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HSE CONTRACT RESEARCH REPORT No. 17/1988

# WORKBOOK ON THE DISPERSION OF DENSE GASES

***R E Britter***
Department of Engineering
University of Cambridge

***J McQuaid***
Research and Laboratory Services Division
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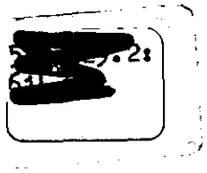

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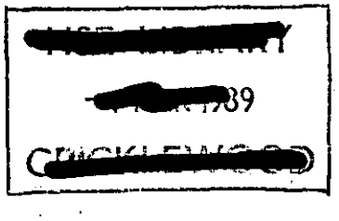

Information on the dispersion of dense (ie denser-than-air) gases in the atmosphere is needed in order to predict the consequences to the surrounding population of large-scale industrial accidents in which hazardous gases are released. The assessment of the potential effects of such accidents is a necessary part of any regulatory strategy for controlling the activities that give rise to the hazard.

The preparation of this workbook is based on the belief that a soundly-based consensus view on many aspects of dense gas dispersion has now been developed. The purpose of the workbook is to consider, in a single format, those areas where simple methods of estimation can now be be provided with some confidence. The workbook seeks to bring together current knowledge in a form in which it can be applied readily by non-specialists faced with meeting the requirements of regulations. The methods are based on straightforward physical principles. Where necessary, indications are given of those circumstances where more elaborate methods may be appropriate.

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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# Foreword

The preparation of this workbook arose out of a need for easily applied methods of estimating the consequences of accidents involving the release to the atmosphere of flammable or toxic gases. This need stems from requirements in the U.K. under the Control of Industrial Major Accident Hazards (CIMAH) Regulations. Similar requirements to those in the U.K. are in force in several other countries, especially in the European Community as a result of the Seveso Directive enacted by the European Parliament in 1984.

Workbooks and handbooks have been available for a number of years enabling non-specialists to prepare estimates of the dispersion of pollutant emissions. No comparable work of ready everyday reference has yet been prepared for accidental releases of dense (i.e. denser-than-air) gases. The methods for estimating dispersion of pollutants (which are generally neutrally or positively buoyant in their behaviour) are not applicable. The absence of workbook methods has been due to the rapid development of the subject of dense gas dispersion over the past ten years or so. Knowledge of these developments is confined to a small number of specialists and the emphasis in practical applications is placed on computerised modelling methods. This workbook seeks to bring together current knowledge in a form in which it can be applied readily by the large body of non-specialists faced with meeting the requirements of regulations. It is hoped that they will find it of use as a guide providing both a review of experimental results and a presentation of methods directly applicable to many of the circumstances in which dense gas dispersion estimates are required. The methods are based on straightforward physical principles. Where necessary, clear indications are given of those circumstances where more elaborate methods may be appropriate.

The final form of the workbook has benefited considerably from comments on the draft by P.W.M.Brighton, D.J.Hall and A.Mercer.

The contents of the workbook represent the personal views of the authors and do not necessarily represent those of the Health and Safety Executive.



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# Chapter 1

# Scope and Purpose

## 1.1 Introduction

Information on the dispersion of dense (i.e. denser-than-air) gases in the atmosphere is needed in order to predict the consequences to the surrounding population of large-scale industrial accidents in which hazardous gases are released. The assessment of the potential effects of such accidents is a necessary part of any regulatory strategy for controlling the activities that give rise to the hazard.

The main concept of relevance to this workbook is that of hazard range, that is, the maximum distance downwind that might be reached by a significant concentration of gas in particular release conditions. This concept is implicit in the requirements of the UK Control of Industrial Major Accident Hazards Regulations (Health and Safety Commission, 1984), derived from the European Commission's 'Seveso' Directive (Commission of the European Communities, 1982). These require that the hazards of certain installations should be assessed and the results be related to safety precautions on-site, emergency planning, and information to the public who might be affected. The concept of hazard range may also be significant in decisions on the siting of major hazard installations or the control of building development in their vicinities, which in the UK is regulated by Town and Country Planning legislation. More recently HSE has moved to a quantified risk approach to its advice on developments near major hazard installations. This requires information on the shape and size of the area affected by gas as well as the hazard range, and this information is also described in this workbook.

Under the CIMAH regulations, a manufacturer in charge of a major hazard installation must assess the hazards and in certain cases submit a formal report to HSE. This report should discuss the measures taken to control the hazards. The principal component of the report of interest in the present context is the identification of the type and likelihood of occurrence of major accidents that are considered possible and the estimation of the consequences of those accidents. It is with this latter facet that this workbook is concerned. The consequences in terms of the concentration at particular distances and times are provided by a dispersion calculation and they have then to be translated into specified levels of harm to the population, whether resulting from exposure to fire, explosion or

toxic gases. Thus, it will be seen that the estimation of dense gas dispersion is but one contributory factor, amongst many, to the overall exercise of judgement. But it is an important factor, for two reasons. Firstly, it enters into very many of the assessments. Secondly, the overall uncertainty will be markedly dependent upon the uncertainty in dispersion estimates. The level of this latter uncertainty, emphasised by a number of authors over recent years (e.g., Havens, 1978, McQuaid, 1979), stimulated major efforts on research in the early 1980's.

Although the need for information to underpin policies for the control of major hazards in the chemical industry has been the most important factor, there are two other areas where a need for knowledge of heavy gas dispersion arises. The first of these is the consideration of knock-on effects on the safety of nuclear power plants. The concern here comes from the possibility that a cloud of flammable gas released in a transport or storage accident may drift with the wind and be ignited near the nuclear power plant. In some parts of Europe, there are plants situated relatively close to storage installations or major transport routes, where 'relatively close' is interpreted as reflecting both the separation distance and the quantity of gas that might be involved in an accident. The resulting explosion might result in damage to the reactor building or to ancillary equipment on the site. The possibility of the primary accident may be so remote that it may be left out of consideration. This is not the case in some situations and it is then necessary to estimate whether the cloud will pose a hazard to the nuclear plant, bringing dispersion, explosive overpressure and structural response into the calculations. This connected sequence of events formed the subject of a European Community research programme (Commission of the European Communities, 1985).

The other area where information on dense-gas dispersion may be required is the forensic investigation of accidents in which flammable or toxic gas has been released. There will often be a number of candidate explanations for the damage caused and the identification of the most probable of these will be assisted by estimates of dispersion. Of importance too is that, with some accidents involving toxic gases, the damage may continue to be manifested over a long period. In such a circumstance, it will be necessary to delineate the levels of exposure beyond those causing immediate effects, in order that long-term remedial measures may be implemented.

A great deal of information has been accumulated as a result of experimental research on dense-gas dispersion, observations following actual accidents and background research on the physics of density-stratified flows in general. This has been accompanied by the development of many predictive models of dispersion based on a variety of modelling assumptions. Very little of the information is available in a form that is easily usable by those, generally non-specialists, who have to assess hazards.

The preparation of this workbook is based on the belief that a soundly-based consensus view on many aspects of dense gas dispersion has now developed. The purpose of the workbook is to consider, in a single format, those areas where simple methods of estimation can now be provided with some confidence. Furthermore, the attempt to do so should identify areas of continuing uncertainty and thus allow



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a clearer assessment of future research priorities.

It is presumed that users of this workbook require estimates for various dispersion parameters that are easily obtained, can be justified within stated bounds and whose uncertainties are known. Specific recommendations, explicitly made, will provide a focus for criticism and improvement within a usable framework. The provision of an easily interpretable framework for comparisons between models, workbook methods and experiment has not previously been made.

## 1.2 The Nature of the Problem

The type of accident that gives rise to the problem at issue involves a loss of containment and resulting release of hazardous material to the atmosphere. The hazardous materials range from fuel gases such as liquefied petroleum gas (LPG) to basic chemicals such as chlorine and ammonia and intermediates in chemical processes such as cyclohexane and methyl isocyanate. The containment may be a process vessel, storage tank, pipeline or transport container (ship, road tanker, rail tank car).

The scale of operations is very large, with a corresponding potential for catastrophic accidents. A modern olefine plant producing ethylene and propylene has typically an annual throughput of 500,000 tonnes and ammonia units associated with nitrogenous fertiliser production are of a similar size. The annual production of chlorine in Europe alone is in excess of 8 million tonnes. LNG is widely transported in ships with a capacity of 125,000 $m^3$. Road tankers of 20 tonnes and rail tank cars of 80 tonnes are commonplace in industrialised countries.

The hazardous nature of many of the materials is a major contributory factor to the hazard. For example, chlorine is rapidly fatal at a concentration in air of about 1000 ppm. Flammable gas clouds, if ignited in certain circumstances, can cause devastating explosions. Indeed, as a broad generalisation, the destructive overpressure generated by the explosion of a cloud containing a given mass of fuel gas can be comparable to that generated by the same mass of a solid, or condensed, explosive such as TNT. For example, the 30 tonnes of cyclohexane estimated to have been involved in the Flixborough explosion (see Figure 1) resulted in damage equivalent to that from the explosion on 16 tonnes of TNT (Sadee et al, 1976). Even if the cloud does not explode, the thermal radiation from a burning cloud can cause severe damage at a distance. The fireball from a 50 tonne LPG release that is ignited can be directly hazardous to humans at a range of 500 m. Of particular relevance is that the physical properties of the materials usually result in the formation of a denser-than-air cloud.

The loss of containment can occur from a variety of causes. The Flixborough explosion and the ammonia accident at Potchefstroom, South Africa in 1974 (Lonsdale, 1975) which killed 18 people were caused by rupture of a pipe and a storage tank respectively. In both cases, the pressure in the containment system was within the design range. The Bhopal accident in India in 1984 which killed 2500 people resulted from a runaway reaction in a storage tank and discharge of

highly toxic gas via a venting system (Varadarajan, 1985). An accident in which failure occurred as a result of excess pressure due to overfilling of a road tanker was that at Los Alfaques, Spain in 1987 in which 250 people died (Hymes, 1985). Release of hazardous material in transport accidents usually results from impact damage. Such was the case in an accident at Houston, USA in 1976 in which an ammonia road tanker ruptured killing 6 people and in Mexico in 1979 where a freight train including chlorine tank cars derailed killing 15 people.

This brief outline of the nature of the problem serves to illustrate that the assessment of the impact of chemical accidents is a complex issue. In particular, chemical accidents give rise to a new class of problems in atmospheric dispersion prediction quite different to standard pollution problems, for the following reasons:

1. The material, in almost all cases, is stored as a liquid, so that the volume of gas is very large.

2. The modes of release can vary widely, whereas pollution problems almost invariably relate to covenanted chimney emissions. The geometry of the source can take many forms and the initial momentum may be significant. The site of the accident may not be a fixed location, e.g., in transportation and pipeline accidents.

3. The process of formation of the gaseous cloud involves the phase transformation from liquid to gas. This can occur in a number of ways, from a flashing jet entraining air to the evaporation of a pool by heat transfer from the substrate.

4. In some cases, a chemical transformation also takes place as a result of reaction with water vapour in the ambient atmosphere e.g. nitrogen tetroxide ($N_2O_4$), hydrogen fluoride ($HF$).

5. The excess density of the cloud has a marked effect on the dispersion characteristics.

6. The release can occur over a short timescale, compared to the steady-state releases characteristic of most pollution problems. This gives rise to the complication of predicting dispersion for time-varying releases and to uncertainty in individual predictions resulting from variability about the ensemble mean behaviour.

7. The dispersing gas forms a low-level cloud that is sensitive to the effects of manmade and natural obstructions and of topography.

The above list, at first sight, presents a daunting prospect to anyone faced with the task of making predictions of the consequences of an accident. However, enormous progress has been made in the comparatively short time since the problem first came into prominence around 1970, mainly as a result of the introduction of large scale transportation of LNG. There are many problems still to be satisfactorily resolved, even to a point that is acceptable for hazard estimation as distinct

from satisfying scientific curiosity on the detailed physics of the phenomena. Answers that can be justified within a stated accuracy are needed and cannot await a full understanding of the influence of every variable. It is with that objective in mind that this workbook has been prepared. Although its concern is primarily to address the topic of estimating dense gas dispersion,some consideration will be given in the next chapter to related issues with the aim of allowing the reader to follow up sources of information.

## 1.3 Strategy of the Workbook

Our realistic goal is to allow predictions of useful measures of dense-gas dispersion to within a 'factor of two'. If greater certainty in a prediction is required alternative approaches are suggested. Our approach is to simplify the problem until only a few dominant variables remain. Correlations involving only these variables are obtained using experimental data regardless of any influence the non-dominant or 'peripheral' variables may have had in the experiments. At a subsequent stage the uncertainty of the correlations is addressed together with the dependence of the correlations on the peripheral variables. Apart from the obvious predictive capability, simple correlations allow assessment of the sensitivity of global analyses to input variables whose specification may be uncertain in practical situations. Explicit guidance on the use of the methods, illustrated by examples, is given in Chapter 6. Limitations imposed by the current state of knowledge and a discussion of research needs are given in Chapter 7.

Much of the information already available to the hazard analyst in the open literature refers to computerised methods, quite often without sufficient detail to allow an independent user to pick up the work, apply it to his circumstances and to know what confidence he can place in the predictions. The validation of the methods against experimental data has taken a variety of forms (see the recent review by Mercer, 1986) so that it is difficult to make comparative judgements of one method against another. A further useful application of the relationships developed here will therefore be to provide simple check tests for such methods which would be expected to be satisfied before the methods could be relied upon in the more complex cases.

## 1.4 Some Limitations of the Available Source Material

The preparation of the workbook has relied on an extensive review of source material. The following notes may be helpful in explaining the attitude adopted towards the source material.

Source material, in general, falls within one of the categories:-

(i) mathematical (analytical or numerical) modelling;

(ii) laboratory or physical modelling;

(iii) large-scale field experiments.

Extensive research has been carried out but there are still uncertainties and limitations peculiar to each category.

Analytical and numerical models with a wide range of complexity are currently available and are discussed in Wheatley and Webber (1985). Broadly they are all limited by poor knowledge of turbulence in stratified fluids and are tuned by comparison with the above mentioned laboratory and field experiments or require appeal to only weakly relevant experiments.

The validity and limitations of physical modelling in laboratory wind and water tunnels have not yet been fully established. In particular the influence of molecular viscosity (through the Reynolds number) has not been established and the interaction of Reynolds number effects with turbulence inhibition by density stratification is a poorly understood field. Further, the Peclet number with physical models in wind tunnels is often such that molecular diffusion is comparable with turbulent diffusion. These points will be considered further in Appendix F. The point here is not to negate physical modelling but to remind the reader that the activity is far less developed than for neutral or positively buoyant releases.

Both mathematical and physical modelling approaches are, of course, valid in model development and allow extrapolation and interpolation of the laboratory and field experiments. When using these models it must be shown that they are able to predict all available experimental results that are comparable and that they correctly incorporate the essential relevant physics. Unfortunately, modellers do not always follow these rules so that it is difficult to assess the validity of the models (Mercer, 1986).

Large-scale field experiments are valid in themselves and require a smaller extrapolation to larger problems than laboratory experiments. The expense involved in mounting field experiments make them less common and very often biased towards specific requirements e.g. LNG releases. Field experiments provide important but often limited data for cases where the source conditions may be poorly specified (for generic analysis) and the influence of variables previously termed 'peripheral' may not be negligible.

## 1.5 General Structure of the Workbook

There is a great diversity of possible release scenarios for which estimates of the dispersion of dense gases are required. Releases near the ground and remaining close to the ground are, as a consequence of that proximity, complicated by local terrain, buildings etc. The variety of both materials released and source release conditions also hinder the development of a workbook of general validity.

In order to provide guidance in a workbook format, we first develop correlations that ignore the complications provided by the following site-specific and release-specific situations:-

(i) buildings, structures, trees and various obstacles upwind and downwind of the source;

(ii) local topographical features such as ground slopes;

(iii) heat transfer between the released gas and its surroundings (including heat transfer from nearby surfaces and as a result of mixing with the ambient atmosphere);

(iv) phase changes (including evaporation of liquefied gas releases and condensation of atmospheric water vapour);

(v) chemical reactions;

(vi) non-perfect gases;

(vii) releases not close to the ground.

