0.0648	0.0681	0.0586	0.0635	0.0669	0.0860
6.00 - 6.99	0.0920	0.1044	0.1033	0.1016	0.1057	0.1149	0.1125	0.1222
≥ 7.00	0.7043	0.6920	0.6900	0.6905	0.6886	0.6775	0.6778	0.6652

Table 4.4.3
Variation in Wind Speed Frequency Distribution for Different Averaging Times (Camborne, Gill Anemometer, June 1994)

Wind Speed Range (knots)	Probability for Various Averaging Time Periods (Minutes)							
	10	20	30	40	50	60	120	180
0 - 0.99	0.0046	0.0018	0.0023	0.0000	0.0000	0.0009	0.0000	0.0000
1.00 - 1.99	0.0132	0.0107	0.0087	0.0093	0.0077	0.0083	0.0056	0.0057
2.00 - 2.99	0.0337	0.0253	0.0258	0.0242	0.0231	0.0250	0.0207	0.0199
3.00 - 3.99	0.0546	0.0557	0.0525	0.0497	0.0523	0.0529	0.0490	0.0484
4.00 - 4.99	0.0635	0.0874	0.0893	0.0857	0.0846	0.0835	0.0734	0.0826
5.00 - 5.99	0.0603	0.1239	0.1201	0.1217	0.1230	0.1206	0.1318	0.1225
6.00 - 6.99	0.0621	0.1580	0.1574	0.1577	0.1583	0.1568	0.1525	0.1481
≥ 7.00	0.7080	0.5373	0.5439	0.5518	0.5511	0.5519	0.5669	0.5726

Table 4.4.4
Variation in Wind Speed Frequency Distribution for Different Averaging Times (Cardington, Sonic Anemometer, February 1988)

From the data in the lowest wind speed ranges in Table 4.4.4, it can be seen that the frequency of winds in the 0 to 1 knot range using 10 minute averaging is 5.1 times greater than that suggested by the hourly data, while taking the 0-2 knot range, this factor is reduced to 1.6. It is emphasised that these results can only be regarded as indicative, and more data would be required in order to draw more general conclusions. However, consideration of frequency distributions, as discussed in Section 4.4.4, does suggest that 10 minute means can be more readily and more accurately extrapolated to low wind speeds than can hourly means.

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Implications for QRA

These results suggest that, if standard hourly data are to be used as the basis for a QRA, then the frequency of low wind speed weather conditions should be increased by a factor depending on the release duration and the precise choice of weather categories being used for the QRA. The preferred method is to use 10 minute means, as discussed in Section 4.4.4.

4.4.4 Frequency distribution of wind speeds

For the purposes of risk assessments, safety cases and emergency planning, it is useful to know how often low wind speed conditions are likely to occur, and it is somewhat surprising that the literature gives very little guidance on the typical frequency distribution of low wind speeds. Figure 10 from **Smith**(1992) appears to indicate that the cumulative frequency increases approximately linearly with increasing wind speed u (for $0 < u < 4$ knots), and Smith states that this implies an 'almost constant probability of the speed lying in any fixed speed band out to about 4 knots'. However, his graph only has three data points and the instrumentation used to obtain this data was almost certainly not particularly accurate in this low wind speed region. Clearly, more accurate data is necessary to make progress in this area.

A substantial amount of standard Meteorological Office wind data has been presented in Section 4.1 in the form of tabulated wind frequencies for standard wind speed ranges, generally based upon the Beaufort scale. Although this clearly lacks resolution at low wind speed, the poor quality of the data at such speeds means that it is not worthwhile applying any more formal fitting techniques. However, the data which have been obtained from sonic anemometers, and from some of the lightweight cup anemometers, give more detail at low wind speed.

For the remainder of this section, most of the analysis is based upon the sonic anemometer data from Cardington. These cover 9 (non-consecutive) months over the three year period 1988-1990 and are expected to provide accurate data down to very low wind speeds. The data for all 9 months have been combined to provide the greatest possible range for data fitting, although the results will not necessarily be representative of annual average data. In addition to the Cardington data, wind speed data at Folkestone and Calais, as collected by Eurotunnel, have also been used. Although these data were not obtained using sonic instrumentation, the lightweight cup anemometers (Vaisala) are expected to provide reasonable accuracy down to low wind speeds. For each of these sites, analysed data for a complete year were made available.

A good visual impression of the relative frequency of the wind speed in various bands can be obtained using a histogram plot, as shown in Figure 4.4.5. The lack of smoothness seen in such a plot is, at least to some extent, dependent upon the grouping of data into classes. These effects can be smoothed by plotting the cumulative frequency, as shown in Figure 4.4.6. This figure includes the same data as in Figure 4.4.5; the low wind speed part of the distribution has been enlarged and presented in Figure 4.4.7, which includes hourly mean data. As expected, the 10 minute and hourly data agree at the higher wind speeds, although any differences at low wind speed are difficult to detect with this form of presentation.

Further progress in understanding wind data can be made by fitting the data to an analytical expression. Various functions can be fitted to the cumulative distribution frequency, but the simplest function that fits over a wide range of wind speeds is the Weibull distribution:

$$\text{Cumulative Frequency } (P) = 1 - e^{-\left(\frac{V}{V_0}\right)^k} \qquad (4.3)$$

where:

V is the wind speed threshold (knots)
V_0 is a reference wind speed ($1.12\ V_{mean}$)
k is a shape factor

As shown in Appendix 4, the values of V_o and k for any particular data set can be found by determining the best straight line fit of ln(-ln(1 - P)) against ln V over a range of moderate - high wind speeds. When the data are grouped in the standard way, it is not usually possible to ascertain whether a good fit at moderate wind speeds can be extended down to low wind speeds. However, with access to the complete record of a data set which has reasonable accuracy at low wind speed, it has been shown, in Appendix 4, that the Weibull distribution parameters can be estimated by plotting <u>all</u> the data ranked in order of wind speed magnitude. The only constraint on the effectiveness of such fitting is then the accuracy of the measurements at low wind speed.

It should be noted that divergence of the data from the Weibull fit implied by Equation A4.2 may be due to a variety of factors. The main cause is generally the paucity of data at the extremes, such that the highest (or lowest) few points represent values which only occur once or twice in the period of the record. Such a feature will always be evident when plotting all the data in this way; grouping the data will reduce this problem, but will also substantially reduce the extent of the plot. A further cause of divergence is the accuracy of the instrumentation. This is particularly relevant at the low wind speed end, as is evident in the data presented below.

Initially, fits to Weibull distributions were determined month-by-month by plotting the cumulative grouped data in the manner indicated in Appendix 4. Results are shown in Figure 4.4.8 for February 1988 at Cardington, and similar plots were obtained for Camborne. Because of the grouping of the data, the lowest wind speed plotted was around 1kt (ie lnV = 0), and it appears that the data diverge from a straight line at around 2 kt. The Camborne data show similar characteristics, although the divergence in that case is below the straight line fit, rather than above as for Cardington.

In order to improve the resolution of the Weibull fit at the lowest wind speeds, the alternative fitting procedure, as described in Appendix 4, was used. This has the advantage that the low wind speed data are plotted at the appropriate frequency, rather than being grouped into a rather broad band (eg. up to 1kt or 1m/s). The results for hourly mean values at Cardington are shown in Figure 4.4.9, whilst those for the corresponding 10 minute means are shown in Figure 4.4.10. As expected, the plots are virtually coincident for wind speeds in excess of 1kt, but the divergence from a straight line which is evident for the hourly means has almost disappeared when the 10 min means are plotted.

Since stability data were also available for Cardington, it was possible to extend this analysis to consider stable conditions. As noted in Section 4.4.2, these have been defined as corresponding to those occasions when $M > 0.01$. Figure 4.4.11 shows the Weibull distribution down to very low wind speeds, with the same slope as for all the data combined. The difference lies in the reference wind speed parameter, V_o, which is 3.2 kt for stable conditions compared with 5.5 kt for all the data. In principle, it is possible to obtain separate data fits for each stability category, but this has not been pursued in this study.

The data which have been made available by Eurotunnel has also been plotted in the same way. Results are presented in Figures 4.4.12 for Folkestone and 4.4.13 for Calais. Both sets of data are for hourly means, and the divergence from the Weibull best fit line is due in part to the slightly poorer sensitivity of the instrumentation. For example, for a given ln(-ln Q), a lower value of u_{mean} was observed than would be expected from the Weibull straight line. This reflects the start-up characteristics of the cup anemometers which were used.

The Folkestone data were re-analysed using 10 min means, and the results are presented in Figure 4.4.14. This shows little difference compared with the hourly mean plot presented in Figure 4.4.12. It is suggested that this is due in part to the poorer instrumentation response, but may also be due to local coastal effects on the frequency of low wind speeds; this latter feature is consistent with the analysis of the data from Camborne, which also showed a divergence *below* the best fit straight line at very low wind speeds.

The results presented in this section have demonstrated the effectiveness of the improved plotting scheme, as presented in Appendix 4, for the estimation of Weibull distribution parameters. The divergence above the Weibull straight line at low wind speeds appears to be due to the averaging process, where, for example, hourly averaging will mask the presence of shorter periods of low wind speed. Divergence below the best fit line is probably due primarily to the poorer accuracy of cup anemometers at very low wind speeds. It therefore appears that 10 minute averages recorded using sonic anemometry produces the best quality data which fit a single, two parameter Weibull distribution over the whole of the wind speed range. The use of other distributions, such as log normal or 3 parameter Weibull, as discussed in Section 3.2.2, is therefore unnecessary.

Implications for QRA

10 minute mean wind speed values should be used wherever possible. Where only hourly data are available, there should only be used for wind speeds in excess of around 2m/s. Where data are available over the moderate to high wind speed range (e.g for standard Meteorological Office sites), the frequency of low wind speeds can

be estimated by extrapolating the Weibull two-parameter fit down to values of order 0.1-0.5 m/s.

4.4.5 Persistence of low wind speed conditions

It is not possible to determine the likelihood of extended periods of low wind speeds directly from an analysis of the wind speed frequency distribution. For example, the worst case weather conditions for a 2 hour duration accidental release might be low winds lasting for a period of two hours, and it is therefore of interest to know how often this occurs during the course of a year, or whether it could only occur at night etc. Similarly, in the event of an accident, it would be useful to have an idea of how long the meteorological conditions are likely to last. In order to address these topics, it is necessary to analyse the persistence of particular wind speeds.

The analysis is presented as graphs in Figures 4.4.15 and 4.4.16 for typical Camborne and Cardington data respectively. Each line on the graphs shows the variation in cumulative percentage frequency of the wind speed remaining below a particular threshold for increasing periods of time. For example, Figure 4.4.15 shows that for 10% of the time the 10 minute averaged wind speed is less than 6 knots for a period of 4 hours or more. These results also show that, although the overall probability of the 10 minute mean wind speed being less than 2 knots is 2%, the probability that an accidental release occurs during a period where the wind speed remains below 2 knots for 1 hour is only 1%.

It must be remembered that the results presented are for very limited data sets, and, although they illustrate that factors such as persistence may be important, the results should not be treated as being generally applicable.

Implications for QRA

The general implications from this analysis are broadly similar to those discussed in Section 4.4.3 relating to averaging time. Most QRAs do not consider the significance of the persistence of particular meteorological conditions, and in many cases it may not be an issue, since releases from major hazard sites are generally of fairly short duration. In fact, the only releases which are assumed to last for long periods are fires, for which the persistence of high wind conditions would be relevant. However, there may be situations in a QRA where it could be important to be able to demonstrate, for example, the remote probability of low wind speeds lasting for a significant period.

4.4.6 Persistence of wind direction

Some hazardous releases are of a very short duration, and can therefore be treated as effectively instantaneous. For such releases, the probability of the wind continuing to blow in a particular direction may have relatively little effect on the levels of risk around the site, provided that the concentration drops below dangerous levels in a relatively short time. However, for releases that continue for 20 minutes or more it is important to know whether the resulting plume is likely to continue to disperse in the same direction, or whether the plume is likely to swing into other sectors. Such wind swings would result in lower toxic loads in the original wind direction, but conversely,

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a greater area would be affected. Maximum hazard ranges would be reduced, but the effect on the level of individual risk near to the site is not immediately obvious and would have to be calculated for the particular circumstances.

In order to assess the importance of such effects, the probability that the wind continues to blow within ±30° for various time periods has been determined, and the variation of this probability with the wind speed at the start of the period has been investigated. The results are summarised in Table 4.4.5.

Wind Speed At Start of Period (knots)	**Overall Probability**	**Conditional probability that wind condintues to blow within ± 30° for various durations (minutes)**				
		20	**30**	**40**	**50**	**60**
0 - 0.99	0.0066	0.563	0.375	0.188	0.125	0.063
1.00 - 1.99	0.017	0.691	0.400	0.237	0.145	0.109
2.00 - 2.99	0.019	0.800	0.600	0.492	0.431	0.338
3.00 - 3.99	0.035	0.829	0.695	0.524	0.429	0.362
4.00 - 4.99	0.060	0.896	0.792	0.713	0.649	0.584
5.00 - 5.99	0.066	0.963	0.921	0.842	0.772	0.722
6.00 - 6.99	0.092	0.955	0.929	0.880	0.848	0.812
≥ 7.00	0.70	0.987	0.962	0.944	0.924	0.899

Table 4.4.5
Directional persistence for Camborne, June 1994

It is clear from this table that directional persistence is strongly correlated with wind speed, with very low wind speeds corresponding to the most rapid directional variability, but the higher wind speeds (6-7 knots in this context) being more likely to be associated with a steady direction. If the time beyond which the probability of maintaining the direction within ±30 drops below 60% is defined as T_{60}, Table 4.4.6 shows the variation of this parameter for 1 month at Camborne, within the accuracy of the data.

Wind Speed Range (knots)	**0 - 1**	**1 - 2**	**2 - 3**	**3 - 4**	**4 - 5**	**5 - 6**	**6 - 7**
T_{60} (min)	< 20	25	30	35	55	> 60	> 60

Table 4.4.6 Persistence timescales, T_{60} for Camborne, June 1994

Implications for QRA

These results show that the directions associated with very low wind speeds are unlikely to persist up to 1 hour. This implies that long duration releases will effectively be spread over a wider sector, but may, as a consequence, give shorter hazard ranges than if the direction remained fixed.

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5. REVIEW OF DISPERSION MODELLING

5.1 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.

5.1.1 Gaussian models

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**(1960,1961)). The cross wind 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**(1979)).

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 m/s, as noted in Section 3.3.1. The more sophisticated model used in UK-ADMS is restricted to the range $1 \leq u \leq 50$ m/s, 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 centre line concentration, C_o, and observing that this can never exceed unity:

$$C_o = \frac{Q}{\pi u \sigma_y \sigma_z} \tag{5.1}$$

where

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

Hence

$$u \geq \frac{Q}{\pi \sigma_y \sigma_z} \tag{5.2}$$

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. Equation (5.2) should therefore be treated with caution, since it is not clear that the same σ_y and σ_z functions will be appropriate to low wind speeds. However, it does indicate that the lower limit for u *increases* with release rate and *decreases* with distance from the source.

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Doury(1980) 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 m/s and it is therefore concluded that the results of plume models are less reliable for wind speeds of less than about 2 m/s, as longitudinal dispersion may become an important factor.

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**(1982) identify a number of such 'puff' models. The main advantage of puff 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 is available. Ideally, this would take the form of raw wind data at each time step considered, although it may be possible to make use of persistence data as discussed in Sections 4.4.5 and 4.4.6. 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 5.2.2.

5.1.2 Box models

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 cross flow. Differential equations for the conservation of momentum, energy, mass, etc. are 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 only be applied 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.

Heavy Gas Dispersion Models (Box Models)

Box models for heavy gas dispersion are similar to integral plume models, except that they generally apply to ground level releases and they 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 in Section 5.1.1. 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.

5.1.3 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 such modelling is such that the results would effectively be means over long periods, unless Large Eddy Simulations are undertaken. Also, 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, and so will not be considered further in this report. 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 HSE are presented by **Gilham et al**(1996), and **Havens**(1995a) has also presented preliminary results of CFD modelling of large scale dense gas releases in low wind speed conditions.

As noted in Section 3.3.4, **Havens et al**(1987) 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.

5.1.4 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 totally 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**(1989).

a) When the wall roughness Reynolds number ($Re_*=u_*z_0/\upsilon$) 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.

b) When the characteristic obstacle Reynolds number ($Re=UL_c/\upsilon$) 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**(1995b) (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(1990) and **Meroney et al**(1989) identify a number of the other operational limitations associated with wind tunnel experiments. These include:

a) Most large wind tunnels cannot operate satisfactorily at very low wind speeds (<0.1 m/s) as the flow becomes sensitive to small disturbances, both external and internal.

b) 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 compared to a shallow dense gas cloud.

c) 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 versus molecular diffusion.

d) 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.

e) 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 to 3 m, but atmospheric turbulence which dominates mixing in the far field region supports ground level integral scales

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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**(1994a) presented results of the modelling of dispersion affected by groups of buildings. **Meroney**(1993) gave a review of bluff body effects on dispersion, which is substantially based on previous wind tunnel studies. Recently, **Havens et al**(1995a,b) 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.

5.2 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.

5.2.1 Simple modifications to Gaussian Plume Models

Hanna(1983) and **Van der Hoven**(1976) 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 using 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 (u) of less than 2 m/s, M takes values of 2, 3, and 6 for stabilities D, E, and F/G respectively. For wind speeds of between 2 and 6 m/s, the value of M is given by assuming that M falls to 1 at 6 m/s, and using log-log interpolation for intermediate wind speeds. For example,

$$\ln M = a - b \ln U \qquad (5.3)$$

where (a,b) = (1.13, 0.63), (1.79, 1), and (2.92, 1.63) for D, E and F/G respectively.

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 is generally interested in 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**(1996). 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:

$$C = \frac{2Q\exp\left[-\beta^2\left(1-\frac{x^2/2\sigma_u^2}{x^2/2\sigma_u^2+y^2/2\sigma_v^2+z^2/2\sigma_w^2}\right)\right]\left(\exp(-p^2)+\frac{\sqrt{\pi}}{2}p(1+\mathrm{erf}(p))\right)}{(2\pi)^{3/2}\,\sigma_u\sigma_v\sigma_w\left(x^2/2\sigma_u^2+y^2/2\sigma_v^2+z^2/2\sigma_w^2\right)} \quad (5.4)$$

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

$$\text{and } \beta = U/(\sqrt{2}\sigma_u)$$

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 >> z, taking exp $(-p^2)$ <<p and $\sigma_u=U\sigma_x/x$ etc, the downwind concentration becomes:

$$C = \frac{Q\exp\left[-\left(\frac{y^2}{2\sigma_y^2}+\frac{z^2}{2\sigma_z^2}\right)\right](1+\mathrm{erf}(\beta))}{2\pi\,\sigma_y\,\sigma_z\,U} \quad (5.5)$$

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 concentration becomes a fraction of that predicted by the standard Gaussian plume model, as shown in Table 5.2.1.

Turbulence σ_u/U	**β**	**erf (β)**	**Ratio C_{Hunt}/C_{GPM} for x/z >> 1**
0	4	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

Table 5.2.1
Ratio Between Concentrations Calculated Using Hunts Model and those Calculated Using the Standard Gaussian Plume Model

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 2.4), then $\sigma_u/U \approx 1$, and the Gaussian model will only over-predict by a factor of 1/0.84 ie. around 20% high.

5.2.2 Puff models

Crabol and Deville-Cavelin(1985) 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:

$$\frac{C}{Q} = \frac{1}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{(x-x_o-Ut)^2}{\sigma_x^2} + \frac{(y-y_o)^2}{\sigma_y^2} + \frac{(z-z_o)^2}{\sigma_z^2}\right)\right] \quad (5.6)$$

where:

C = concentration of the pollutant
Q = total quantity of the released pollutant
σ_x, σ_y = standard deviations in horizontal direction
σ_z = standard deviation in vertical direction
U = mean wind speed
x_o, y_o, z_o = 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:

$$\sigma_x = \sigma_y = \sigma_h = (A_h t)^{B_h} \qquad \sigma_z = (A_z t)^{B_z} \quad (5.7)$$

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, based on 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 such 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

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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(1980) describes two simple methods to account for calm periods. In the first method, calm winds are assumed to equal 0.5 m/s, but Draxler prefers an improved method in which calm situations are simulated by summing the source term until the wind 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 to radioactive releases which can travel tens of kilometres. The application would therefore be inappropriate to short duration accidental releases where relatively near-field concentrations are required.

5.2.3 Analytic solutions of the diffusion equation

Apsley(1987) describes a model for diffusion in light wind conditions which is based on an analytic solution of the complete diffusion equation:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}(k_x\frac{\partial C}{\partial x}) + \frac{\partial}{\partial y}(k_y\frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(k_z\frac{\partial C}{\partial z}) \qquad (5.8)$$

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:

$$C = \frac{Q}{4\pi K r} e^{-\delta^2 \sin^2(\phi/2)} \qquad (5.9)$$

where:

δ^2 = Ur/K
r = the distance from the source to the receptor
R = the off-axis distance = $(y^2 + z^2)^{1/2}$

ϕ = the angle made by the source-receptor vector with the mean wind direction = $\sin^{-1}(R/r)$

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

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

that is, 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:

$$\chi_{3D} = \frac{C_{3D}\,UH^2}{Q} = \frac{Pe}{4\,\pi}\left[\frac{e^{-\frac{1}{2}Pe(R_1-X)}}{R_1} + \frac{e^{-\frac{1}{2}Pe(R_2-X)}}{R_2}\right] \qquad (5.10)$$

where:

Pe = Peclet number = UH/K
X = non-dimensional downwind distance = x/H
R_1 = non-dimensional source to receptor distance = r_1/H
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:

$$\chi_{GPM} = \frac{C_{GPM}\,UH^2}{Q} = \frac{Pe}{4\,\pi\,X}\,e^{-\frac{Pe\,Y^2}{4X}}\left[e^{-\frac{Pe\,(Z-1)^2}{4X}} + e^{-\frac{Pe\,(Z+1)^2}{4X}}\right] \qquad (5.11)$$

where:

Y is the non-dimensional crosswind distance = y/H
Z is the non-dimensional vertical distance = z/H

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

$$\frac{C_{GPM}}{C_{3D}} = \frac{(1 + X^2)^{1/2}}{X}\,e^{-1/2\,Pe\left(\frac{1}{2X} - (1+X^2)^{1/2} + X\right)} \qquad (5.12)$$

This ratio is plotted in Figure 5.2.1 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 Figure 5.2.1.

Typical values of the Peclet 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, Figure 5.2.1 indicates that the standard Gaussian model only breaks down for $x/H < 3$. Taking 100m as a typical minimum value of interest suggests that the Apsley model would only give significantly improved predictions 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:

$$C_{GPM} = C_{3D} = Q/(2\pi\, K\, x) \qquad (5.13)$$

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, and 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:

$$\frac{C_{GPM}}{C_{3D}} = \left(1 + \frac{y^2}{x^2}\right)^{1/2} e^{-\frac{x^2}{\sigma^2}\left(\frac{y^2}{2x^2} - (1+\frac{y^2}{x^2})^{1/2} + 1\right)} \qquad (5.14)$$

Figure 5.2.2 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_{GPM}/C_{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 under-predicts 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; an example of the application of this method is given in Section 6.4.4.

Pasquill and Smith$^{(1983)}$ 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 3 dimensions, which indicates that CFD modelling would be required in order to investigate the various turbulence models.

5.2.4 CFD models

Calculation of gas dispersion can be made using the solution to the full equations of motion, within a CFD code. Such methods are primarily used for complex flow problems, and would not generally be applied to dispersion problems unless there were significant obstruction effects.

In the low wind speed context, CFD models have the advantage that they do not require a uniform or regular velocity field to be present. They can in fact be used to demonstrate how the source term affects the near-field flow, and then follow the dispersion through, taking account of regions of both relatively high and low wind speed in the context of obstructions such as may be present on a typical site. However, where there is not a strong pre-existing flow, there are frequently problems in obtaining convergence of such models. They may therefore be of some use in low wind speeds for special applications, but would certainly not be considered for routine use, due also to the high costs involved in obtaining sound solutions.

Mihu(1981) describes the numerical simulation of dispersion from a point source in a calm atmosphere. This involves a solution to the diffusion equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[k_x \frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y \frac{\partial C}{\partial y}\right] + \frac{\partial}{\partial z}\left[k_z \frac{\partial C}{\partial z}\right] - k_a C \qquad (5.15)$$

All that is necessary to apply the model is a specification of the initial concentration, the diffusion parameters and the height of an inversion base above ground level. This approach has not been widely used, possibly because of the difficulty in specifying the values of k_x etc. Although a perfectly 'calm' atmosphere might suggest the use of the molecular diffusivity, in practice this is likely to underpredict dispersion significantly. It therefore appears to have limited use in the risk assessment context.

5.3 Current usage of models

In general, none of the low wind speed models described above in Section 5.2 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 m/s, which means that the standard dispersion models used in these assessments are usually applied to cases for which they are reasonably well validated, although, as noted in Sections 1.1, 2.4 and 5.1.1, there may be conditions for which even 2m/s could be considered too low for a sensible use of such models.

However, it has been shown in Sections 4.1 and 4.4 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. In general, risk assessments do not include any consideration of the significance of this fact.

At present, the best which 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 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 usually likely to be small compared with the other uncertainties involved in a QRA, such as the event frequency,

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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. In most cases, puff models (Section 5.2.2) should give improved estimates, and there may also be scope for using one of the analytical models, such as that of Hunt (Section 5.2.3).

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 & Ott**(1996)). 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 1 has a wind speed less than 2 m/s. In the second table, 28 data sets from Lathen are presented, of which 2 have u≤ 2 m/s. In the third, however, a further 21 data sets from Lathen are presented, of which 15 have u≤ 2 m/s. Of these 15, 7 have fence obstacles, 6 were vertical jet releases and 2 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 the data have not yet been used for model validation outside the project of which they 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 sensitivity studies presented in the next section 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 over-estimated 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.

6. RELEVANCE TO SAFETY REPORTS

6.1 UK requirements

Almost all of the data used in safety reports and quantified risk assessments in the UK, including the risk assessments undertaken by the HSE, are based on standard meteorological data from Meteorological Office weather stations located around the country. The Meteorological Office is able to provide a range of data, in a variety of formats, including information on:

- Pasquill Stability Analyses
- Boundary Layer Depth Analyses
- Input Data for UK-ADMS (Sophisticated Gaussian plume model for pollution modelling)
- Climatological Summaries
- Wind Frequency Analyses
- Wind Rose
- Upper Air Data

Data can be obtained for any period, and may be subdivided to show hourly/diurnal/monthly/yearly variations. Since data are recorded as hourly means, it is not generally possible to obtain data for shorter timescale variations. It is generally recommended that at least 10 years of weather data are required in order to ensure that representative average conditions are obtained, which is obviously important in terms of carrying out a risk assessment.

For the majority of safety cases and QRAs, the basic information required is an analysis of the average frequency of various weather conditions for each wind direction, where the weather conditions are defined in terms of the wind speed and Pasquill stability. The HSE Guide to the Control of Industrial Major Accident Hazards (CIMAH) Regulations, HS(G)21(Rev), states that the prevailing weather conditions in the vicinity of the site should be determined from data obtained from the nearest Meteorological Office weather station. This information is used to determine the probability of a set of representative weather conditions. For example, the HSE currently use the following four representative weather conditions in risk assessments using RISKAT, as discussed in Sections 3.4.3 and 4.1.2.

i) 2.4 m/sD stability
ii) 4.3 m/sD stability
iii) 6.7 m/sD stability
iv) 2.4 m/sF stability

The probabilities of each combination of wind speed and stability are assigned to one of these four categories based on the methodology described by Corlett(1995) and Clay(1995). One of the main objectives of this study is to determine the adequacy of using this restricted set of representative conditions, and whether the explicit consideration of lower wind speeds could significantly affect the results of a risk assessment.

It is noted that detailed risk assessments may take account of diurnal or annual variations. For example, the probability of F stability is generally much lower during the day than at night, and low wind speeds tend to be more common in summer months.

6.2 Source term considerations

When deciding which dispersion models are best suited to the assessment of dispersion for QRA applications, it is important to consider the characteristics of the release and the extent to which they can be incorporated in the model. For example, many dispersion models were originally developed to model releases from elevated stacks, and so they provide good estimates of average concentrations for such releases. However, in safety cases and QRAs, the concern is generally in ground level releases for a relatively short time and the main interest for toxic dose calculations is in the actual time varying concentration, rather than the average concentration. For risk assessments involving flammables, the maximum concentration and hazard range to the lower flammability limit (LFL) are important.

The main source term considerations are:

- Release duration (generally no more than 20 to 30 minutes)
- Time dependence of release rate
- Buoyancy or momentum of release
- Release location and height
- The effect of nearby structures (building wake effects, etc.)

It is worth considering the above source term factors in the context of the main types of event that are considered in safety reports and QRAs, namely:

- Fires
- Toxic releases
- Flammable vapour releases (leading to fire or vapour cloud explosion)
- Explosions and BLEVEs

6.2.1 Fires

The main off-site hazards from a major fire arise from the smoke, toxic combustion products and unburnt material in the fire plume. In low wind speeds, the fire plume will tend to rise vertically due to its buoyancy and so the off-site risks at ground level are substantially reduced. The off-site risks from such fires are much greater in windy conditions (e.g. ~10 m/s) where the fire plume may not lift off from the ground and hence will disperse as a simple Gaussian plume from a ground level source (see **Carter**(1989)). High wind speeds are also likely to be of more concern because of the increased rate of fire spread and escalation.

6.2.2 Toxic releases

This is likely to be one of the areas of greatest concern in terms of low wind speeds. A low mean wind speed generally results in less mixing and hence higher concentrations.

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Furthermore, a toxic cloud may take longer to pass over a point, so that people may be subjected to both higher concentrations (c) and longer exposure durations. Since dose is calculated as an integral of c^n with respect to time ($n \geq 1$), such effects would suggest a substantially increased probability of injury or fatality.

A mitigating factor for the spillage of toxic liquids is that the rate of evaporation in low wind speeds is generally significantly reduced. However, this does not apply to the initial flash vaporisation of liquefied gases held under pressure (such as chlorine) or cryogenically stored liquids (such as ammonia) when they came into contact with the ground.

6.2.3 Flammable vapour releases and vapour cloud explosions

If a flammable vapour cloud is formed, then there is little doubt that the probability of ignition is greatest in low wind speeds. Indeed, it is questionable whether a flash fire can occur at all in high wind speeds. The reason for the increased risk in low wind speeds is that the vapour cloud remains above the LFL over a wider area and persists for a greater period of time. It may also be that the ignition energy required in low wind speed conditions is reduced. Another major factor is that the quantity of gas within the flammable limits is generally greatest in low wind conditions, resulting in an increase in the severity of a VCE.

6.2.4 Explosions and BLEVEs

In addition to the explosion of a vapour cloud (see Section 6.2.3), it is possible to generate overpressure effects as a result of condensed phase explosion (e.g. TNT) or sudden releases of pressure, such as a BLEVE.

It is considered unlikely that low wind speeds could have any influence on the likelihood of such an explosion or BLEVE. For these types of explosion, it is unlikely that low wind speeds could significantly affect the consequences in terms of the thermal radiation, blast overpressure or missile effects.

6.3 Specific kinds of release

In the previous section, the main types of event that are generally involved in QRAs, and the influence that low wind speeds might have on such incidents, have been identified. The general conclusion is that the significance of low wind speeds is greatest for releases of toxic or flammable material, rather than for fires or explosions. HSE have identified four specific kinds of release which fall into this category, and these are considered in more detail below. The types of release are:

- A continuous flashing liquid or vapour release with momentum
- An instantaneous release of flashing liquid or vapour with momentum
- A boiling/evaporating pool
- A low velocity vapour release from a building

In each case, the results from earlier sections of this report are used to provide an indication of the significance of low wind speeds, and of the applicability of various kinds of dispersion model which could be used as part of the risk assessment. The fundamental point which should be remembered throughout is that it is only worth considering low wind speed conditions in detail if they are likely to lead to significantly larger or smaller risks than would be predicted using current standard data and methodologies, although such effects may not be evident unless detailed calculations are undertaken.

6.3.1 Continuous flashing liquid or vapour release with momentum

The initial dispersion of a continuous release which has either momentum or buoyancy is not strongly affected by moderate or low wind speeds. For example, the initial dispersion of a jet release of liquid chlorine from a pipework rupture will not be significantly different in 5D or calm conditions. As the influence of momentum and buoyancy decreases, due to air entrainment, a transition point is reached where the vapour begins to be affected by the wind. Clearly, in low wind speeds it will take longer for this point to be reached.

The medium and far field dispersion of such continuous releases is clearly very dependent on the wind speed, as can be shown by the application of either standard dispersion models or more sophisticated models of the type described in Section 5.2. It is therefore important that the uncertainties associated with the risks in low wind speeds are appreciated. An indication of the sensitivity of the risks from a continuous release to the specific inclusion of low wind speeds in a QRA is given in Sections 6.4.1, 6.4.2, 6.4.4 and 6.4.5.