Once the basic correlations have been established, we consider the influence of (i), (ii), (iii) and, to a lesser extent, (vii) in later chapters. There is little information available about others in suitable format so that no specific guidance can be given at this stage.

As a preliminary to the consideration of technical material, a review of users' needs is appropriate. This sets the remainder of the workbook in its proper context.

# Chapter 2

# The Information Needs of the User

## 2.1 Introduction

The workbook is aimed at non-specialists faced with the task of performing a hazard analysis. The types of input information available to the hazard analyst and the forms in which he requires his outputs are kept to the forefront throughout. The workbook is not intended to be a once-for-all-time treatment of the whole field of dense-gas dispersion but rather will concentrate on those relationships which seem to be sufficiently soundly based to have a degree of permanence.

Dense-gas dispersion estimation has an important place in the assessment of the impact of accidents. It is instructive to describe first the place it occupies and the way in which it interfaces with other components of the assessment procedure. This chapter describes the context of the workbook's purpose and the issues raised for it by the user's needs.

## 2.2 Summary Statement of the User's Problem

The hazard analyst will first compile a portfolio of potential accidents reflecting the specific circumstances e.g., the type of installation or the transport mode. Such a portfolio can be derived by systematic examination of the circumstances using a technique such as the Hazard and Operability Study (Chemical Industry Safety and Health Council, 1977). For each specified accident, the analyst wishes to be able to estimate the risk (i.e., the probability per unit time) of death or injury to an individual at any stated location. This risk is composed of two factors. The first is derived from the distribution in space of the predisposing physical effect (e.g. concentration of toxic gas, thermal radiation level, explosion overpressure, etc), given that the accident has happened. This information is converted to a specification of the resultant harm to the individual, again as a distribution in space. The second factor takes account of the various probabilities determining whether the individual will actually suffer exposure. These include, of course, the

probability of occurrence of the accident per unit time but also other (absolute) probabilities such as the wind being in a given direction, the individual being evacuated or seeking effective shelter, the ignition of a flammable cloud, and so on depending on the circumstances. For further detail on the methodology, the reader is referred to published case studies such as Health and Safety Executive (1981), COVO (1982), Pape and Nussey (1986).

The information on dense-gas dispersion that is of interest to the hazard analyst is contained primarily in the distribution of concentration as a function of the spatial coordinates and time and secondarily in derived quantities from that distribution. Very often, the information is required only in summary form such as

1. the distance to a given concentration, for example the lower flammability limit (LFL). This distance is one measure of the hazard range beyond which conditions may be considered to be safe.

2. the size, composition and shape of the cloud. These are needed for thermal radiation estimates in the event of burning or as input to methods of estimating explosion propagation. The shape of the cloud also affects the estimates of distance to a given concentration. The distance may well be significant in directions other than directly downwind. Dense gas clouds can have extensive upwind and crosswind travel.

3. the mass of gas in the cloud between the upper and lower flammability limits. This is often regarded as the appropriate mass to be used in estimating the TNT-equivalence of a flammable cloud.

4. the concentration and its time history at a given distance, needed to define toxic effects on human and non-human biota.

In order to arrive at these points, the hazard analyst will proceed through a decision process broadly along the following lines:

1. What are the source conditions for the postulated accidents in his portfolio? How should these conditions be specified for compatibility with dispersion models?

2. Is the dispersion problem one that is appropriate to a passive or a dense gas dispersion calculation?

3. What level of sophistication is required? Is the estimate needed for a simple screening between different releases for comparative purposes? Is it a problem of a standard or routine type for which interpolation between previously derived results will suffice?

4. Which model or interpolation scheme should be used or should specialist advice be sought?

As background information, the hazard analyst will wish to be assured that the model or scheme proposed for use has been satisfactorily validated for the conditions of the problem. In some cases, the analyst may wish to have supplementary information on, or at least to have an appreciation of, for example:

1. How sensitive are the estimates to the conditions he has to specify (which are judgemental in may cases)? These include the weather conditions, release conditions, ground conditions, etc. The cost of performing many repeat calculations will be an important constraint on eliciting these sensitivities.

2. What are the effects of man-made or natural obstructions in the path of the cloud? Under what circumstances do these need to be taken into account? For example, there is strong evidence that it is only the flammable gas held up within and around obstructions that contributes to the energy release in an explosion.

3. When should a physical rather than a mathematical model be considered?

4. What reliance can be placed on a model prediction where a large extrapolation is needed beyond the range of scales over which the model has been validated?

5. How should allowance be made for uncertainties arising from the randomness of atmospheric flow?

## 2.3 Implications for the Workbook

The types of question and the form of the information requirements outlined above lead naturally to the identification in more specific terms of the topics which in one case or another will have to be considered.

For the source conditions, the essential requirements are to be able to specify the mode of release including the geometry of the source, release rate or total quantity released and the composition and physical properties of the material. These parameter values are required at the time when source specific effects, e.g. the momentum of release, have subsided. In some cases, a continuous model description will be possible but more often,especially for rapid or pseudo-instantaneous releases, a separation into two phases — formation of the cloud or plume and its subsequent dispersion — will be an advantageous simplification. The types of source for which the conditions need to be defined can be classified according to (i) the geometry, e.g. pipe breaks, catastrophic vessel failures, (ii) the storage conditions of the fluid, e.g. a superheated liquid, a fully refrigerated liquid or a gas, and (iii) the surroundings into which the fluid is released, e.g. bunds, unconfined ground or water.

Whether it is permissible to treat a release as passive from the source can be estimated from the value of a suitably defined stability parameter and this question is addressed later in the workbook.

The central theme — the dispersion calculation — will draw on the outcome of the source specification to indicate whether an instantaneous (i.e. cloud) or continuous (i.e. plume) model is required, or perhaps some intermediate type e.g. a time varying or limited duration release model. Criteria for classifying releases into one or other category will be given, or alternatively an approach which provides an acceptable (i.e. conservative) answer.

Regarding obstructions and topographical features, it is necessary to know whether their presence is important and screening criteria are desirable for this purpose. It may be sufficient, for example, to know that an obstruction, such as a fence or vegetation screen, will cause calculations, in which the obstruction is ignored, to err on the safe side. If more definitive information is required, it will probably be necessary, at the present time, to opt for a physical (i.e. wind or water tunnel) model in anything other than the simplest cases. Other considerations will be the costs relative to mathematical modelling (for those cases where the available mathematical models may be applicable) and the scope for study of phenomena such as concentration variability between experiments. Information on these phenomena is not provided by existing mathematical models nor by the results of the available field trials since the acquisition of comprehensive information of those types at large scale is prohibitively costly.

The purpose of this workbook is to consider dense-gas dispersion but it is desirable for completeness to consider briefly the status of those topics which determine the input information to, and require the output information from, a dispersion calculation. The presentation will be oriented towards identifying sources of useful and applicable information and where possible giving an opinion on their worth.

## 2.4 The Source Conditions for Dispersion Problems

A comprehensive source of guidance and recommended formulae for quantities and rates of release is the 2nd Canvey Report (Health and Safety Executive, 1981). This presents formulae according to whether the release occurs as a result of a catastrophic vessel failure or a pipe break and whether the storage conditions are pressurised or non-pressurised. Suitable reservations are stated where appropriate. Later work that may modify the methods recommended in the report is discussed below. Reference should also be made to Grint (1984) which is an update of the method of estimating the dispersion of instantaneous releases of LNG and LPG presented in the 2nd Canvey report.

The behaviour during release depends on whether the liquid is pressurised or refrigerated, or more precisely on the degrees of superheat possessed by the liquid. The superheat is the elevation of the storage temperature above the boiling point at atmospheric pressure. It is thus zero for a fully refrigerated liquid such as LNG and, for example, is $22°C$ for butane (boiling point at atmospheric pressure -2°$C$) stored under pressure at $20°C$.

### 2.4.1 Pressurised Releases

A fundamental study at laboratory scale of the effects of superheat on the fraction of liquid that is discharged following a catastrophic failure has been reported by Fletcher (1982). The fraction depends also on the ratio of the area of the breach to the area of the liquid surface. Fletcher's work provides specific guidance and he corroborated his conclusions by comparing estimates of liquid fraction discharge with observations in several large-scale accidents.

A common assumption is often made that the liquid fraction that contributes to the initial size of the vapour cloud (over and above the vapour fraction resulting directly from flashing) can be allowed for by equating it to the theoretical vapour flash fraction, thus in effect doubling the latter. Lees (1980) has suggested that the liquid fraction should be even larger, at double the vapour fraction. The 2nd Canvey report expressed reservations about such rules-of-thumb and instead assumed that all the liquid fraction becomes airborne. A further assumption was then made about the amount of air entrained by the expanding cloud and a heat balance was performed to determine the proportion of the liquid that would be vapourised, the remainder of the liquid raining out of the cloud. Sample calculations showed that this procedure predicted that the whole of a propane release and around 80% of a butane release would be vapourised. A similar calculation can be performed for LPG although it is somewhat more complicated.

Recent work by Bettis and Moodie (1987) showed that the liquid fraction can exceed Lees' recommendations as given above. A further complication they found was that the fraction is dependent on the fill level of the vessel, as well as on the superheat. Grint (1984) concluded, on the basis of Fletcher's work, that an assumption that the whole of the vessel inventory becomes vapourised is reasonable for hazard assessment and this still seems the only acceptable procedure, given the state of uncertainty of the evidence. It is subject, of course, to the criteria given originally by Fletcher for cases where the superheat and/or the area ratio are low.

The assumption in the Canvey report about the amount of air entrained by the expanding cloud was based on evidence (admittedly somewhat sketchy) from accidental releases of pressurised ammonia examined by Kaiser and Walker (1978). Analyses of the amount of air entrained up to the time when the pressure-driven expansion has subsided and gravitational slumping begins have been given by Jagger and Kaiser (1981) and Griffiths and Kaiser (1982). However, comparison with direct experimental evidence is lacking and relevant work is currently in progress on the subject. The rule-of-thumb used in the 2nd Canvey report amounts to assuming that the volume of air entrained equals 60 times the vapour flash fraction, independent of material properties and physical conditions. Wheatley et al (1988) assume the mass of air entrained to be that which would be required to effect complete vapourisation of the liquid content of the cloud at the boiling point corresponding to atmospheric pressure. The sensible heat loss of the entrained air as its temperature falls from ambient to the boiling point of the liquid provides the latent heat of vapourisation. The procedure assumes that there is no raining-out of liquid from the cloud and the calculation thus provides the upper limit on the

mass of air entrained. However, this is an area where there is considerable research activity and rapid developments can be expected in the next few years.

The usual and sensible procedure is to test the sensitivity of one's conclusions to whatever assumption is adopted. Grint (1984) presents useful guidance in the form of repeat calculations for different air entrainment ratios and the same approach has been used by Wheatley et al (1988) in comparing model predictions with the results of experiments in which the source conditions were somewhat ill-defined.

The catastrophic failure of pressurised ammonia storages is a special case which has received much attention. Ammonia as a gas is, of course, less dense than air at the same temperature but when released as a pressurised liquid it can form a denser-than-air mixture with air, as has been described by Haddock and Williams (1979) and Griffiths and Kaiser (1982). These references provide guidance on the density of the ammonia-air mixture for particular release and atmospheric humidity conditions. A programme of large-scale releases of pressurised, liquefied ammonia has been reported by Goldwire et al (1985) and provides valuable data for checking the theoretical predictions.

In the case of non-catastrophic failures, such as pipebreaks or small penetrations of vessels, specific guidance on release rates is again given in the 2nd Canvey report. Further developments since then include the comprehensive investigation by the Design Institute for Emergency Relief Systems (Fisher, 1985). Important developments have also been reported by Fletcher (1984) and Fletcher and Johnson (1984) for release rates of flashing, two-phase liquids from pipes. A useful practical source of guidance is Carter (1986).

Outside the orifice, the release will be a single-phase liquid (for which the calculation is straightforward) or gas or two phase liquid/gas. For storage pressures below the critical pressure for sonic flow at the orifice, the calculation for single-phase gas discharge is also straightforward; see for example the 2nd Canvey report. Above the critical pressure, an underexpanded jet is obtained. This has been the subject of a recent study by Ramskill (1984) with a view to predicting the far field velocity decay of such jets. Data for high pressure jets have been published by Brennan et al (1984) and Ewan and Moodie (1986), together with excellent correlations of the results in terms of a virtual orifice diameter. Both these works can now be taken as providing satisfactory treatments for this case. The interaction of the jet and the wind, and the transition to a plume dominated by entrainment and buoyancy can be described by the model of Ooms et al (1974) which has recently been verified experimentally by Xiao-yun et al (1986). Appleton (1984) has carried out a comprehensive review of information on the two-phase discharge case. He found very little that was relevant to the problem of specifying the source term for a calculation of atmospheric dispersion.

### 2.4.2 Refrigerated Releases

For a release of a fully-refrigerated liquid, the procedures recommended in the 2nd Canvey report retain their general validity in terms of specifying the form of the source term for the various combinations of rapid (or quasi-instantaneous) and

continuous releases in bunded and unbunded configurations. The procedures are subject to later developments on the specification of the spread and evaporation of the pool which affect calculations of the maximum pool radius and the vapour evolution rate, especially for liquids with boiling points near ambient temperature. These developments are reported by Webber and Brighton (1984) for pool spreading and by Brighton (1985) for evaporation. Gravity spreading by the vapour will enlarge the source dimension beyond the confines of the liquid pool. This effect has been considered by Britter (1980) and he provides a correlation which allows the enlarged source dimension to be estimated.

### 2.4.3 Initial Geometry

In addition to the released quantity and the physical composition, it is necessary to specify the initial geometry. For example, in the case of a cylindrical cloud (a commonly assumed shape for catastrophic releases from pressurised containment), the initial aspect ratio i.e. the ratio of the diameter to the height, was assumed in the 2nd Canvey report to be unity and this assumption is still commonly used. The effect of aspect ratio on dispersion will be considered in Section 4.3.

For a refrigerated release, the liquid will generally form a pool which is either contained in a bund or spreads over the ground (or the sea as appropriate). The source geometry is thus well-defined and the references cited in Section 2.4.2 provide the necessary information.

## 2.5 The Uses of Dispersion Estimates

The objective of a dispersion estimate is to provide the distribution of concentration of the released gas as a function of space and, for non-steady releases, of time. That broad general statement covers a multiplicity of requirements in terms of the detail of the distribution. The hazard analyst will need to be aware of the requirements for different applications. The purpose of this section is to review briefly the main applications and to indicate the nature of the demands they place on dispersion modelling.

### 2.5.1 Toxicity Effects

The quantitative description of the effects of exposure to a toxic gas requires both the concentration and its variation with time. For acutely-toxic gases, it is generally the case that the influence of concentration is more pronounced that that of exposure time. That is to say, a high concentration for a short time has a more severe effect than a low concentration for a longer time. The simple definition of dosage, i.e. the integral over the exposure time of the concentration, is not an adequate measure of the resultant effect, other than in exceptional circumstances.

A widely-used relationship defines the specified levels of harm to be dependent on the product $C^n t$ where the index $n$ depends on the gas and in general has a value greater than 1. For example, for chlorine a common value used for $n$ is 2.75

(Eisenberg et al, 1975). A 'level of harm' is not a deterministic quantity but must be related to the statistical variation of vulnerability over the population. Infants and elderly people will be more vulnerable to ill-effects than a fit adult for the same exposure. Because of this, it is customary to define values of $C^n t$ that produce a specified harm (e.g. death) in given proportions of the population. Thus, for example, the LD50 is the Lethal Dosage (although 'dosage' here no longer has the simple restricted meaning as described above) that would produce death in 50 per cent of the population. The value of $C^n t$ corresponding to particular levels of harm (e.g. LD05, LD50, LD95, etc) may be obtained from published Probit relationships (e.g. Eisenberg et al, 1975). In relating probability of death to 'dosage', the Probit model assumes that the former and $ln(C^n t)$ are related by a cumulative normal curve.

The determination of the value of $n$ and of the dependence of each level of harm on $C^n t$ has to be based on sparse information on human exposure or on data from animal experiments whose application to humans is of uncertain validity. Although there is a considerable literature on the subject, the debate tends to be underlined by little hard information. Care must be exercised in selecting the relationship to use, since quite wide disparities exist between different published relationships. For further information on these uncertainties, the reader is referred to Griffiths and Megson (1984) and Nussey et al (1984). Extensive consideration of the toxicity data relating to chlorine and ammonia has been given by Withers and Lees (1985) and Withers (1986).

Dispersion models predict time-averaged concentrations of one kind or another. The use of such time-averaged concentrations in the toxicity relationship merits some discussion. The data on which the toxicity relationships are based are generally derived from exposure to steady (or assumed to be steady) concentrations so that the averaging time implicit in the relationships is the exposure time. Thus a dispersion model is required to give the average concentration at a point over the passage time of the gas or over the time taken to induce the specified harm if that time is shorter. However, there is a complication due to the fact that the index $n$ is greater than 1. Variations of concentration over time scales shorter than the exposure time cannot be simply averaged out since the harm caused by a varying concentration is greater than that which would be caused by a steady concentration with the same time-mean value. This effect has been considered by Ride (1984) and Griffiths and Harper (1985). Although an appreciation of the effect is naturally desirable, applying a correction for it is a refinement that is hardly justified given the state of uncertainty pertaining to toxicity relationships (and be it said the often complete lack of information provided by dispersion modellers on the averaging times implicit in their models).

### 2.5.2 Fires and Explosions

Many flammable gas releases are ignited at or near the source so that the dispersion behaviour is not relevant and many others are not ignited at all. Nevertheless for the purposes of hazard analysis it is necessary to estimate the distance required

to achieve dilution to a 'safe' concentration in order that the extent of the area potentially at risk may be defined. A separate judgement has then to be made on the probability that the gas will encounter an ignition source within the area so defined. Given that an ignition occurs, it is then necessary to estimate the consequences of the resulting fire or explosion.

Various ways of defining the boundary of a flammable cloud or plume have been proposed. The simplest and most commonly used is to equate it to the contour of the time-average concentration corresponding to the lower flammability limit (LFL) of the gas. The LFL is the concentration below which a propagating flame is not possible under defined conditions in a standard test apparatus. It is a property of the gas and the relevant measure is the molar (i.e. volume/volume) concentration. Values are given by Zabetakis (1965). This definition of the boundary is appropriate if an estimate is required of the quantity of fuel likely to be involved in an explosion.

However, if the boundary is set by the limits within which ignition is possible, problems arise if the averaging time is taken as that associated with predictions of dispersion models. This is usually a 10 minute average for a plume or a few seconds for a cloud, although these are more often the implicit consequence of the model assumptions or calibration than an explicit statement by the modeller. Since short-time fluctuations above the LFL will be present within the averaging time, it follows that a cloud or plume may be ignited beyond the boundary defined by the LFL contour. Whether ignition in such a circumstance will lead to a self-propagating flame is not certain; it will depend on whether or not the concentration fluctuation is associated with an isolated patch of gas above the LFL. In early experiments on LNG plumes, Burgess et al (1972) were able to achieve burning back to the source from ignition at a point where the $3\frac{1}{2}$ minute average concentration was only about $\frac{1}{10}$th of the LFL. This was clearly associated with intermittent detection of a plume that was subject to considerable meander. Puttock et al (1982) considered the problem of meandering of the plumes in the Maplin Sands tests and proposed a method of interpreting the concentration records in order that realistic comparisons could be made with the predictions of mathematical models. Koopman et al (1982) in reporting the results of the China Lake tests described concentration measurements which showed a significant probability of short-term (i.e. peak values from data sampled at 3-5 Hz) concentrations above the LFL at positions where the 10 sec average was $\frac{1}{5}$th of the LFL. Hirst (1984) reports results of large-scale experiments on releases of pressurised liquefied propane in which the flammable extent of the plume was assessed from both concentration measurements and from observations of flame propagation distance. It was found that the latter were consistently larger than indicated by the concentration measurements. The response time of the gas sensors was 2 to 3 s and the increased distance was attributed by Hirst to smoothing of 'instantaneous' concentrations above the LFL by the gas sensors.

The probability that flame propagation occurs will be a function of the mean concentration expressed as a fraction of the LFL at the position where ignition takes place. The smaller this fraction the less likely will it be that short-term

concentration fluctuations above the LFL will be present. The probability characteristics have been investigated experimentally by Birch et al (1980) and theoretically by Chatwin (1982) and with particular reference to dense gas dispersion by Carn and Chatwin (1985) and Carn (1987). The probabilistic problem is often abbreviated (in a non-rigorous way) by redefining the 'safe' concentration assuming a unique value for the ratio, $r$, of the short-term peak concentration which will result in flame propagation to the mean concentration as given by a dispersion model. The procedure, in effect, deems the probability of flame propagation to be zero when the mean concentration has decreased to a value of $1/r$ times the LFL and this value becomes the 'safe' concentration. The statistical inadequacy of relying on a peak-to-mean ratio to characterise a fluctuating concentration record has been spelled out by Barry (1971, 1972). Nonetheless, it can be used to provide a conservative answer to a difficult problem. However, since hazard analysis is essentially a probabilistic description, it is hardly consistent to seek a deterministic answer to the dispersion/combustion question. A wholly probabilistic approach must emerge in time, as argued by Chatwin (1982), although its development is currently inhibited by inadequate data on the probability density function of the concentration.

A cloud or plume of flammable gas that is ignited will result in either a fire or explosion. The distinction between the two is somewhat arbitrary but an explosion generally implies that destructive overpressures are generated and this in turn implies that the flame velocity reaches values in excess of about 200 m/s. The mechanism by which flame acceleration occurs is still uncertain but it is increasingly accepted that high flame velocities are only attained where there is some degree of confinement of the gas. This can occur within obstructions whose effect is to enhance turbulence levels in the unburnt mixture ahead of the flame (van Wingerden, 1984; Adomeit and Willms, 1984). For assessing explosion hazards, a useful review is provided in Health and Safety Commission (1979). The method recommended relies on estimating the combustion energy available in the cloud which then provides the mass of TNT to which the cloud is 'equivalent'. Information on the destructive effects of TNT explosions can then be used to assess damage caused by the cloud explosion. The method requires the mass of gas within the flammable range in the cloud to be estimated and ignores the shape of the cloud and the location of ignition. A dispersion calculation, giving mean concentration contours, allows this mass to be calculated. In accordance with the conclusion above, it is now considered that it is only necessary in this calculation to have regard for the region of the cloud within obstructed areas (Van den Berg, 1985).

The alternative to a TNT-equivalence calculation is to use a computer code for explosion propagation. Considerable developments on this subject have taken place in recent years and codes are now beginning to be used for routine analysis. For further information, see for example Strehlow et al (1979), Hall et al (1984), Phillips (1982, 1986).

In the case of a cloud or plume burning without destructive overpressure, the hazard to the surrounding population is the received thermal radiation flux. This

depends on the size of the cloud and it seems reasonable to take this as being defined by the mean LFL concentration contour, with averaging over a few seconds for a cloud and over 10 minutes for a steady plume. It also depends, of course, on the emitted radiation flux and on the separation distance; for a description, see Roberts (1982). The human response to thermal radiation is described by Hymes (1983).

## 2.6 Mitigation of the Hazard of a Dense Gas Release

A brief summary of ways in which the hazard of a dense gas cloud or plume might be mitigated is appropriate, since these will be relevant to the assessment of risk. The most obvious course of action is to provide forced ventilation to supplement the wind. The methods that have been proposed rely on the entrainment properties of water sprays and steam jets. Information on the design of installations and experimental results can be found in Simpson (1974), McQuaid (1978) and Moodie (1985), while wind tunnel modelling of the action of a water spray on a dense gas plume is described by Meroney et al (1983). The practicability of these methods is limited to moderate release rates that persist for a time, for example from pipe breaks. Examples of the successful use of water sprays have been given by Beresford (1981).

A different kind of mitigation relates to the response of the individual at risk, especially in the case of toxic releases. The main factor is the dosage experienced by remaining, or moving, indoors during releases of limited duration. The magnitude of the benefit for different circumstances has been evaluated by Wilson (1986) and Davies and Purdy (1986).

Yet another kind of mitigation results from the gross dilution due to obstacles such as fences, buildings or tree lines and from the diversion of the dense gas by topographical features into directions other than directly downwind. These matters will be considered in Chapter 5. Wind tunnel experiments on the dilution induced by vortex generators around the source have been described by Kothari and Meroney (1982). Some installations in practice are completely surrounded by a fence or bund. Should a release occur, the bunded area may, depending in the windspeed, be flooded with the dense gas and concentrations outside the bunded area will be reduced below those in the absence of the bund. Such a layout has been investigated in large scale field experiments and in a wind tunnel (Davies and Inman, 1987).

# Chapter 3

# Development of the Workbook Methods

## 3.1 Historical Background and Observational Evidence

An appreciation that density difference can considerably influence the motion and mixing of accidental gas emissions has long been evident. The first involvement of science in the phenomenon was, in all probability, connected with the inverted problem of the poor mixing of lighter-than-air methane with the (usually inadequate) ventilation in early underground coal mines. Roberts and King (1986) quote from illuminating communications by a Mr Jessop of Sheffield, Yorkshire to the Philosophical Transactions of the Royal Society in 1675. Referring to four different sorts of damp (from the German dampf = vapour), he wrote:

'The fourth, which they also call a damp, is that vapour, which being touched by their candle presently takes fire, and giving a crack like a gun produceth the like effects, or rather those of lightening..... . Damps generally are considered to be heavier than air but this was manifestly lighter, for it lay towards the top of the bink'.

The propensity of methane to form layers at the roof continued to be a major cause of mine disasters until modern ventilation practices and drainage of the methane brought the problem under control. In this achievement, the scientific understanding of the influence of density difference, in relation to the rate of emission of methane and the ventilation velocity, played its part.

An early example of an accident unrelated to underground mining in which the density difference played a role was that at Crarae in Scotland in 1886. In the accident, 7 members of the public died from exposure to a toxic gas cloud. The accident happened at a quarry which was elevated above the surrounding country and with an approach road driven through a cut. All those who died were on the road and were overcome by the toxic fumes from a large blast of gunpowder in the quarry. The report of the public inquiry into the accident concluded that 'the lack of wind had prevented the gas from being dispersed and, being heavier than

air, had rolled down the sloping floor of the quarry into the cut'.

These illustrations from two different industries bring out the two features that dominate the description of dense gas dispersion. The density difference reduces the rate at which the gas mixes with the ambient air and it gives rise to a motion of the gas which interacts in a complex way with any prevailing motion of the ambient air. The density-driven motion does itself induce mixing between the gas and the ambient.

The physical processes that are involved in the motion and mixing and the way they influence the modelling of dense gas dispersion will be described in the following sections. We shall first give some qualitative descriptions, drawing as necessary on related phenomena and on observations from accidents and directly-relevant experiments.

The influence of the density difference on mixing arises primarily from the associated buoyancy force i.e. the Archimedian force on a body submerged in a fluid of different density. Although the density difference also affects the inertia forces acting on a fluid in motion, the changes to the fluid accelerations due to the density difference are generally assumed to be small compared to the accelerations arising from the buoyancy forces. This assumption, known as the Boussinesq approximation, will be called into play when we come to analyse the problem.

The buoyancy forces follow a sign convention. Negative buoyancy implies a buoyancy force in the direction towards the boundary i.e. opposite to the positive direction of the z-coordinate. Thus a dense gas layer at ground level in the atmosphere and a light gas layer at roof level in a mine are both defined to be negatively buoyant flows. The converse situation is a positively buoyant flow such as an emission from a hot source in the atmosphere. It is customary to refer to the neutrally buoyant case as 'passive' although strictly the term implies that the conditions of emission play no dynamic part in the way in which the emission subsequently diffuses into the ambient flow, a condition that will not be satisfied if the emission has significant momentum.

Flows into which a secondary fluid of different density is released are generically described as density stratified. Apart from the obvious case where the density difference arises from the emitted gas having a molecular weight different to that of air, density stratified flows also commonly occur as a result of a temperature difference. The most familiar example is the atmosphere itself and this provides a ready source of illustration of the effects of density stratification on the flow structure. The density stratification is conventionally classified as either stable, neutral or unstable and these correspond to the above classification of negatively, neutral or positively buoyant releases. The alternative description derives from the effect of the buoyancy forces on the random motions of atmospheric turbulence. For example, a negatively buoyant flow is stratified such that the density decreases upwards in accordance with our earlier sign convention. A parcel of fluid which is displaced upwards as a result of a turbulent fluctuation will move to a new height at which the density is lower. There will therefore be a downward force acting on the parcel and this will tend to restore it to its original position. Thus the equilibrium of the parcel is statically stable. The stratification is such that

random vertical excursions tend to be damped out. In a positively buoyant flow the random motions are amplified and the equilibrium is statically unstable.

A stable atmosphere results when the ground has been cooled and the overlying air is at a higher temperature, conditions that generally occur only at night, whereas an unstable atmosphere is most pronounced on clear sunny days when the ground is heated by solar radiation. In terms of observed features, a stable atmosphere is characterised by low levels of turbulence or gustiness. A passive pollutant emitted in stable conditions mixes only slowly with the ambient air. The converse is observed in unstable conditions in which turbulence generated by the upward heat convection leads to increased gustiness and large scale motions whose influence on the spreading of pollutants such as chimney plumes is a matter of everyday observation. The clear dependence of the spreading or dispersion on the stability state of the atmosphere led to a need for a finer stability classification scheme and associated relationships for the parameters of the spreading (e.g. the standard deviations of the concentration distributions in the three coordinate directions) in terms of the stability classifications. The best known scheme is that due to Pasquill (1961). He divided the range of stability into six categories, A to F, ranging from extremely unstable to moderately stable respectively. The stability categories were defined in terms of easily observable parameters — the fractional cloud cover and the windspeed at a reference height of 10 m. The scheme continues to be in widespread use in methods of estimating passive dispersion. A full account is given in Pasquill and Smith (1983).

The Pasquill scheme is also used in several current dense gas dispersion models as a ready means of calling up information needed in relationships for the dependence of cloud entrainment on atmospheric turbulence parameters such as turbulent length and velocity scales. Other ways of classifying the stability in terms of ranges of numerical parameters directly related to turbulence, and hence to the needs of dispersion models, have been proposed (see Sedefian and Bennett, 1980; Holtslag and Van Ulden, 1983). Of course, if information on atmospheric turbulence is available directly, no recourse need be made to a stability classification scheme.

The descriptions up until now have for convenience been couched in terms of the density difference or density gradient. This influence, and hence that of the buoyancy force, on the dynamics of the flow is relative to the influence of the other forces that are acting. The ratios of the various forces in a fluid in motion to each other are expressed as dimensionless numbers, of which the one directly relevant to dense gas dispersion is the Richardson number or $Ri$. This is the ratio of the buoyancy forces to the inertia forces. (More correctly, this ratio is the particular form of the Richardson number known as the gradient Richardson number). The Richardson number is the parameter that determines whether a dense gas release will exhibit dense gas effects of the kind to be described presently or can for practical purposes be treated as a passive release. Such a criterion will be developed later in the Workbook. The Richardson number naturally and repeatedly enters the relationships for dispersion that will be presented in the Workbook. It can be formulated in various ways but the basic property — that it

expresses the relative influence of buoyancy and inertia forces — applies to each one. It should be noted that the dominant influence of the Richardson number does not conflict with the Boussinesq approximation stated earlier. The approximation only implies that the influence of the density difference on the fluid inertia is small, not that the inertia is itself small. For a fuller account of the basics of turbulence and flow structure in density stratified flows, see Lumley and Panofsky (1964), Turner (1973) and Panofsky and Dutton (1984).

Turning to the second way in which density difference manifests itself (i.e. on the motion of the emitted gas), there are many examples in nature of such density-driven flows. These include sea breezes, avalanches, outflows from volcanoes, dust clouds in the desert and so on. The flows are driven by the buoyancy pressure and characteristically advance into the surroundings behind a gravity front. The velocity of this gravity front is determined by the application of Bernouilli's theorem expressing the balance between the driving (buoyancy) pressure and the dynamic pressure of the displaced flow ahead of the front. This is easier to visualise if the front is imagined to be arrested by an opposing flow. The relevant dynamic pressure is then that of the flow required to arrest the front. This configuration is widely used in laboratory experimentation on the dynamics of gravity fronts and the results of these experiments have been applied to dense gas dispersion modelling. An example of such a study is that of Britter and Simpson (1978). A review of this subject has been given by Simpson (1982) and more fully in the monograph by Simpson (1987). The motion of a gravity front will be affected by the slope of the ground, a factor important, for example, in the methane layering problem in mines where the roadways are often inclined as they follow the coal seam. The layer can move uphill against the ventilation and similarly a dense gas release in the atmosphere can move downhill against the wind. For a review of terrain effects on dense gas dispersion, see Britter (1982). A summary of relevant information will be given in Chapter 5.