6.3.2 Instantaneous release of flashing liquid or vapour with momentum

As for the case considered above, the initial dispersion of an instantaneous release which has either momentum or buoyancy is not usually strongly affected by the wind speed. As the influence of momentum and buoyancy decreases, due to air entrainment, a transition point is reached, and, for an instantaneous release, a time is reached, beyond which the vapour begins to be affected by the wind. Clearly, in low wind speeds it will take longer for this point to be reached.

The medium and far field dispersion of such instantaneous releases is very dependent on the wind speed, in the same way as for the continuous case. In this case, however, meandering in low wind speeds may result in the cloud actually missing some downwind locations. It is therefore important that the uncertainties associated with the risks in low wind speeds are appreciated. An indication of the sensitivity of the risks from an instantaneous release to the specific inclusion of low wind speeds in a QRA is given in Sections 6.4.3 and 6.4.4.

6.3.3 Boiling or evaporating pool

For a simple evaporating pool, where the boiling point of the liquid is greater than the ambient temperature, the rate of evaporation is greatest in high wind speeds. For low wind speeds, although hazard ranges increase, there is the competing effect of a lower effective source term. Therefore, in terms of the off-site risk, the dispersion of vapour

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in low wind speeds is unlikely to be a significant factor, and the results of a QRA would not be sensitive to the dispersion model used for the low wind speeds.

For a spillage where the boiling point of the liquid is below the ambient temperature, the liquid will extract heat from the ground and air above the pool and will boil, releasing large quantities of vapour. The vapour release rate is therefore only slightly dependent on the wind speed. Typically, the initial release rate would be high, as the liquid came into contact with the warm ground, resulting in an initial 'puff' of vapour, which would be followed by a gradually decaying vapour release rate as the ground cooled. Eventually, an equilibrium rate would be reached which would be determined by the wind speed over the pool.

This kind of release (puff followed by continuous plume release) has been modelled by **Grint and Purdy**(1990) using the straightforward R-91 Gaussian plume model, which implies that, as the release quantity is not greatly affected by the wind speed, the concentrations would be significantly higher in low wind speeds. The sensitivity of risk calculations to low wind speeds, using such Gaussian models, is assessed in Section 6.4.1.

6.3.4 Low velocity vapour release from a building

Since many releases of hazardous materials occur inside buildings, it is necessary to assess the rate at which the material leaks from the building. In general, the building volume acts as a 'buffer' so that the release rate from the building is less than the source release rate. The release rate from the building will depend on factors such as:

- The source release rate inside the building
- The degree of mixing inside the building
- The volume of the building
- The degree of pressurisation within the building
- The extent to which the building is well sealed, i.e. the number of air changes per hour (ach)
- Whether forced ventilation is in operation

It is important to note that the number of air changes per hour for the building is generally dependent on the ambient wind speed, so that, in low wind speeds, the release rate from the building is reduced. Therefore, for small (or short duration) releases inside buildings the importance of low wind speeds is also somewhat reduced. However, the so called 'building buffer effect' becomes much less important for higher continuous release rates (e.g. several kg/s for ~20 minutes), where the release itself may effectively 'drive' the ventilation. In such cases, the assessment of dispersion in low wind speeds may become significant.

Work is currently underway to characterise the building buffer effect by use of CFD modelling (**Gilham and Ferguson**(1996)) and simpler 'zone' modelling (**Deaves**(1996)).

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6.4 Case studies - QRA

In order to investigate the potential effect of low wind speeds on risk assessments, a number of simple cases have been investigated. In each case, the risk has been calculated 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.

In this section, 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', as it is based on the condition that the accident has occurred and so 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 definite 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.

6.4.1 Continuous release of chlorine - 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 a type of release which might contribute to 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, whilst Schemes B and C incorporate additional refinements to take account of low wind speeds. The dispersion data relating to each of these risk calculation schemes is presented in Table 6.4.1.

Scheme 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^{2}min. 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° = **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.

Wind Speed U (m/s)	At 500 metres					At 1000 metres				
	σ_y (m)	Centreline Conc. C_o (ppm)	Width y_{DTL} (m)	Conditional Risk		σ_y (m)	Centreline Conc. C_o (ppm)	Width y_{DTL} (m)	Conditional Risk	
				DTL	Probit				DTL	Probit
2.4	37.52	160.12	46.82	0.030	0.0018	74.58	49.08	0.00	0.000	0.000004
2.3	38.11	164.50	48.38	0.031	0.0020	75.77	50.41	0.00	0.000	0.000005
2.2	38.75	169.16	50.03	0.032	0.0023	77.04	51.83	0.00	0.000	0.000006
2.1	39.43	174.15	51.79	0.033	0.0025	78.42	53.34	0.00	0.000	0.000008
2.0	40.17	179.50	53.67	0.034	0.0029	79.90	54.97	0.00	0.000	0.000010
1.9	40.96	185.26	55.70	0.035	0.0032	81.51	56.72	0.00	0.000	0.000012
1.8	41.84	191.49	57.89	0.037	0.0036	83.26	58.62	0.00	0.000	0.000015
1.7	42.79	198.24	60.27	0.038	0.0041	85.17	60.67	0.00	0.000	0.000019
1.6	43.83	205.60	62.87	0.040	0.0047	87.27	62.91	0.00	0.000	0.000025
1.5	44.99	213.67	65.73	0.042	0.0053	89.59	65.37	0.00	0.000	0.000032
1.4	46.27	222.57	68.89	0.044	0.0061	92.17	68.07	0.00	0.000	0.000042
1.3	47.72	232.46	72.41	0.046	0.0070	95.07	71.08	0.00	0.000	0.000055
1.2	49.34	243.52	76.38	0.048	0.0082	98.34	74.44	15.70	0.005	0.000074
1.1	51.20	256.02	80.89	0.051	0.0095	102.06	78.24	36.10	0.011	0.000102
1.0	53.34	270.31	86.09	0.054	0.0112	106.36	82.59	51.36	0.016	0.000142
0.9	55.85	286.86	92.17	0.058	0.0133	111.39	87.62	66.04	0.021	0.000203
0.8	58.84	306.35	99.41	0.062	0.0159	117.38	93.55	81.52	0.026	0.000299
0.7	62.46	329.77	108.23	0.068	0.0194	124.65	100.67	98.88	0.031	0.000458
0.6	67.00	358.71	119.29	0.075	0.0240	133.74	109.48	119.38	0.038	0.000699
0.5	72.87	395.75	133.71	0.083	0.0303	145.50	120.75	144.98	0.046	0.001200
0.4	80.89	445.68	153.57	0.095	0.0394	161.56	135.93	179.16	0.056	0.002140
0.3	92.72	518.41	183.26	0.112	0.0533	185.24	158.07	229.25	0.072	0.003640
0.2	112.71	639.66	234.46	0.140	0.0779	225.27	194.98	314.67	0.097	0.010100
0.1	158.20	911.48	355.00	0.197	0.1325	316.29	277.74	515.73	0.152	0.034200
	Result using Scheme A =			**0.029722**	**0.001800**	**Result using Scheme A =**			**0.000000**	**0.000004**
	Average for Scheme B =			**0.061770**	**0.020017**	**Average for Scheme B =**			**0.023812**	**0.002229**
	Average for Scheme C =			**0.053017**	**0.012438**	**Average for Scheme C =**			**0.015752**	**0.000342**

Key		
	Scheme A	2.4 m/s
	Scheme B	0.1 to 2.4 m/s
	Scheme C	0.5 to 2.4 m/s

Table 6.4.1
Calculation of the Conditional Risk Based on a Gaussian Plume Model Using Various Schemes

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Scheme 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 is shown in Table 6.4.1 for distances of 500 and 1000 m. For each distance the following parameters are given:

σ_y(m)	The horizontal standard deviation (m)
C_o(ppm)	The centreline concentration predicted using the Gaussian plume model (ppm)
y_{DTL}(m)	The crosswind distance (half-spread) above which the DTL would be exceeded
Risks	DTL Probability of being within the arc where the DTL would be exceeded
	Probit Probability of fatality based on a probit equation (see Equation (6.1)).

This refined methodology increases the probability of exceeding the DTL at 500 m by a factor of 2.08 to **0.062**.

Scheme 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 by a factor of 1.78 compared with that in Scheme A, to **0.053**.

At 1000 m, the centreline concentration in a wind speed of 2.4 m/s is only 49 ppm, and so the probability of exceeding the DTL is predicted to be **zero** (Scheme A). The concentration can be seen (Table 6.4.1) to exceed 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 there is a finite risk for all wind speeds less than 1.3 m/s, and the overall probability of exceeding the DTL at 1000 m is calculated as **0.023** (Scheme B), reducing to **0.016** (Scheme C) if 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 initially be expected. This conclusion is generally valid for distances less than the hazard range (~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 6.4.1 shows the variation in the risk of receiving a dangerous toxic load for each of the three schemes. It should also be noted that the more sophisticated risk assessments 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.

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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 the following probit equation (from AIChE$^{(1989)}$) for fatality due to chlorine exposure to convert toxic loads to risk of fatality:

$$\text{Probit} = -8.29 + 0.92 \ln (c^2t) \qquad (6.1)$$

The results of these calculations are also presented in Table 6.4.1. These revised calculations 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 following conditional risks of fatality at 500 m and 1000 m:

	500 m	**1000 m**
Scheme A	0.0018	0.000004
Scheme B	0.0200	0.002229
Scheme C	0.0124	0.000342

Figure 6.4.2 shows the variation in the risk of fatality based on the probit equation for each of the three schemes.

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 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 than that predicted by Scheme A. This factor increases 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 use 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.

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Indoor Risks

The majority of QRA models can allow for the mitigating effect of people being or escaping indoors. Most risk assessments assume perfect mixing within the building, so that the gas concentration builds up during the passage of the cloud, and then decays exponentially after the cloud has passed. This approach has been described by various authors including **Davies and Purdy** (1986).

Simply using a wind speed of 2.4 m/s in the example considered above, and allowing for indoor effects, using an air change rate of 2 ach, leads to the result that there is a zero probability of the DTL being exceeded indoors at a distance of 500 m. However, consideration of lower wind speeds shows that there is a significant risk for all wind speeds of less than about 1.8 m/s. Hence, unless low wind speeds are explicitly considered, it is again possible that some risks are neglected altogether.

It is noted that the number of air changes per hour (ach) for a building may be slightly dependent on the wind speed, and so lower wind speeds may be of less significance, since the infiltration rate will be rather lower. This effect has not been quantified here, but it is unlikely to alter the general conclusions given above, since the ventilation rate generally approaches a finite value as the wind speed falls towards zero.

6.4.2 Continuous release of chlorine - dense gas dispersion model

This case also considers a 1 kg/s release of chlorine, continuing for 20 minutes in F stability. However, 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:

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

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

Scheme C The probability of wind speeds 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 wind speeds of 1.5 m/s.

The reason for choosing 1.5 m/s is that this is the lowest wind speed that can be modelled using HEGADAS-S.

The variations in the conditional risk results with increasing distance are shown in Figures 6.4.3 and 6.4.4, based on the risk of exceeding the DTL and based on a probit equation respectively. Figure 6.4.3 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 a zero risk. Figure 6.4.4 shows that the difference in the risks based on a probit for the three schemes increases steadily with increasing distance. Scheme B predicts that the risks are about a factor of two

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greater at 500 m than those using Scheme A, but this increases to a factor of greater than 10 beyond 2000 m.

6.4.3 Instantaneous release of chlorine - dense gas dispersion model

This case considers an instantaneous release of 1 tonne of chlorine vapour, such as might occur following the catastrophic failure of a chlorine drum. It is assumed that this would rapidly form a cylindrical cloud with an aspect ratio of 0.1 and with 10 volumes of air entrained per volume of chlorine. The subsequent dispersion of this cloud can be modelled using a standard box-type dense gas dispersion model (the WS Atkins in-house model, SLUMP), and the risks of exceeding a DTL and the risk of fatality based on a probit can be calculated. The calculation is slightly more complex in that, for an instantaneous release, it is necessary to model the time dependent downwind concentration in order to calculate the toxic loads and the risks. The conditional risk results were calculated according to the same three schemes as were used in Section 6.4.1, and are presented in Figures 6.4.5 and 6.4.6.

These graphs show that, if lower wind speeds are incorporated into the analysis then the conditional risks are increased at all downwind distances. This is partly due to increased centreline concentrations and partly due to increased cloud widths. Using Scheme C, the risk of exceeding the DTL is approximately a factor of 2 times greater than that using Scheme A at most downwind distances. However, the risk based on a probit may be up to a factor of 10 greater in Scheme C than in Scheme A.

The results of using Scheme B must be treated with caution, as it is extremely doubtful whether the dispersion model is valid for wind speeds as low as 0.1 m/s. Nevertheless, it is clear from Figure 6.4.6 that the risks based on a probit in the medium to far field may be several orders of magnitude higher with Scheme B than with Scheme A. If such results were to be genuinely valid, then this could have very significant implications for any risk assessments involving such situations.

6.4.4 Instantaneous and continuous chlorine releases - using RISKAT

The HSE's current risk assessment tool (PC RISKAT v2.0) was used to determine the conditional risks associated with the following two release scenarios:

i) Continuous release of 1kg/s of chlorine for 20 minutes
ii) Instantaneous puff release of 1000kg of chlorine.

The dispersion programs used by RISKAT are CRUNCH for continuous releases and DENZ for instantaneous puff releases. These were used in wind speeds of 2.4, 1.2, 0.5 and 0.1m/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),

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provided that this is not sooner than the minimum evacuation time, which was taken as 30 minutes.

The results are shown in Figures 6.4.7 to 6.4.10. Figure 6.4.7 shows that the risks predicted for the continuous release in 1.2 m/s can be up to factor of 5 greater than those predicted at 2.4m/s. At 0.5m/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 6.4.9 and 6.4.7 shows that, in this case, the mitigating effect of being indoors is negligible, probably due to the relatively high air change rate (2.0 ach) and long release duration (20 minutes). In fact, it appears that, at some distances, the risk is marginally lower for the outdoor population than for the residential population. This is probably partly due to the approximations made by RISKAT when considering indoor risks, and partly due to the continued dose received by an indoor population after the cloud has passed but before evacuation to fresh air has taken place.

Figure 6.4.10 shows how the risks from an instantaneous release to a residential population increase as the wind speed decreases. The corresponding outdoor risks (Figure 6.4.8) are somewhat less sensitive to the wind speed, and at 1000 m are actually greatest in the 2.4m/s case. This may be because, for this higher wind speed, the cloud has had less time to disperse, and so is still at a relatively high concentration.

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.

6.4.5 Continuous release of chlorine - low wind speed model

The preceding examples have used models which are known to be not strictly valid at low wind speeds, although they may provide a reasonable approximation for the purposes of a QRA. In order to determine whether a model developed for low wind speeds would lead to significant differences in the risk results when compared with a standard model, the example considered in Section 6.4.1 above is reassessed using Apsley's low wind speed model (see Section 5.2.3) for comparison with the results of using the standard Gaussian plume model.

Apsley has shown that, by setting $\sigma^2 = 2Kx/U$ in his model, it reduces to the standard Gaussian plume formulation in the appropriate limits, as discussed in more detail in Section 5.2.3. σ varies with x according to a power low with exponent 0.8-0.9. Thus, if it is assumed that, in the Gaussian plume model, $\sigma^2 = 2Kx/U$, then taking an approximately linear increase of σ with x gives the eddy diffusivity as $K=0.001Ux$. Using this formulation for K, it can be shown that the crosswind distance corresponding to the DTL is very similar in both the Gaussian and 3D models, implying that the risks are not significantly affected by the choice of model. This point is demonstrated in Figure 5.2.2 which shows that, provided $y/x < 0.5$, the 3D and

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Gaussian plume models predict similar concentrations. However, very close to, or just upwind of the source, the 3D model can lead to higher risks.

At low wind speeds, it may be more appropriate to take the eddy diffusivity as a simple constant, independent of the mean wind speed. Figures 6.4.11 and 6.4.12 show the 73.5 ppm iso-concentration contour for two different values of K. Figure 6.4.12 emphasises the differences in the predictions of the 3D and Gaussian plume models. The 3D model clearly shows the upwind spreading of the plume, which implies that the 3D model leads to greater risks close to the source. Conversely, at greater distances, the Gaussian plume model predicts a wider plume and hence a greater risk of exceeding the DTL.

There are various other ways of defining the eddy diffusivity, such as $K = 0.4u_{*}z(1 - z/h)$ (see **Pasquill and Smith**(1983)), which could lead to different results. For a ground level release, z is small, but could realistically be taken as 2.5m. Since the boundary layer depth $h >> 2.5$m, this gives $K \simeq u_{*}$. In low wind speed, $u_{*} \simeq 0.1$-0.3m/s, suggesting that $K \leq 1$. If this is the case, the results presented in Figures 6.4.11 and 6.4.12 indicate that the 3D and Gaussian models would give similar results in the range of interest.

6.4.6 Instantaneous LPG release - using HEGABOX

The worst case conditions for a release of a material such as LPG are generally taken to be low wind speed conditions, such as 2F. In this section, a simple dense gas box model (HEGABOX) is used to estimate whether the use of lower wind speeds would lead to significantly greater hazard ranges . In this case, the hazard range concentration is taken to be the lower flammability limit (LFL), irrespective of release duration, which differs from the time-integrated dose concept used for toxics.

The release to be considered is an instantaneous release of 25 tonnes of propane vapour. This has been modelled in a range of wind speeds and the results are summarised in Table 6.4.2. (The lowest wind speed considered is 1.0 m/s as this is the lowest value that can be modelled by HEGABOX).

Consequence Parameter	**Wind Speed (m/s)**			
	1.0	**1.5**	**2.0**	**2.4**
Hazard range to LFL of 2.1% (m)	322	316	310	305
Time taken for leading edge of cloud to reach hazard range (s)	230	203	180	165

Table 6.4.2
Sensitivity of Instantaneous LPG Release
Consequences to Low Wind Speeds

The results in Table 6.4.2 show that, for a release of this type, there is only a slight increase in the hazard range at low wind speeds, but the effect is not significant. As the bulk Richardson number remains high down to the hazard ranges considered, the lack of sensitivity of the results to wind speed is due to the dispersion being dominated by the density driven slumping of the gas.

6.4.7 Continuous LPG release - using HEGADAS-S

This case considers a continuous release of 10kg/s of propane vapour. The HEGADAS-S model has been used to assess the dispersion of this release in a range of low wind speeds in stable F conditions, and the results are presented Table 6.4.3.

Consequence Parameter	Wind Speed (m/s)		
	1.5	2.0	2.4
Hazard range to LFL of 2.1% (m)	96	83	76
Maximum half-width to LFL (m)	184	125	98
Mass of vapour between flammable limits (kg)	1276	813	613

Table 6.4.3
Sensitivity of Continuous LPG Release Consequences to Low Wind Speeds

Clearly, the results above show that using this type of model at low wind speeds can lead to anomalous results, in that the cross-wind spread of the plume is predicted to be greater than the downwind hazard range. This is largely due to the inability of the code to account properly for along-wind dispersion, which becomes important at these low wind speeds, even for the calculation of areas above the LFL.

Bearing in mind the above problems, the results in Table 6.4.3 show that lower wind speeds lead to much larger increases in cross-wind spread than in downwind hazard range. This increase in the area of the cloud would be particularly important when considering the risk from flash fire scenarios. The mass of vapour within the flammable limits also increases significantly at the lower wind speeds, being more than a factor of two greater at 1.5 m/s than at 2.4 m/s. However, the hazard ranges to particular levels of blast overpressure tend to depend on the cube root of the mass of fuel, and so a factor of two increase in mass is probably rather less significant in terms of a risk assessment.

6.5 Implications for emergency planning

Regulations 10 and 11 of the CIMAH Regulations require the preparation of on-site and off-site emergency plans for all top-tier major hazard sites. In the event of an emergency at such a site, one of the key parameters which is communicated immediately to the emergency services as part of the off-site plan is the wind speed and direction at the site where the accident has occurred. This information allows the emergency services to decide which access route to the site is least likely to be affected by, for example, a drifting cloud of toxic gas, and also enables an assessment to be made of how long it might take a toxic gas cloud to reach a populated area.

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In the event of low wind speeds, it is possible to envisage a situation where the site anemometer reads zero, and the wind vane is stuck at some angle which may not be representative of any actual air movements. This could lead to the emergency services being given misleading information. Clearly it is important that the anemometers at major hazard sites are capable of providing accurate information, especially at low wind speeds.

Another consideration which becomes more important at low wind speeds is that, even if an accurate measurement of wind speed and direction is available, the direction may vary significantly over a relatively short period. This has been demonstrated in Section 4.4.6, using the high quality wind data from Camborne. It should therefore be emphasised that, in low wind speed conditions, it is inappropriate to assume that the consequences will be limited to a single sector, since they could potentially affect a number of sectors. These factors are rarely considered explicitly in emergency plans, so it is vital that those responsible for dealing with an emergency are aware of these issues.

The Meteorological Office can also be contacted to provide information on the current and predicted weather conditions. Such advice is provided through the CHEMET (CHEmical METeorology) scheme, which is designed to support the emergency procedures of Police Forces and Fire Brigades, but which is also available to other organisations involved in chemical emergencies. The advice available under CHEMET is divided into two parts, which can be provided within the timescales noted:

Part A	2-3 minutes	A best estimate of the wind speed and direction, together with a brief description of the behaviour of any released material.
Part B	20-30 minutes	More detailed information , including an estimated 'area-at-risk' map.

A description of the basis on which this information is produced is given in the Meteorological Office **'Guidance Notes on the Spread of Pollution'** (1990), which has been discussed in Section 3.2.3 of this Report.

HSE liaise with emergency planning officers, and provide advice based upon the results of the Safety Cases submitted to them. Currently, the advice is not extensive, and relates primarily to the provision of early warning systems. However, the following points were made by the MHAU emergency planning contact in relation to low wind speeds:

- Area covered by the release will be more circular rather than the elliptical shape typical of higher winds
- Slower movement of gas cloud would allow a better chance of providing appropriate warnings for escape, or, in certain (very unlikely) cases, evacuation
- Emergency plans will focus on specific regions of concern, such as hospitals, schools etc, which may only be affected for some wind directions; hence directional variability in light winds may be relevant

- In view of the greater distances involved for toxic hazard ranges, the effects of toxic releases are likely to be modified to a greater extent by light winds than are the effects of flammable releases. (See, for example, results presented in Section 6.4.6).

Finally, it is also worth noting that this project has demonstrated that the consequences of an accident in low wind speed conditions may be worse than those predicted for the nominal 'worst case' weather conditions (e.g. 2.4F or 2F), and that the frequency with which these low wind conditions may occur is likely to be significant. The quoting of 'worst case' hazard ranges may therefore be misleading, and should generally be qualified by some assessment of the wind speed used. For example, the hazard ranges for a toxic release in 0.5G conditions are likely to be considerably in excess of those quoted for 2.4F conditions. The fact that the accuracy of dispersion models begins to degrade at these low wind speeds is no justification for ignoring the potentially more severe consequences that could arise.

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7. CONCLUSIONS

7.1 Main findings of this research project

This project has reviewed the literature relating to low wind speeds, and has conducted some detailed analysis of meteorological data. The main findings which are relevant, in that they have clear implications for quantitative risk assessment, are summarised below, divided into those which deal with frequency, dispersion and risk assessment respectively.

Frequency

- Completely calm conditions (say < 0.5 m/s) are very rare in the UK, and therefore explicit consideration of such conditions is unlikely to have significant effects on the results of a risk assessment.

- Low wind speeds are generally associated with stable conditions, and the definition of what constitutes a low wind speed will depend on stability class.

- The lowest wind speed generally used by the HSE in QRAs for toxic releases is currently 2.4 m/s in both F and D stability conditions. The frequency of wind speeds less than 2.4 m/s at sites in the UK is typically 20 to 30%, and lower wind speeds generally imply greater hazard ranges for vapour or gas releases. This implies that such QRAs are underestimating the risks associated with low wind speed conditions, specifically by underpredicting risks at greater distances.

- The cumulative frequency distribution of wind speeds approximates reasonably to a Weibull distribution of the form:

$$\text{Cumulative Frequency (P)} = 1 - e^{-\left(\frac{V}{V_o}\right)^k} \qquad (7.1)$$

where:

V is the wind speed (knots)
V_0 is a reference wind speed ($1.12\ V_{mean}$)
k is a shape factor

This allows an estimation of the frequency of low wind speeds for sites where the low wind speed data is not available.

- Provided that 10 minute rather than hourly mean wind speeds are used, it has been demonstrated that the Weibull distribution can be extrapolated to determine the frequency of very low wind speeds with reasonable confidence.

Dispersion

- For the purposes of a practical QRA, it is a reasonable approximation to use a wind speed of 0.5 m/s to model all wind speeds less than this value. In some cases this may not be possible as the dispersion model may not allow such low values, in which case the lowest reasonable threshold should be used.

- 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 in Section 5.3, 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 0.5G conditions may be much greater than that in 2.4F 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 m/s 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 m/s in stable conditions, although in convective conditions the lower limit should be at least 1 m/s. 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 m/s) 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.

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Risk Assessment

- It is more important to include low wind speeds in risk assessment than it is in estimates of hourly average or long term concentrations, since the releases considered in risk assessments may be of short duration so that the increased plume meander at low wind speeds does not have as great a mitigating effect.
- 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 as 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 up to a factor of ten or more by comparison with those predicted using a more realistic distribution of low wind speeds, depending on the event and the distance.
- It is worth noting that, 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.
- It appears that, in general, the results of risk assessments for flammable gases are less sensitive to low wind speeds than those for toxic releases.

7.2 Potential improvements

It is beyond the scope of this project to recommend that alternative improved methods should be used in QRAs, as the main aim of this project was to determine the significance of the uncertainty that arises in risk assessments due to current methods for assessing low wind speed conditions. However, based on the results of this study, it is perhaps worth outlining some of the potential strategies that 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

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consultation zones and for land use planning advice. The results of this project provide an indication of the situations where the uncertainty is likely to be greatest, and of the way in which the results could be affected.

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.

For example, the existing categories F2.4 and D2.4, could be replaced by the following 10 categories:

a)	F0.5	F1	F1.5	F2	F2.5
b)	D0.5	D1	D1.5	D2	D2.5

The 0.5 m/s category should include the frequency of all winds in the range 0 to 0.75 m/s, and similarly the 1 m/s category should include 0.75 to 1.25 m/s etc. Other combinations of weather categories could also be used. For example, the F2.4 and D2.4 could simply be replaced by F1.2 and D1.2.

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. It is also noted that some re-analysis of meteorological data may need to be undertaken in order to obtain the more detailed wind rose data which would be required.

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 of the type described in this report 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. It is also emphasised that there is little point going to this level of refinement unless a wider range of representative weather conditions is also adopted, as described in b) above.

7.3 Potential areas of further work

A comparison of inter-annual and inter-decade variability in standard Meteorological Office data for weather stations, and the factors that can affect it. Such factors might include natural variability, changes to instruments and recording systems or climatic changes. The project would be run in association with the Meteorological Office. This could include the effect of such variability on the results of a risk assessment.

Use our improved understanding of the frequency distribution of low wind speeds (i.e. Weibull) to generate improved estimates of the likelihood of a range of representative weather categories for use in risk assessments. This could be done for several specific sites. The frequency of each category could be modified to allow for different averaging times, to improve the assessment of releases lasting less than 1 hour. Recommendations could be made regarding the adequacy of the current D2.4, D4.3, D6.7 and F2.4 weather categories, and possible ways of choosing a more representative set of conditions could be suggested.

A comparison of the risks calculated on the basis of a probit or on the basis of exceeding a Dangerous Toxic Load. No such comparison has been widely published and different companies and organisations favour different approaches. The project would compare the two approaches identifying the advantages and disadvantages of each, with specific reference to the inclusion of low wind speed effects. Risks from radiation and blast overpressure could also be considered.

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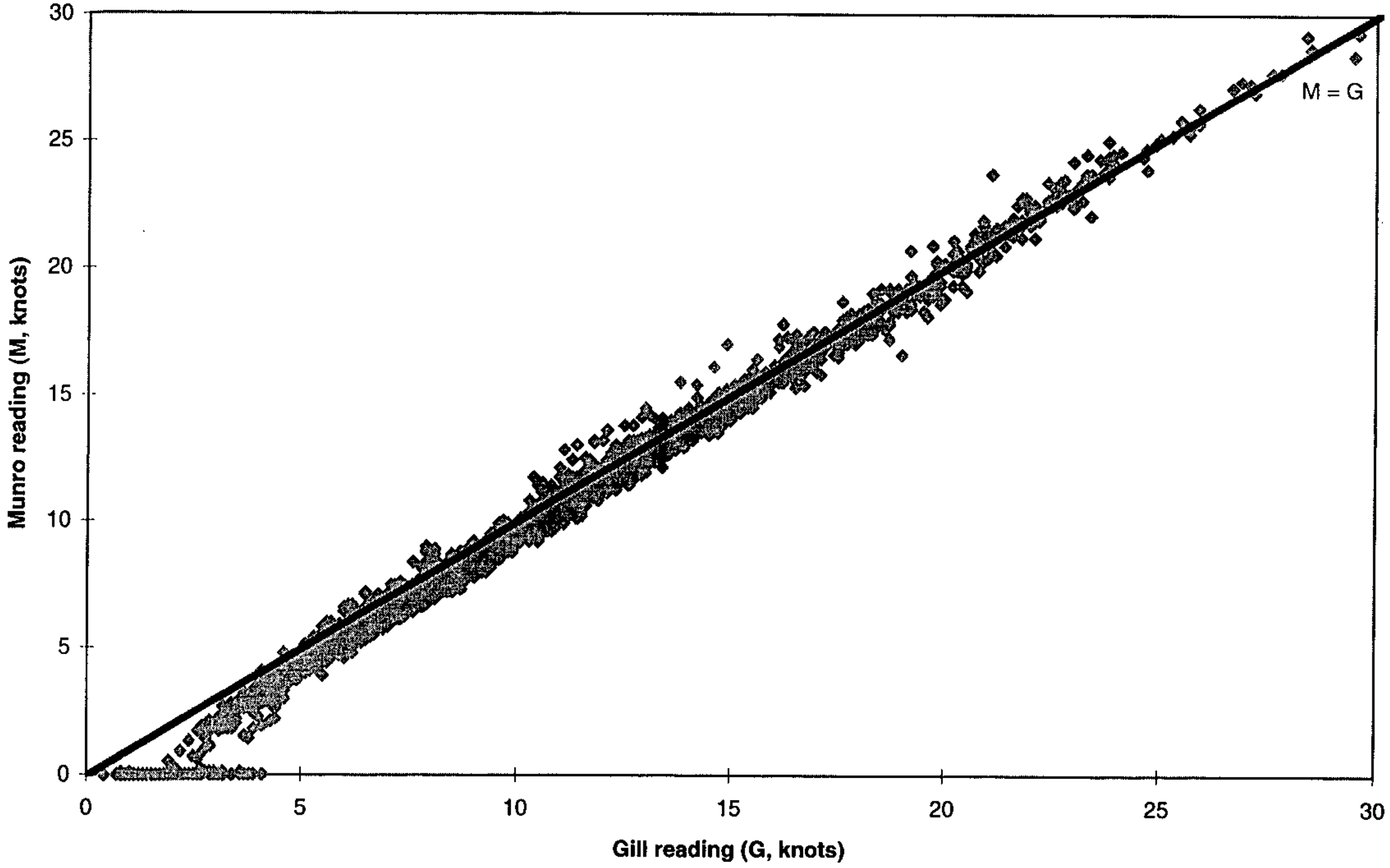