The features so far described are exhibited in releases from chemical accidents and in experimental releases of dense gases both in the laboratory and in the field. In all cases, the dispersion proceeds through several phases, distinguished from each other by the dominant physical mechanism involved. A detailed account of these phases is given in Hunt et al (1984) and the following is a brief summary. Firstly, there is a gravity-spreading phase in which the mixing is governed by entrainment across the edge and top of the cloud as a result of the gravity-induced motion. The former component is the more important. This phase includes the initial interaction between the cloud and the wind and the distortion of the cloud thereby produced. There follows a phase in which mixing by atmospheric turbulence is influenced by gravitational forces and the gravitational forces continue to produce enhanced lateral spreading of the cloud. Finally, the gravity influence subsides as the density difference between the cloud and the ambient air becomes small and mixing by atmospheric turbulence becomes dominant i.e. passive dispersion prevails.

Observations following accidents and in experiments show that the effects of density difference are most obviously manifested in a greatly increased spread of

the cloud in the lateral (crosswind) direction and a much reduced vertical extent. The interface between the dense gas cloud and the ambient atmosphere shows little of the highly turbulent engulfing motions found with passive releases. These engulfing motions are the means by which the cloud entrains ambient air and is thus diluted and increases in depth. The reduction in the rate of entrainment on the dispersion (and hence on the downwind distance to a given concentration) is to an extent counterbalanced by the increased lateral spread. Dense clouds or plumes have a lower advection velocity (i.e., the depth-averaged velocity at which a cloud or a section of a plume appears to move downwind) than passive clouds or plumes in which, by definition, the gas moves at the local windspeed. They also exhibit much less meander, or responsiveness to large scale atmospheric motions, than is observed with passive releases.

Some of these features are well illustrated in photographs from large-scale field experiments e.g. Koopman et al, 1982; McQuaid and Roebuck, 1985. The latter reference reports a study of the dispersion of clouds of dense gas carried out at Thorney Island, England. The cloud in each of the experiments was formed in a container which could be rapidly removed. The container was 14 m diameter and 13 m high and the gas was stored in it at ambient temperature and pressure. Following the removal of the container, the cloud rapidly slumped and spread radially, forming a pronounced gravity front. Figures 2a to 2c show several stages in the early motion of the cloud viewed from the side and Figures 3a to 3c show views from an overhead camera. The experimental design was intended to be consistent with the sequence of events following a release from pressurised storage, as described earlier. The initially stationary cloud represented the end result of the formation phase. The sequences in Figures 2 and 3 are representative of the first phase in Hunt et al's description summarised above.

Figure 4 shows the cloud at a much later stage, corresponding to the second phase. The conditions of the experiments did not cover the final, passive dispersion phase.

The Thorney Island experiments represented one end of the spectrum of release conditions i.e. an instantaneous release of a fixed volume of gas, giving rise to a cloud. At the other extreme, there is the continuous release at a steady rate, giving rise to a plume. The features of dense gas dispersion are also well illustrated in laboratory experiments on plumes reported by Hall (1987). Several photographs from these experiments at increasing Richardson numbers are shown in Figures 5a to 5d. The progressive increase in lateral spreading and reduction in the interfacial mixing are evident as the Richardson number increases.

Finally, an example of a release intermediate between instantaneous and continuous is shown in Figure 6. The photograph was taken during a controlled release of LNG from the stern of a tanker carried out in the Bay of Biscay in 1973 (Kneebone and Prew, 1974). The release was of limited duration and the cloud was still developing when the release was terminated. The gravity front at the lateral edges, the small height to width ratio and the very stable nature of the cloud are clearly evident.

The spectrum of release conditions illustrated in the figures is an added com-

plication in any attempt to develop dispersion prediction methods. It is clearly necessary to simplify, in a way satisfactory for practical purposes, the release condition that should be adopted in preparing consequence estimates for a postulated accident. Criteria for doing so will be described later.

To round up this outline, it is appropriate to give a brief description of the methods used in mathematical modelling of dense gas dispersion. The models can conveniently be classified as box, intermediate (or 'slab') and three-dimensional (3D). The distinguishing feature is the way in which the models represent the distribution of properties within the cloud. Box models assume that all properties are distributed uniformly over the volume of the cloud or a transverse slice of the plume. 3D models retain spatial distribution of properties in all three coordinate directions. Intermediate models apply some kind of spatial averaging in the vertical direction and thus fall between the other two types in their complexity. Although many models have been published by different authors, they exhibit a considerable degree of commonality within each type. All the 3D models so far published use the gradient transfer hypthesis for turbulence closure (although turbulent stress modelling to provide closure is under development by a number of workers). Webber (1983) reviewed the variety of box models and found that all the published box models fall into one or other of two basic classes. He derived analytic solutions for the two classes and within this framework, he was able to highlight the differences in scaling properties incorporated in the models in an explicit and illuminating way. The division into two classes was made possible by restricting consideration to the basic case of flows in which buoyancy was conserved. This refers to the constancy of the buoyancy force (i.e. the local density difference times gravitational acceleration) per unit volume integrated over a cloud, or the flux of buoyancy force per unit volume (i.e. the buoyancy force per unit volume times the volume flux) through any transverse section of a plume. These quantities are not affected by entrainment of air if the gas is at the air temperature (in which case the release is called isothermal) since dilution increases the cloud volume or plume volume flux exactly inversely as it decreases the density difference. The Thorney Island experiments were isothermal and the total buoyancy of the cloud remained constant as it dispersed. A release of LNG, on the other hand, may have significant addition to its buoyancy as a result of heat input from entrained air and by transfer from the ground.

Box models, because of their relative simplicity, can readily be assessed for the physical correctness of their assumptions, especially in the framework proposed by Webber (1983). They can therefore be readily compared with the experimental results, in isolation from any numerical solution procedure that might be used to solve the model equations. The model is centred on an equation for the rate of increase of mass of the cloud as a result of entrainment of ambient air. This entrainment is hypothesised to be compounded of entrainment through the edge of the cloud and through its top surface. The two processes are modelled separately. They make a changing relative contribution to the growth of the cloud. Near the release position, edge entrainment is dominant and decreases in importance as the cloud spreads and moves away from the release position (in the presence of

a wind). For a plume, corresponding equations can be set up using the plausible assumption that gravitational spreading in the direction of the wind can be neglected. Numerical solution of the model equations is straightforward and, in some formulations, analytic solutions are possible. Computing costs per run are modest and the models are readily usable (after some experience) as an everyday working tool. However, they cannot be applied without further development (and some heroic assumptions) to problems involving terrain or time-varying releases. In selecting a model, the user should take note of the remarks in Chapter 1 concerning validation and assessment of reliability.

It is clear from inspection of Figure 3 that the assumption of a uniform concentration distribution is a gross simplification. However, the volume averaging applied in box models is consistent with practice adopted for other turbulent flows. The assumption of a uniform distribution, coupled with an entrainment hypothesis, has found wide application to jets, wakes and plumes and provides useful practical results without having to resort to numerical solution of approximations to the 3D conservation equations. More appropriately, for any particular flow, similarity of form for the concentration profiles can be assumed and the scales of the profile determined from an analysis using a uniform concentration assumption. McQuaid (1984a) has discussed the merits of the box model and concluded that at the present time there is no strong case for replacing it with more complex models, at least for straightforward applications.

3D models use basic equations which are reasonable approximations and are in principle applicable to complex terrain and time-varying releases. The validity of the gradient transfer hypothesis that they use is questionable for dense gas dispersion. The solutions are obtained using numerical integration schemes which are not usually separately evaluated for their contribution to the overall errors in prediction. It is therefore difficult to make judgements on the accuracy of the models based on the comparisons with experiment that have been published. They are expensive to develop and to run and thus are unsuitable for routine use in hazard analysis. A comprehensive evaluation of some of the available 3D models has recently been completed (Havens et al, 1987).

Intermediate models retain many of the advantages of 3D models while largely avoiding excessive computing costs and possible numerical solution problems. Analytic solutions are possible in some cases. Their development and running costs fall between those of the other two types. They have been comparatively neglected up to the present.

A particularly comprehensive review of the different types of model has been given by Wheatley and Webber (1984). They provide an objective and rigorous assessment of models and also describe how the box model could be improved to correct the deficiencies they identify.

A release of dense gas in the atmosphere results in a density-stratified flow dispersing in an ambient flow which can also be density stratified. However, the equivalent 'stability' of the dispersing flow is much larger in its initial stages than the stability of the atmosphere even at the stable end of the Pasquill range. Thus the large dependence on atmospheric stability of the dispersion characteristics of

passive materials is not repeated for dense gases and many current models do not include explicit allowance for atmospheric stability. Any dense gas release will at some stage cease to exhibit dense gas effects and thus will become totally influenced by atmospheric turbulence and hence stability. The progression from dense gas to passive dispersion can be modelled as a continuous process and this is an implicit characteristic of 3D and intermediate models. It can also be done with box models but quite a few make the somewhat artificial assumption of an abrupt transition from one regime to the other. The transition is taken to occur when a criterion (for example, equality of the rate of lateral spreading with that for passive dispersion) is satisfied. The methods to be presented in this Workbook provide continuous correlations over the range from dense gas to passive dispersion.

## 3.2 Some Physical Processes in Dense Gas Dispersion

The density difference between the released material and its environment introduces four major effects with regard to dispersion problems:-

1. The velocity field set up by the horizontal density difference, in a gravitational field, is an additional transport mechanism to that provided by the environmental flows. This self-generated flow produces a plume or cloud with, generally, an increased horizontal, and reduced vertical, extent when compared with a similar release having no density difference. In addition the self-generated component of the motion is predominantly deterministic, not random, in nature and, as a result, profiles of concentration in the lateral direction are frequently quite uniform with little meandering of the plume due to random environmental flow.

2. The velocity shear introduced by this velocity field may lead to a gross intermingling if the two fluids and eventually turbulence generation and consequential turbulent mixing and plume or cloud dilution. This mechanism of dilution is of principal importance when the self-generated velocities are large compared with the mean environmental velocity.

3. The variation of density in the vertical direction will, in a gravitational field, be stably-stratified and turbulence and turbulent mixing can be significantly reduced or entirely inhibited. This effect can extend to the atmospheric turbulence in the windflow over the cloud, as well as to the cloud itself.

4. The inertia of the released material is directly dependent upon the density of the material. When the density difference is small compared with either density the influence of the density difference on the inertia is small and may be neglected, i.e. the Boussinesq approximation already discussed.

There exists an extensive literature on the dispersion of materials released with the same density as the environment. We refer to such releases as 'passive',in

contrast to those where the density difference influences the motion and these are referred to as 'dynamically active'. The extent to which the existing literature for passive releases can be applied to scenarios involving the dispersion of dense gases is of course of considerable relevance to users of this workbook. There are circumstances where it is intuitively obvious that the density difference of a released material from its environment is not a significant variable, for example, if the amount released is small and the environment velocities are large. Under these conditions the dispersion of the released material may be considered to be 'effectively' passive. A quantitative assessment of this statement is presented in Section 3.5. Criteria are presented there which, if satisfied, allow the use of the results based on the study of passive released material.

It is instructive to consider two extremes of release mode : continuous and instantaneous. The classification of a release as one or the other of these modes is not uniquely fixed by the duration of the release but is also dependent on the downwind position of the observer faced with the question. The plume from a release that is maintained for a finite time becomes detached from the source when the release terminates. The isolated plume thus formed is advected downwind and is subjected to longitudinal dispersion of its leading and trailing fronts. The fronts gradually encroach into the plume and at some point will merge. Thereafter, an observer will interpret the passage of the released gas as a 'cloud' with characteristics appropriate to an instantaneous release but from some hypothetical source not necessarily coincident with the actual source. The specification of a continuous source must necessarily be related to the duration over which a steady concentration is observed at a particular position. It follows that a release which one observer would deem as 'continuous' may be deemed as 'instantaneous' by another observer further downwind. Further elaboration of these concepts is provided in Section 3.6 and Appendix B.

A continuous release, which has attained a steady-state structure, will mix with the environment as it is advected downwind. A mean and turbulent velocity field consistent with the density stratification, the boundary conditions and the flow outside the plume will be developed. The plume spreads laterally as a result of buoyancy-driven motion and becomes thinner. This thinning and weak vertical turbulent diffusion produces a flat, wide plume.

Although the vertical turbulent diffusion (mixing) is weak, the larger surface area over which it takes place may lead to a variation of plume concentration in the downwind direction along the axis of symmetry not markedly different from the concentration development in the absence of density effects. Sufficiently far downwind the buoyancy-driven motions become weak and the vertical density stratification is not sufficient to inhibit the turbulence or turbulent mixing. The plume may now be considered passive and passive plume calculations may be introduced with an initial condition of an effective line source of finite length and some vertical extent.

The flow nearer the source is more complicated and uncertain. The plume material will be accelerated by the environmental fluid when there is significant intermingling (mixing) of the two fluids. Thus transport of the plume material

downwind is intimately connected with plume dilution. If the release mode is such that mixing between the plume and the environment is large (e.g. a jet), the downwind momentum is immediately imparted to the plume material. Otherwise the plume material must be accelerated by either a scouring of the plume material by the incident turbulence in the ambient flow or an instability of the shear layer separating the plume material from the ambient. If these mechanisms are not sufficient to remove the plume material at the same rate that it is supplied from the source an accumulation of plume material would be evident at the source. This is observed for continuous releases that develop eventually into a steady state condition. The accumulation of plume material is accommodated by horizontal, buoyancy-induced, motions near the source providing a much larger plume area near the source and, as a result, a removal of plume material to match the source rate. As a result there is an effective source size, increasing with increasing density difference, often considerably larger than the physical source size.

An instantaneous release with an aspect ratio (typical vertical dimension/typical horizontal dimension) of about unity collapses to form a wide shallow cloud as a result of the density difference. Mixing between the cloud and the environment during this collapse accelerates the plume material in the downwind direction. In the main the resulting flow is a cloud spreading radially, being advected downwind and diluting due to self-generated and environmental turbulence. A complication to this simple picture is caused by the non-uniform mean velocity profile in the ambient flow. This shear distributes the cloud in the downwind direction; however, the radially symmetric cloud is a useful approximation. Subsequent development is similar to that for the plume where a buoyancy-driven motion persists with an inhibition of vertical turbulence and mixing. These effects weaken and may eventually be ignored.

Three further points are appropriate:-

(i) A unit aspect ratio instantaneous release is likely to be the outcome of catastrophic failure of containment of a pressurised liquified gas and as such will have already mixed with, and been accelerated by, the ambient flow.

(ii) If the density difference is small the cloud will accelerate by an intermingling of the two fluids as the vortex sheet separating them distorts (see Rottman et al, 1985). This effect is present even in the absence of a density difference. If the cloud takes a long time to collapse (because the density difference is small or zero), this mechanism will produce intermingling of the two fluids. It is additional to the intermingling that results from the buoyancy-driven motion and will be the dominant effect when the latter is small.

(iii) Little self-generated turbulence and mixing occurs when the initial aspect ratio is small and development is similar to that for the plume where environmental turbulence and shear instabilities are required before the cloud is advected downwind.

It is appropriate to note here that although there is an extensive literature on passive releases (though largely concerned with steady continuous releases) there

is a far more limited subset directed towards problems in which large volumes or volume flow rates are released. For example, standard workbooks e.g. Turner (1970) refer implicitly to large dilutions (or equivalently distances well downstream of the source) where the plume width is large compared to the original plume width at the source (the source size). If the width is already large at the source, as a result of the large scale of the release, the apparent starting conditions will not be as specified in the workbook methods, which are based on point sources. One way of dealing with this is to hypothesize that the plume or cloud from a large-scale release originates from a virtual source at some distance upwind of the actual source.

## 3.3 Form of Workbook Correlations

### 3.3.1 Introduction

The environmental flow is taken to be steady in the mean and completely characterised by:-

a reference mean velocity $U_{ref}$ m/s evaluated at a reference height $z_{ref}$ (or a friction velocity $u_*$ m/s)

a roughness length $z_o$ m

and a non-dimensional measure of the atmospheric stability.

A further length scale that may be relevant is the atmospheric boundary layer thickness $\delta$ but as dense gases are constrained by gravity to remain close to the surface the significance of $\delta$ is unlikely to be great.

The reference velocity will have an associated averaging time and the averaging time that is naturally relevant is the transit time from source to receptor. In diffusion studies, however, it is conventional to use the velocity averaged over 10 minutes and furthermore to take the reference height as 10 m. This is the reference velocity that is likely to be available and as a pragmatic response we adopt it for use in this workbook; denoting it by $U_{ref}$. Where an alternative reference velocity is required e.g. in Chapter 5 in considering the effect of obstacles, the alternative definition is given where the need arises. For transient releases over a shorter time period, for example an instantaneous release, this velocity may appear less relevant. This is particularly so for the release of small amounts of material with no density difference from the environment where the released material responds to the velocity (magnitude and direction) at the moment of release. For this workbook, the interest is in a large release volume with a consequent large horizontal extent of the cloud due to the excess density. In such a circumstance, the cloud as a whole will respond to a velocity representative of the spatial variation of velocity over a region similar to the cloud size. This velocity will in turn have to be averaged over an appropriate time. However, Brighton et al (1985) demonstrated that such concern is hardly necessary since the release appears to respond in a way that is adequately represented by $U_{ref}$ measured at or near the source. Hence we use $U_{ref}$ as the reference velocity for any release. The result of doing so will be to contribute some uncertainty to the relationships for dispersion; estimates of

this uncertainty will be explicitly stated. If there is a need for information on the effect on dispersion of variations about the 10 minute average velocity, a numerical solution of the conservation equations will need to be used.

The roughness length $z_o$ is a gross measure of the effect on the velocity profile of the drag forces resulting from separation about individual roughness elements and is not in general simply related to the geometrical height of the elements. The effect on the velocity profile is seen most simply for neutral density stratification where the velocity profile is given by

$$\frac{U}{u_*} = \frac{1}{\kappa} log_e \frac{z}{z_o}$$

where U is the velocity at height z, $u_*$ is the friction velocity and $\kappa$ is von Karman's constant. The friction velocity is the velocity scale fixed by the surface shear stress i.e. $\tau_o = \rho u_*^2$ where $\rho$ is the local fluid density. The connection between the drag coefficient, $C_D$, due to the surface roughness and the value of $z_o$ implied by the velocity profile follows as

$$C_D = \frac{\tau_o}{\frac{1}{2}\rho U_{ref}^2} = 2\kappa^2 (log_e \frac{z_{ref}}{z_o})^{-2}$$

where $U_{ref}$ is the velocity at a reference height $z_{ref}$ well above the height of the roughness elements. A single measure of the surface roughness may be less adequate for characterising the dispersion of pollutants at heights comparable to the height of the drag-producing elements than for describing the velocity profile well above them. However, no useful alternative to $z_o$ is obvious.

Two release types have been conventionally considered, namely continuous and instantaneous. A continuous release has a time-dependent volume-flow rate $q_o(t)$ $m^3/s$ from a ground-level source of characteristic horizontal dimension D and particular source geometry G; that is square, circular etc. An instantaneous release has a released volume of $Q_o$ $m^3$ from a source of characteristic dimension D and a particular source geometry parameter G. The source geometry parameter of specific relevance will be the ratio of the height of the released volume to its characteristic horizontal dimension, that is the aspect ratio of the released volume.

As a pragmatic response to the wide variety of, and uncertainty in specifying releases we provide criteria in Section 3.6 for determining which of either conventional release type should be used. If both are inappropriate a suitably weighted average of the two will be used to characterise transient releases.

For each release type the released material has a uniform density $\rho_o$ which is different to that of the environment $\rho_a$. The initial concentration $C_o$ may be expressed as the mass of material per unit volume or volume of material per unit volume. The convention adopted throughout this workbook will be to use the latter definition and furthermore to express local concentration as a ratio to the initial concentration.

Techniques for determining relevant magnitudes for $q_o(t)$, $Q_o$, $C_o$, D and $\rho_o$ applicable to a realistic scenario are treated in Section 3.4.1. The influence of G is considered in Section 4.3.

A broad view of the literature on the dispersion of dense gases (see, for example, Britter and Griffiths, 1982; McQuaid, 1984b) leads to the following conclusions.

For the study of dense gases the dominant independent variables are

(i) a characteristic measure of the amount of material released expressed as either a released volume, $Q_o$, or a released volume flow rate, $q_o(t)$;

(ii) a characteristic density of the material released $\rho_o$ and of the ambient environment $\rho_a$;

(iii) a characteristic mean velocity $U_{ref}$ and,

(iv) a characteristic dimension of the source, D.

Relevant variables, but of lesser importance are

(i) the surface roughness characterised by the roughness length $z_o$ m;

(ii) the atmospheric stability;

(iii) the length scales of the turbulence in the atmospheric boundary layer, $l_i$ (to be compared with $D$, say), and,

(iv) the source geometry $G$ or $Q_o^{\frac{1}{3}}/D$

Variables of little or no importance at full scale include

(i) molecular properties, for example (a) viscosity $\nu$ and (b) mass diffusivity $\mathcal{D}$. The kinematic viscosity of the fluid is of little relevance if, as will be the case, the Reynolds number of the environmental flow is large, except in determining the size of the smallest turbulent eddies that contribute to the turbulent velocity fluctuations.

(ii) the scale of the atmospheric boundary layer characterised by $\delta$.

The concentration $C$ as a function of space (x, y, z) and time t can be written in dimensionless form, neglecting molecular properties and $\delta$, as

$$\frac{C}{C_o} = \mathcal{F}\{\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \frac{tU_{ref}}{D}, \frac{q_o(t)}{U_{ref}D^2} \text{ or } \frac{Q_o^{\frac{1}{3}}}{D}, \frac{U^2_{ref}}{gD}, \frac{\rho_o}{\rho_a}, \frac{z_o}{D}, \frac{l_i}{D},$$
$$\text{atmospheric stability, } G \text{ or } \frac{Q_o^{\frac{1}{3}}}{D}\}$$

where x is measured in the mean wind direction, y in the direction transverse to the wind in the horizontal plane and z in the vertical direction. (Where alternatives occur in the expression, they are the parameters for the continuous and instantaneous cases, in that order).

To maintain a sufficiently large data set for workbook development the variables $l_i/D$, $z_o/D$, atmospheric stability and source geometry, $G$, are relegated to peripheral variables. Justification for their relegation is addressed in Chapter 4.

Thus

$$\frac{C}{C_o} = \mathcal{F}\{\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \frac{tU_{ref}}{D}, \frac{q_o(t)}{U_{ref}D^2} \text{ or } \frac{Q_o^{\frac{1}{3}}}{D}, \frac{{U_{ref}}^2}{gD}, \frac{\rho_o}{\rho_a}\}$$

### 3.3.2 Steady Continuous Source Flow Rate $q_o m^3/s$

For a constant source flow rate a time-mean concentration $\bar{C}$ may be suitably defined (see Section 3.4.2) and

$$\frac{\bar{C}}{C_o} = \mathcal{F}\{\frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \frac{q_o}{U_{ref}D^2}, \frac{{U_{ref}}^2}{gD}, \frac{\rho_o}{\rho_a}\}$$

In the main we anticipate that the ground-level concentration on the plume centreline will be the maximum concentration at any downstream distance. This is clearly the case well away from the source but need not be so in close proximity to the source, particularly for an elevated source (even after the plume has reached the ground) or for a source with significant vertical momentum (see Section 5.3).

Thus the ground level concentration on the plume axis is given by

$$\frac{\bar{C}_m}{C_o} = \mathcal{F}\{\frac{x}{D}, \frac{q_o}{U_{ref}D^2}, \frac{{U_{ref}}^2}{gD}, \frac{\rho_o}{\rho_a}\}$$

This gives a four-dimensional plot for which there is unlikely to be sufficient information to provide a useful workbook.

A simplification is to invoke the Boussinesq approximation which relies on neglecting density variations in the inertial terms of the governing equations of motion while retaining the density variation in buoyancy terms. The problem is therefore restricted to $\frac{\rho_o - \rho_a}{\rho_a} << 1$ formally or, in practice, $\frac{\rho_o - \rho_a}{\rho_a} < 1$. We note that the mode of release can produce considerable dilution so that the initial conditions for the dispersion calculation will be such that $\frac{\rho_o - \rho_a}{\rho_a} \tilde{<} 1$.

The Boussinesq approximation allows the variables $\frac{{U_{ref}}^2}{gD}$ and $\frac{\rho_o}{\rho_a}$ (or equivalently $\frac{\rho_o - \rho_a}{\rho_a}$) to be replaced with $\frac{{U_{ref}}^2}{g_o' D}$ where $g_o' = g(\frac{\rho_o - \rho_a}{\rho_a})$. The approximation has proved particularly useful in many problems involving buoyancy-driven or buoyancy-influenced flows (Turner, 1973). However, there is little specific, definitive work in the context of the dispersion of dense gases in which the Boussinesq approximation alone has been tested.

A further major simplification arises if the effect of the only remaining external length scale, $D$, is not significant. To be more specific, the plume development may be seen in terms of three groups of variables with units of length (that is, length scales) viz. $D, (q_o/U_{ref})^{\frac{1}{2}}$ and $q_o g_o'/{U_{ref}}^3$. The first is the external length scale characterised by the source dimension $D$. The second characterises the displacement of the ambient flow by the source flow in the absence of any buoyancy-driven flows induced by the density difference. The third characterises the horizontal dimension of the plume resulting from the density-driven flow.

Downstream of the source, the source size $D$ becomes progressively less relevant as the plume forgets its past history. Thus provided the concentrations of interest do not occur within the vicinity of the source (that is $x \tilde{<} 5D$, say) the source size $D$ is not significant. This is unlikely to be an important constraint in practice and if concentrations closer to the source are required a more situation-specific study is probably necessary. As the source size provides an increased lateral extent of the plume over an idealized point source, the neglect of $D$ can only lead to a reduced dilution of the plume and further distance to a given concentration. Further to this point, it can be noted that when the buoyancy length scale ${g_o}'q_o/{U_{ref}}^3$ is much greater than $D$, the buoyancy length scale alone determines the width of the plume near the source (see Britter, 1980; Neff and Meroney, 1982).

As a result of these assumptions the ground-level concentration on the plume centreline, $\bar{C_m}$, is characterised by the internally set length scales $(q_o/U_{ref})^{\frac{1}{2}}$ and $({g_o}'q_o/{U_{ref}}^3)$ and so

$$\frac{\bar{C}_m}{C_o} = \mathcal{F}\{\frac{x}{(q_o/U_{ref})^{\frac{1}{2}}}, \frac{{g_o}'q_o/U_{ref}^3}{(q_o/U_{ref})^{\frac{1}{2}}}\}$$

$$= \mathcal{F}\{\frac{x}{(q_o/U_{ref})^{\frac{1}{2}}}, (\frac{{g_o}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}}\}$$

where the introduction of the $\frac{1}{5}$-power in the second group is simply to give convenient numbers.

An alternative, more useful, presentation of the same information is to plot non-dimensional distance to a given value of $\frac{\bar{C}_m}{C_o}$ e.g. 0.05, 0.02, 0.01 etc. as a function of the variable $(\frac{{g_o}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}}$ , for example

$$\frac{x_2}{(q_o/U_{ref})^{\frac{1}{2}}} = \mathcal{F}\{(\frac{{g_o}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}}\}$$

where $x_2$ is the distance to the 0.02 concentration.

### 3.3.3 Instantaneous Released Volume $Q_o$ m$^3$

In framing the functional dependence of $C/C_o$ on the dimensionless groups, the source was taken to be characterised by a single dimension, D. An instantaneous release of a fixed volume may, in principle, have one of a variety of shapes and a single dimension will only characterise source volumes which are geometrically similar. However, consideration of the geometries observed in accidental releases (see McQuaid, 1979) and the dominant attention given in experimental programmes to volumes with an aspect ratio of unity, leads naturally to restricting attention initially to unit aspect ratio as the archetypal case. Other aspect ratios will be considered in Section 4.3. The immediate effect is to allow the external length scale, D, to be replaced by the internally set length scale, $Q_o^{\frac{1}{3}}$.

Using arguments similar to those for the continuous release in Section 3.3.2 the ground-level concentration on the centreline in this case is characterised by $Q_o^{\frac{1}{3}}$ and the other internally set length scale $U_{ref}^2/g_o'$ and so

$$\frac{\bar{C}_m}{C_o} = \mathcal{F}\{\frac{x}{Q_o^{\frac{1}{3}}}, \frac{U_{ref}^2/g_o'}{Q_o^{\frac{1}{3}}}\}$$

The result for the distance to a given concentration contour, for example the 0.02 contour, is given by

$$\frac{x_2}{Q_o^{\frac{1}{3}}} = \mathcal{F}\{(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}\}$$

where again the introduction of the $\frac{1}{2}$-power is simply to give convenient numbers. No requirement for the neglect of the source size D is required here as $D = Q_o^{\frac{1}{3}}$ and is not separately determined from $Q_o$.

## 3.4 Specification of Variables

### 3.4.1 Input Variables

In order to provide the inputs to the correlations that follow, the physical variables need to be put in a suitable format.

The reference velocity, $U_{ref}$, is conveniently formulated by defining the reference velocity as the 10 minute average velocity at a height of 10m.

Treatment of the other variables is less straightforward. Specification of the source variables $Q_o$ or $q_o$, $D$ and $\rho_o$ is required.

The source momentum is assumed to be unimportant. This will be the case when an exit velocity of the dense gas is small compared with the reference velocity $U_{ref}$. If the source momentum is important a separate calculation[1] is required to determine $q_o(t)$ and $\rho_o$ after the influence of source momentum has become less significant than the influence of the density difference. The associated concentration $C_o$ is determined by species conservation.

Actual releases occur over a finite duration. In order to determine whether an instantaneous or steady continuous treatment is appropriate, some judgement needs to be used in deciding how the release is to be treated in terms of specifying the three parameters — release time, flow rate and density. We regard the release time as the one most easily specifiable in practice. For example, it will be fixed by such factors as the shut-off time for emergency isolation valves, the emergency response time for the particular installation and so on — in other words, factors for which the hazard analyst will have first-hand knowledge. The release time thus estimated in denoted by $T_o$.

[1]Simple elevated releases and associated dilution are treated in Section 5.3

The source volume flow rate $q_o(t)$, after any necessary respecification that takes account of dilution resulting from source momentum effects, is redefined as an equivalent constant $q_o$ for $0 \leq t \leq T_o$. Depending on the magnitude of $T_o$ (see Section 3.6), one of the following release modes will be applicable:-

(i) a steady continuous release for which $q_o(t) = q_o$, $0 \leq t \leq \infty$;

(ii) an instantaneous release for which $Q_o = q_o T_o = \int_0^\infty q_o(t)dt$;

(iii) a transient release, for which neither (i) or (ii) is appropriate.

In practice, the decision as to which mode of release is appropriate may not be clearcut. The simple correlations that follow allow the implications of various ways of specifying the source to be quickly evaluated. The respecifications are at the discretion of the user. The source density $\rho_o(t)$ is respecified as an equivalent constant $\rho_o$ for $0 \leq t \leq T_o$ using the condition of continuity of mass of the released material, that is, the total mass of released material is given by

$$\int_0^\infty \rho_o(t) q_o(t) dt = \rho_o q_o T_o \text{ for a continuous release or}$$

$$\int_0^\infty \rho_o(t) q_o(t) dt = \rho_o Q_o \text{ for an instantaneous release.}$$

Specification of the source size $D$ for the instantaneous release is simply $Q_o^{\frac{1}{3}}$. For the continuous release the source size needs to be specified but only so that the user is broadly aware of the region of validity of the correlations. It could, typically, be

(i) (a characteristic surface area of an evaporating liquid pool)$^{\frac{1}{2}}$;

(ii) (the bunded area of a release from a bunded tank)$^{\frac{1}{2}}$, or,

(iii) the plume width from a jet after source momentum effects have become unimportant.