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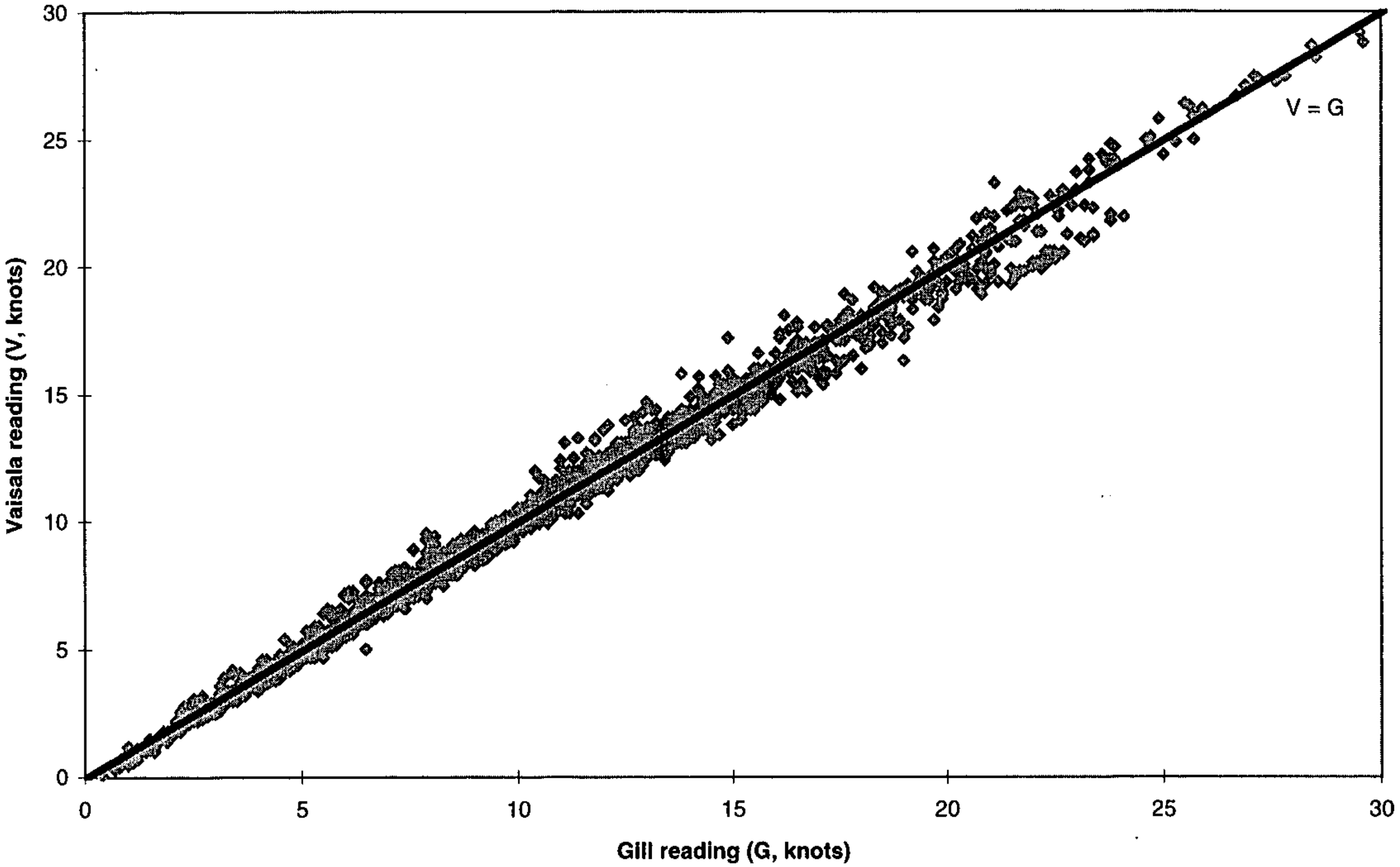

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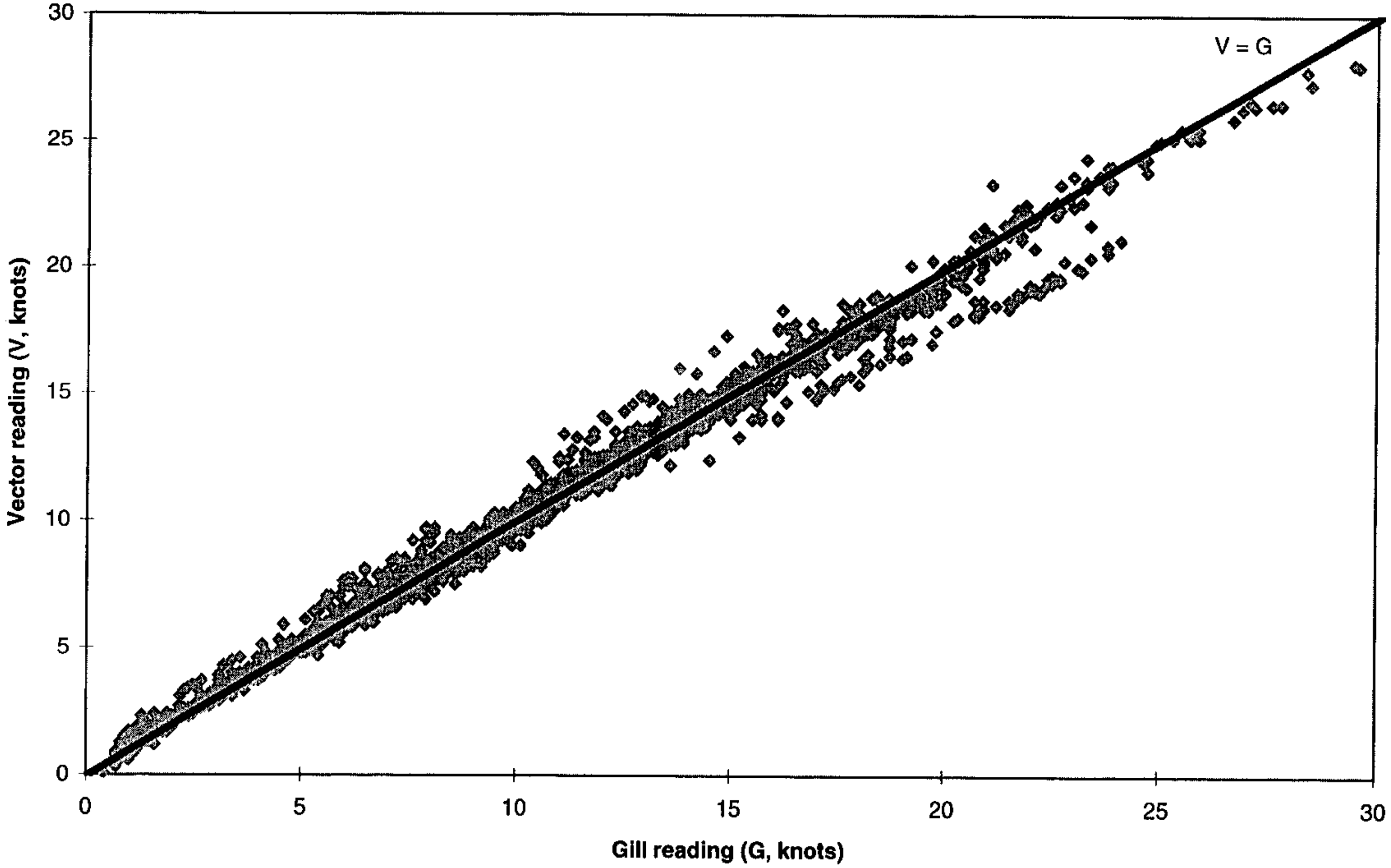

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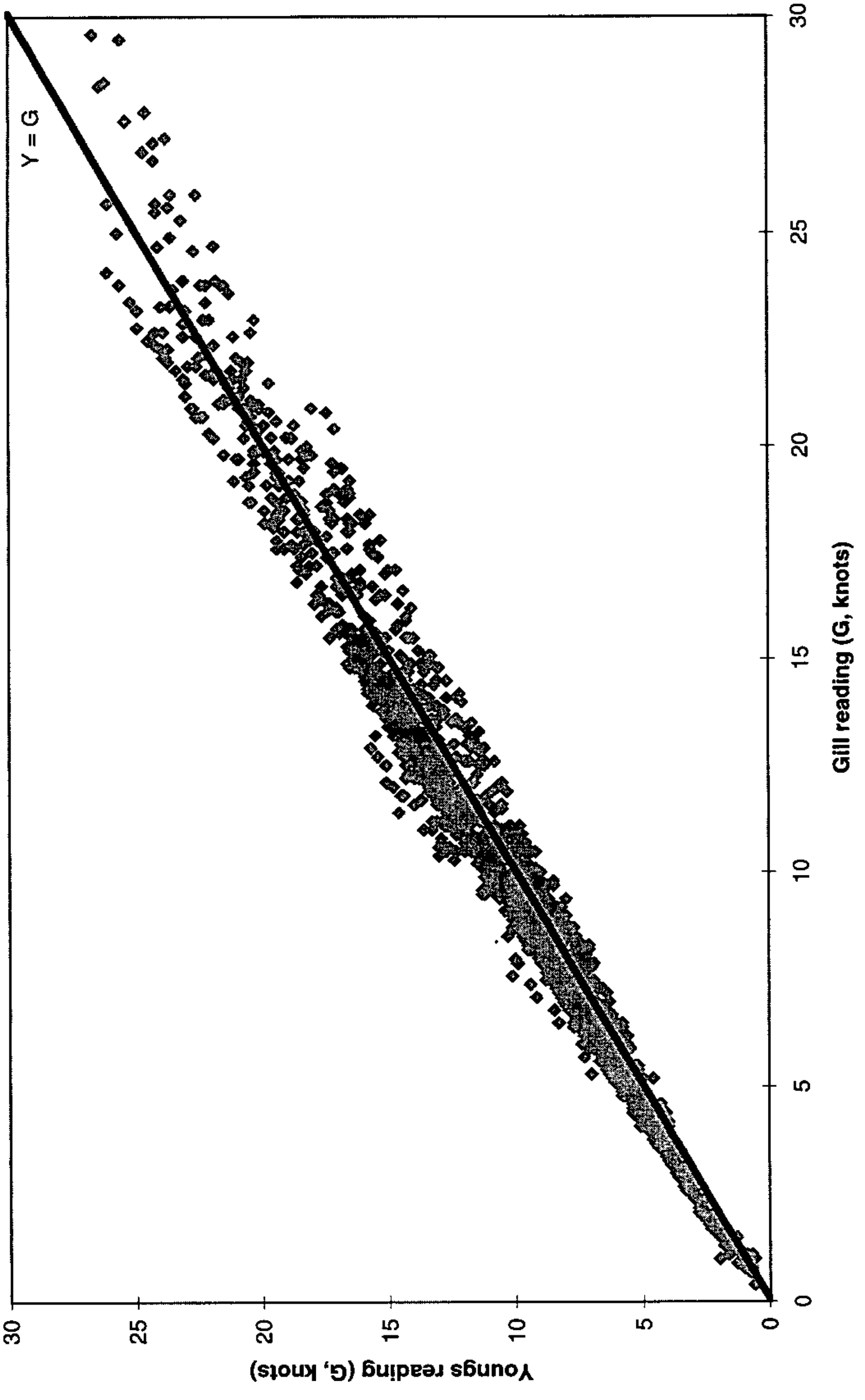

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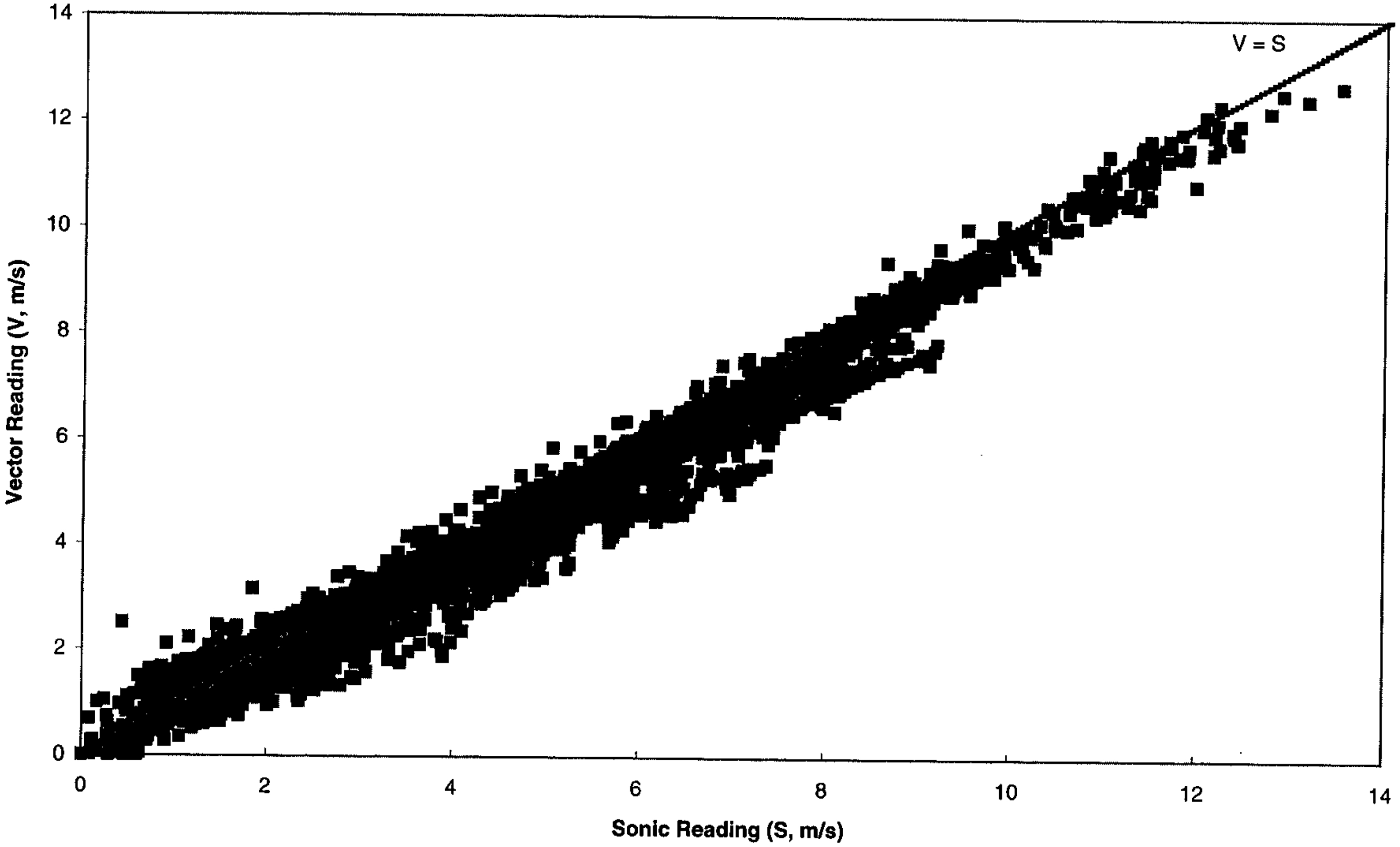

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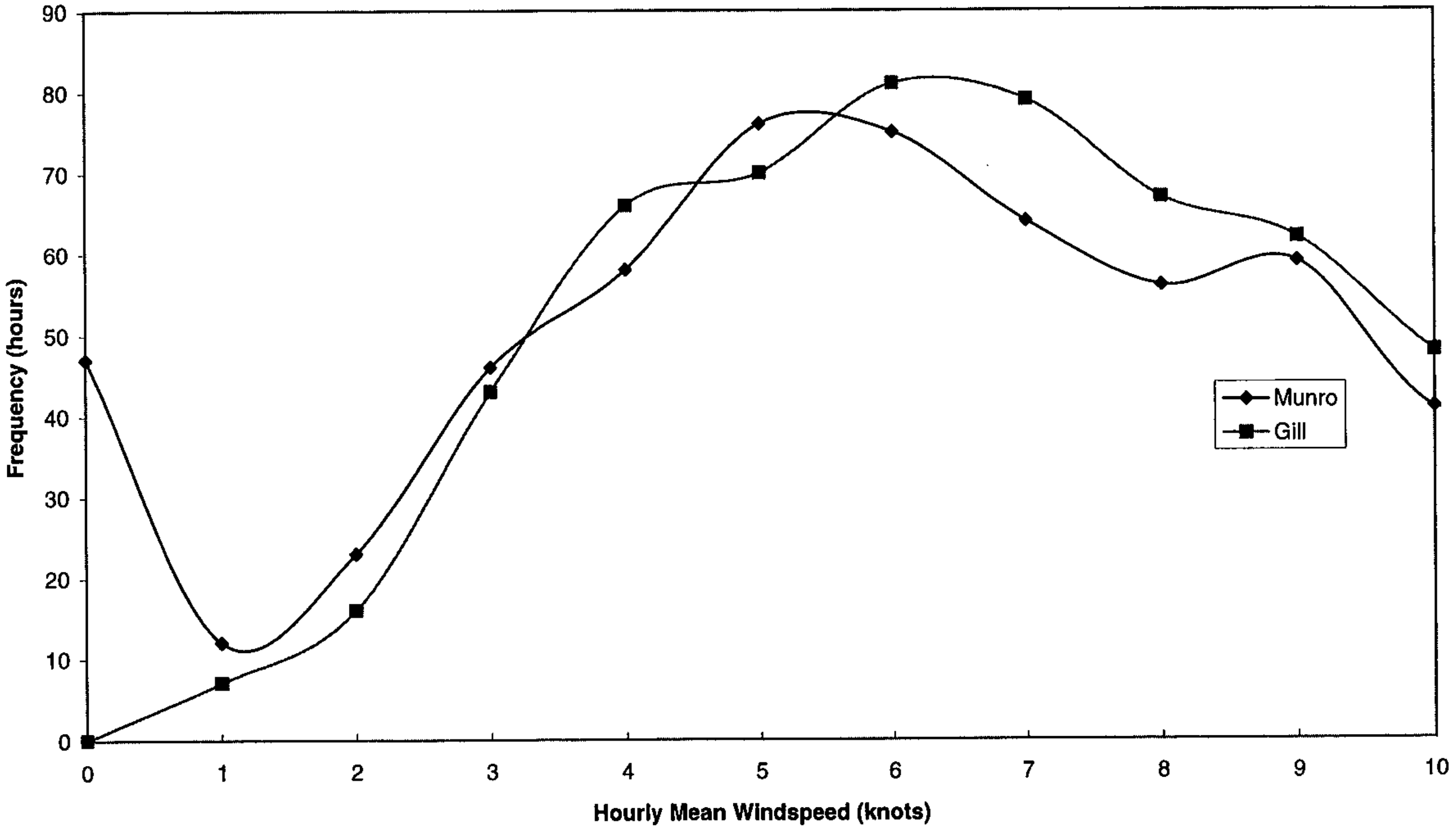

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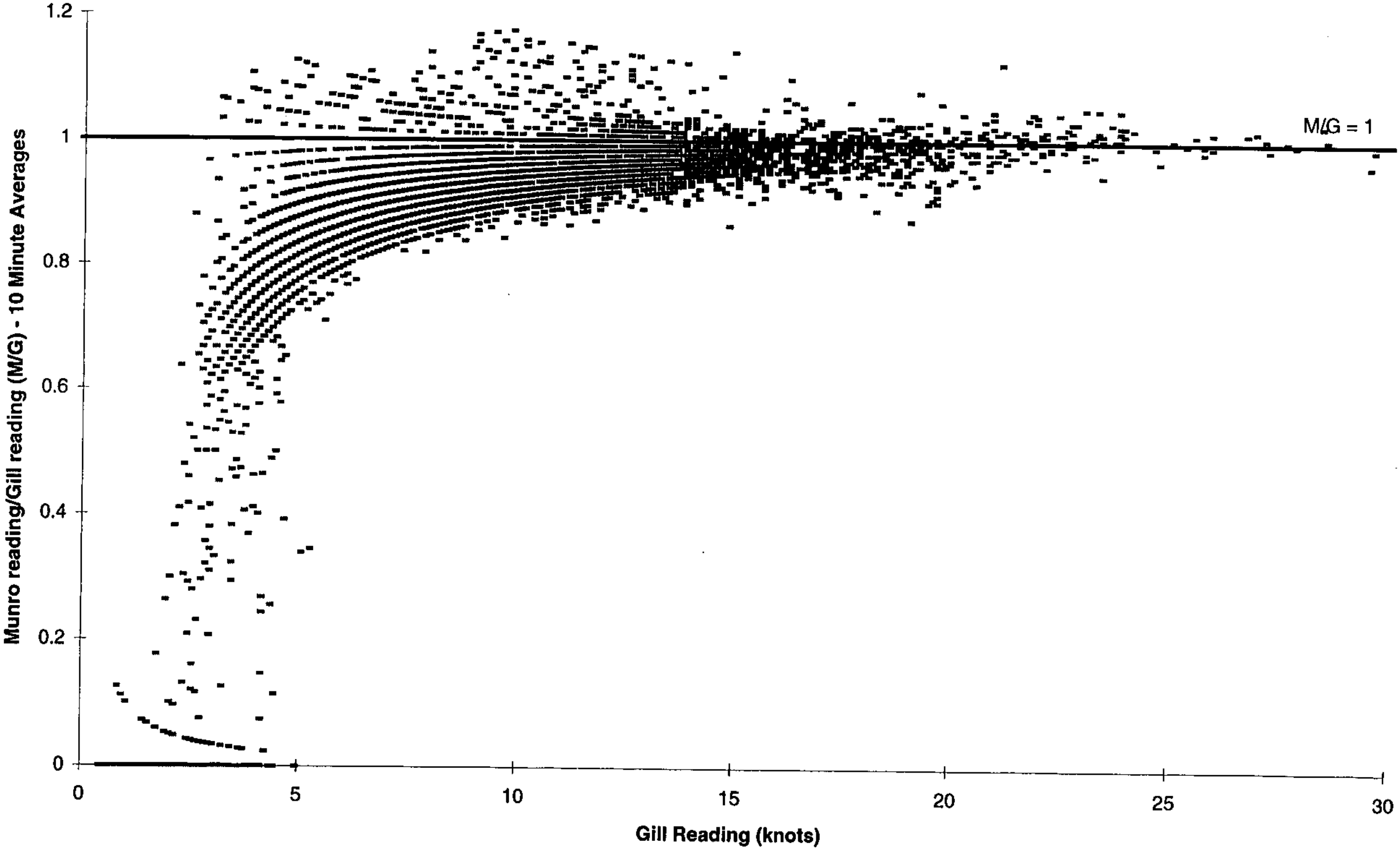

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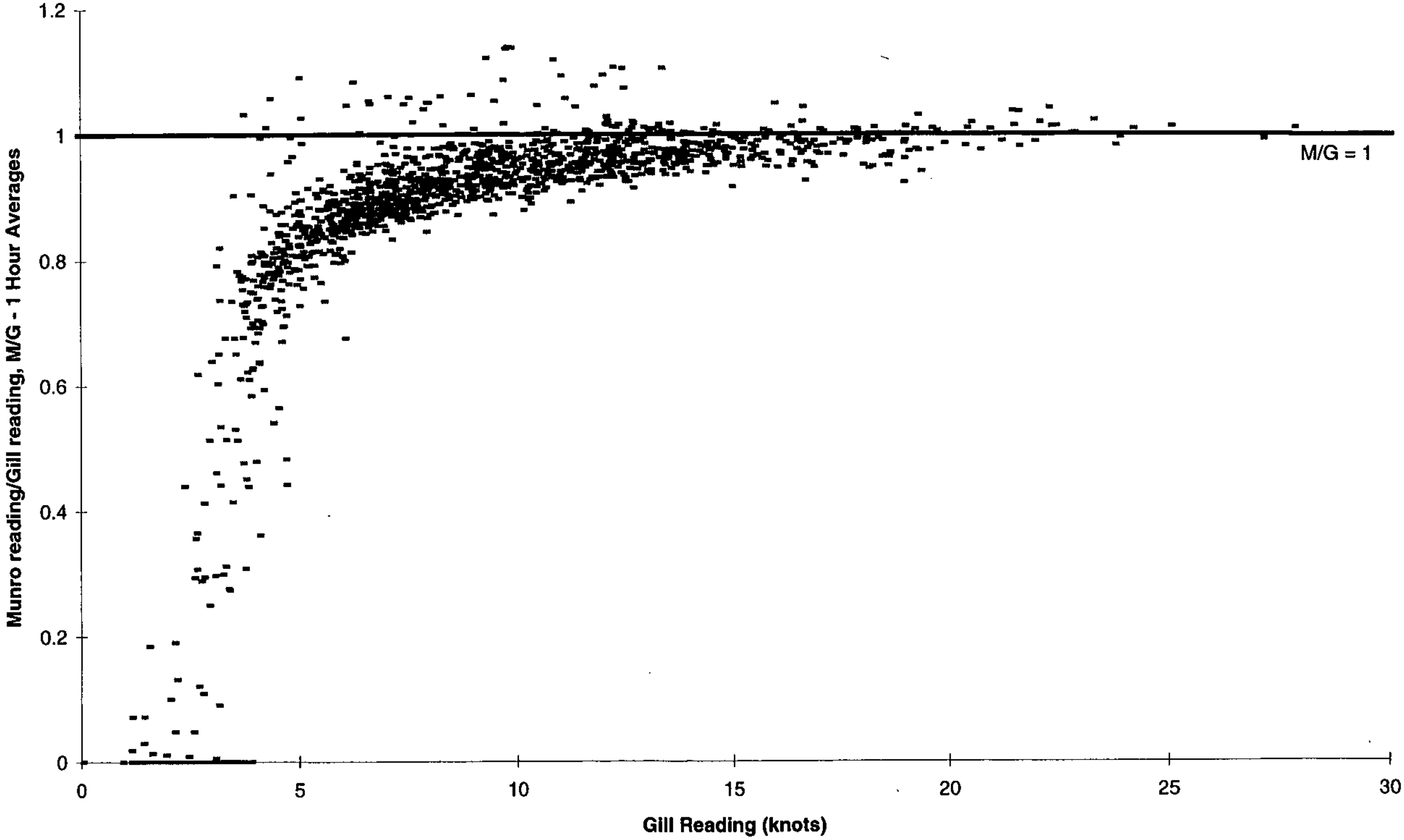

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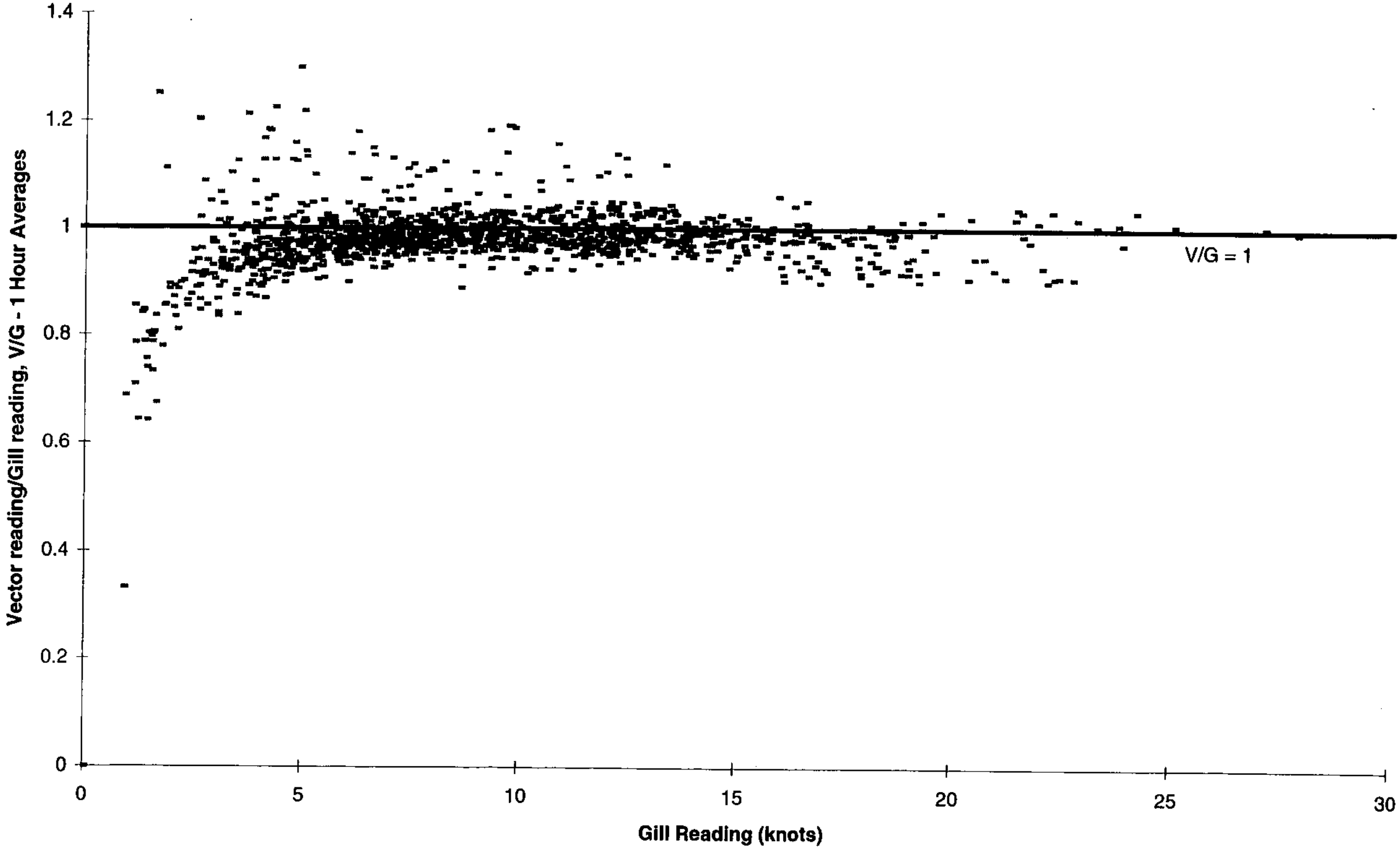

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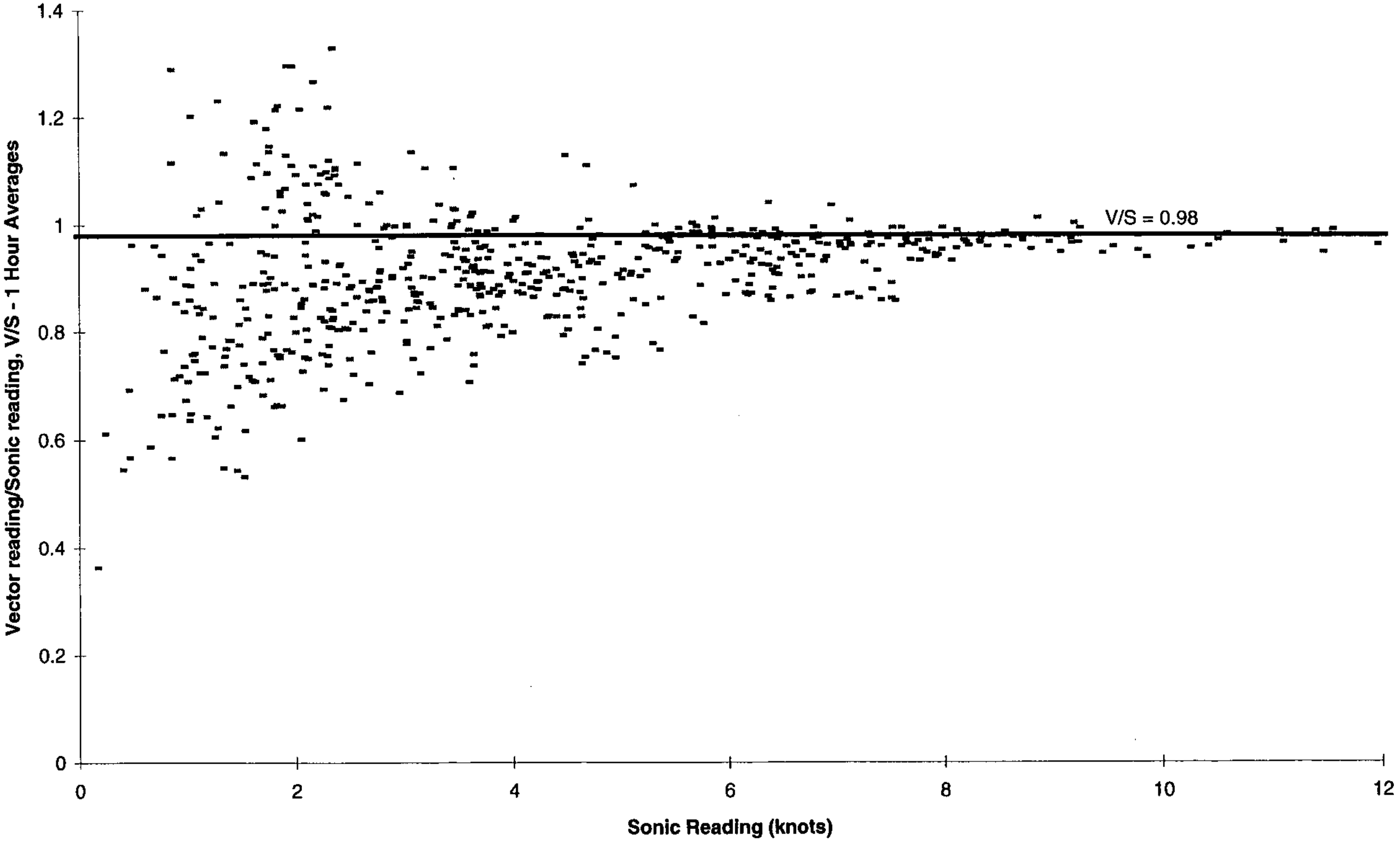