### 3.4.2 Output Variables

For a particular release the concentration equation becomes, in dimensional form,

$$C = C(x, y, z, t)$$

The spatial variation of concentration will occur on length scales down to those set by molecular diffusivity. The temporal variation at a point is principally a spatial variation being advected by a mean velocity in accordance with Taylor's hypothesis (Townsend, 1976).

It is unlikely to be the case that one requires information on the concentration field at scales set by molecular processes. More typically it is likely that length scales of order 1 metre or above are required for both toxicity and flammability considerations.

The measurement of the concentration field provides a spatial (spatial resolution of the measuring instrument) and temporal (frequency response of the measuring instrument) filter on the concentration field.

For the steady continuous release a time-averaged mean concentration can be defined. The mean concentration for passive releases which are continuous and steady depends significantly upon the averaging time (Pasquill and Smith, 1983) as the diffusion is influenced by turbulence with time scales greater than the averaging time. The influence of averaging time is less important (and will be neglected) for dense gas releases as the buoyancy-induced (and predominantly deterministic) flow frequently dominates over the random atmospheric and/or cloud-generated turbulence. Thus we present our results in terms of a concentration averaged over a long time, which is taken to be 10 mins to correspond to the averaging time for the reference wind velocity.

When the release is instantaneous or transient the analysis of the concentration distribution requires more subtlety. Formal definition of a 'mean' concentration and concentration statistics requires averaging over an ensemble of many similar releases. These statistics are the counterpart of the time-averaged statistics for the previously considered continuous, steady release. Mathematical modelling is directed at determining this ensemble average but the limitations of current mathematical modelling precludes information on the variation between members of the ensemble. The high cost of field trials leaves physical modelling as the most effective way of studying the variation between members of an ensemble.

For releases of limited duration, a short-time averaged concentration is used with averaging over several seconds in time or several metres in space at full scale. We make the assumption that, at any given position, the largest concentration will occur at ground level and that, at any given time, the concentration at a fixed height is uniform throughout the cloud. At any ground-level location, the short-time averages will vary with time, exhibiting a maximum at the time of arrival of the cloud at the point. Thereafter, it will decrease continuously with time as the cloud, which, is being continuously diluted, is advected past the point. We present our results as estimates of the ensemble mean of the maximum of the short-time averaged concentration-time histories at ground level in the direction downwind from the release. In deriving the estimates from experimental data, the effect of the local spatial maximum near the front of the cloud due to the front vortex has to be disregarded since it cannot be separated out. The effect will be most pronounced near the source. In summary, the representation that we adopt is illustrated in Figure 7. The instantaneous spatial distributions of concentration when the cloud just reaches (at time $t_a$) and just departs (at time $t_d$) from the point is shown in Figure 7a. The concentration-time history at the point is shown in Figure 7b. For comparison, a typical concentration-time history at a point at ground level from the Thorney Island trials results is shown in Figure 7c.

The deterministic aspects of the flow resulting from the density difference and the likely large spatial extent of the release will reduce the importance of the meandering resulting from atmospheric turbulence. Observations in the field (Brighton et al, 1985) support this view. On the other hand, laboratory experiments some-

times exhibit large variability about the ensemble mean estimates (e.g., Hall et al, 1982; Meroney and Lohmeyer, 1982). At the present time, we prefer to give more weight to the field observations.

With mean concentrations defined in accordance with the above descriptions, the workbook provides the following output variables or allows their calculation using straightforward techniques.

(i) The downwind distance to a given concentration.

(ii) The size and shape of the contour of any given concentration.

(iii) The mass of the released material at any instant between any two given concentrations.

(iv) The concentration and persistence at a given distance i.e. the $C - t$ history.

For both toxicity and flammability considerations more information may be required than the time mean (for a plume) or ensemble mean (for a cloud) concentration. Concentration fluctuations around either mean may be quantified by their root-mean-square value $c'$ where, as noted above, the limited spatial and temporal resolution of the measuring instrument may reduce the observed $c'$.

For instantaneous releases $c'$ is made up of two components. There is an inherent variability from run-to-run and there are spatial variations in concentration within any realization. The latter is most easily estimated by considering the spatial variations of concentration (advected past a fixed probe) in any individual member of the ensemble which could be broken down into a 'running mean' and a variation from that. This variation has been excluded from consideration in the workbook as we have specifically concentrated on the maximum (or peak) values occurring in any individual run. Thus estimates of $c'$ for instantaneous releases should refer to the variability in the maxima between different realizations which, in principle, might best be expressed in terms of the standard deviation. However, given the limitations of the available data, our estimates of variability are expressed simply as the range of the maxima.

## 3.5 Criteria for Effectively Passive Behaviour

Under what conditions might a release be analysed using correlations from passive dispersion experiments that are widely available, have been well studied and exist in workbook form already (e.g. Turner, 1970; Clarke, 1979)?

For continuous releases of $q_o m^3/s$ we recommend on the basis of Appendix A that the flow will be effectively passive and passive dispersion results may be used when

$$\left(\frac{g_o' q_o}{U_{ref}^3}/D\right)^{\frac{1}{3}} \leq 0.15$$

where $U_{ref}$ is the velocity at $z = 10$ m.

For an instantaneous release of $Q_o m^3$ we recommend, also on the basis of Appendix A, that the flow will be effectively passive and passive dispersion results may be used when

$$\frac{(g_o' Q_o^{\frac{1}{3}})^{\frac{1}{2}}}{U_{ref}} = (\frac{g_o' Q_o}{U_{ref}^2})^{\frac{1}{2}} / Q_o^{\frac{1}{3}} \leq 0.2$$

where $U_{ref}$ is again the velocity at $z = 10$ m.

This result assumes an aspect ratio of near unity for which $Q_o^{\frac{1}{3}}$ is representative of the height of the cloud. The criterion is unlikely to be very sensitive to the aspect ratio of the release but a possible approach is to use the same result with the initial height of the cloud replacing $Q_o^{\frac{1}{3}}$.

When the relevant criterion indicates that a cloud or plume cannot be treated as passive, redefinition in terms of the local length scales allows the criterion to be used to determine when the development of the plume or cloud may subsequently be treated ignoring density effects. The criteria become

$$(\frac{g_o' q_o}{U_{ref}^3} / L)^{\frac{1}{3}} \leq 0.15$$

for a continuous release, with $L$ as the plume width, and,

$$(\frac{g_o' Q_o}{U_{ref}^2})^{\frac{1}{2}} / L \leq 0.2$$

for an instantaneous release, with $L$ as the cloud diameter. Relationships for the plume and cloud length scales as functions of the downwind distance are given in Sections 3.7 and 3.8.

## 3.6 Criteria for Distinguishing Continuous and Instantaneous Releases

As described in Section 3.2, the classification of a release as continuous or instantaneous depends on the position of the observer.

The dimensionless group

$$\frac{U_{ref} T_o}{x} \text{ (or } \frac{u_* T_o}{x})$$

is an appropriate parameter to demarcate releases that are perceived as continuous (i.e., effectively continuous) at a distance x from the source for transient releases. We recommend (see Appendix B) that an effectively continuous plume may be assumed if

$$\frac{U_{ref} T_o}{x} \geq 2.5 \text{ or } \frac{u_* T_o}{x} \geq 0.15$$

These results are only applicable on or near the centreline of the plume and larger numerical values will be required for positions off the centreline. Note that

for a fixed source flow rate any reduction of $T_o$ will move closer to the source that position at which effectively continuous behaviour ceases to apply. Beyond this position (given by $x \geq \frac{u_* T_o}{0.15}$) an assumption of continuous behaviour would result in the calculated concentration at any point $x$ or the calculated distance $x$ to a given concentration both being too large.

To consider the release as being effectively instantaneous we suggest, in the absence of experimental data, that the numerical value should be reduced by $\frac{1}{4}$ of that above. Thus we recommend

$$\frac{U_{ref} T_o}{x} < 0.6 \text{ or } \frac{u_* T_o}{x} < 0.04$$

We may note that a transient release of a fixed volume $Q_o$, released over a period $T_o$, might be modelled either as a continuous release or an instantaneous release. In the former case the average release rate, $Q_o/T_o$, is taken, for the purpose of determining the downwind concentration field, as persisting for a time such that the definition of a continuous release applies. However, a transient release for a time $T_o$ will experience longitudinal dispersion and consequent reduction in concentration below that derived from the continuous release assumption. Hence, provided the initial source conditions are unchanged, the continuous release model will always provide an upper bound estimate of concentration for a transient release.

The alternative method of modelling a transient release is to assume an instantaneous release of the same total volume $Q_o$. Provided the initial source conditions are equivalent and ignoring any near-source dilution, etc., this method will again lead to an overestimate of the concentration at a fixed position.

Our recommendation is that the method providing the smaller overestimate is accepted. That is, the smaller of the concentration estimates based on the relevant continuous release and the relevant instantaneous release provides the upper bound on the concentration for any release.

The above considerations apply where the ambient velocity is the only velocity of relevance in transporting material downwind. Of course the buoyancy-induced motion also transports material downwind (or away from the source for $U_{ref} = 0$) and a similar criterion but with $U_{ref}$ replaced by the buoyancy-driven radial velocity $(\frac{Q_o g_o'}{x})^{\frac{1}{2}}$ is also applicable where $Q_o$ is the total volume released. The characteristic transport times for the two mechanisms are $\frac{x}{U_{ref}}$ and $\frac{x^2}{(Q_o g_o')^{\frac{1}{2}}}$ but the mechanisms do not of course act independently. For simplicity, we shall require that $T_o$ should be small or large (for releases to be deemed instantaneous or continuous, respectively) compared to the smaller of these timescales, since it is only the smaller that is relevant. We assume that the numerical criterion should be the same as above. Thus, for the general case, we adopt as our criterion that $T_o / \frac{x}{U_{ref}}$ and $T_o / \frac{x^2}{(Q_o g_o')^{\frac{1}{2}}}$ must both be less than 0.6 for the release to be deemed instantaneous.

For a release at a rate $Q_o m^3/s$, the characteristic transport time for the buoyancy-driven motion is $(\frac{g_o' q_o}{x})^{\frac{1}{3}}$. The equivalent result for such a release to

be deemed continuous is that both $T_o/\frac{x}{U_{ref}}$ and $T_o/\frac{x^{\frac{1}{3}}}{(g_o l q_o)^{\frac{1}{3}}}$ should be greater than 2.5.

## 3.7 Correlations for Continuous Releases

### 3.7.1 Downwind Distance to a Particular Ground-Level Concentration

The basic relationship for the distance to a given concentration was developed in Section 3.3.2 as

$$\frac{x_n}{(q_o/U_{ref})^{\frac{1}{2}}} = \mathcal{F}\{(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{6}}\}$$

where subscript $n$ is the value of the concentration of interest.

Data from several relevant full-scale experiments have been analysed in this form and the results are summarised in Figure 8. Precise information on the data used are available as Appendix C. It should be noted that no attempt has been made in the correlations to separate the effects of the peripheral variables (atmospheric stability, ground roughness) in accordance with the arguments leading to the above relationship and presented in Section 3.3.2. Their possible influence will be discussed later.

It should be remembered that the reference wind velocity is taken at $z = 10m$ and concentrations may be taken as long-time averages. Acceptance of the latter follows from the definition of a continuous release as treated in Section 3.6 and Appendix B. Thus, a steady concentration observed for any finite period at a receptor is taken as the steady concentration that would apply at that position for a release of infinite duration.

Similarly, further extensive data from selected laboratory experiments have been analysed and plotted. These plots, accompanied by relevant descriptions, appear as Appendix C. Again $U_{ref}$ may be interpreted as the velocity at 10m height at full scale and the concentrations are long-time averages at full scale. The range of the correlation with $(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{6}}$ covered by the full-scale data has been extrapolated by appeal to the laboratory data and the extrapolated ranges are shown in Figure 8.

The estimates at the passive limit (i.e. $(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{6}} = 0$) for each concentration used in the correlations in Figure 8 are derived in Appendix E. The estimates are based on information for a neutrally-stable atmosphere.

The correlation provided is valid for concentrations between 0.002 and 0.1 and $(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{6}}$ from 0 to 4. Extrapolation to smaller concentrations will be considered in Section 5.4.

The correlations show that, for fixed $q_o$ and $U_{ref}$, the distance to a particular concentration initially increases as the density difference increases from zero and

then decreases when

$$(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{5}} \geq 1$$

It appears that when

$$(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{5}} \geq 1,$$

$$\frac{x}{(q_o/U_{ref})^{\frac{1}{2}}} = A\{(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{5}}\}^{-\frac{1}{2}}$$

or

$$x = A q_o^{0.4} g_o l^{-0.2}$$

Here $A$ is a constant particular to the concentration of interest and is plotted in Figure 9 as a function of concentration. This plot may be used for interpolation within the range of concentration covered. In this expression for $x$, it will be noted that there is no dependence on $U_{ref}$, only a weak dependence on $g_o l$ but a strong dependence on source volume-flow rate. For these large values of stability parameter $(\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{5}}$ it is of considerable interest that the distance to a given concentration decreases as the stability parameter increases. It would appear that the increased lateral spreading of the plume as a result of its negative buoyancy more than offsets the inhibition of the vertical mixing of the plume with the environment.

It is a further useful observation that for a broad range of the stability parameter the distance to a particular concentration is dependent only upon the length scale $(q_o/U_{ref})^{\frac{1}{2}}$. Specifically, within the range

$$0 \leq (\frac{g_o l^2 q_o}{U_{ref}^5})^{\frac{1}{5}} \leq 3$$

simple interpolation provides

$$x = 17.5(\frac{C_m}{C_o})^{-\frac{1}{2}}(\frac{q_o}{U_{ref}})^{\frac{1}{2}}$$

where there is an uncertainty in $x$ of $\pm 40\%$.

The data represent long-time averaged results. Fluctuations in concentration will produce greater concentrations over short times (or, equivalently, averaged over a small spatial extent). Limited field data (McQuaid and Roebuck, 1985) are available. For ground-level positions near the plume centreline, there is little evidence of concentrations (averaged over the time for transport of gas over a spatial extent of a few metres) greater than 1.4 times the long time-average concentration. This multiplicative factor may be larger for passive plumes (Fackrell and Robins, 1982) in the laboratory. A multiplicative factor of about 1.6 may be deduced from the laboratory experiments of Stretch (1986) using both area and line sources of passive and dense fluids.

### 3.7.2 Area Covered by an Iso-Concentration Contour

The motions driven by the density differences lead to a relatively sharp edge to the plume and only a weak variation of the ground-level concentration in the lateral direction.

We take advantage of this characteristic of the dispersion of dense gases and characterise an iso-concentration contour with

(i) an upwind plume extent $L_U$

(ii) a lateral plume extent at the source position $L_{ho}$

(iii) a lateral plume extent $L_h$ increasing with downstream distance and

(iv) a downstream extent, dependent upon concentration, determined from correlations provided in 3.7.1

Inspection of data and analyses in Britter (1980), Neff and Meroney (1981), Fay and Zemba (1986), Cheah et al (1984), together with available full-scale results has led to the following recommendations based on a reference velocity measured at $z = 10$m and the buoyancy scale $l_b = q_o g_o{}' / {U_{ref}}^3$.

The time-averaged plume will extend upwind a distance

$$L_U = D/2 + 2l_b$$

and spread laterally at the source position a distance

$$L_{ho} = D + 8l_b$$

The downwind growth of the lateral plume width is given by

$$L_h = L_{ho} + 2.5{l_b}^{\frac{1}{3}} x^{\frac{2}{3}}$$

where x is the distance downwind from the source position.

The vertical depth of the plume $L_v$ may be estimated from continuity of the source material as $q_o/U_{ref}L_h$. This is the depth for a plume vertically homogeneous at the ground-level concentration $C$ and advected with the reference velocity $U_{ref}$. The precise concentration profile in the vertical is uncertain and will depend on $(\frac{q_o}{U_{ref}})^{\frac{1}{2}}$, $\frac{g_o{}' q_o}{U_{ref}^3}$ and $x$. However, laboratory experiments (Stretch, 1986) show that the bulk of the plume material is contained within the depth $2(q_o/U_{ref}L_h)$. An improved estimate will be obtained using an advection velocity which is the mean velocity at a height of $L_v/2$ in the undisturbed atmosphere.

The assumed lateral homogeneity of the plume is an unduly conservative (i.e., pessimistic) approach. A less conservative estimate of the area covered by a specific concentration (and one that is consistent with experimental observations) would be to connect the plume boundaries, at 2/3 of the furthest downwind distance to that concentration, with straight lines to the furthest distance downwind, as illustrated in Figure 10.

## 3.8 Correlations for Instantaneous Release (Unit Aspect Ratio)

### 3.8.1 Downwind Distance to a Particular Ground-level Concentration

The basic relationship for the distance to a given concentration in this case was developed in Section 3.3.3 as

$$\frac{x_n}{Q_o^{\frac{1}{3}}} = \mathcal{F}\{(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}\}$$

where subscript n is the concentration of interest.

Field and laboratory experimental data are available for the range

$$0.7 \leq (\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \leq 10$$

as described in Appendix D, and for the passive case i.e.

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} = 0$$

as described in Appendix E. Laboratory data exist for the case of no ambient flow, i.e.

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \rightarrow \infty$$

The large-scale data from Thorney Island generally show distances (to given concentrations) about 50% larger than the laboratory data (see Appendix D). The cause of this is uncertain though it may be due to inadequate frequency response and spatial resolution of instruments in the laboratory experiments. The range of the correlation with

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}$$

covered by the field data has been extrapolated by appeal to the laboratory data (see Appendix D.2) and the resulting curves plotted in Figure 11. The region for which large-scale data are available is indicated. The curves plotted represent ensemble averages of the maximum in short-time averaged (0.6 second) data. There is consensus amongst the four different sets of laboratory data for the case where there is no ambient flow (Appendix D.2) and these are plotted as solid symbols on the righthand side of the figure. The correlations are for the range of concentration from 0.001 to 0.10.

For a fixed $Q_o$ and $U_{ref}$ and for concentrations greater than 0.002 there is an increase in the distance to a particular concentration as the density difference increases from zero until

$$\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}} \geq 2$$

beyond which the distance decreases.

There is very strong dilution of the cloud in the absence of any ambient flow, a result of the strong buoyancy-induced flow.

When density effects are predominant,

$$\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}}$$

is large and the environmental flow will be unimportant for the dilution and advection of the cloud. The form of the correlation suggests that

$$\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}} = 10$$

is equivalent to

$$\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}} = \infty$$

down to concentrations of 0.001.

Over a range of

$$\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}} \text{ (apparently } \left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}} \geq 2 \text{ )}$$

the cloud dilution is principally due to this buoyancy-induced flow and consequent turbulence and not the environmental flow or turbulence. Over this range the downwind distance to a given concentration will increase with velocity, as the cloud is advected by the entrained fluid, the entrainment being a result of the buoyancy-induced flow.

For concentrations between 0.001 and 0.02 and

$$2 \leq \left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}} \leq 10$$

the correlation may be approximated by

$$\frac{x}{Q_o^{\frac{1}{3}}} = \mathcal{B}\{\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}}\}^{-\frac{1}{2}}$$

where $\mathcal{B}$ is a constant particular to the concentration of interest. The equation may also be taken to apply, but with somewhat less precision, to the correlations for 0.05 and 0.10 concentrations. It can be rearranged to

$$x = \mathcal{B} Q_o^{\frac{1}{4}} g_o{}'^{-\frac{1}{4}} U_{ref}^{\frac{1}{2}}$$

The variation of B with concentration is plotted in Figure 12 and may be used for interpolation within the range of concentration covered.

On the other hand at large wind speeds

$$(\text{small } (\frac{g_o{}' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}})$$

there will be enhanced dilution by environmental turbulence and the distance $x$ to a specific concentration will stop increasing. At even larger velocities the buoyancy-generated flows (and attendant turbulence) may be inhibited and $x$ decreases with velocity down to a passive limit.

Extrapolation to smaller concentrations will be considered in Section 5.4.

Within the range

$$1 \leq (\frac{g_o{}' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \leq 5,$$

the non-dimensional distance $x/Q_o^{\frac{1}{3}}$ has little variation with

$$(\frac{g_o{}' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}$$

and simple interpolation provides

$$x/Q_o^{\frac{1}{3}} = 2.8(C_m/C_o)^{-\frac{1}{2}}$$

where $C_m/C_o$ is the concentration of interest. Similar interpolation at the limit

$$(\frac{g_o{}' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \rightarrow \infty$$

provides

$$x/Q_o^{\frac{1}{3}} = 1.8(C_m/C_o)^{-\frac{1}{2}}.$$

The correlations presented are intended to be for the ensemble average of the maximum of short-time (0.6s) mean concentrations. The limited data available for any particular value of the parameter

$$(\frac{g_o{}' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}$$

precludes strict ensemble averaging. However, with the reasonable assumption that the correlation of the strict ensemble average will be a smooth curve, data from all values of

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}$$

might be used to estimate the ensemble average. In practice smooth curves are drawn subjectively as 'good fits' to the available data and these correlations are presented as ensemble averages. Any curve increased by a factor of 1.3 encompasses nearly all of the short-time averaged data and this is suggested as a general indication of the extent of variability about the ensemble average.

### 3.8.2 Area Covered by an Iso-Concentration Contour

The development of the cloud from an instantaneous release is a complicated interaction of density-driven flows, the environmental wind field (in particular shear dispersion resulting from the mean velocity profile) and the inertia of the released fluid.

In order to simplify the problem, we take advantage of the characteristic horizontal spreading of the cloud as a result of the density difference. The cloud is considered to be a horizontally and vertically homogeneous cylinder which is growing radially with time and being advected downwind by the mean wind. It should be stressed that this is a very simple model of a complex flow.

The advection velocity will depend upon, amongst other variables, the cloud height which is time dependent in a complex manner. From the laboratory results of Hall et al (1982) and the analysis of the Thorney Island experiments by Wheatley and Prince (1987) we select as a typical advection velocity $0.4U_{ref}$.

When

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} > 10$$

a smaller advection velocity may be appropriate due to the substantial reduction in the depth of the cloud but little specific information is available.

Thus after a time $t$ the advection of the centroid is given by $0.4Ut$. The gravity spreading velocity is given by

$$\frac{dh}{dt} = K(g'H)^{\frac{1}{2}}$$

where $R$ is the cloud radius, $g'$ is the reduced gravitational acceleration $= g\frac{\Delta\rho}{\rho_a}$, $H$ is the cloud height $(= Q/\pi R^2)$ and $K$ is a constant (=1.07 from Brighton et al, 1985). Since there is no heat transfer, the total buoyancy is conserved i.e., $g'Q = g_o' Q_o$ and the resulting integration of the above expression gives

$$R = (R_o^2 + 1.2(g_o' Q_o)^{\frac{1}{2}} t)^{\frac{1}{2}}$$

To find the arrival time $t_a$ of a cloud at any downstream distance $x$ on the centreline, we solve the equation

$$x = 0.4U_{ref}t_a + (R_o^2 + 1.2(g_o'Q_o)^{\frac{1}{2}}t_a)^{\frac{1}{2}}$$

To find the departure time $t_d$ of the cloud at distance $x$, we solve the equation

$$x = 0.4U_{ref}t_d - (R_o^2 + 1.2(g_o'Q_o)^{\frac{1}{2}}t_d)^{\frac{1}{2}}$$

Alternatively $t_a$ and $t_d$ may be obtained as the two roots of the quadratic equation

$$(x - 0.4U_{ref}t)^2 = R_o^2 + 1.2(g_o'Q_o)^{\frac{1}{2}}t$$

The concentration in the cloud at $x$ at any time $t_c$ with $t_a \leq t_c \leq t_d$ (and throughout the cloud at this time) is found by first finding the position of the leading edge of the cloud :

$$x = 0.4U_{ref}t_c + (R_o^2 + 1.2(g_o'Q_o)^{\frac{1}{2}}t_c)^{\frac{1}{2}}$$

(which is $x$ itself for $t_c = t_a$). The concentration $C$ is then found by inversion of the correlation

$$\frac{x_c}{Q_o^{\frac{1}{3}}} = \mathcal{F}\{\frac{C}{C_o}, (\frac{g_o'Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}\}$$

because the maximum distance at which the concentration is $C$ is the same as the distance at which the maximum concentration is $C$, as will be clear from the description in Section 3.4.2.

These relations can also be used to find the lateral extent of the contour of maximum concentration $C$. The correlation is used to find $x_c$, and then the arrival time relation is used to find the time $t_c$ at which the cloud concentration is $C$. The half-width of the cloud at that time is

$$y_c = (R_o^2 + 1.2(g_o'Q_o)^{\frac{1}{2}}t_c)^{\frac{1}{2}}$$

The complete contour of maximum concentration $C$ consists of a parabola enclosing the source closed off by a circular portion of radius $R = y_c$ at the downwind end.

The mean cloud height at time $t$ may be estimated as $\frac{C_oQ_o}{\pi R^2 C}$. This assumes a vertically and horizontally homogeneous cloud. It would be expected that the bulk of the cloud material would be contained within a region twice this height.

## 3.9 Releases of Limited Duration

When $0.6 < \frac{U_{ref}T_o}{x} < 2.5$ the previous correlations for instantaneous or continuous releases are not directly applicable.

Calculations may be performed based on an instantaneous and a continuous release and the smaller of the concentration estimates provides the upper bound on **any** release, as discussed in Section 3.6. The application of the correlations to transient releases will be illustrated in Chapter 6.

# Chapter 4

# Influence of Peripheral Variables

## 4.1 Influence of Surface Roughness

The surface roughness, characterised by $z_o$, affects the mean velocity and turbulence of the ambient flow into which the dense gas is released. The influence of $z_o$ on the mean velocity, relevant to the dispersion of dense gases, is probably negligible if the mean velocity at a fixed height, say 10 m, is used. For a given $U_{ref}$, the turbulence and the surface shear stress will increase with $z_o$.

The overall effects of surface roughness will be to apply a retardation to the horizontal, buoyancy-induced spreading of the plume or cloud and to enhance the mixing between plume and environment as a result of the ambient and plume turbulence (Hall et al, 1982). The combination of these effects is likely to, but need not, reduce the downwind distance to a given concentration and reduce the cross-stream dimension to a given concentration.

Picknett (1981) considered the effects of $z_o$ on the results of field trials of instantaneous releases. With $\left(g_o' Q_o^{\frac{1}{3}} / {U_{ref}}^2\right)^{1/2}$ between 1 and 3 there was little effect when the surface roughness changed from 2 mm to 20 mm or from 10 mm to 150 mm, other release conditions being unchanged. Any variation was within that observed for virtually identical releases. It should be noted that observations and comparisons were made for a very limited downstream distance.

Hall (1977) and Cheah et al (1984) concluded from laboratory experiments on continuous plumes that the effects of surface roughness were small and could be considered negligible while Janssen (1981) found that the influence was much smaller with dense gases than with passive releases.

With wind tunnel models of dense gas flow through industrial sites a significant increase in dilution (reducing distances to concentrations of a few per cent by half) has been observed, e.g. Bradley and Carpenter (1983), Builtjes and Guldemond (1984), together with a slight increase in the lateral plume spread. In these studies the obstacles were comparable to or larger than the vertical plume dimension and are better treated as individual obstacles (see Section 5.1) rather than distributed surface roughness.

In conclusion the influence of surface roughness (at least up to that corresponding to rough grassland) on the dispersion of dense gases is less than for a

comparable passive release and probably negligible at the level of this workbook.

## 4.2 Influence of Atmospheric Stability

With a given reference velocity, the influence of atmospheric stability is to provide smaller ambient levels of turbulence for a stably-stratified atmosphere and a larger level for an unstably-stratified atmosphere. A small variation in the profile of mean velocity is also observed. As the density variation within the dense gas cloud is typically much more stably stratified than the atmosphere, the influence of atmospheric stability on the dispersion of dense gas clouds will be less than on passive releases. The influence of atmospheric stability on the dispersion of dense gases (as a result of altered levels of turbulence) is likely to be similar to that from surface roughness (as a result of altered levels of ambient turbulence).

The Thorney Island instantaneous releases were conducted over a variety of atmospheric stabilities from Pasquill category B to F. No significant influence was observed (McQuaid and Roebuck, 1985).

The LNG trials in the Burro and Coyote series (Morgan et al, 1984) did show an effect of atmospheric stability, with the distance to a given concentration (of a few per cent) increasing with atmospheric stability. Morgan et al (1984) use

$$\Phi = 1 + 5Ri;\ (Ri > 0 \text{ i.e. stable}) \textit{ or}$$
$$\Phi = (1 - 16Ri)^{-\frac{1}{4}};\ (Ri < 0 \text{ i.e. unstable or neutral})$$

as the stability variable where $Ri$ is the Richardson number at a height of 2 m.

The distance to a given concentration is less sensitive in the dense gas dispersion problem (proportional to $\Phi^{0.57\pm0.18}$) compared with a Gaussian plume model (proportional to $\Phi^{1.29}$) over the range of the experiments. From these results, it is possible to conclude that the proportional influence of atmospheric stability is about half that for a comparable passive release.

The recommendation here is that a stable atmosphere will increase the downwind distance to a given concentration (and an unstable one reduce it) by an amount between zero and half the proportional effect of atmospheric stability on a comparable passive release whether continuous or instantaneous. This recommendation is obviously only applicable when density effects are of consequence over much of the region between the source and the point at which the concentration is required. Otherwise the proportional affect of atmospheric stability should be that relevant to a passive release. There is little further guidance, numerical models producing a considerable variety of effects both quantitative and qualitative which are a necessary consequence of the various model assumptions.

## 4.3 Influence of Source Geometry

The results for instantaneous releases presented in Section 3.7 were based, essentially, on experiments with source geometries of unit aspect ratio (height to hori-

zontal dimension). Such a geometry may result as the outcome of a catastrophic failure of a pressurised containment vessel.

At large values of $(g_o' Q_o^{\frac{1}{3}} / {U_{ref}}^2)^{1/2}$ much of the plume dilution is a result of buoyancy-induced motion particularly in the early stages of plume development. Although little data are available it is apparent that dilution as a result of buoyancy-induced motion will depend upon initial aspect ratio, decreasing as the initial height is reduced (but with $g_o'$ and $Q_o$ held constant). Rottman et al (1985) suggested that the structure of the cloud, and hence the initial dilution, is strongly dependent on the aspect ratio of the initial cloud. If the initial aspect ratio is much smaller than unity little dilution is anticipated as a result of the self-induced mean and turbulent motions.

Webber and Wheatley (1987) have used an integral model, which treats the turbulent energy in the cloud as a variable which determines the entrainment rate, to consider the influence of initial aspect ratio on subsequent cloud dilution. They concluded that the effect of aspect ratio on non-dimensional entrainment velocity was small. This should not be interpreted as implying (for a fixed $g_o'$ and $Q_o$) that the maximum concentration at a given distance from the source is only weakly dependent upon aspect ratio.

Havens and Spicer (1985) found that there was little evidence of cloud dilution changing with aspect ratio in the range of aspect ratio from 0.4 to 1.57. Huq (unpublished) has shown that in laboratory experiments with no wind there is very little dilution of the cloud as a result of buoyancy-induced motion when the initial aspect ratio is less than 0.1.

At small values of $(g_o' Q_o^{\frac{1}{3}} / {U_{ref}}^2)^{1/2}$ when the release is effectively passive and noting that unit aspect ratio provides minimum surface area for a given volume, we expect that any aspect ratio much larger or much smaller than unity will produce reduced maximum ground-level concentrations particularly in the near field close to the source. Passive dispersion calculations may be undertaken for various release geometries.

However, in general, there is little quantitative guidance for instantaneous releases which are not effectively passive and have an aspect ratio different to unity.

## 4.4 Influence of Turbulence Length Scales

The relegation of the turbulent length scales to peripheral variables is, in part, a pragmatic response to the lack of information about the influence of the turbulent length scales on the dispersion of dense gases.

However, there is evidence from passive dispersion studies that support this approach. In particular, for the neutrally stratified boundary layer, the length scales of the vertical velocity fluctuations depend approximately linearly on the distance from the surface. As a result the ratio of these turbulent length scales at, say, the plume or cloud top to the height of the plume or cloud is not a variable.

The length scales of the horizontal turbulent velocities depend upon both distance from the ground and the overall atmospheric boundary layer depth, and

they are typically similar to the atmospheric boundary layer depth. As a consequence the horizontal growth of passive plumes is dependent principally upon the turbulent velocities and not the horizontal turbulent length scales. A similar result would be anticipated for the more deterministic, less stochastic, dense gas plumes. This is particularly so for plumes whose study is restricted to only a few kilometres downwind.