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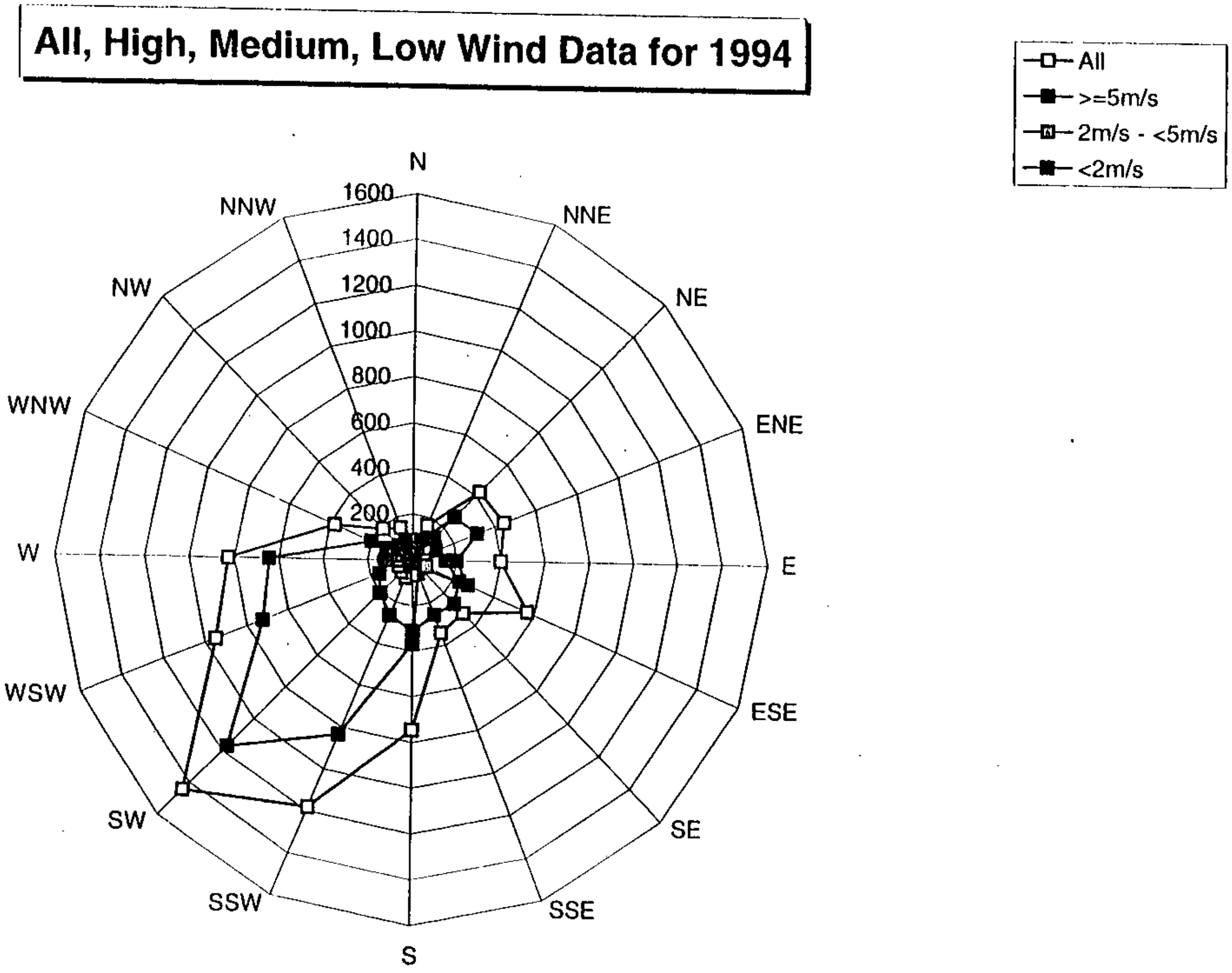

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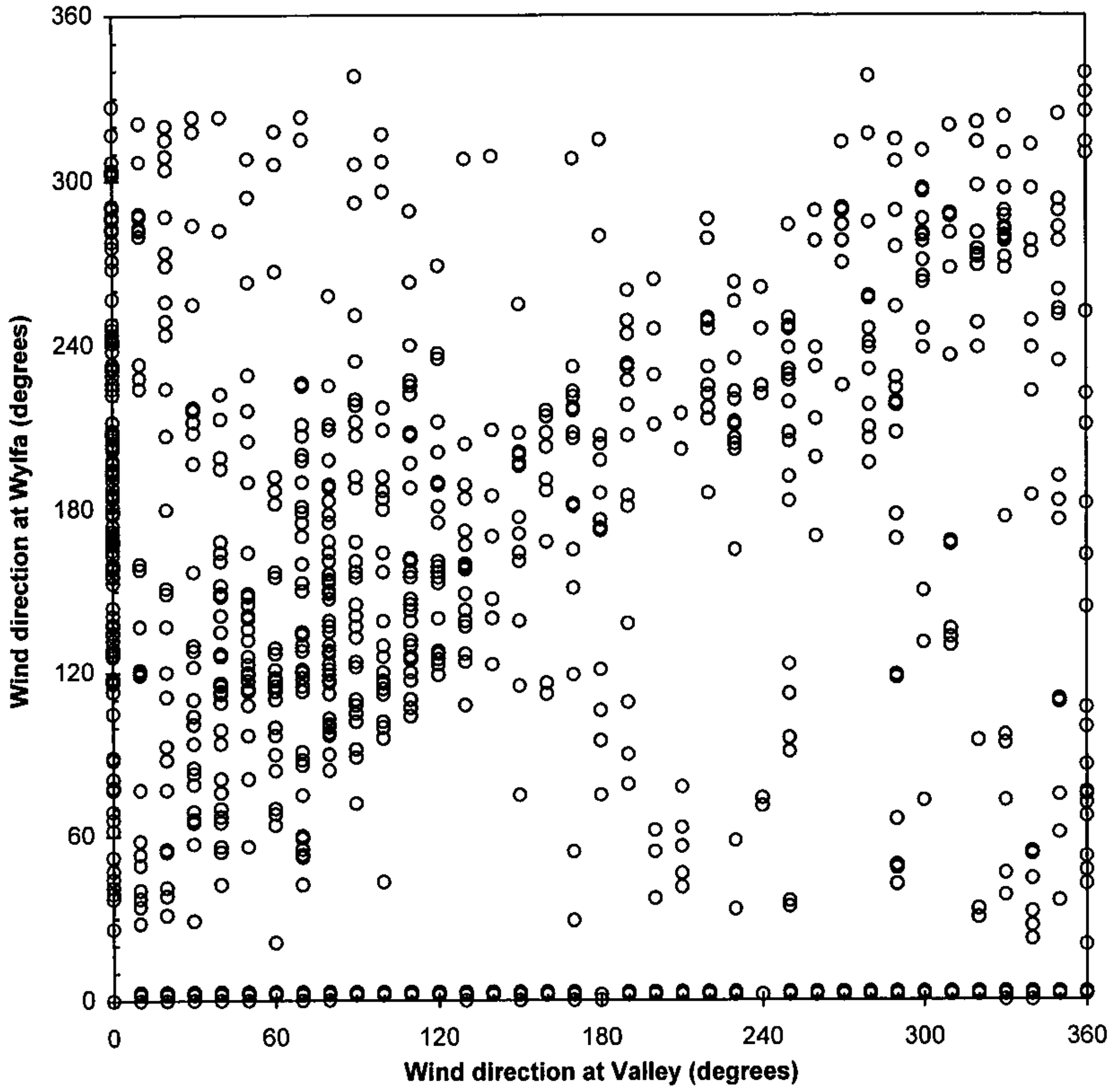

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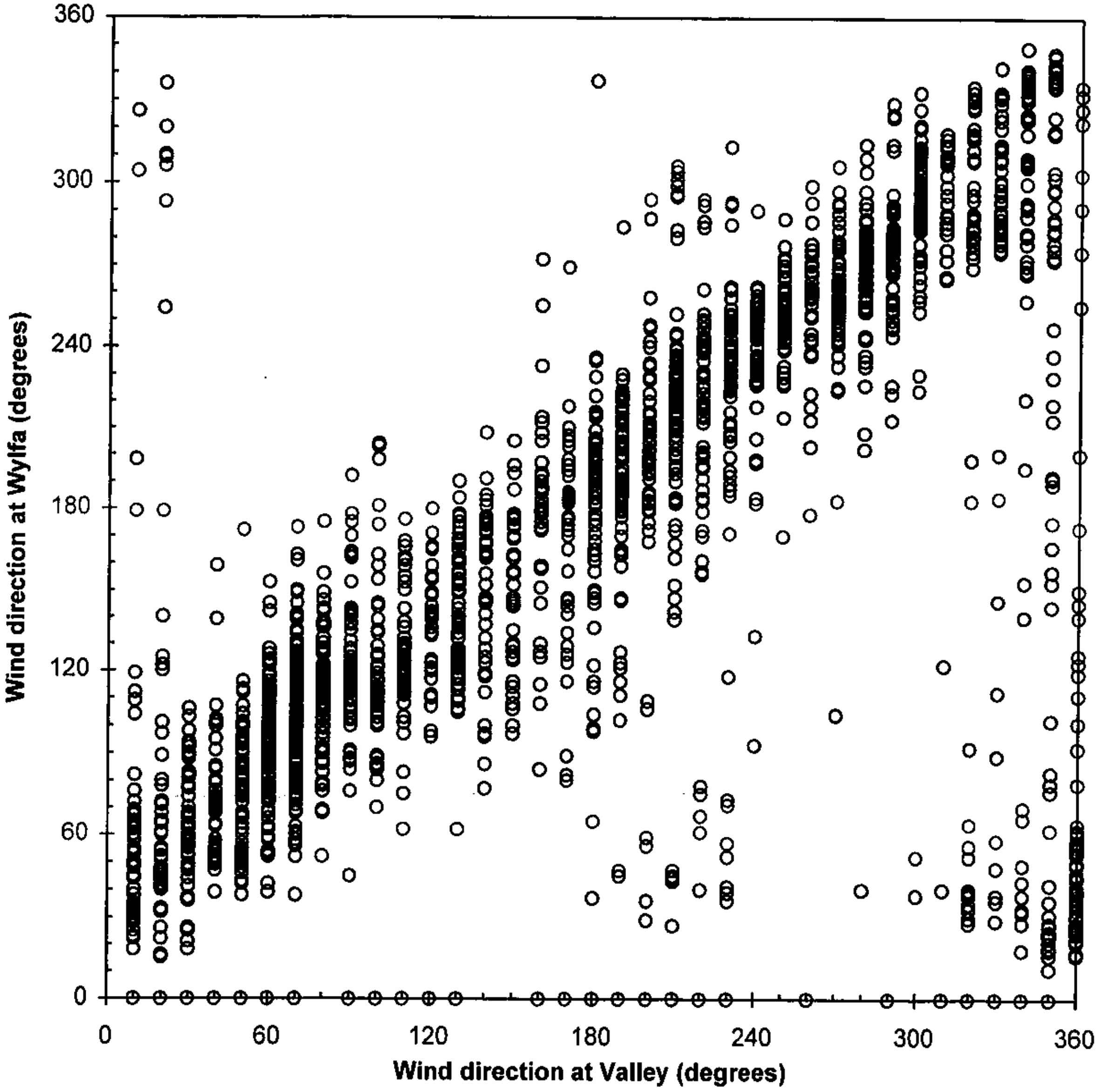

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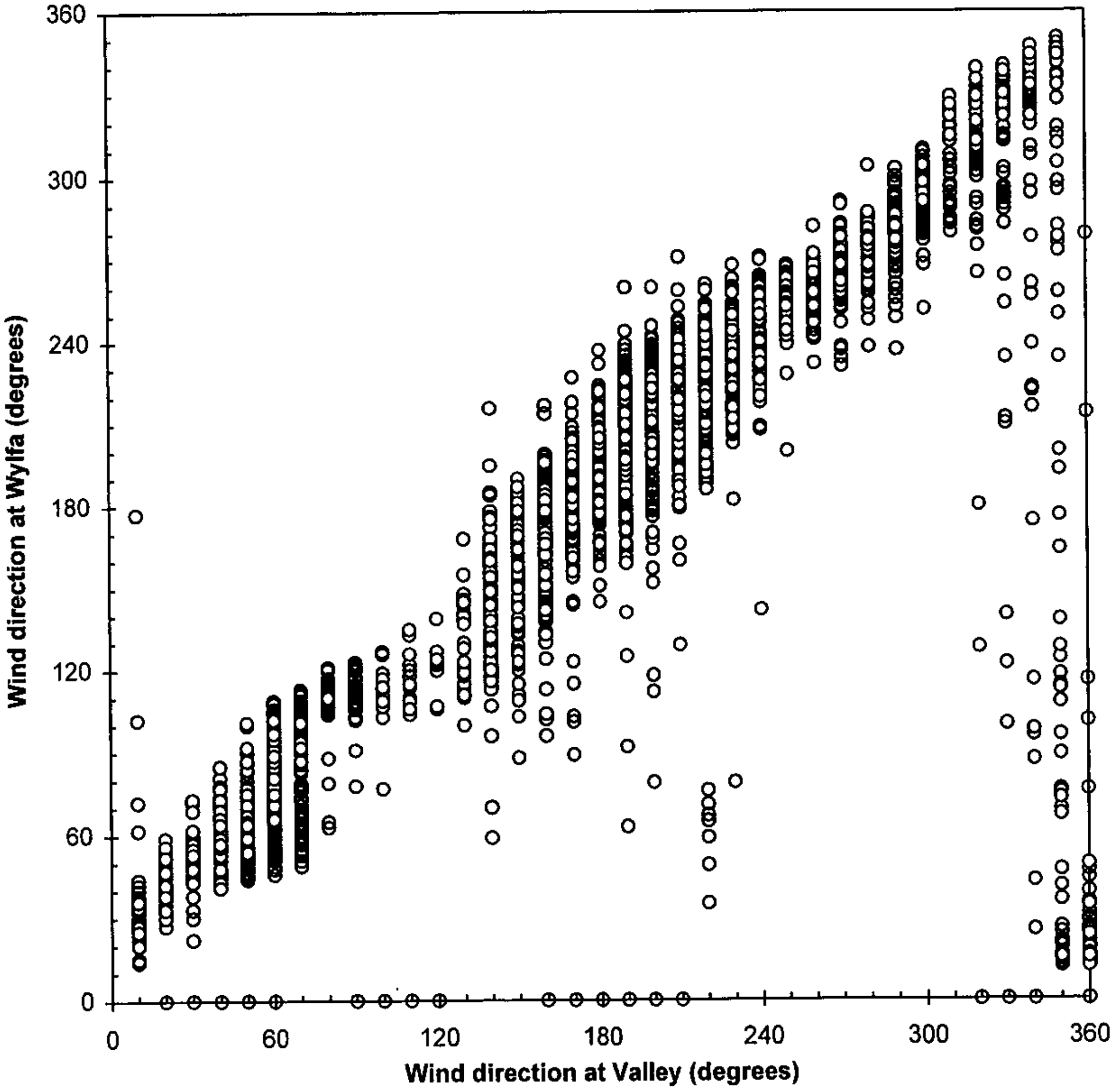

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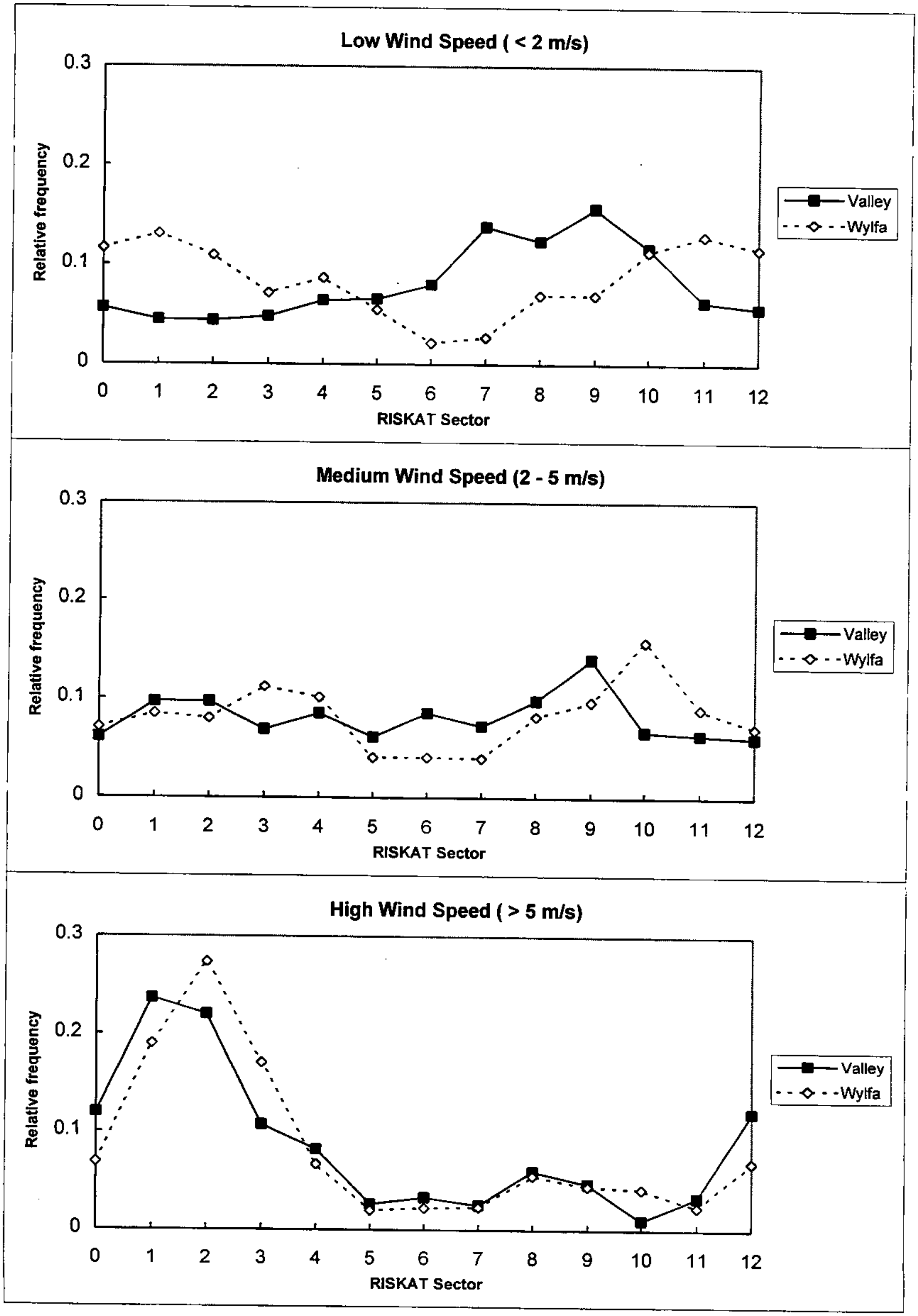

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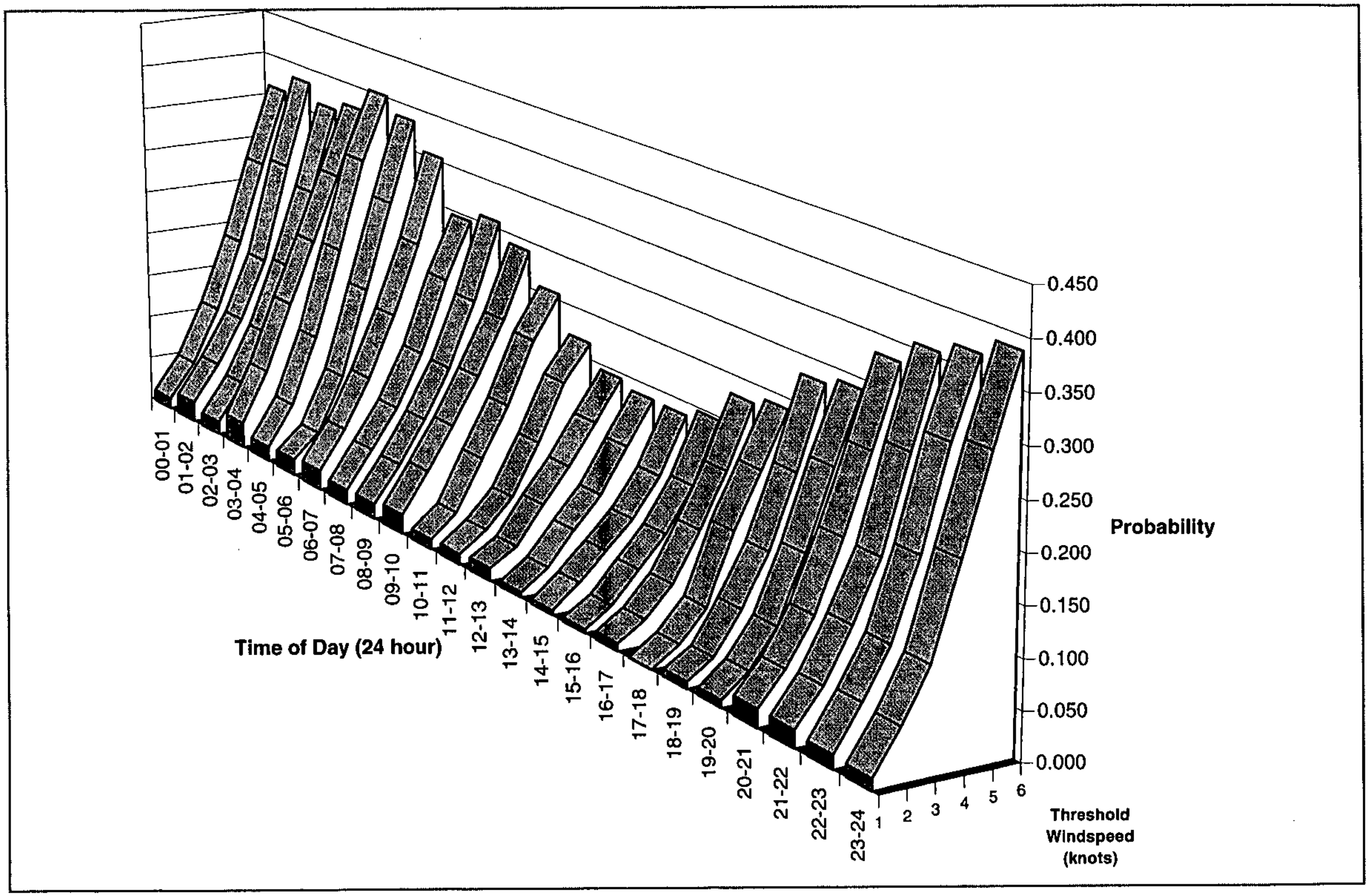

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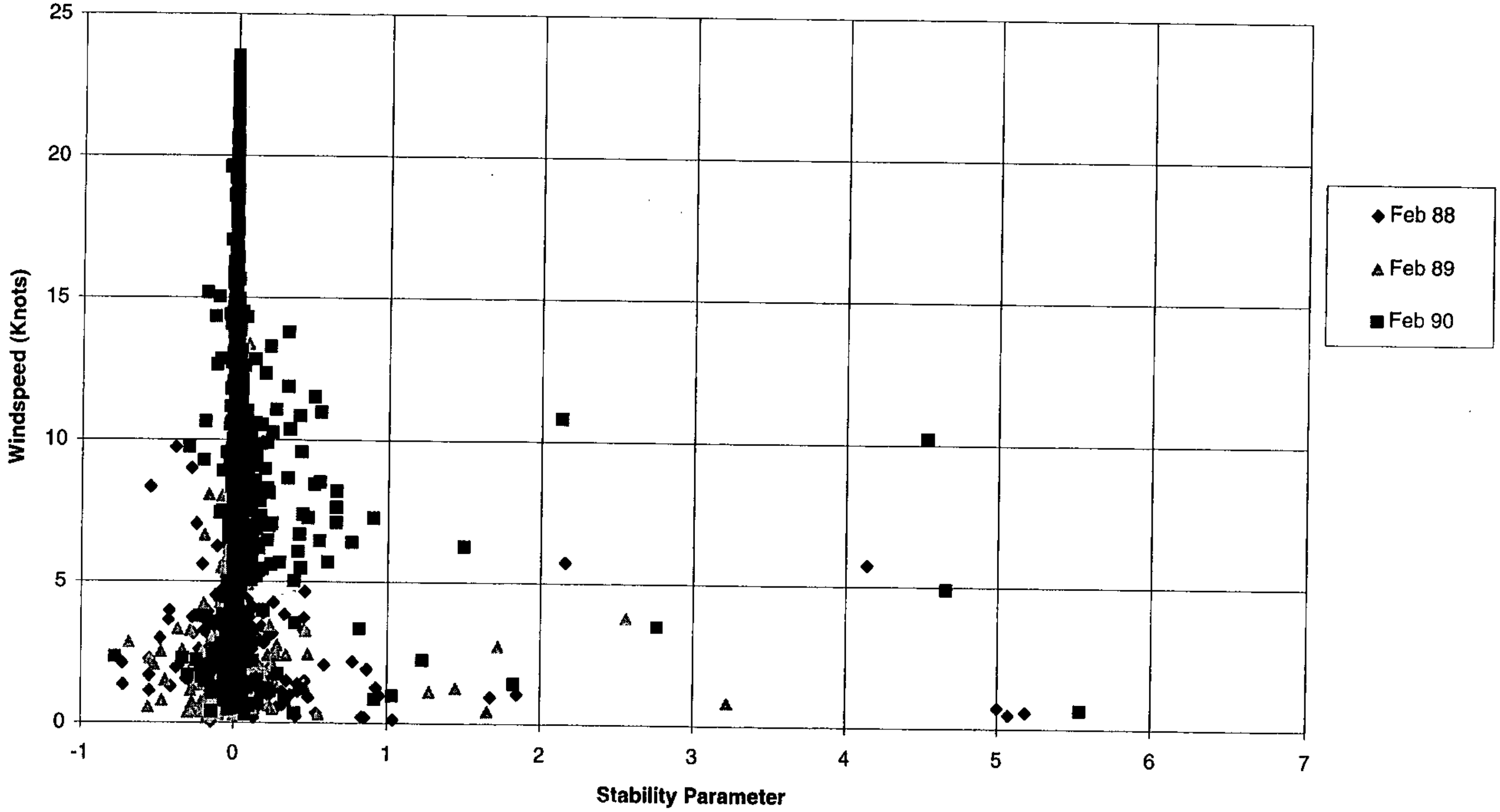

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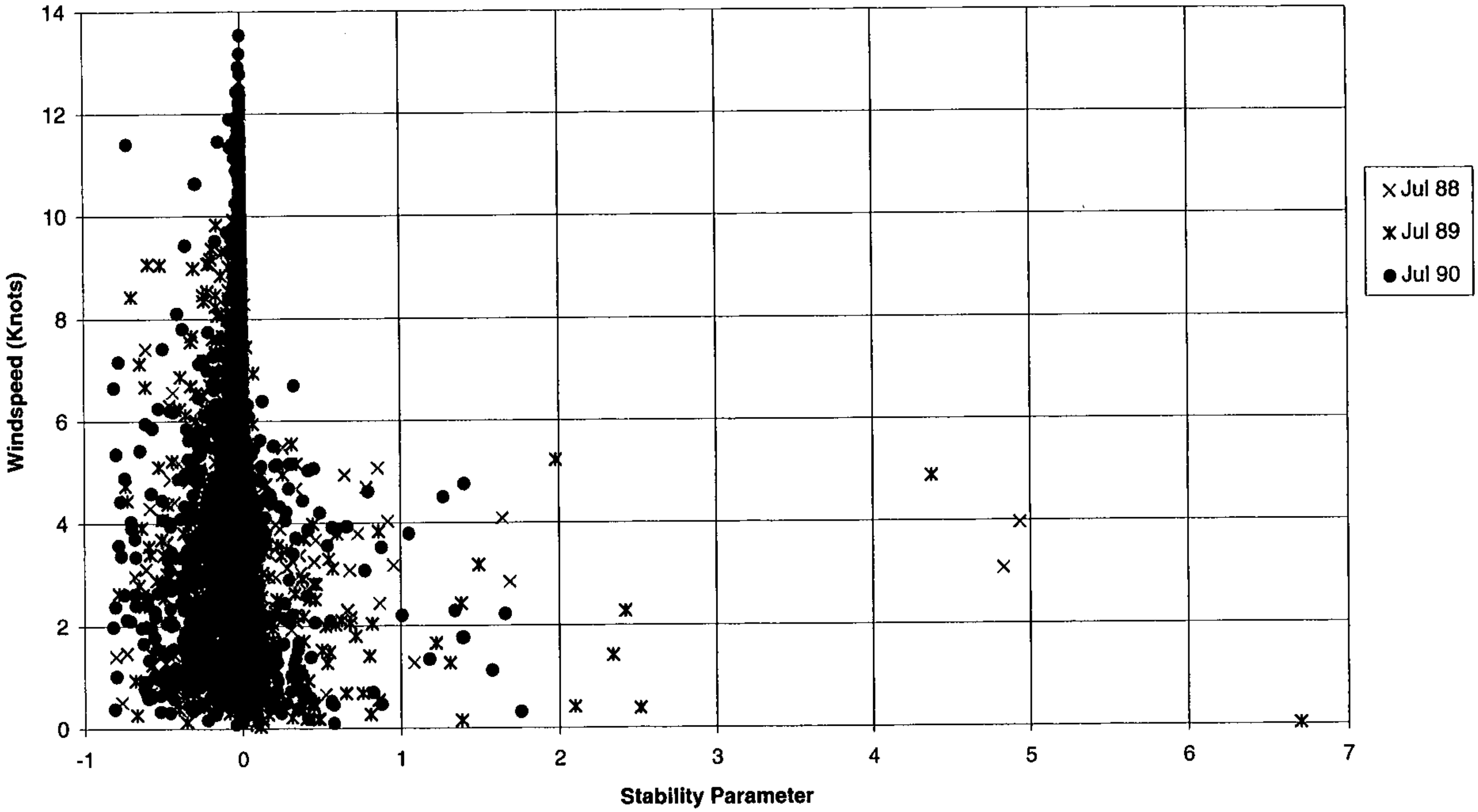

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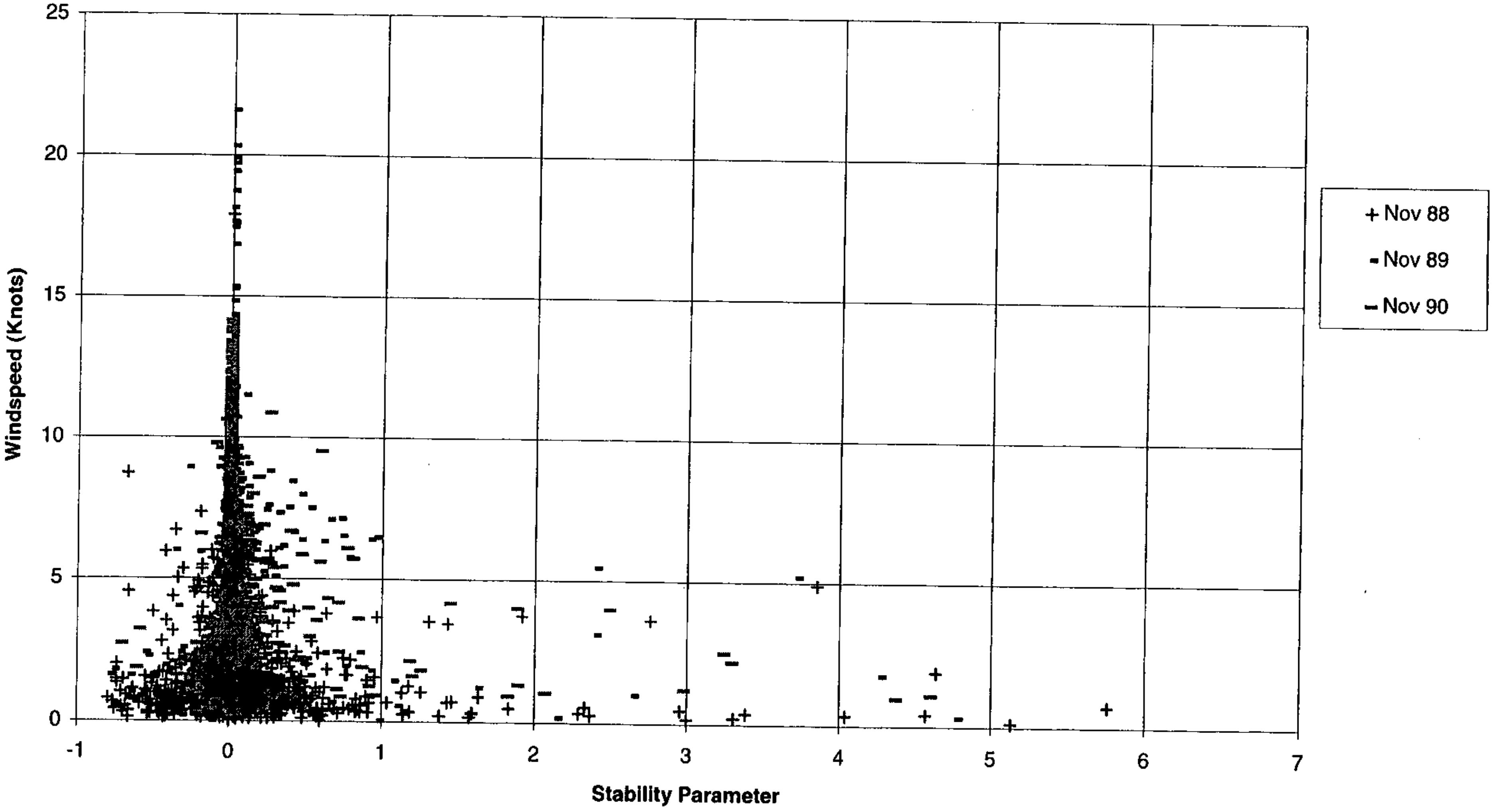

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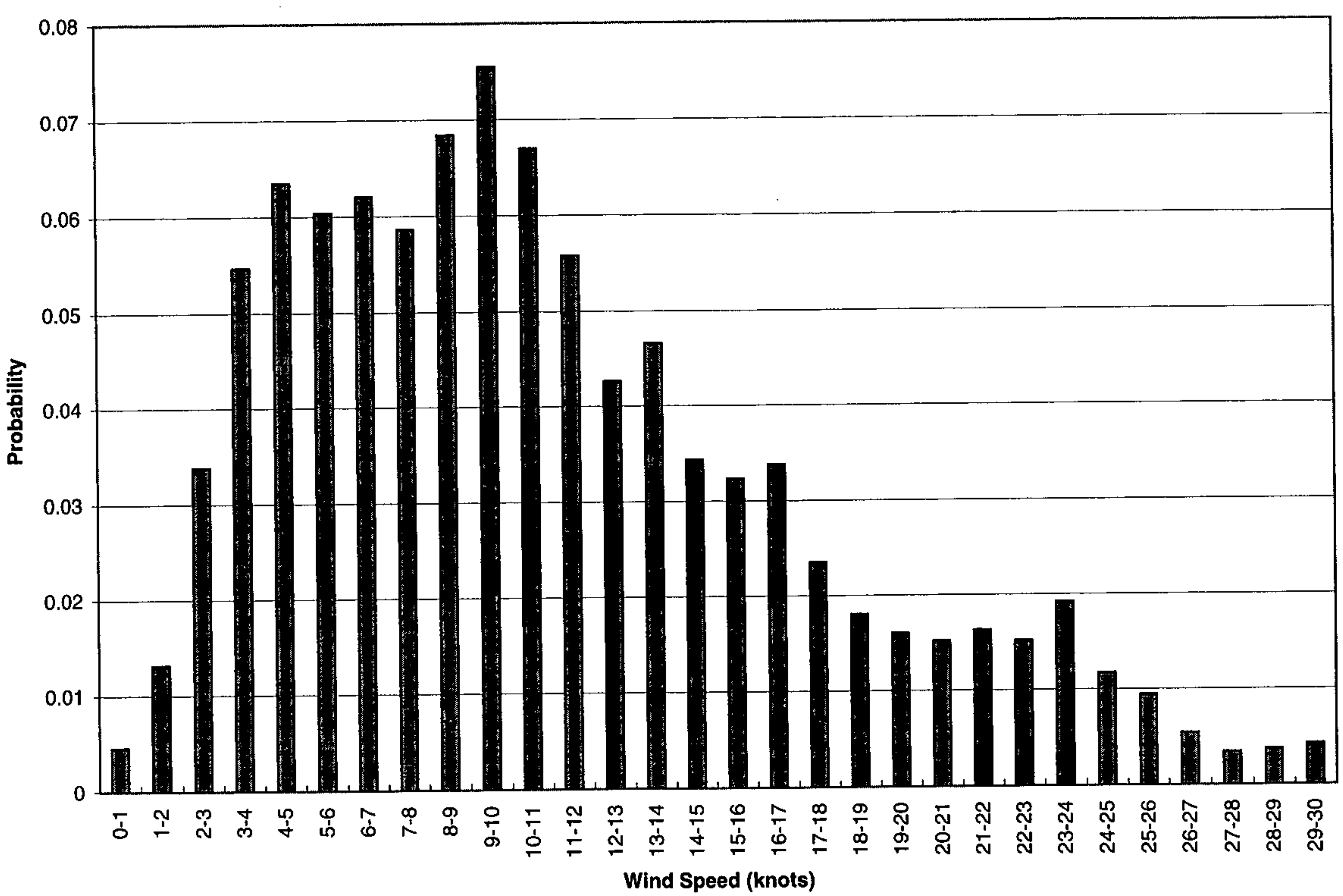

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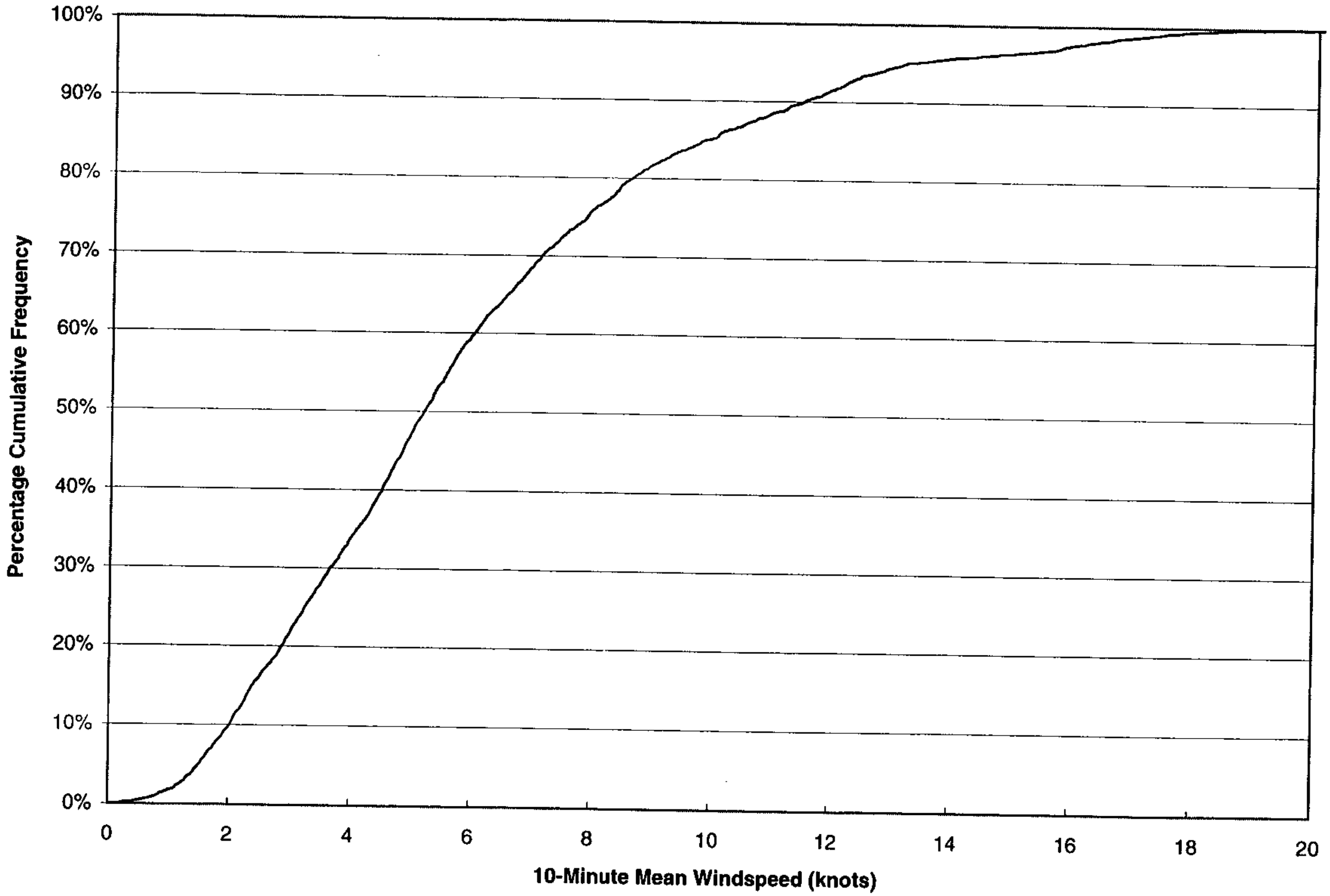

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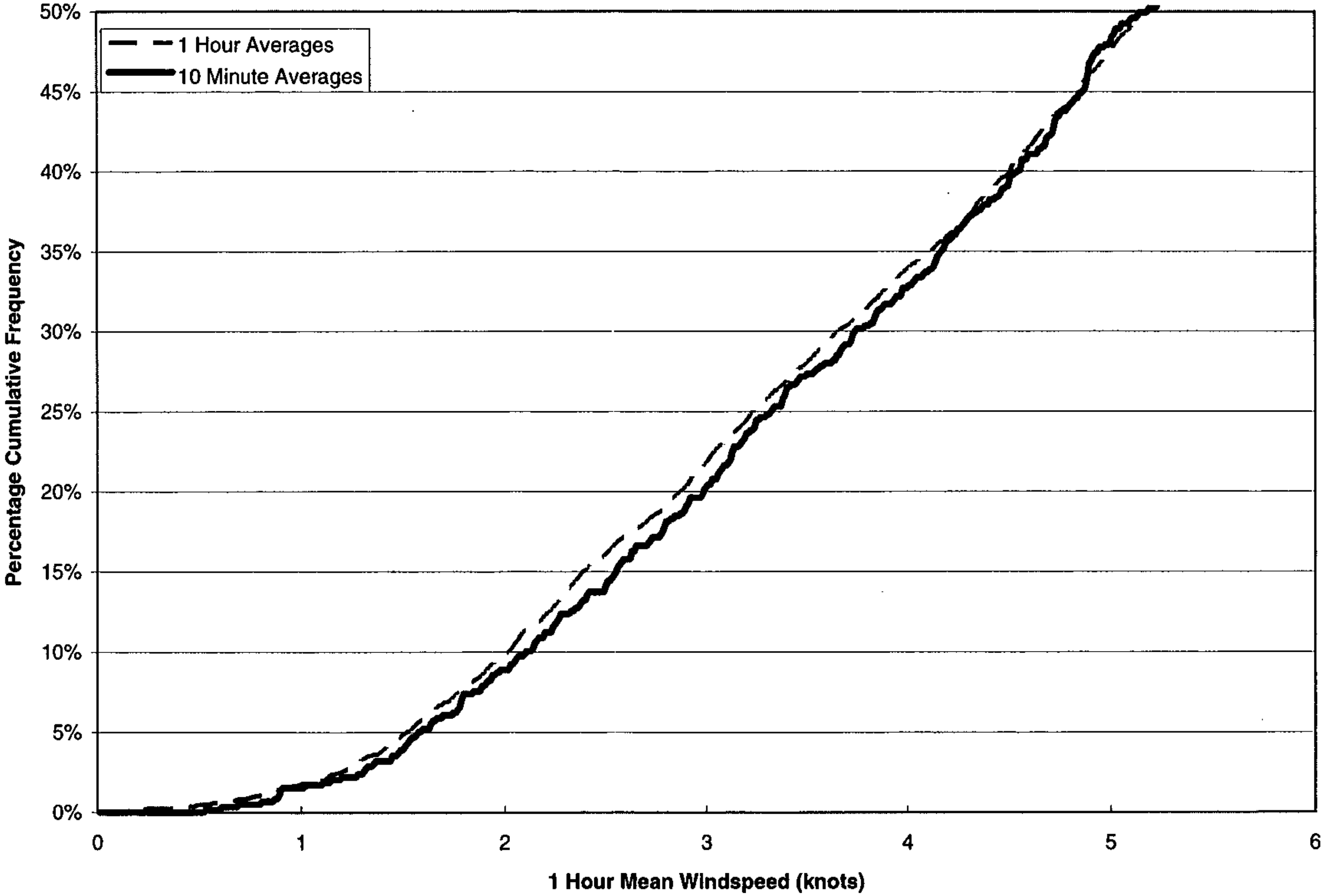

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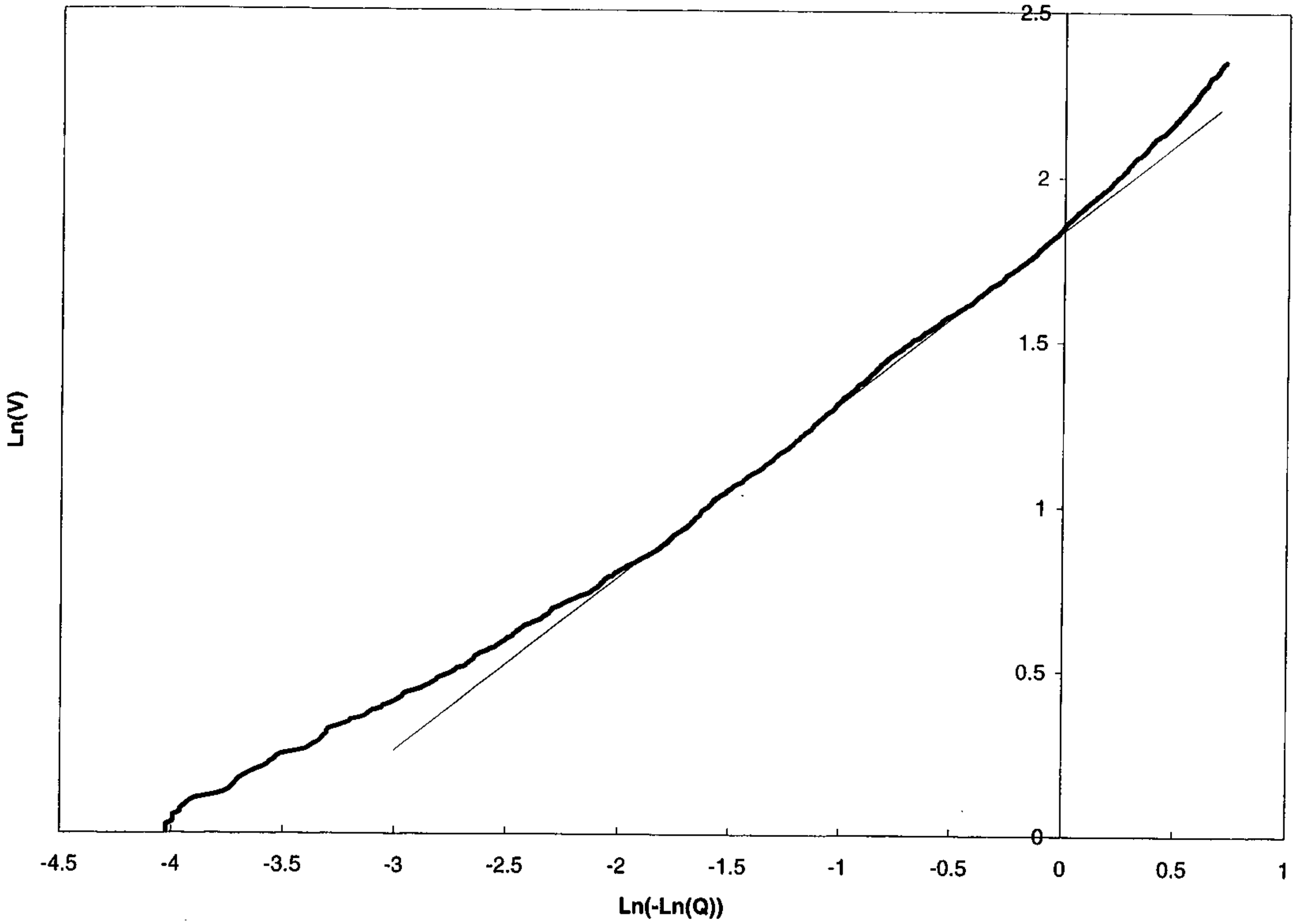

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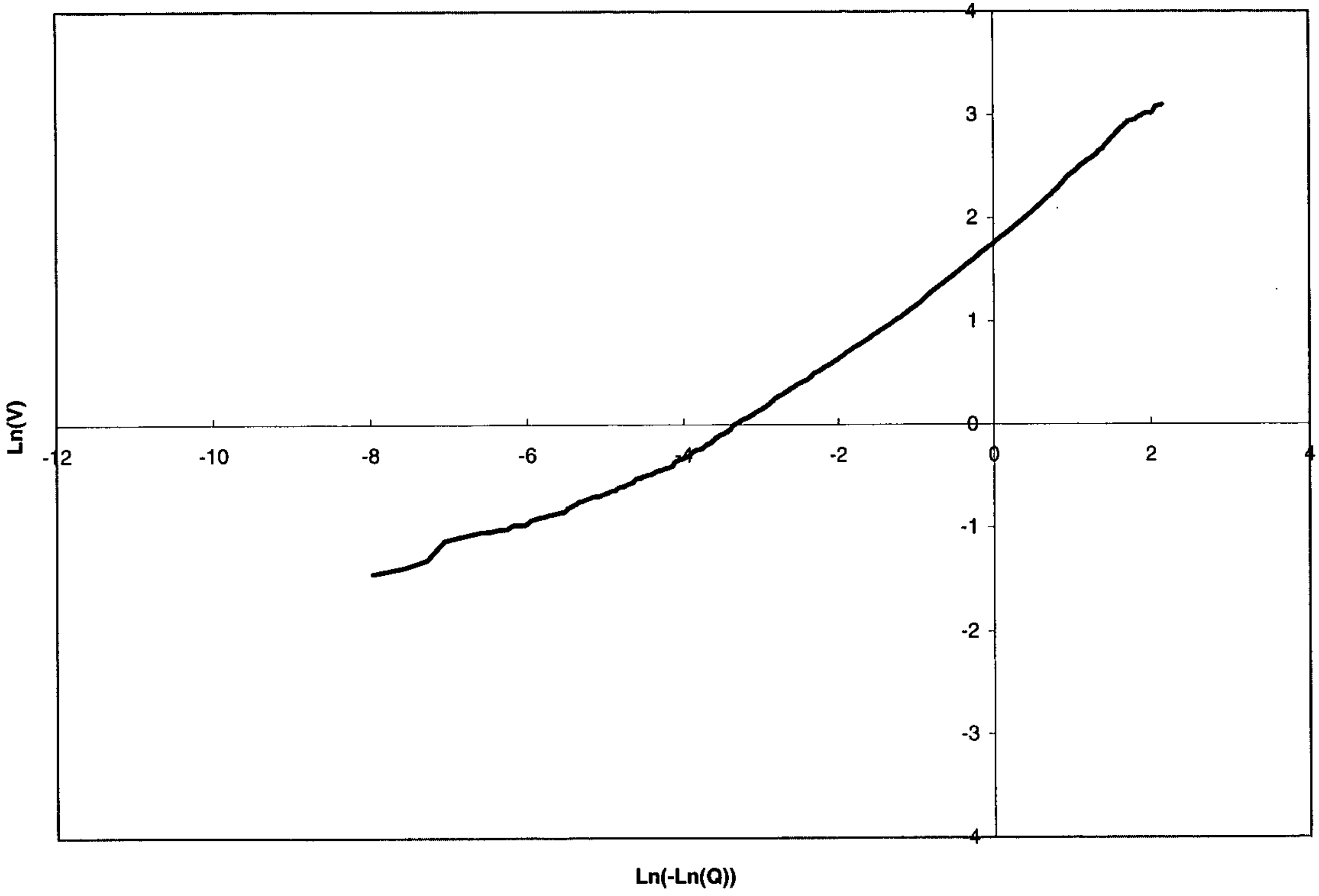

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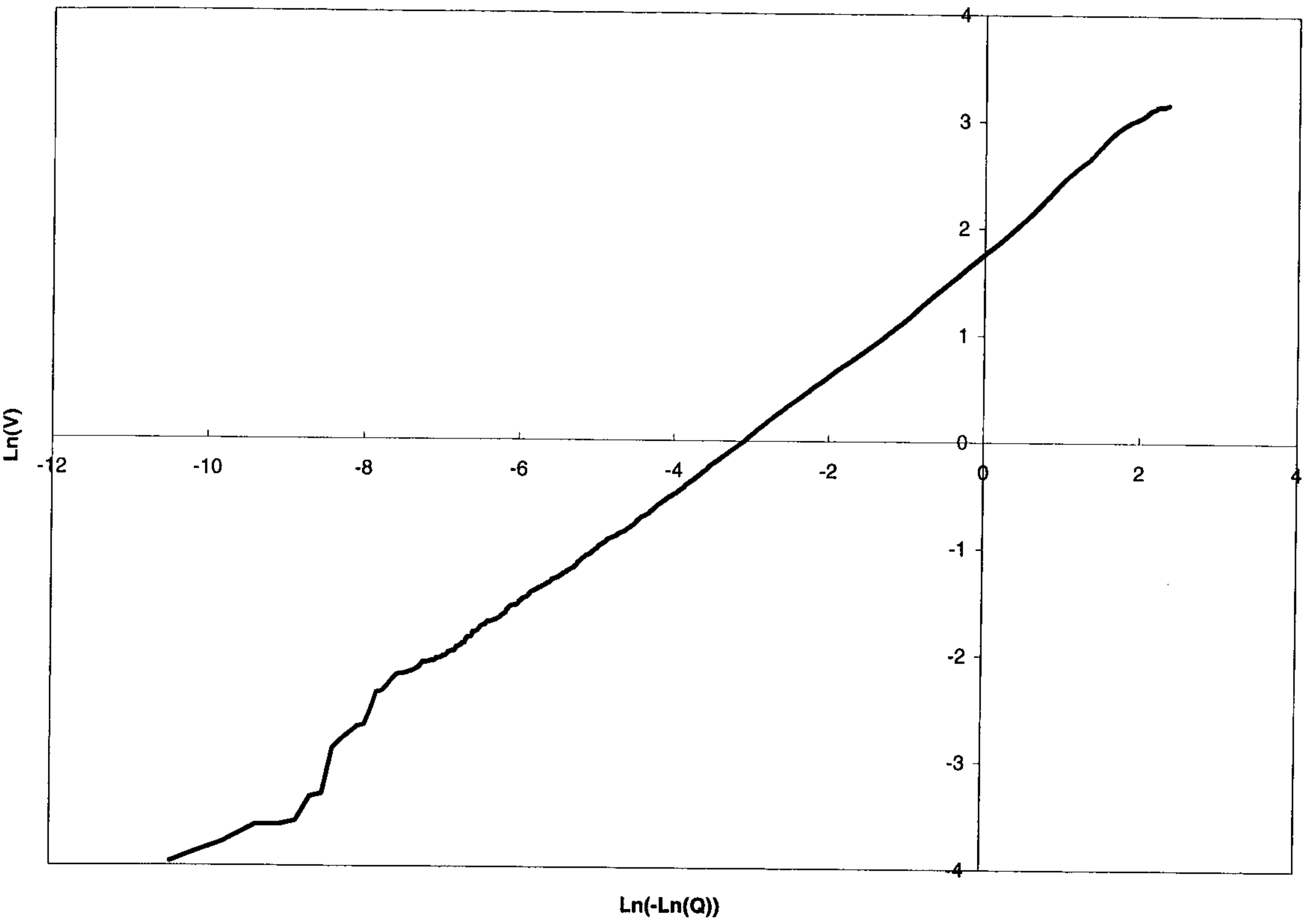
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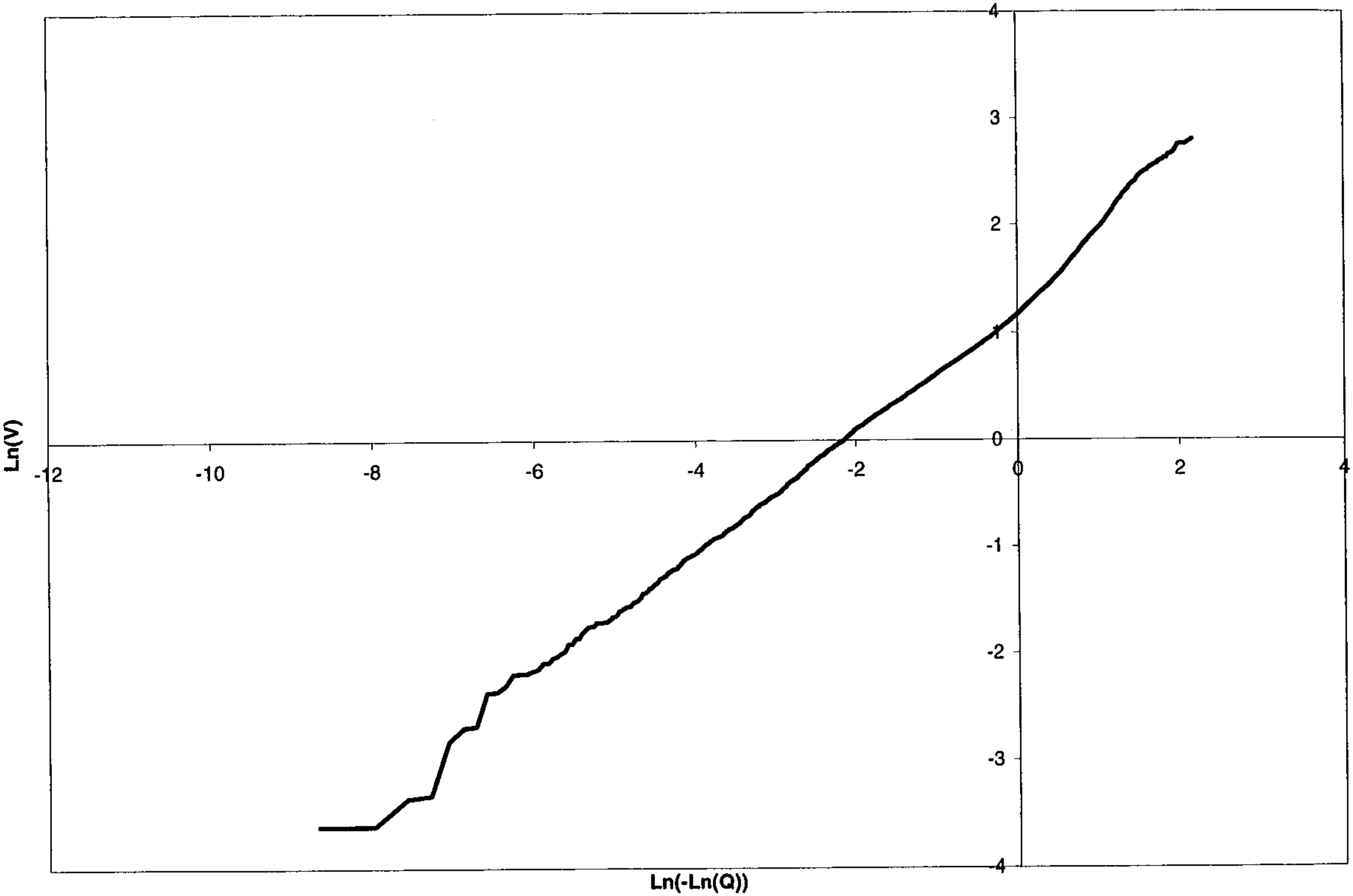
4
3
2
1
0
-1
-2
-3
-4
-12
-10
-8
-6
-4
-2
0
2
4
Ln(-Ln(Q))

[illegible]



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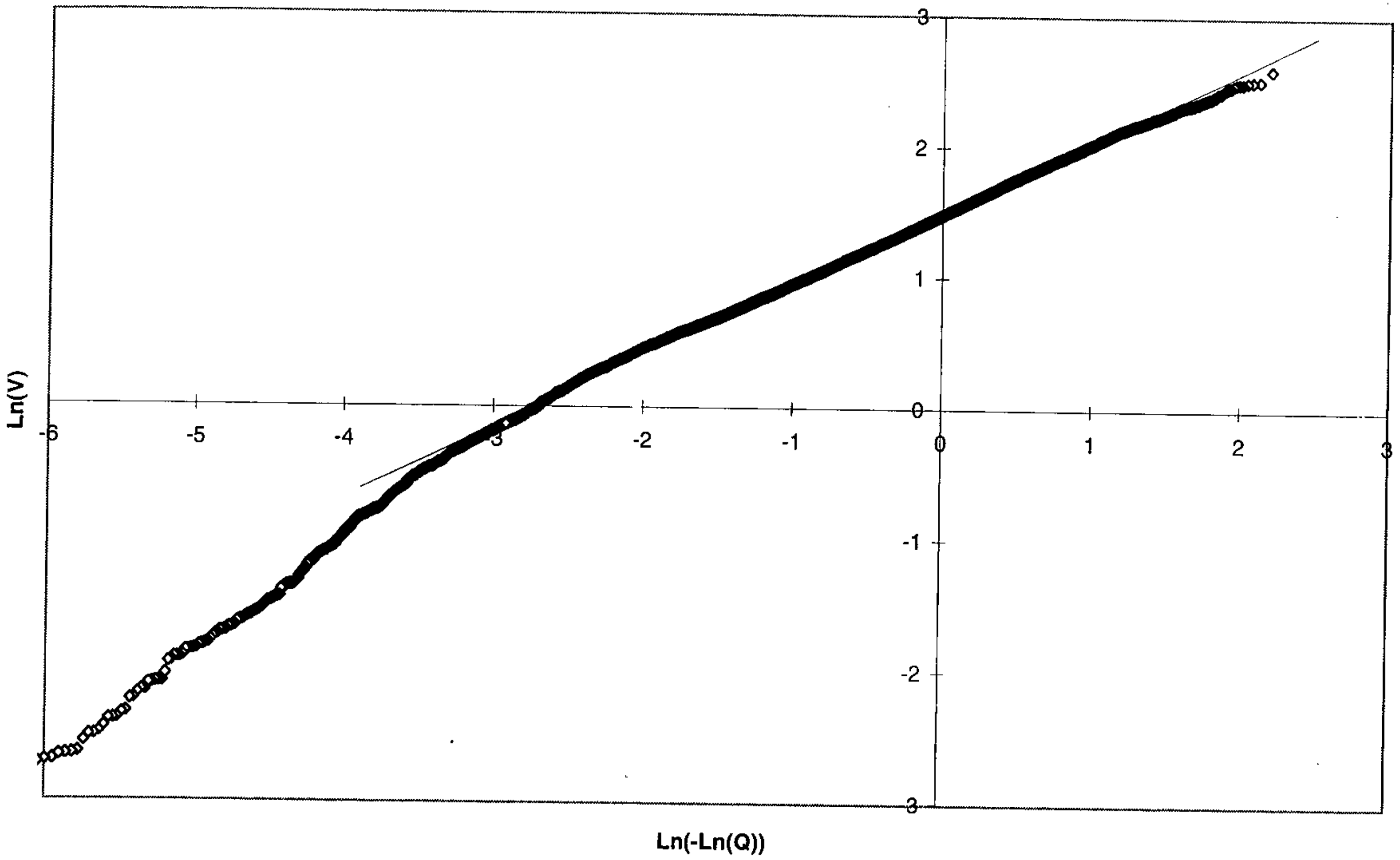

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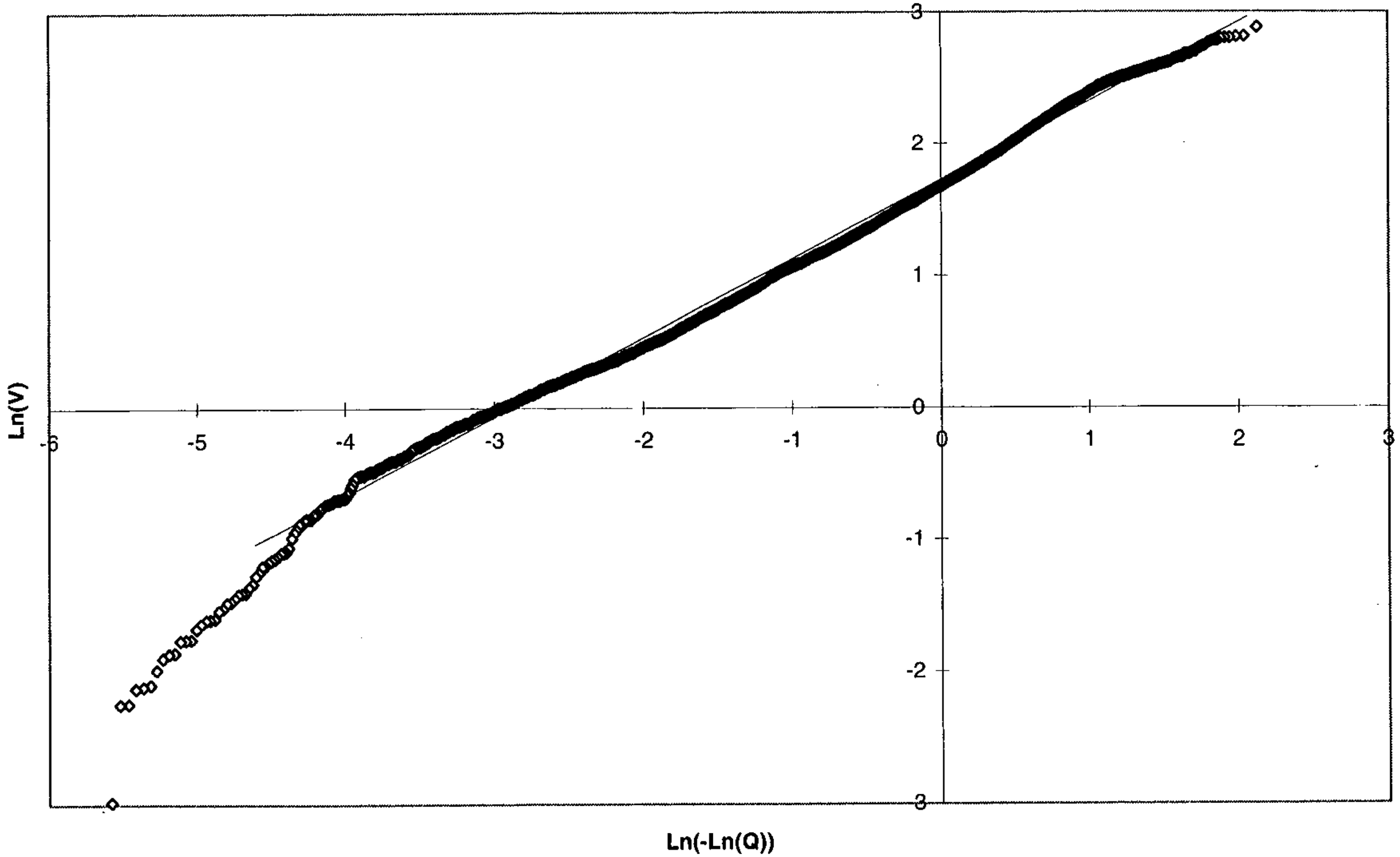

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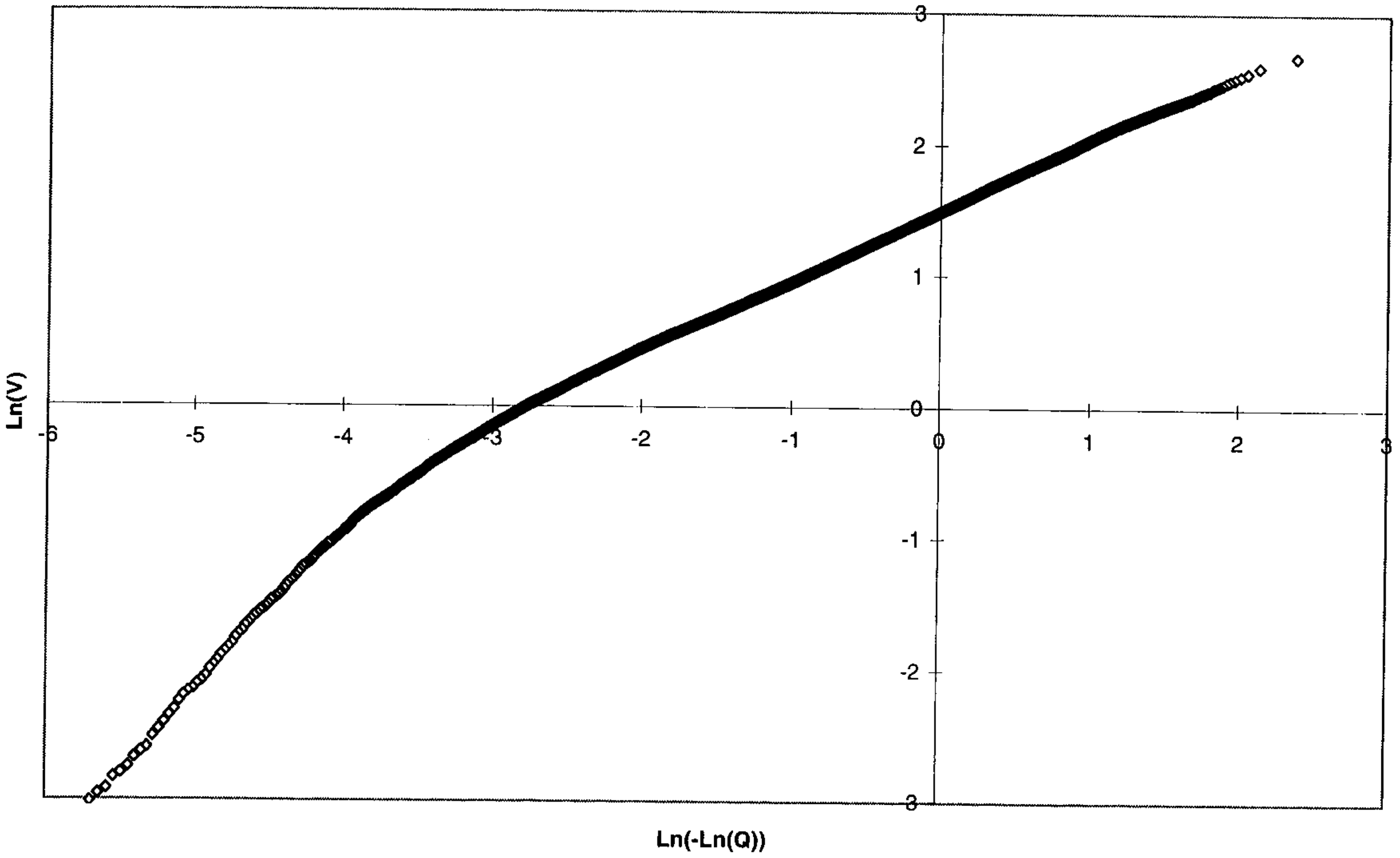

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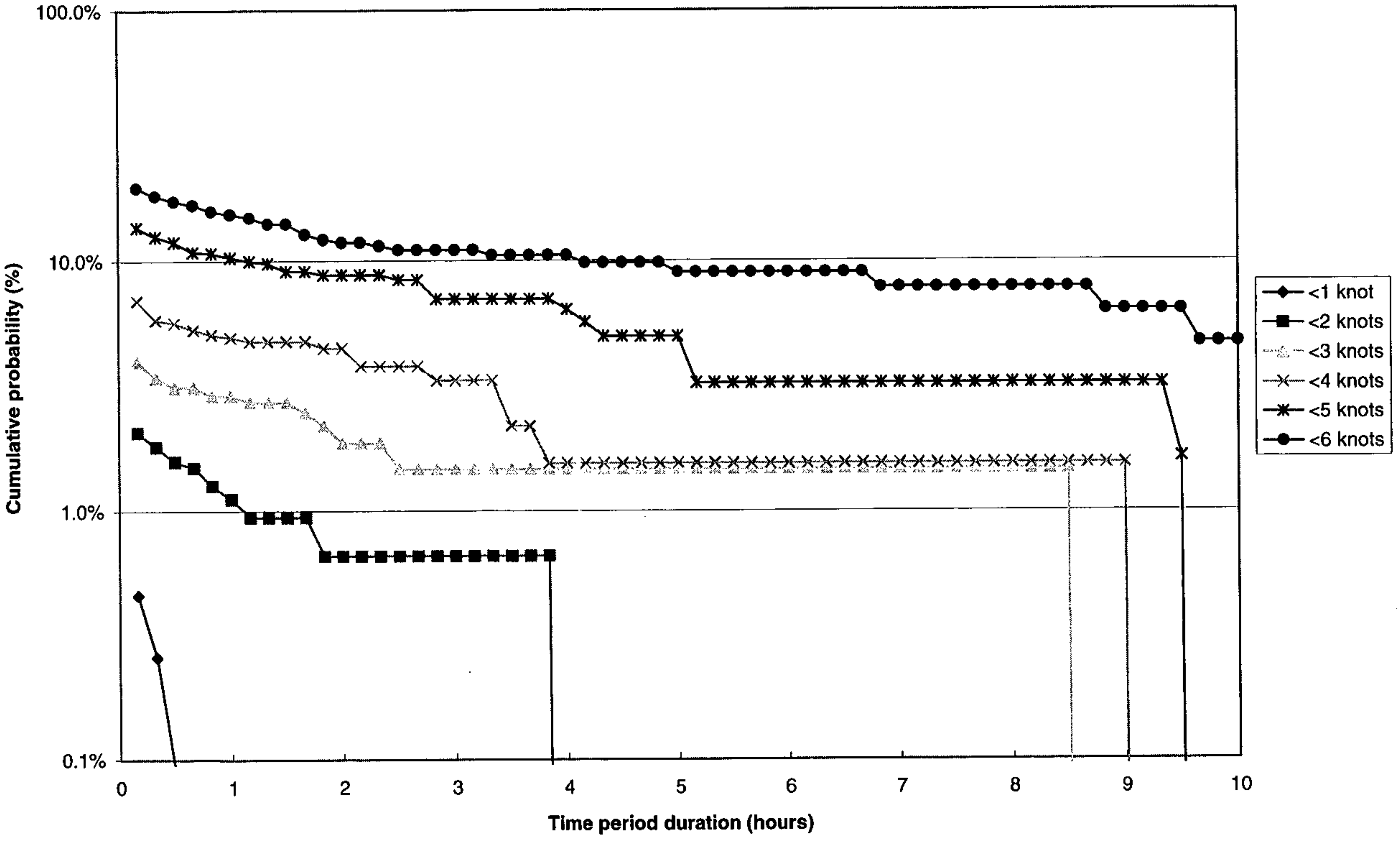
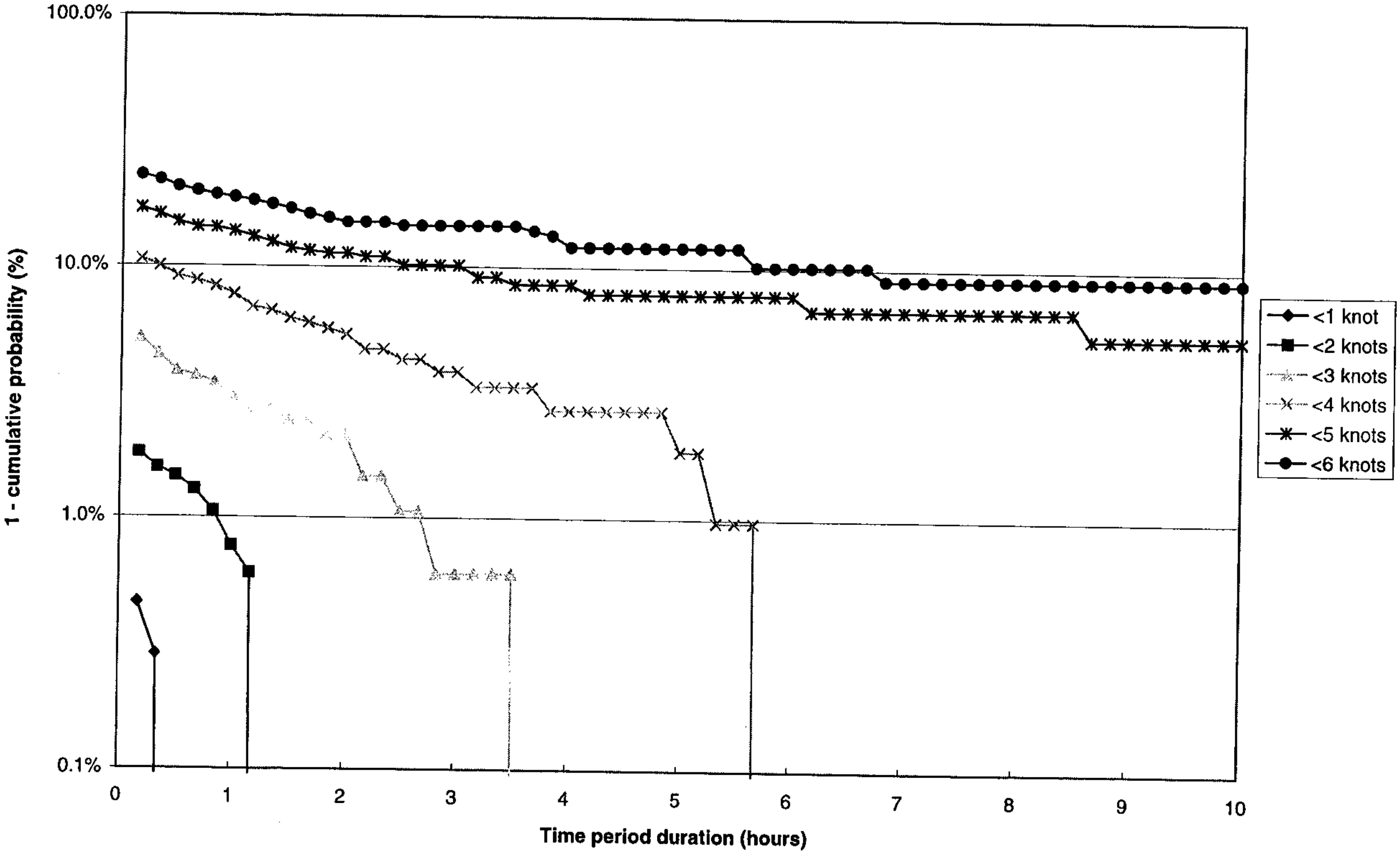


Figure 4.4.15 Persistence of Windspeeds Below Various Thresholds for Camborne, Gill Anemometer, 10 Minute Averages, June 1994



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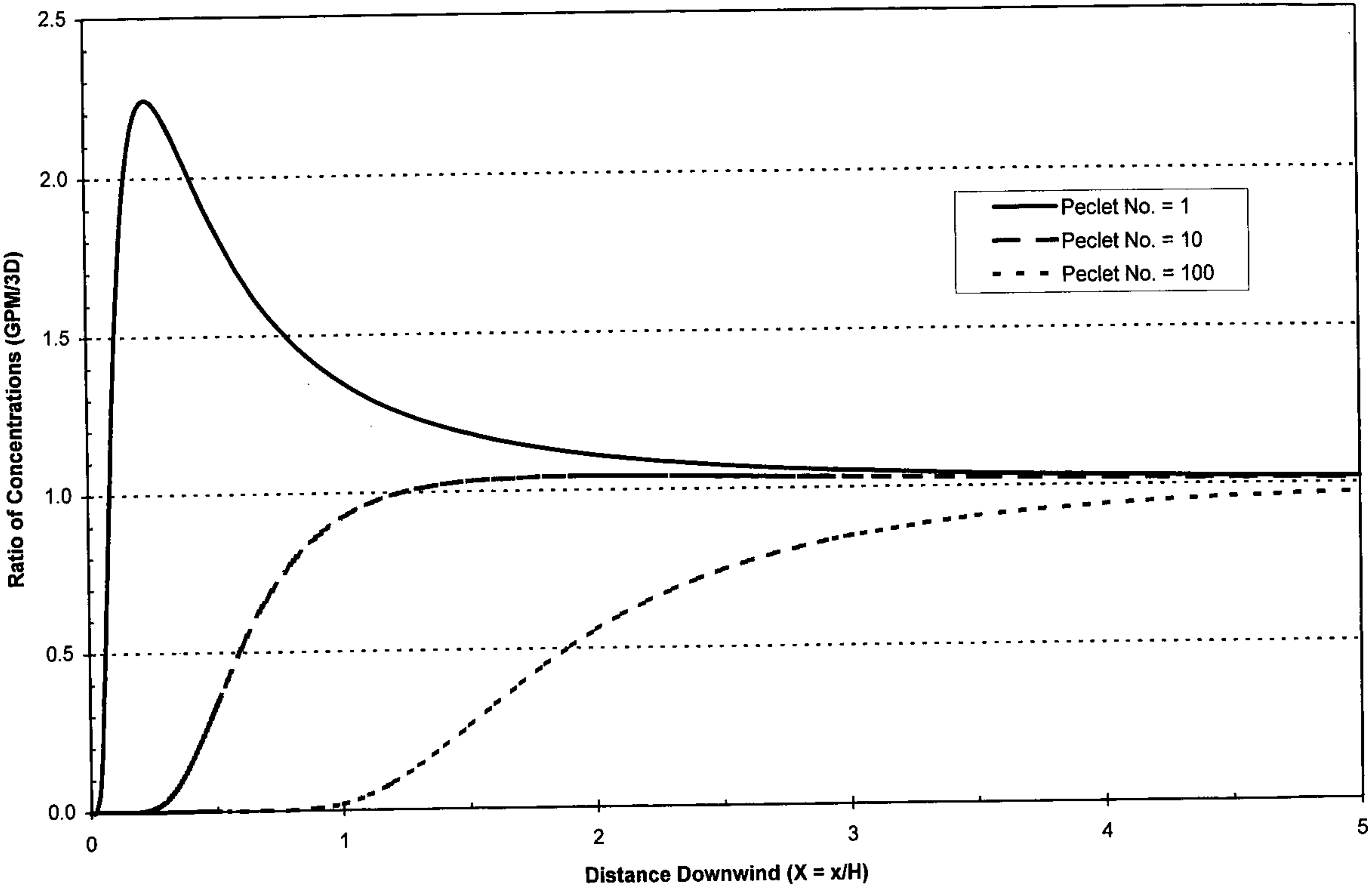

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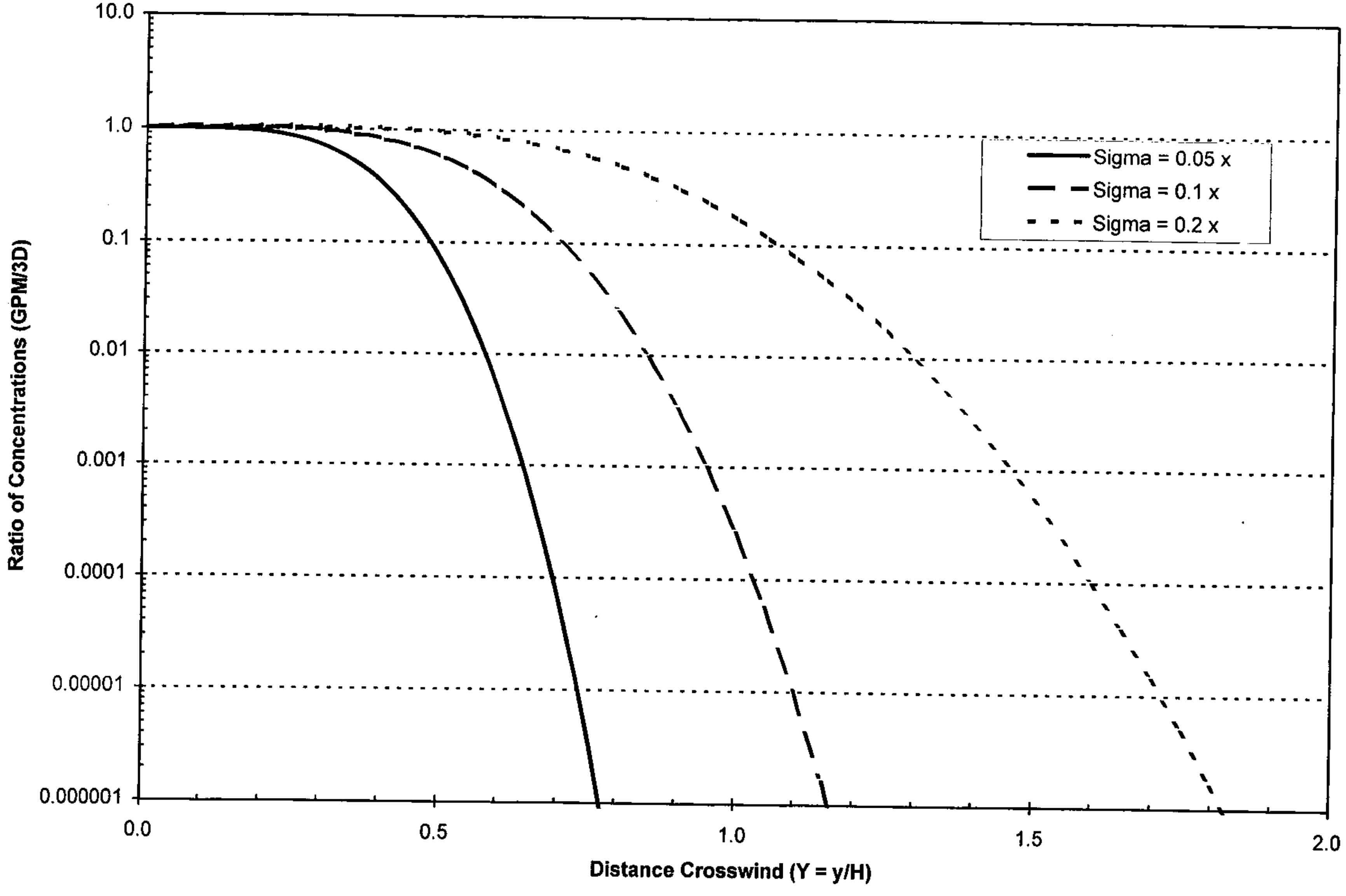

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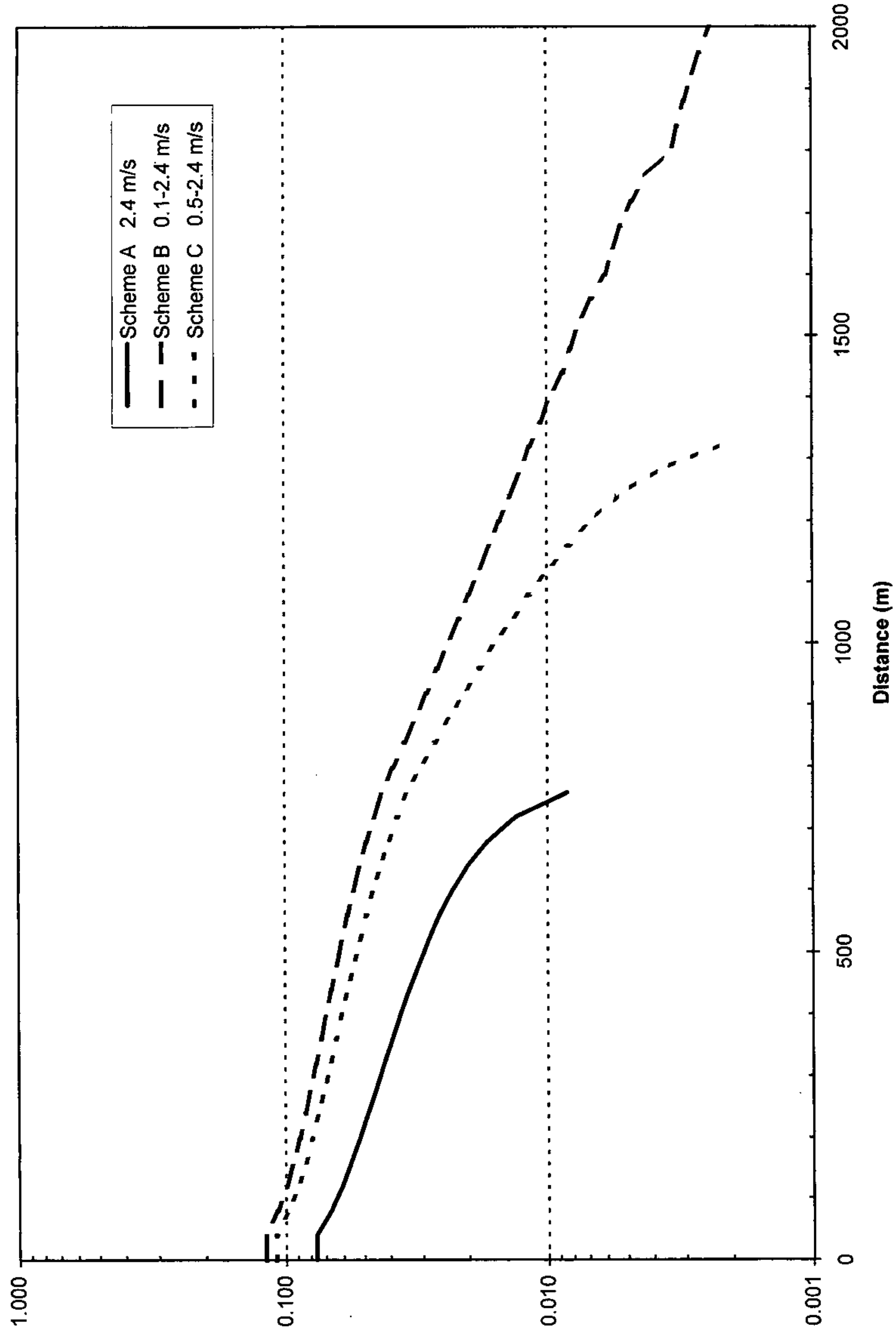

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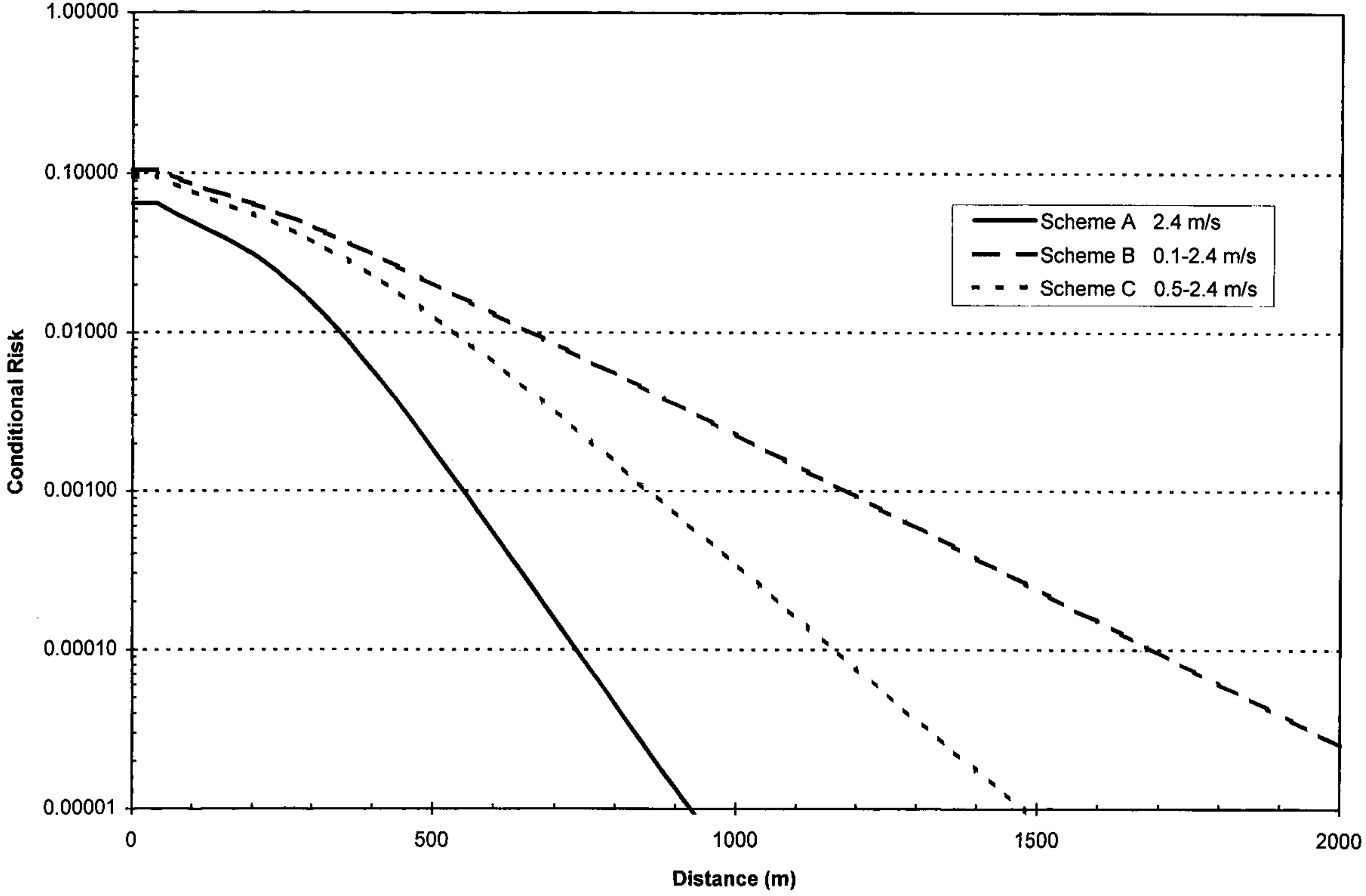

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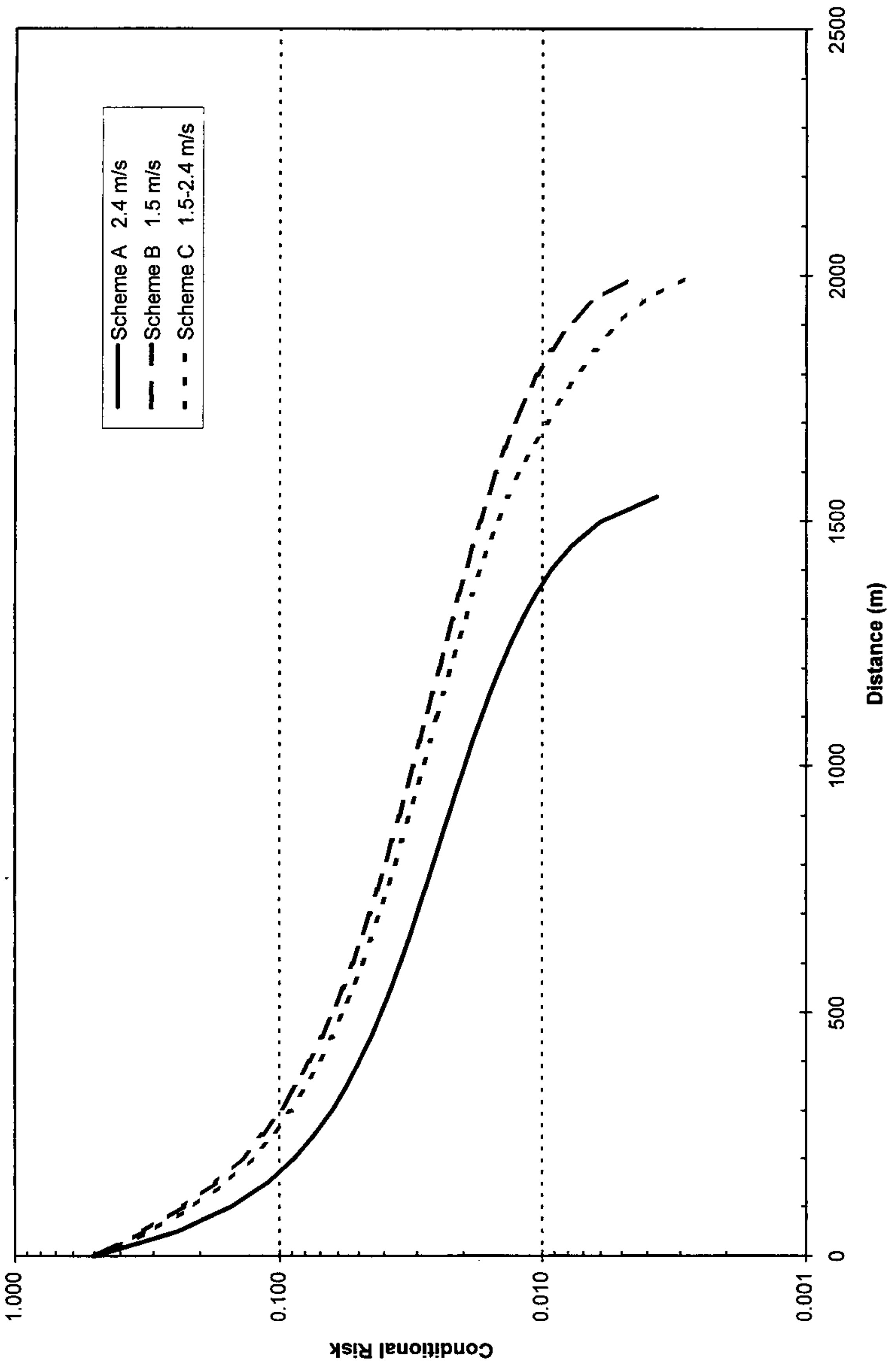

Figure 6.4.3 Risk of Exceeding DTL - 1 kg/s of Chlorine Using HEGADAS-S

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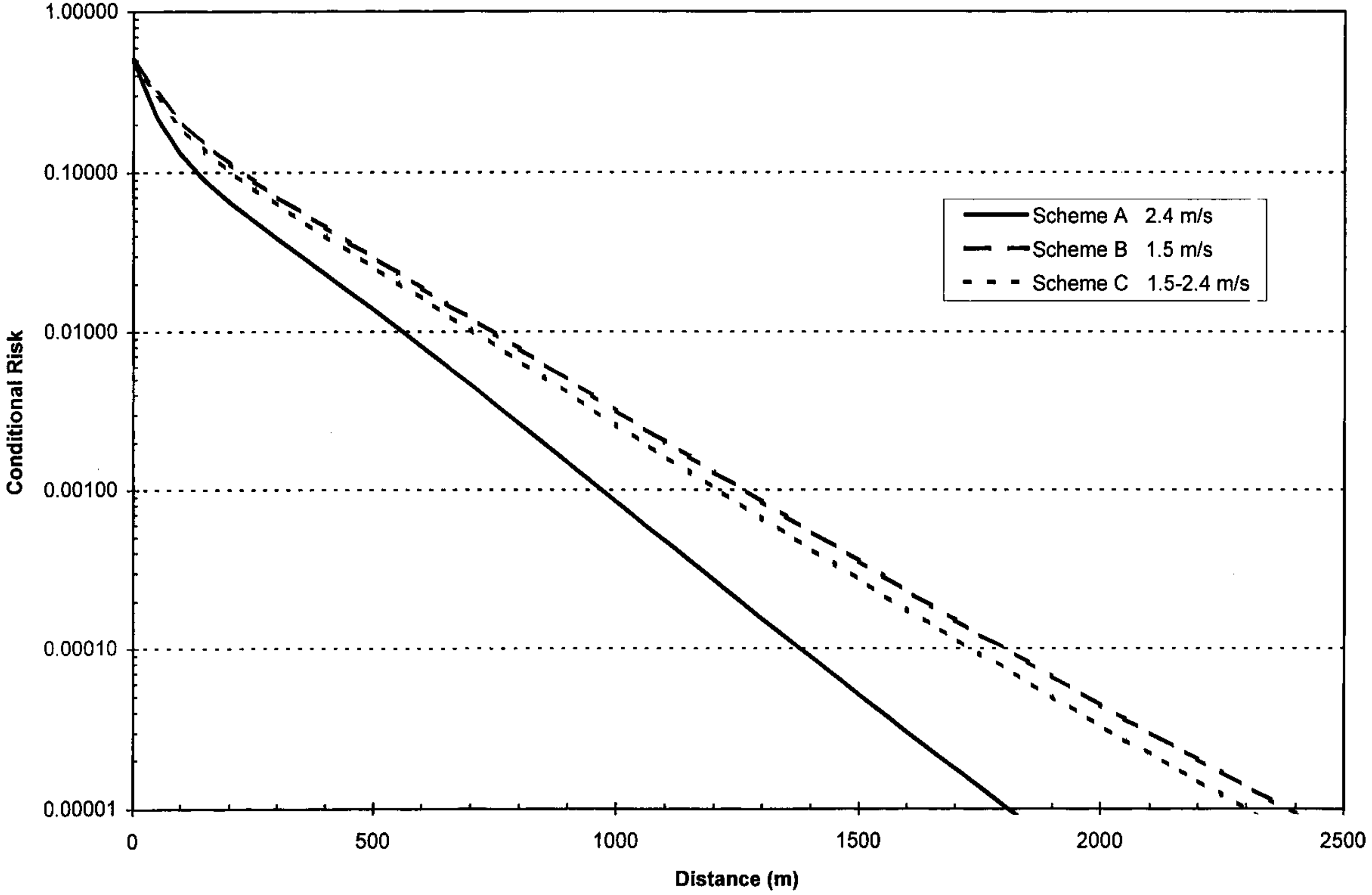

Figure 6.4.4 Risk Based on Probit - 1 kg/s of Chlorine Using HEGADAS-S

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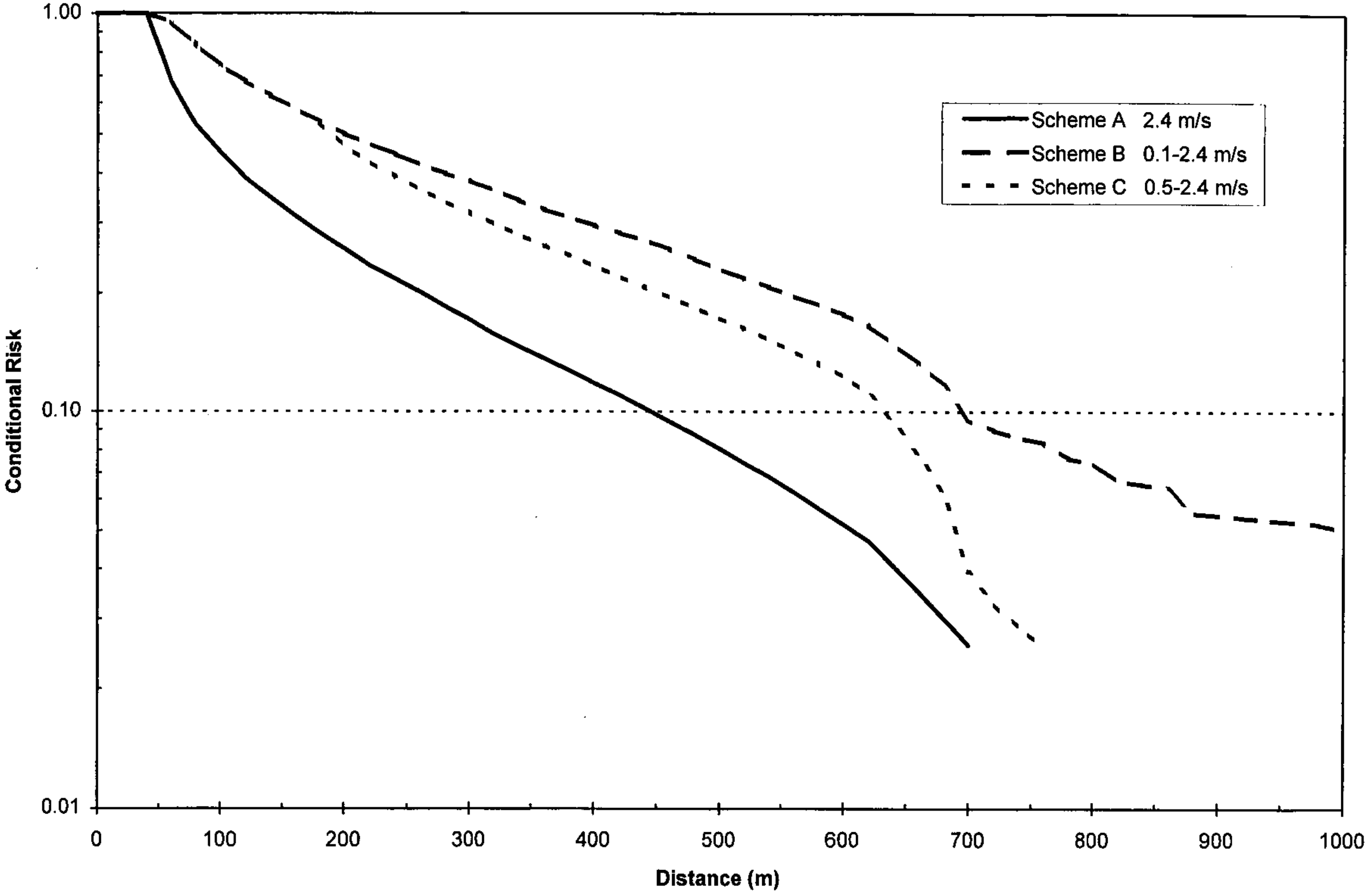

Figure 6.4.5 Risk of Exceeding DTL - 1000 kg of Chlorine Using SLUMP

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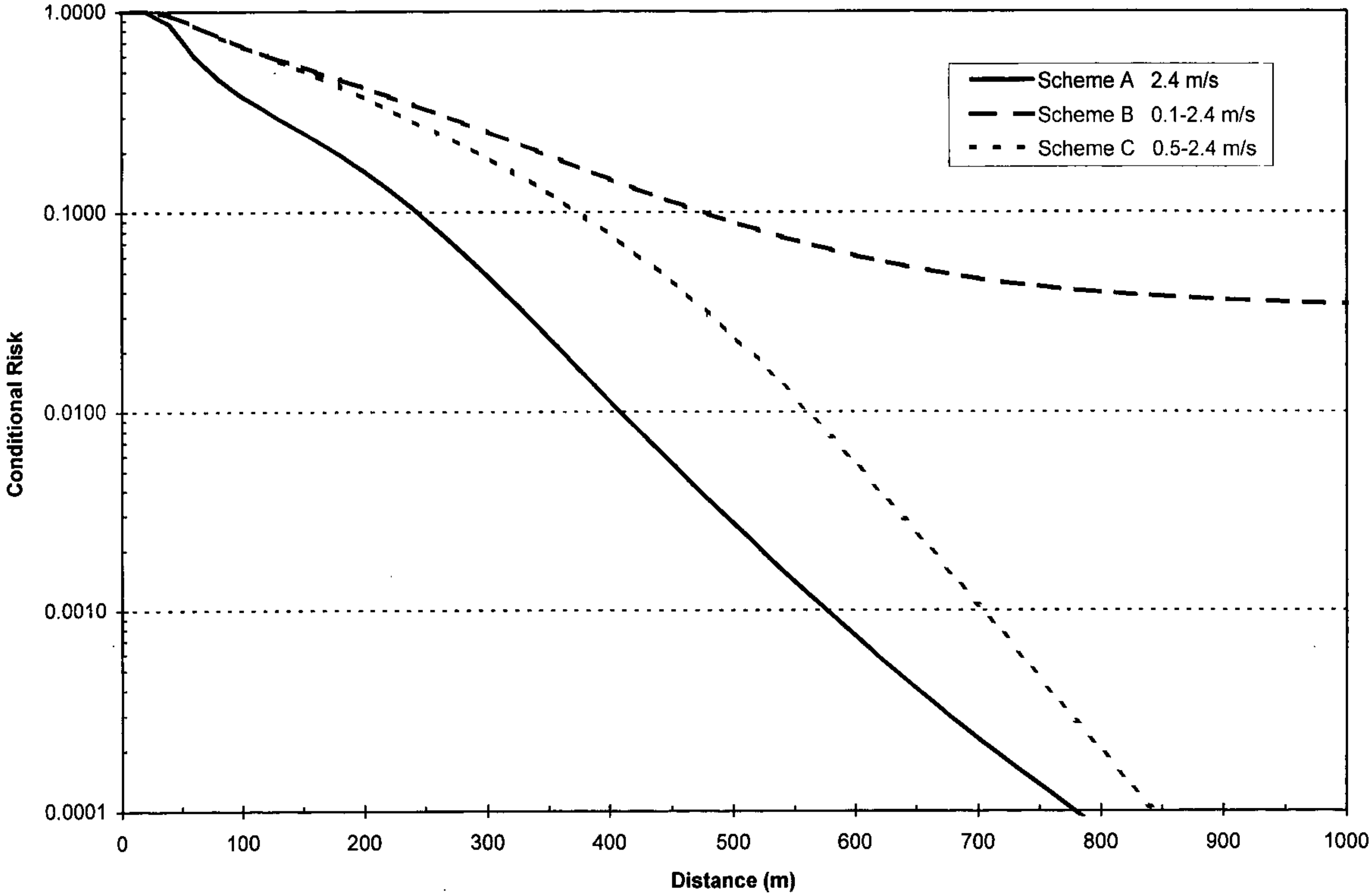

Figure 6.4.6 Risk Based on Probit - 1000 kg of Chlorine Using SLUMP

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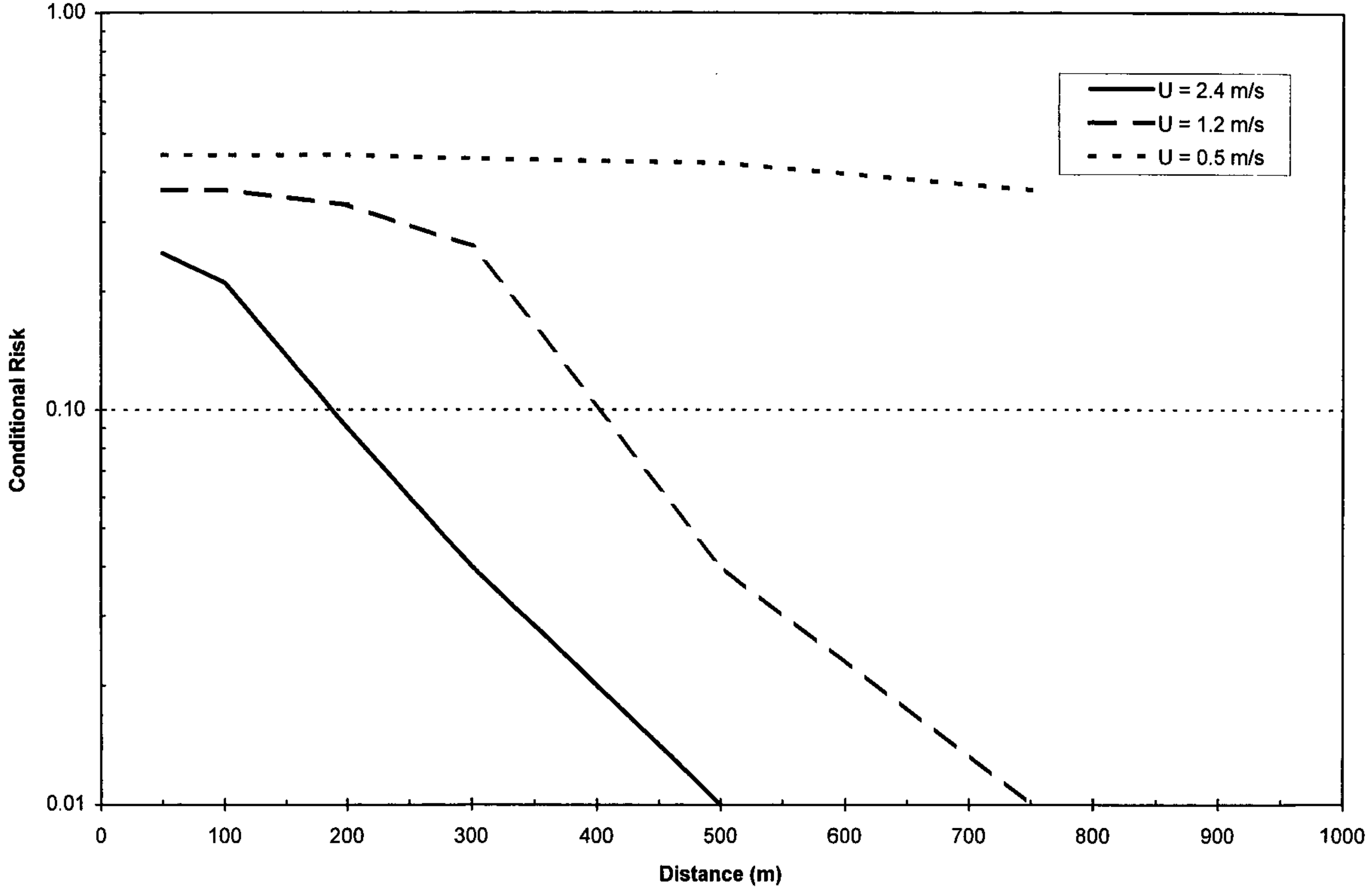

Figure 6.4.7 Risk of Exceeding DTL for Outdoor Population - 1 kg/s of Chlorine Using RISKAT

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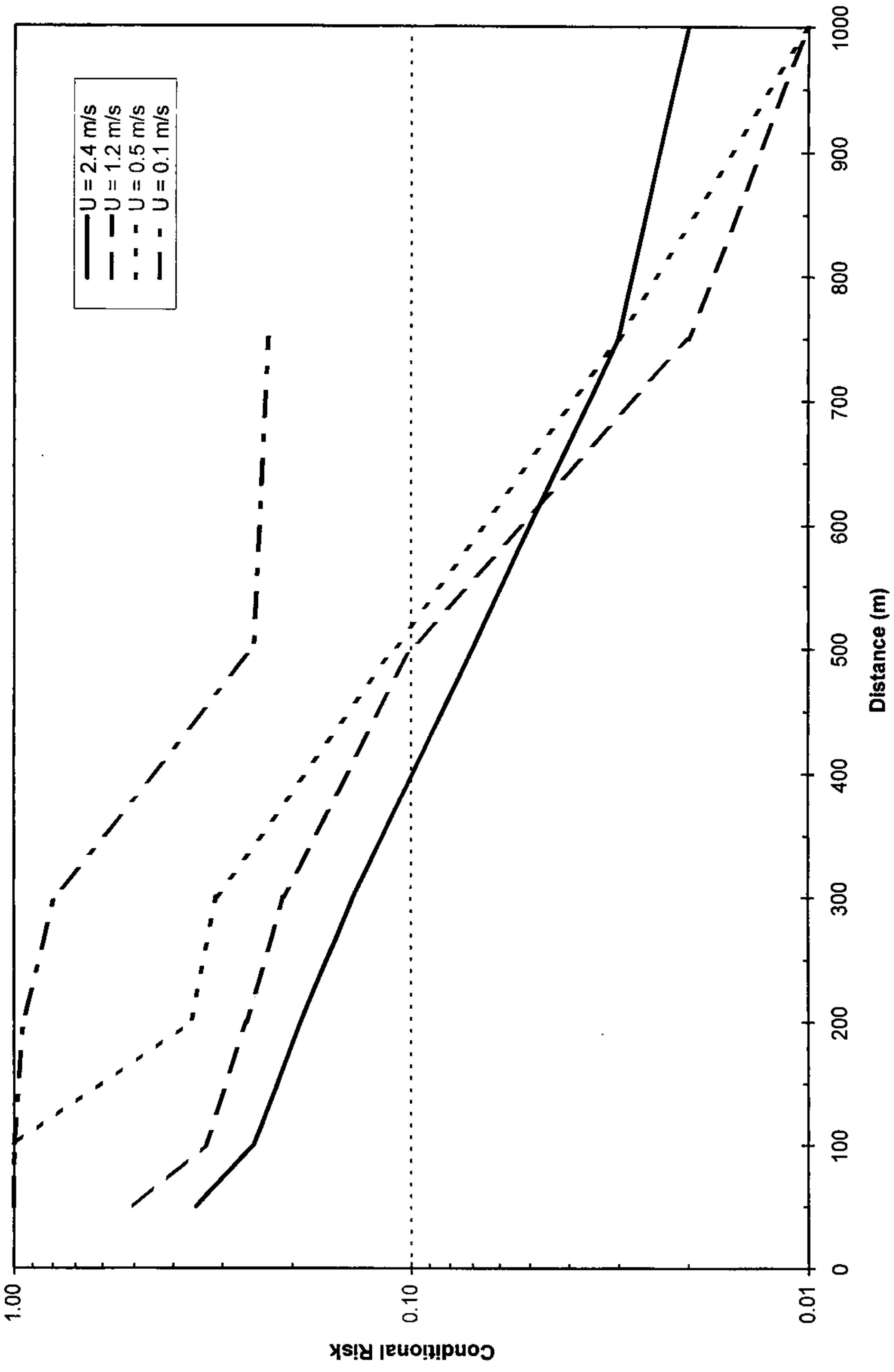

Figure 6.4.8 Risk of Exceeding DTL for Outdoor Population - 1000 kg of Chlorine Using RISKAT

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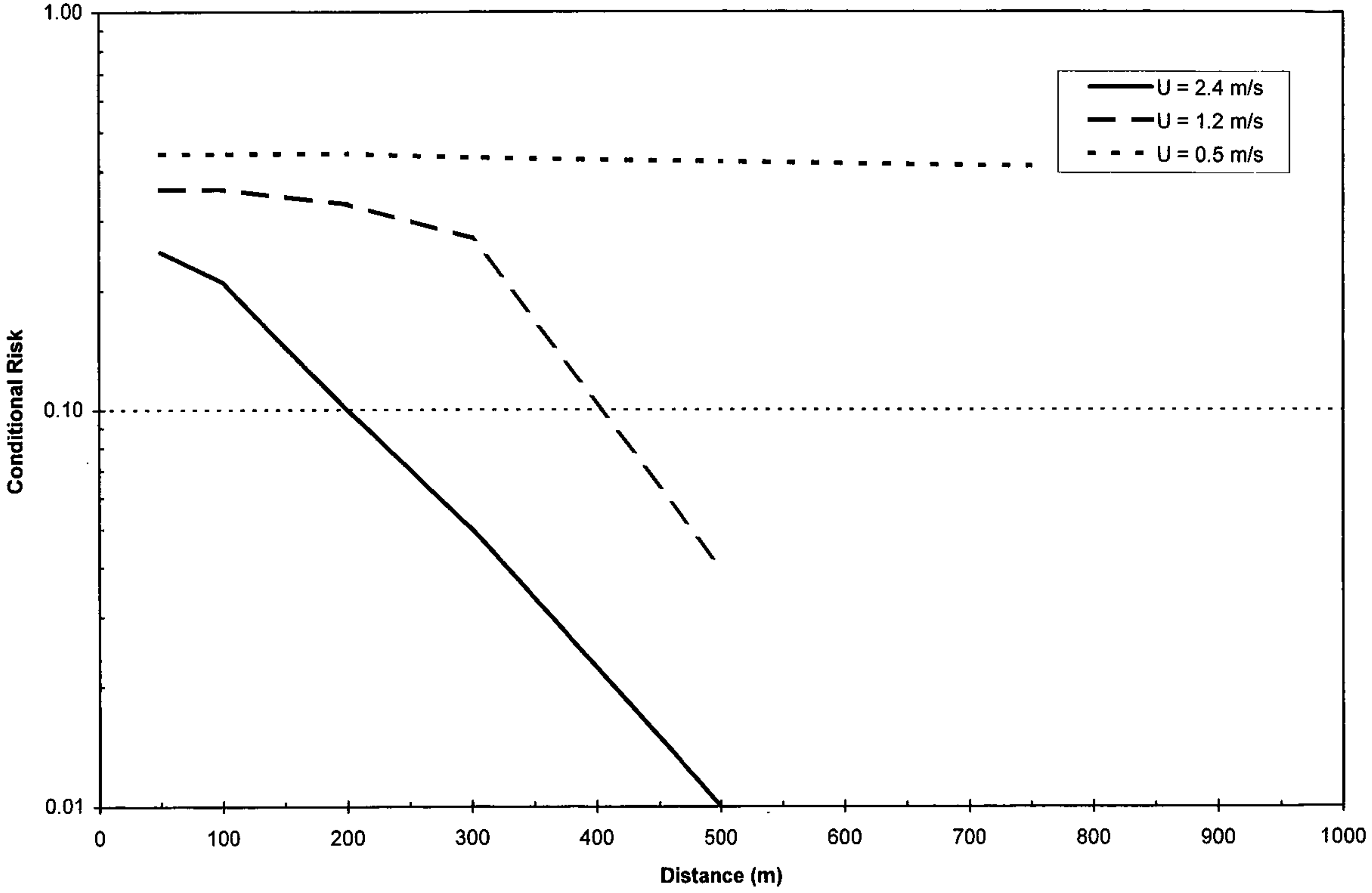

Figure 6.4.9 Risk of Exceeding DTL for Residential Population - 1 kg/s of Chlorine Using RISKAT

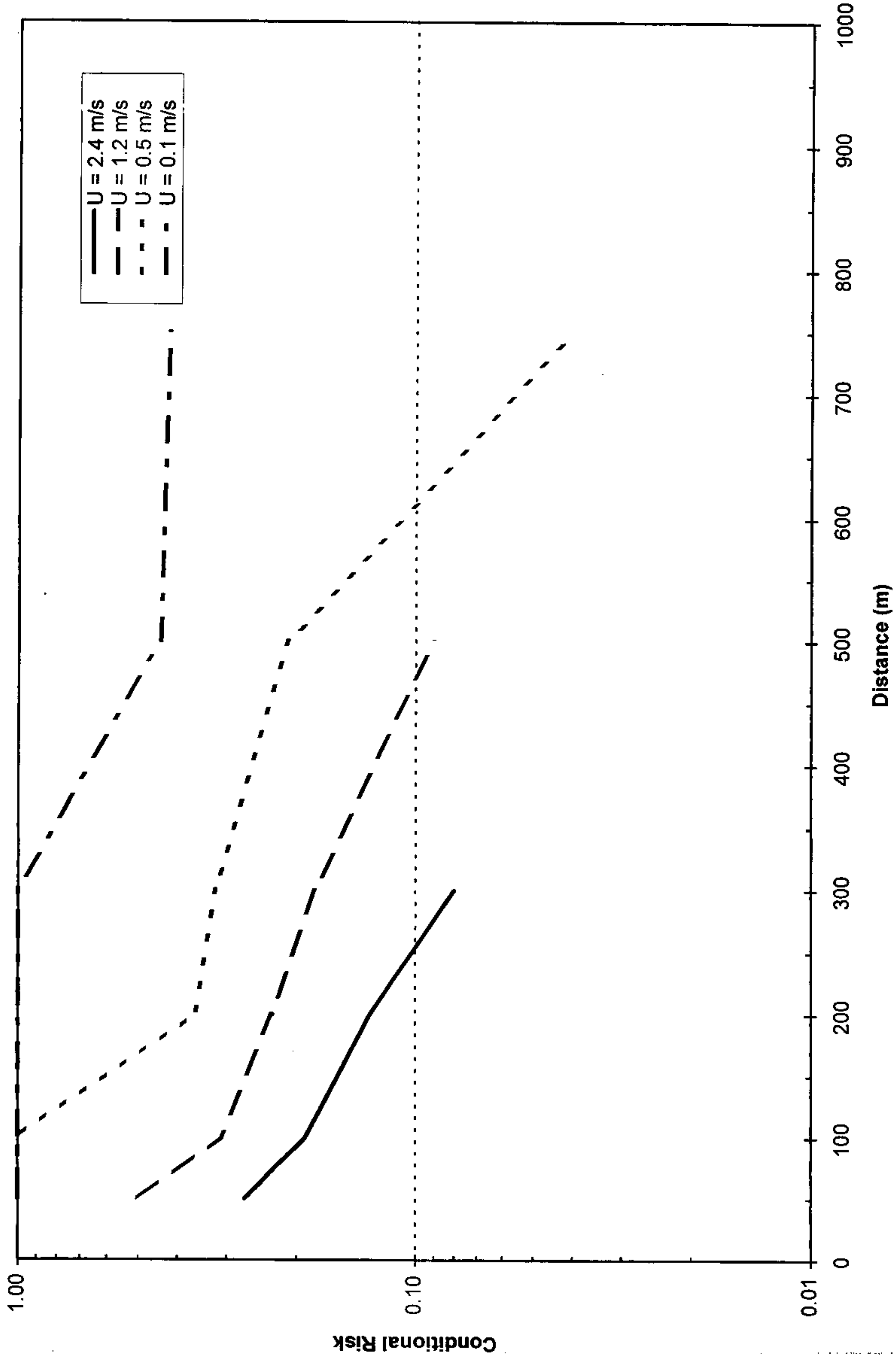

Figure 6.4.10 Risk of Exceeding DTL for Residential Population - 1000 kg of Chlorine Using RISKAT

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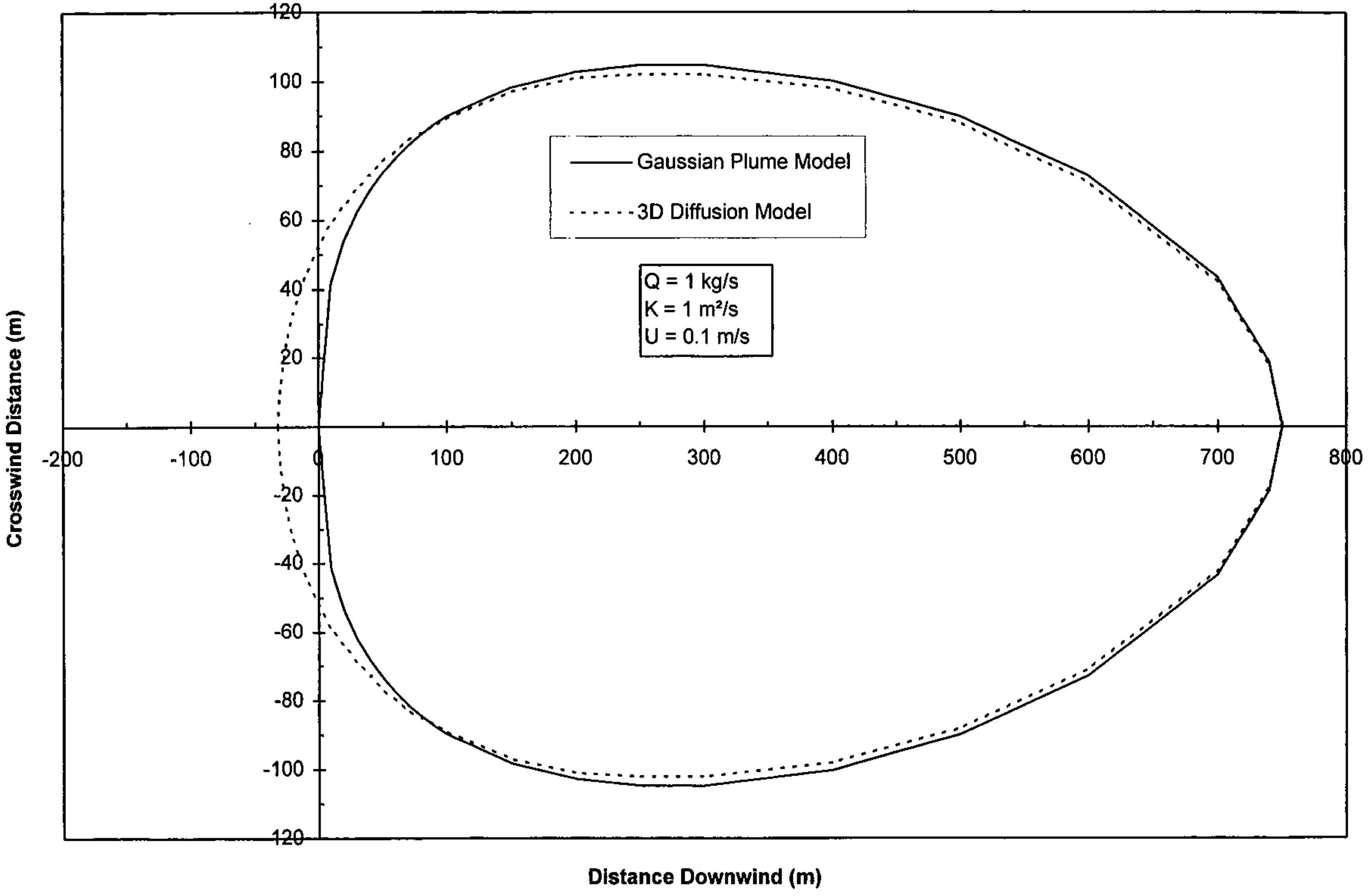

Figure 6.4.11 Comparison of 73.5 ppm Ground Level Concentration Contours for Gaussian Plume and 3D Diffusion Models - Source at x = y = z = 0

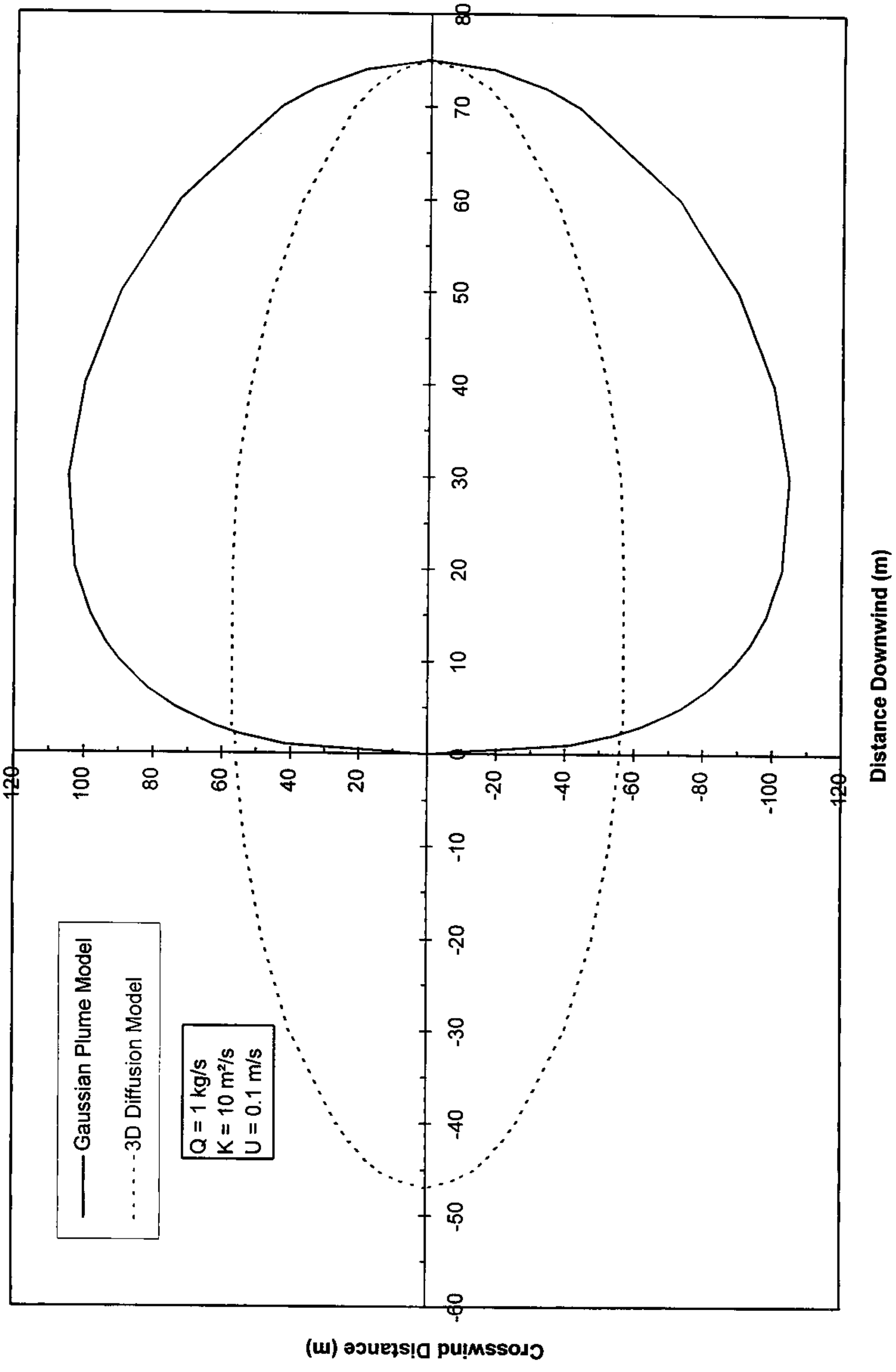

Figure 6.4.12 Comparison of 73.5 ppm Ground Level Concentration Contours for Gaussian Plume and 3D Diffusion Models - Source at x = y = z = 0

APPENDIX 1

Comments of the Accuracy of Low Wind Speeds Recorded by Meteorological Office Systems

Note: The authors gratefully acknowledge the specific detailed input of the Meteorological Office to the text and graphs presented in this Appendix. It is included so that the analysis of 'standard' data, as presented in Section 4.1 of the main report, can be considered in the correct context of the instrumentation and systems which were used to obtain them.

The Meteorological Office is aware of, and concerned about, the poor characteristics of the Munro Mk 4 anemometer at low speeds. As a result, there are moves to change the standard instrument to Vector Anemometers as soon as possible.

However, the Meteorological Office recognises that, not only is the response of the Munro instrumentation poor at low winds, but that differences in the recording methods may influence the frequency of recorded low wind speeds. Specifically, the following methods of data recording which use the Mk 4 anemometer and vane have been or are in place :-

i)	Manual	The observer analyses the anemograph chart records and tabulates hourly wind speed and direction.
ii)	DALE	Digital Anemograph Logging Equipment. A magnetic tape logging system that stores one minute averages of speed and direction; hourly totals are obtained when the tape is processed.
iii)	SAMOS	Semi Automatic Met Office Observing System . A modern digital system sampling values at 4 hz.; hourly totals are calculated and transmitted to Bracknell each hour.

Two different approaches to overcoming the instrumentation performance at low wind speeds have been employed.

a) For many years, hourly means have been extracted either manually from anemograph records, or automatically using the Digital Anemograph Logging Equipment (DALE). Since the wind vane is more sensitive than the anemometer, the records of both sensors are examined. When the anemometer indicates zero, then if the wind vane shows movement during the measurement period, an assumption is made that the wind speed is 2 knots. This results in a few hourly means with zero wind speed, none of 1 knot, and an exaggerated number of means of 2 knots. Graphs 1 to 3 show this effect. These graphs cover a period of about 10 years, from 1980 to 1989. Note that the values labelled 'SYNOP' are taken from manual observations made by the observer using the above assumptions, but which cover only the 10 minute period before the hour. The stations shown are geographically close to each other and could be expected to show similar low speed characteristics.

b) In the last 5 years, the Met Office designed Semi Automatic Meteorological Observing System (SAMOS) has been introduced, and this calculates hourly means using only the anemometer records. This results in an excessively high number of calm values, but a much more realistic distribution at 1 knot and above. The values shown in Figure 4.2.6

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use this method of calculating hourly means. There is also another Met Office system that has been in use since 1984, which calculates hourly means in this way, the Synoptic Automatic Weather Station (SAWS). However, as cloud data are not available, these records are not normally used in dispersion studies. Graph 3 shows the low wind speed characteristics for the 10 minute synoptic observations recorded at Church Lawford SAWS station, which was used because of its long record.

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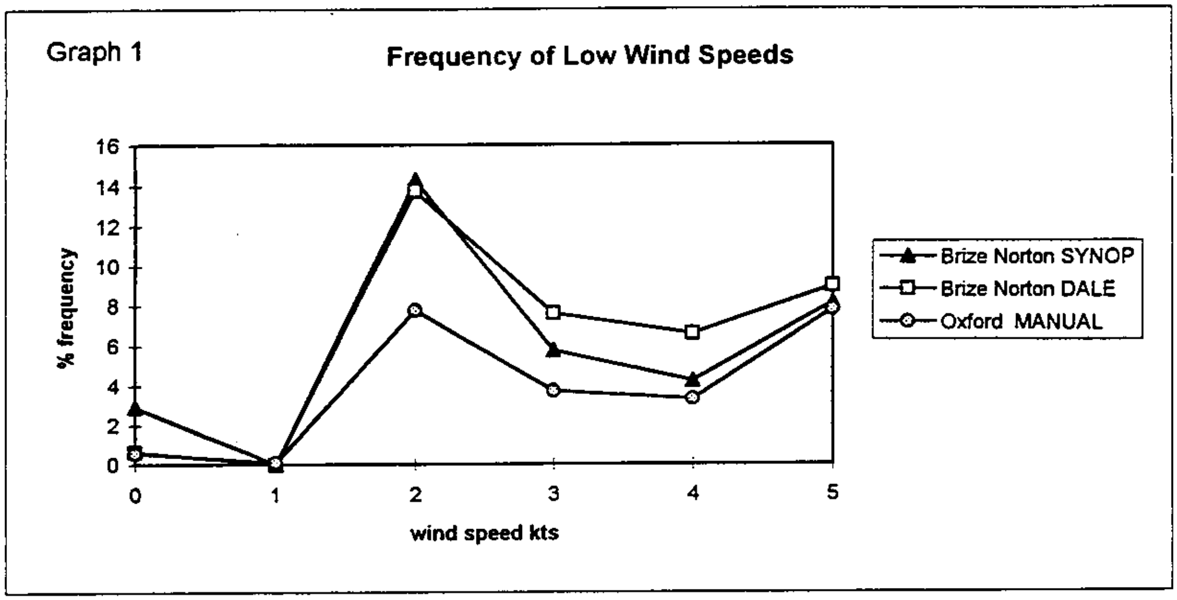
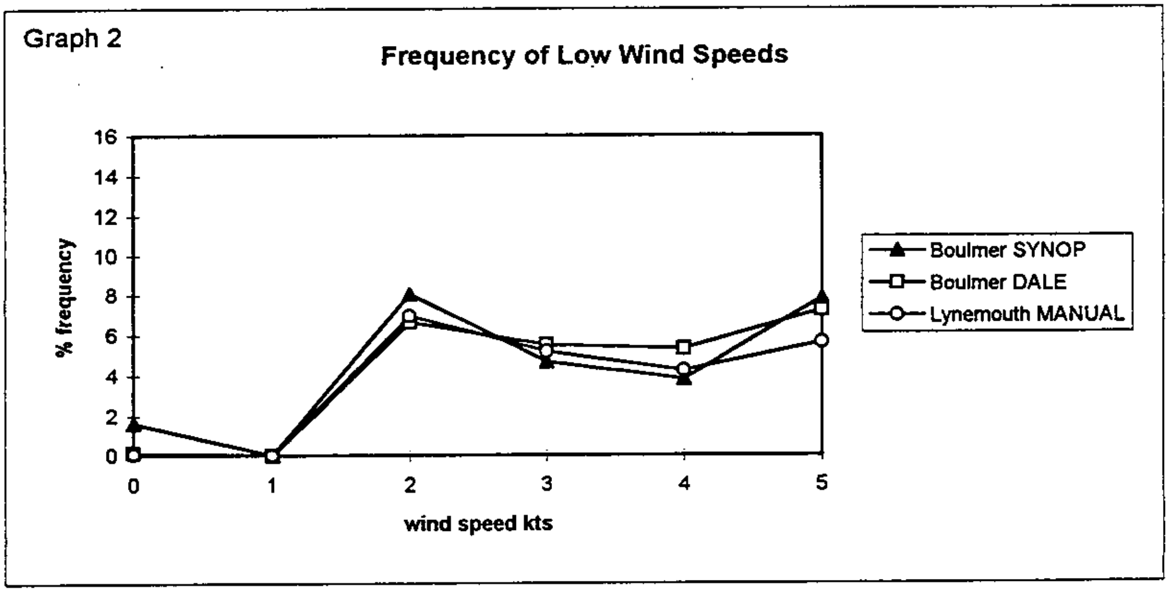
Graph 1

Frequency of Low Wind Speeds



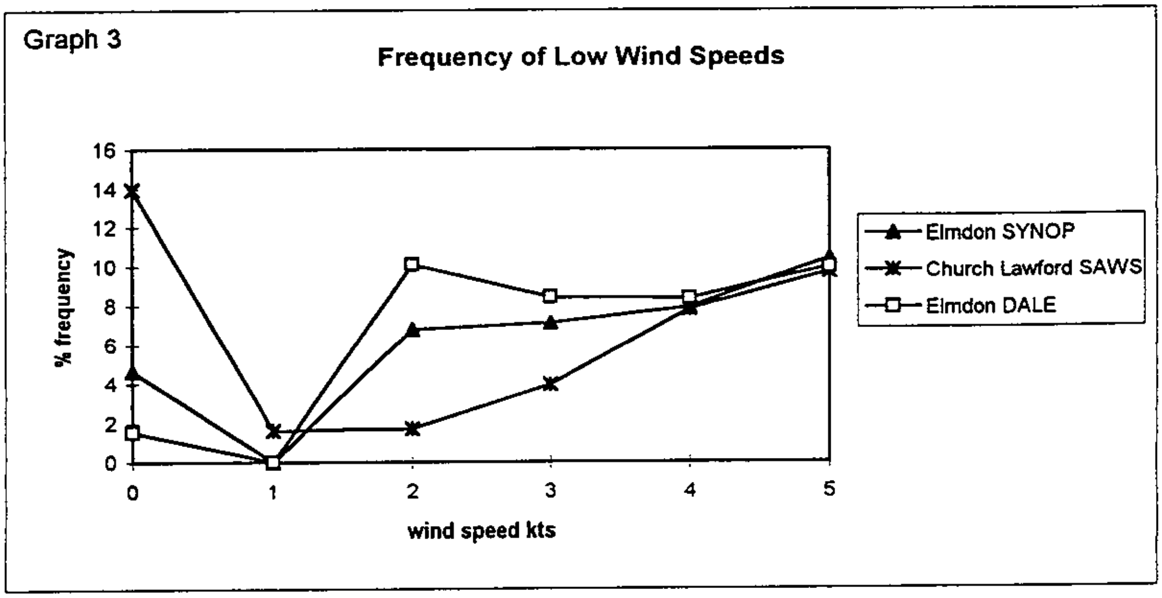
Graph 2

Frequency of Low Wind Speeds



Graph 3

Frequency of Low Wind Speeds



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APPENDIX 2

WIND TRIAL DATA FROM CAMBORNE METEOROLOGICAL OFFICE SITE FOR WS ATKINS

Contents

WIND TRIAL DATA FROM CAMBORNE METEOROLOGICAL OFFICE SITE FOR WS ATKINS

INTRODUCTION

The data consists of 10 minute average wind speeds for five sensors that took part in the Meteorological Offices wind trial (phase 4) at Camborne. The data are in two data sets JUNE.DAT and JULY.DAT, covering the periods 08:01 on 3/6/94 to 23:54 on 30/6/94 (3358 values) and 00:07 on 1/7/94 to 23:55 on 31/7/94 (3654 values). The periods when there were faults in either the logger or sensors are listed in section 5, Faults.

1. SENSORS

A list of the sensors used in phase four at Camborne, and their forms of output are given in table 1. They employ a variety of different sensing principles: rotating cup and vane, ultrasonic and integral propeller and vane.

TABLE 1

Manufacturer	Model	Output
Gill Instruments Ltd	Solent 3-axis standard (4Hz) ultrasonic anemometer	digital - serial
Penny & Giles	WS 2000 aerodynamic propeller & vane	digital - serial
R W Munro Ltd	Met Office Mk4b - IM 204 anemometer - IM 205 windvane	analogue voltages from frequency to dc converter synchro to dc converter
Vaisala	WAA15 rotating cup WAV15 vane	analogue from WAT12 interface
Vector Instruments	A100 rotating cup anemometer W200P/M vane	analogue voltages
R M Young	05103 propeller & vane	analogue voltages from 05603 interface

The Penny & Giles sensor has not been included in the data sets due to the fact that the output looked erratic and possibly faulty.

Contents

2. SITE DETAILS

Camborne Meteorological Office, the chosen site for phase four of the Meteorological Offices wind trial (the others being at Beaufort Park), is situated on the Northern Coast of Cornwall, 10km east of St Ives at Kehelland Village and approximately 1½km from the coast.

The site, at a height of 87m above mean sea level, is approximately 155m long by 60m at its widest end, narrowing at its furthest end where a 10m tower is sited, see figure 5. The offices are sited at the other end of the site from the tower approximately 140m away, with a balloon shed in the middle, see figure 3 (the photograph was taken with back to the offices, facing east).

The site is surrounded by flat fields and has a clear sight of the sea in the North and North-Westerly directions. The wind is predominantly from South to South Westerly and North to North Westerly directions.

The selected instruments were mounted on a 4.3m boom attached to the top rail of the tower, except for the Munro which was mounted in the middle of the tower, see figures 4 and 6. It was not possible to reposition the Munro as it was the operational site anemometer.

The boom laid in an orientation of approximately East-West (105° - 285°) as the tower was constructed with an offset of about +15° from North, see figure 6. It was necessary to mount the boom East-West due to orientation of the instruments' crossarms, see figure 6.

3. LOGGING

Each sensor was sampled every 0.25 second for a 10 minute period when various calculations were carried out, including 10 minute average speeds, and the 10 minute values saved to disk. The time it normally took to do the calculations and saving the data was about 15 seconds, giving a delay of about 15 seconds between consecutive periods.

Also being saved during the trial were raw 4Hz (0.25 second) data. Only certain raw data sets were being saved to disk to conserve disk space, depending on wind speed and direction. When these data sets were also saved to disk the time delay between consecutive logged periods increased to about 1 minute 25 seconds.

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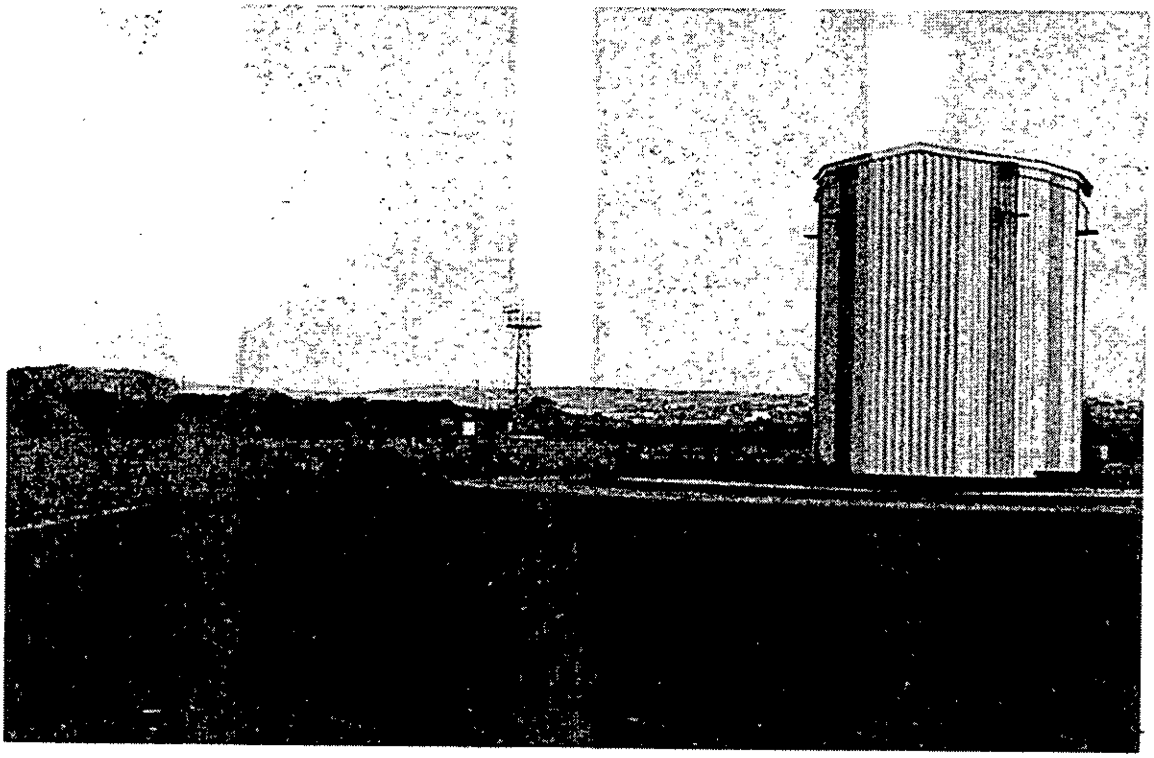

Figure 3 – Camborne Meteorological Office

Figure 4 – Camborne instrument mounting

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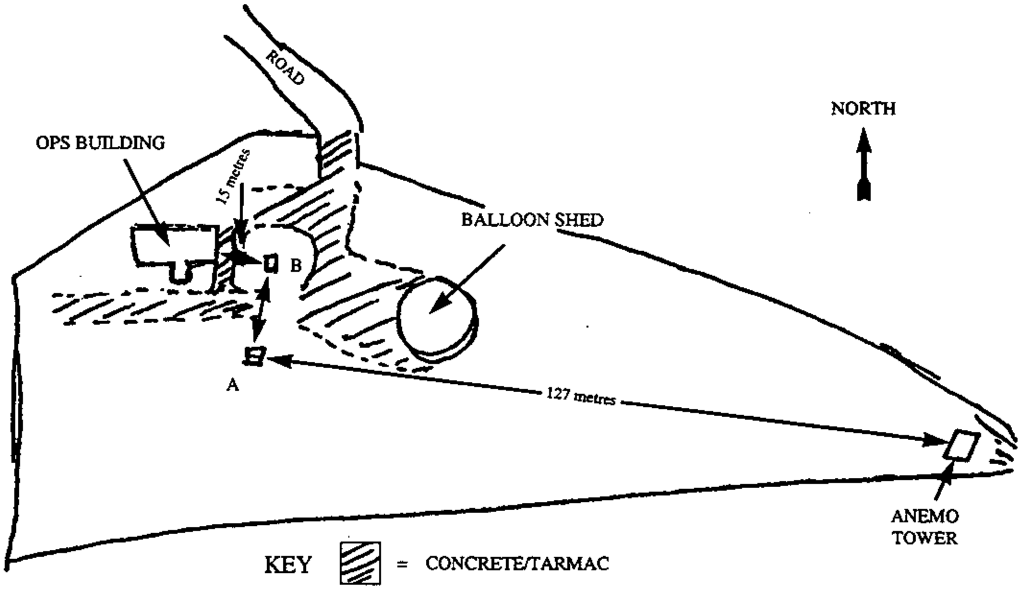

Figure 5 – Site plan of Camborne Meteorological Office

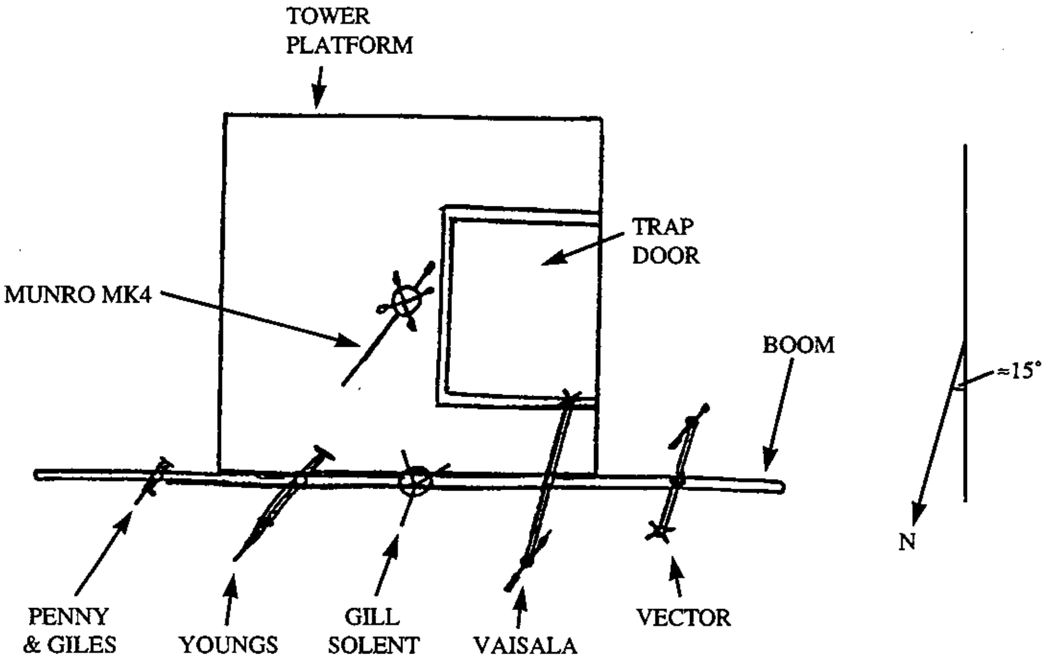

Figure 6 – Plan of instrument mounting at Camborne

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4. DATA FORMAT

```
{Date      }  {Time   }    {WS1}   {WS2}   {WS3}   {WS4}   {WS5}  {WD6}
06-03-1994  08:01:01      20.8    20.4    21.0    20.5    19.7   237
06-03-1994  08:12:26      21.1    21.4    22.0    21.3    20.4   252
06-03-1994  08:23:51      17.8    18.2    18.7    18.3    18.1   237
06-03-1994  08:35:15      20.2    19.9    20.3    19.8    18.8   263
06-03-1994  08:46:40      17.5    17.5    17.9    17.5    15.6   245
06-03-1994  08:58:05      20.7    21.4    21.9    21.3    20.4   245
06-03-1994  09:09:29      21.6    21.8    22.4    21.8    20.8   235
06-03-1994  09:20:54      21.7    22.5    22.9    22.3    22.2   238
06-03-1994  09:32:18      22.0    22.0    22.7    22.1    20.8   259
06-03-1994  09:43:43      21.4    21.7    22.2    21.7    21.3   240

1234567891123456789212345678931234567894123456789512345678961234567897
         0         0         0         0         0         0         0
```

(This line is not shown in the data set and is shown to give the position of characters along the line).

{Date } = Date mm-dd-yyyy (10 characters)
{Time } = Time hh:mm:ss (8 characters)
\- = Space (1 character)
{WS1} = Wind Speed Instrument 1 - Gill
{WS2} = Wind Speed Instrument 2 - Munro
{WS3} = Wind Speed Instrument 3 - Vaisala
{WS4} = Wind Speed Instrument 4 - Vector
{WS5} = Wind Speed Instrument 5 - Youngs
{WD2} = Wind Speed Instrument 2 - Munro

Speeds are formatted to 8 characters with right justification.
Direction is formatted to 4 characters with right justification.

Due to the mounting of the sensors being along a single boom, effects of blocking by the other sensors could occur along the boom axis, so the Munro direction is included so speeds in those directions can be taken into account of.

5. FAULTS

There were three periods when there was a fault with the logger. The problem was that there was a gap between each 10 minute period of about 50 minutes. Each recorded value during this time was logged over exactly 10 minutes but there was a delay between the next 10 minute period being logged. The periods at fault were:

Contents

1) 05:20 22/6/94 to 04:48 23/6/94
2) 04:14 6/7/94 to 04:06 7/7/94
3) 09:43 20/7/94 to 22:19 22/7/94

The only sensor to have a fault during June and July 1994 was the Youngs. The fault was that it under-read for periods. The amount of under-reading varied, below 5 knots it was about 1-2 knots, between 5 to 10 knots it was 2-3 knots, and above 10 knots it was consistently about 5 knots low. This effect occurred during two periods listed below:

1) 05:47 24/6/94 to 13:51 3/7/94
2) 10:09 19/7/94 to 09:32 26/7/94

Andrew Scott
Met O (OI)1a
Room B10a
Beaufort Park

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APPENDIX 3

DESCRIPTION OF THE DATA ACQUISITION SYSTEM (AT CARDINGTON) USED IN COLLECTING THE DATA FOR WS ATKINS

W P Hopwood
Meteorological Office Research Unit
Cardington
Bedford
MK42 0TH

Apr 1995

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The data required by W.S.Atkins was collected almost continuously over a three year period (1989-90) at the Meteorological Office Research Unit field site at Cardington, Bedfordshire (52° 06'N, 00° 25'W). The site is in river that is approximately 60m deep and 8km wide. The measurements were made about 3km from the southern edge of the valley. About 2.5km south-east of the site there is a ridge oriented approximately north-east, south-west. The ridge rises 50m above the site over a horizontal distance of about 1km. To the south-west, which corresponds to the prevailing wind direction, the fetch is flat, consisting of fields with a scatter of low bushes and trees. About 0.5km north-east of the sonic anemometer mast are two large hangars. The town of Bedford is about 3km to the north-west of the site. A contour map is included for reference.

The wind data was obtained with a sonic anemometer-thermometer, mounted on top of a 20m cylindrical mast, and a Vector Instruments A100 porton anemometer placed on a separate cylindrical mast at a height of 16m. The sonic anemometer used was a Kaijo-Denki DAT-300 model with a TR61A sensor head. The TR61A sensor head has two horizontal transducer paths with an angle of 120° between them and a single vertical path. Errors due to interference by the sonic frame and transducers are small, within about 30° of the main axis of the sensor head, and to minimize these errors the head was mounted on a manually operated rotator so that the instrument could be pointed into wind for as much time as possible. Studies of the TR61A sensor head show that errors of about 8% in the wind speed and about 5° in wind direction are to be expected. The direction of the rotator is estimated to be accurate to 5°. For the porton anemometers errors of about 10% in the wind speed are to be expected, partly due to the tendency in cups to 'overspeed' as a result of their non-linear response to fluctuations in wind speed and, sensitivity to the vertical velocity component.

The analogue outputs from the sonic processing unit (three wind components and temperature) and the portons were sampled at 1Hz and various statistical sums (*e.g.* $\Sigma_n U_i^n$, $\Sigma_n U_i^n U_j^n$, $\Sigma_n U_i^n T^n$, etc., where U_i^n is the nth sample of the ith wind component and T^n is the corresponding temperature sample) were calculated over 10 minutes by a Microvax II computer.

The following quality control checks were carried out on the sonic data.

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1. The standard deviation of the sonic temperature over each 10-minute average had to be less than 0.4°C. This test provides a reasonable method of detecting periods when the sonic data was seriously affected by rain.
2. The x component of the shear stress, averaged over 30 minutes, had to be less than zero.
3. The standard deviation of the vertical wind component had to satisfy the requirement $0.7<1.79\sigma_w(\ln(20/0.01)-\psi_m(20/L))/U<1.5$. This assumes that $\sigma_w/u_*=1.4$ and is independent of stability. This is consistant with the present data. (U is the mean wind speed, $\sigma_w$is the standard deviation of the vertical velocity component, L is the Monin-Obukhov length defined later, ψ_m is the integrated wind profile and the roughness length is assumed to be 0.01m)

The stability of the data is described by the Monin-Obukhov length, L, and is defined by the ratio of the surface shear stress and the surface heat flux,

$$L=-\frac{T}{kg}\frac{u_*^3}{\overline{w\theta}}$$

where k is the von Kármán constant (0.4), g is the gravitational acceleration, T is the temperature, u_* is the surface friction velocity and $\overline{w\theta}$ is the surface heat flux. L gives the relative importance of mechanical and buoyant forces in the production of turbulence. A negative value implies instability where buoyant forces are contributing to the turbulent production, a positive value implies stratification where the buoyant forces are attempting to suppress turbulence and a value close to zero implies little contribution to the production of turbulence by buoyant forces. In the atmospheric surface layer, normally defined as the lowest 100m of the boundary layer, it is valid to consider normalising L by height z to obtain,

$$\frac{z}{L}=-kz\frac{g}{T}\frac{\overline{w\theta}}{u_*^3}$$

It is this quantity that has been evaluated in the requested data.

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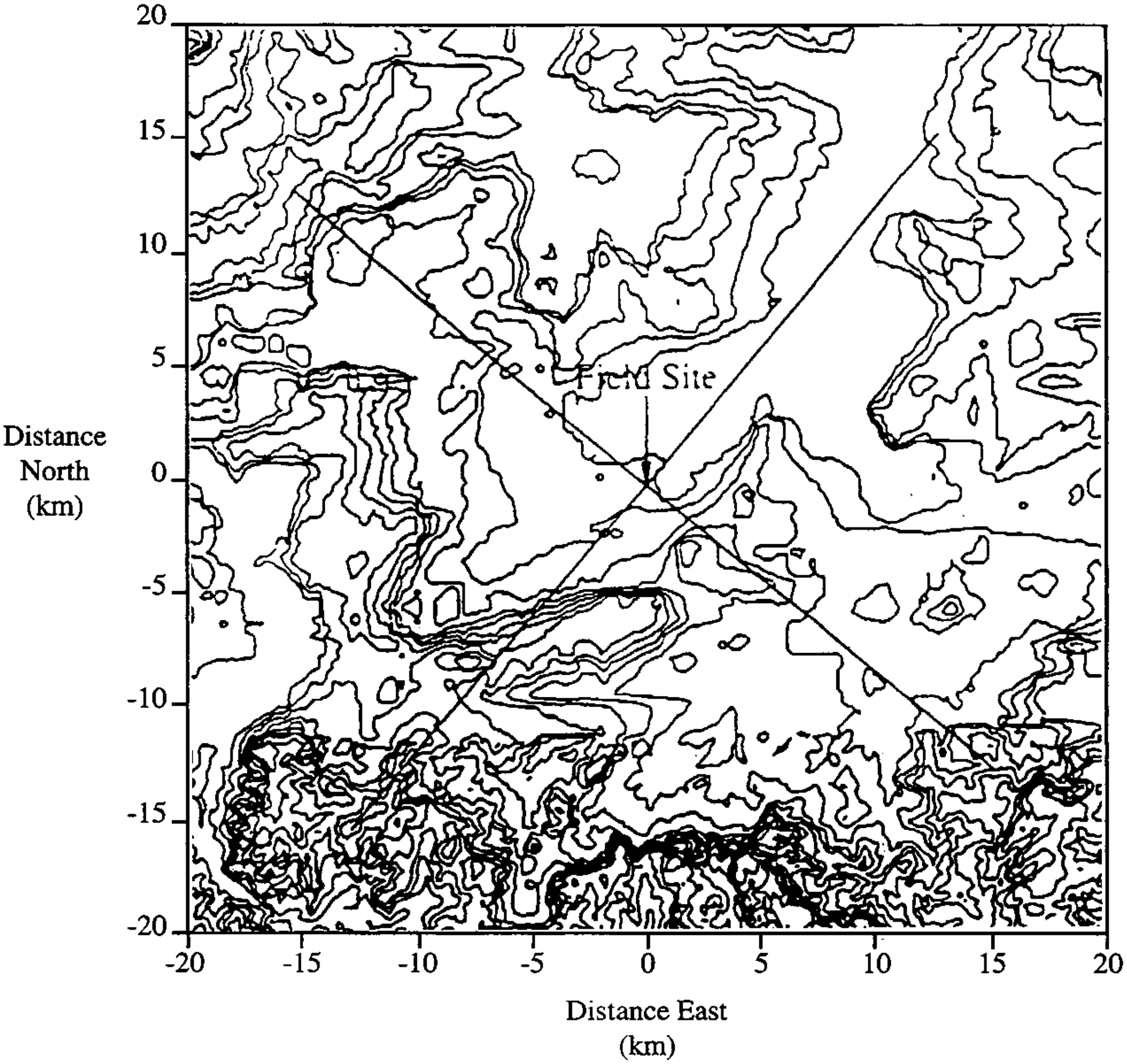

20
15
10
5
0
-5
-10
-15
-20
Distance North (km)
Field Site
-20
-15
-10
-5
0
5
10
15
20
Distance East (km)

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APPENDIX 4

DETERMINATION OF PARAMETERS FOR WEIBULL WINDSPEED DISTRIBUTIONS

It is well known that most mean windspeed data in the moderate - high windspeed range can be represented by the Weibull distribution, for which;

$$P(V) = 1 - e^{-(\frac{V}{V_o})^k} \qquad \text{(A4.1)}$$

where

P(V) is the probability that the mean windspeed is less than V
V_o is a reference windspeed
k is a shape factor

Equation A4.1 can be manipulated to give

$$\ln V = \ln V_o + \frac{1}{k} \ln\left(-\ln(1-P)\right) \qquad \text{(A4.2)}$$

Parameter estimation can then be readily undertaken by plotting lnV against ln(-ln(1-P)), from which the slope is 1/k and intercept $\ln V_o$. This technique is generally based upon standard meteorological data, which is presented as the frequency with which the windspeed falls within discrete bands, usually of width at least 2kts.

When considering the low windspeed region of the data, it is useful to be able to use all the data without having to group it into relatively broad bands. The data from standard Munro instruments is known to be unreliable at very low windspeeds, so that such refinement is not usually justified. However, 9 months of sonic anemometer data from Cardington have been obtained and analysed within this study, and an alternative data fitting method was sought which enables the more accurate low windspeed information which these anemometers introduce to be used.

It is noted that the LHS of Equation A4.2 corresponds in form to the 'reduced variate' which is used when undertaking a standard extreme value analysis. Since it is normal in such analyses to rank the data in magnitude order, such ranking was considered as an alternative to grouping the data and hence losing resolution.

Suppose there is a data set of N mean windspeed observations. If these are arranged in order of increasing magnitude, the sequence:

$$S = u_1, u_2, u_3 \ldots\ldots\ldots\; u_N \qquad \text{(A4.3)}$$

is obtained, where $0 \leq u_1 \leq u_2 \leq \ldots\ldots \leq u_N$, so that u_1 is the lowest value and u_N the highest value recorded. Since there are n observations less than or equal to u_n, the probability of the windspeed

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being greater than u_n is

$$Q(u_n) = 1 - P(u_n) = 1 - \frac{n}{N+1} \tag{A4.4}$$

where the denominator is set to N+1, rather than N, to ensure the use of both highest and lowest values, at finite locations on the ln(-ln(Q)) plot. For large N, any differences which this introduces will be negligible.

Using the simple result in Equation A4.4, it is possible to plot ln(-ln(Q)) against u for all points from n=1 to N and this has been shown to be formally equivalent to the normal plotting of Equation A4.2. The Weibull parameters k and V_o may then be obtained from the gradient and intercept as described above.

Plotting in this way has the following advantages:

a) It uses all the data, down to the very lowest values recorded.

b) It is not dependent upon the particular grouping of the data.

c) The data covers a greater part of the plot, allowing more accurate parameter estimation and also enabling variations from a straight line fit to be detected more easily.

However, there are the following disadvantages:

a) It is necessary to have access to the complete recorded dataset without it having been grouped into windspeed bands.

b) A significantly greater data analysis effort is required to produce the plot.

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