The typically small ratio of source size to horizontal turbulent length scales does, however, mean that, for a passive plume, the ratio of the concentration fluctuations $c'$ to the mean concentration will be large. This, a result of plume meander close to the source, will be less obvious for dense gas plumes.

The influence of the horizontal turbulent length scales on instantaneous releases is little studied but is again likely to influence the movement of the centre of mass of the release rather than dilution of the cloud.

# Chapter 5

# Further Effects

## 5.1 The Influence of Obstacles or Buildings

### 5.1.1 Introduction

The presence of buildings or obstacles will act to divert the mean flow streamlines and to alter, generally increase, the intensity of turbulence. As the air flow near individual obstacles or groups of obstacles is extremely complex, it is normally difficult to generalise results for such flows and, if detailed concentration maps are required, the problem is best considered by full-scale tests or physical simulation. Nevertheless some broad observations and recommendations can be made.

There is a reduction of velocity ahead of an obstacle with an increase at the sides or over the top. With bluff obstacles, the flow separates from the obstacle producing a region of reverse velocities in the lee and a large increase in the turbulence. The region of reversed flow extends of the order of 10 obstacle heights downstream when the obstacle is two-dimensional but only about 2 obstacle heights when the obstacle has the same width and height. Downstream of the region of reverse flow the magnitudes of the mean velocity deficit and the turbulence decrease and their spatial extent increases. A further complication is the existence of one or more pairs of counter-rotating vortices aligned with the flow and with a rotational sense such that there is a mean downward velocity along the axis. These vortices have their origin in the interaction of the velocity shear of the boundary layer with the obstacle. They are frequently referred to as forming a 'horse-shoe vortex' and are illustrated in Figure 13, taken from Rottman et al (1985). They are very pronounced when, in addition, the obstacle is not normal to the mean flow and two strong vortices are also shed from the upwind leading edges.

As regards the dispersion of dense gases, it is difficult to envisage situations in which the obstacles will result in ground-level concentrations in excess of those observed in the absence of the obstacle, although the position of the maximum may not be on the downwind centreline. The evidence from the Thorney Island experiments (McQuaid and Roebuck, 1985) is that, even very close to the face on the upwind side (i.e., within two fence heights), the maximum concentration at ground level is not increased whilst it is significantly reduced at all downwind

locations. Possible contradictions to the above general statement would be where the lateral spreading of the plume is inhibited by obstacles e.g., flow along a 'street canyon', where longitudinal vortices capture release material and are not broken up by the environmental turbulence or where the obstacle results in the gas being diverted into regions where it would not go in the absence of the obstacle e.g., possible increased upwind spreading where a fence is very close to the source or widening of a plume along the line of a two-dimensional fence. This latter case is considered in Section 5.1.3.

These aside, we anticipate a reduction of the maximum ground-level concentration (on a radius centred on the release position) produced by the presence of one or more obstacles near or removed from the source.

Relevant data of a specific rather than generic nature may be found in Krogstad and Pettersen (1986) and McQuaid (1986).

### 5.1.2 Releases into the Immediate Lee

#### Continuous Releases

As a result of the intense turbulence in the immediate lee of a bluff obstacle, Britter (1982) estimated that the dilution there would be as if the released material had the same density as the environment provided the ratio of the buoyancy length scale to the width of the obstacle $\frac{g_o' q_o}{U^3 W} < 5.10^{-2}$, where $U$ is the mean velocity at the obstacle height in the absence of the obstacle and $W$ is the obstacle width normal to the mean flow.

Experiments by Britter (1986), using an archetypal obstacle in the form of a square flat plate of side $H$ normal to the flow, showed that, when $\frac{g_o' q_o}{U^3 H} < 4.10^{-3}$, the influence of the release density was negligible. This criterion for the irrelevance of density effects is larger than that for a wide source of no vertical extent (see Appendix A). $\frac{C}{C_o}\frac{UH^2}{q_o}$ was approximately 5 at $x/H = 1$ and approximately 1.5 at $x/H = 2$ (near the edge of the region of reverse flow) where $C/C_o$ is the ratio of time-mean concentration at ground level to the source concentration. These results are comparable to those obtained for passive releases (see Robins and Fackrell, 1983).

When $4.10^{-3} < \frac{g_o' q_o}{U^3 H} < 4.10^{-2}$, the plume is maintained (laterally) within the recirculation region in the immediate lee of the obstacle, again with a concentration at $x/H = 2$ of about $\frac{C}{C_o}\frac{UH^2}{q_o} \simeq 1.5$. This observation is superficially consistent with the estimate of Britter (1982). However, there is some density-stratification of the released material in the immediate lee such that $\frac{C}{C_o}\frac{UH^2}{q_o} \simeq 20$ at $x/H = 1$.

At the other extreme, when $\frac{g_o' q_o}{U^3 H} > 1$, the obstacle is irrelevant to the plume growth and dispersion. When $\frac{g_o' q_o}{U^3 H} > 2.10^{-1}$, the plume spread near the source (in the absence of the obstacle) is very wide and although plume dilution in the immediate lee is enhanced, the distance to any given concentration is unlikely to be significantly influenced by the obstacle.

Further experiments (Britter, 1986) on the interaction of a two-dimensional plume encountering a two-dimensional fence may be interpreted to show that,

provided $\frac{g_o' q_o^*}{U^3} \leq 4.10^{-2}$, where $q_o^*$ is the release rate per unit width, the dilution at the downstream edge of the recirculation lee will be equal to or less than that given by $\frac{C}{C_o}\frac{UH}{q_o^*} = 2.0$ (similar to a passive release) where $H$ is the obstacle height.

The results quoted above are for small values of $\frac{q_o}{UH^2}$ or $\frac{q_o^*}{UH}$, less than 0.1, say. Further information is given in Britter (1986). Another point to note is that, although the intense turbulence in the lee may allow the use of results obtained in the absence of any density difference between the plume and the environment, the influence of the density difference may become of consequence further downstream when the obstacle-generated turbulence has decayed.

If estimates of the plume concentration are to be made downstream of the obstacle, a new $g_o'$ and $q_o$ may be formed from the derived value of $C$ and used with the correlations provided in Section 3.7.1 for flow with no obstacles.

#### Instantaneous releases

Very little information is available for releases that are not continuous. However, for obstacles that might be approximated by square flat plates of side $H$ and releases of volume $Q_o$ and near unit aspect ratio, then the flow in the immediate lee appears passive when $(\frac{g_o' Q_o^{\frac{1}{3}}}{U^2})^{\frac{1}{2}} \leq 1.5$. When $(\frac{g_o' Q_o^{\frac{1}{3}}}{U^2})^{\frac{1}{2}} > 3.0$, the influence of the obstacle might be neglected. These results were obtained for the specific case of $\frac{H}{Q_o^{\frac{1}{3}}} \simeq 1.5$. Britter (1986) speculates that the flow is effectively passive in the immediate lee when $\frac{H}{Q_o^{\frac{1}{3}}} > (\frac{g_o' Q_o^{\frac{1}{3}}}{U^2})^{\frac{1}{2}}$ or when $(\frac{g_o' Q_o^{\frac{1}{3}}}{U^2})^{\frac{1}{2}} < 0.5$ and the influence of the obstacle may be neglected when $\frac{H}{Q_o^{\frac{1}{3}}} \leq \frac{1}{2}(\frac{g_o' Q_o^{\frac{1}{3}}}{U^2})^{\frac{1}{2}}$.

### 5.1.3 Releases Upwind of Obstacles

#### Continuous Releases

The following conclusions were arrived at by Britter (1986), for the case of a two-dimensional plume encountering a two-dimensional fence or step of height $H$ normal to the mean wind.

(i) If $\frac{U}{(g_o' q_o^*)^{\frac{1}{3}}} > 5$ and $\frac{H}{h} \leq 30$ the plume is not blocked by the fence. For $4.5 \leq \frac{H}{h} \leq 15$ the ground-level concentration in the immediate lee was as if the plume was not dense and $\frac{C}{C_o}\frac{UH}{q_o^*} = 1.7 \pm 0.3$. The plume height $h$ is that estimated in the absence of the obstacle from $C_o U h = C_o q_o^*$ where $U$ may be taken (to provide conservative results) as the mean velocity at the fence or step height and $C_o$ is the ground-level concentration.

(ii) At smaller values of $\frac{U}{(g_o' q_o^*)^{\frac{1}{3}}}$ down to 3.5, $\frac{C}{C_o}\frac{UH}{q_o^*} = 2.2 \pm 0.4$.

(iii) The fence has little effect on ground-level concentration when $\frac{h_{0.8}}{H} \geq 2$ and $\frac{U}{(g_o' q_o^*)^{\frac{1}{3}}} \geq 3.5$.

When a plume from an area or point source encounters a two-dimensional fence or step, the plume widens at the base of the fence or step and then rises to clear it. If the plume width may be estimated at the fence position, in the absence of the fence (and denoted by $W_{nf}$), then it was noted by Britter (1986) that the ratio $W_f/W_{nf}$ increases as the fence height increases and $U/(\frac{g_o' q_o}{W_{nf}})^{\frac{1}{3}}$ increases. The ratio $W_f/W_{nf}$ was approximately 3 for $h/H \simeq 0.05$, with a weak dependence on $U/(\frac{g_o' q_o}{W_{nf}})^{\frac{1}{3}}$.

$W_f/W_{nf}$ decreases to 1.5 for $h/H \simeq 0.15$, again with a weak dependence on $U/(\frac{g_o' q_o}{W_{nf}})^{\frac{1}{3}}$. For $U/(\frac{g_o' q_o}{W_{nf}})^{\frac{1}{3}} \geq 4$ and $0.04 < \frac{h}{H} < 0.2$ the dilution in the lee of the fence was as if there was no density difference, that is $\frac{C}{C_o}\frac{UHW_f}{q_o}$ was approximately $2.1 \pm 0.3$.

**Instantaneous Releases**

Some general conclusions regarding instantaneous releases encountering obstacles are available in Rottman et al (1985) while analyses of relevant field trial results are presented by McQuaid (1986) and Brighton and Prince (1987). Wind tunnel simulations are reported by Davies and Inman (1987) and Knudsen and Krogstad (1987).

## 5.2 Relevance of Topography

### 5.2.1 Topographic Features Large Compared to the Scale of the Release

In this case the topography reduces to a local scope.

Picknett (1981) found that instantaneous releases on slopes of 1 in 13 were influenced by the slope under very low wind speed conditions. Hall et al (1974) observed that slopes of 1 in 12 altered their continuous plume results. The release will tend to move down the slope while being advected by the wind. When the wind and slope are opposed, the plume/cloud widens and its dilution is enhanced. When the wind is down the slope, the plume/cloud is narrower and the dilution is decreased.

The variation of the lateral growth of the plume results from an effective vector summation of the wind and the buoyancy-induced motion down the slope thus widening the plume/cloud for an upslope wind and decreasing the width of the plume/cloud for a downslope wind. Slope-induced motions are retarded by surface stress and entrainment of ambient fluid, the latter dominating for slopes greater than about one degree (Britter, 1982). The entrainment is influenced by the velocity shear and will, therefore, be enhanced by an upslope wind and reduced by a downslope wind.

In the case of cross winds, Hall et al (1982) found that the dilution is not greatly affected, although the conclusion is based on a single wind tunnel experiment. The vector sum of the ambient wind and a downslope, buoyancy-driven flow should indicate the plume/cloud trajectory.

Three velocities are relevant:

(i) $U$, the ambient wind;

(ii) $U_{bf}$, the buoyancy-generated velocity found on flat terrain, and

(iii) $U_{bs}$, the buoyancy-generated velocity found on slopes — the downslope flow.

The latter two velocities will both scale on $(g'h)^{\frac{1}{2}}$ where $g'$ is the modified gravity relevant for the plume/cloud and $h$ is the related plume/cloud depth. Somewhat surprisingly, the coefficient in the expression for $U_{bs}$ is only a weak function of slope. As a result slopes will have a significant effect on plumes/clouds for which any buoyancy-generated velocities are relevant.

Note that for a continuous plume, $g'h$ might be estimated from $g_o'q_o/UW$ where $U$ is a plume advection velocity (see Section 3.7.2) and $W$ is a plume width. For an instantaneous release, $g'h$ can be estimated from $g_o'Q_o/A(t)$ where $A(t)$ is the area covered by the release.

A further useful point is that the ambient velocity required to reverse a downslope flow of a plume or cloud is a weak function of slope and is typically 3 to 4 times $(g'h)^{\frac{1}{2}}$. For further discussion of these points, see Britter (1982).

**Topographic Features Small Compared to the Scale of the Release**

In this case, the dense gas may flow around the topographic feature. When a plume/cloud is very wide compared with the lateral scale of the topography the plume/cloud will carry over the crest of the topography when $\frac{U^2}{g'h} >> 2(\frac{h_c}{h} - 1)$ and will flow around the feature when $\frac{U^2}{g'h} << 2(\frac{h_c}{h} - 1)$, where $h_c$ is the height of the crest.

When the width of the plume/cloud is similar to the lateral dimension of the topography, the plume/cloud will be more easily diverted around the topography than suggested by the above criteria. The above results can also be applied to obstacles.

A more detailed discussion of these points is provided in the review by Britter (1982).

## 5.3 Releases from Elevated Sources

Limited information is available on releases from elevated sources and it is generally restricted to continuous, steady releases directed vertically upwards.

In the absence of any wind, the plume top fluctuates about a height of rise $\Delta h$ where $\frac{\Delta h}{D_o} = 3\frac{U_e}{(g_o'D_o)^{\frac{1}{2}}}$ and $D_o$ is the source diameter, $U_e$ is the efflux velocity,

$\frac{4Q_o}{\pi D_o^2}$, and $g_o\prime = g\frac{\Delta\rho}{\rho_o}$ (Hoot and Meroney, 1974). The height $\Delta h$ is about 0.7 times the height to which the plume initially rises, the reduction at later times being due to the increased drag on the ascending plume resulting from the descending flow. The formulation holds up to a specific gravity of 3.0, that is well beyond the region of validity of the Boussinesq approximation although it must be noted that $g_o\prime$ has been defined here, unusually, with the source density in the denominator rather than the more customary ambient density. The expression may be rewritten using the ambient density in the definition so that $g_o\prime = g\frac{\Delta\rho}{\rho_a}$ to provide $\frac{\Delta h}{D_o} = 3\frac{U_e}{(g_o\prime D_o)^{\frac{1}{2}}}(\frac{\rho_o}{\rho_a})^{\frac{1}{2}}$ where $(\frac{\rho_o}{\rho_a})$ is the density ratio of the source to the ambient fluid.

No information is available on plume concentrations.

When there is a crossflow, the plume rises to a maximum height and then descends to the ground, as illustrated in Figure 14. Laboratory experiments with a uniform and laminar crossflow $U_o$ have been reported by Meroney (1982). The results showed a considerable lateral spread of the plume when it reached the surface, with little variation of concentration laterally across the plume. The maximum height to which the plume rises is

$$\frac{\Delta h}{D_o} = 1.32\{\frac{U_e}{(g_o\prime D_o)^{\frac{1}{2}}}\}^{\frac{2}{3}}(\frac{\rho_o}{\rho_a})^{\frac{2}{3}}(\frac{U_e}{U_o})^{\frac{1}{3}}$$

and this occurs at a distance downwind from the source of

$$\frac{X_m}{D_o} = 1.0\{\frac{U_e}{(g_o\prime D_o)^{\frac{1}{2}}}\}^{2}(\frac{\rho_o}{\rho_a})(\frac{U_o}{U_e})$$

The plume eventually touches down at a further distance downstream given by

$$\frac{X_{TD} - X_m}{D_o} = 0.56(\frac{\Delta h}{D_o})^3[(\frac{H}{\Delta h} + 2)^3 - 1]^{\frac{1}{2}}\frac{U_e}{(g_o\prime D_o)^{\frac{1}{2}}}(\frac{U_o}{U_e})^{\frac{3}{2}}$$

where H is the source height.

In many cases $(\frac{H}{\Delta h} + 2)^3 >> 1$ and this result simplifies to

$$\frac{X_{TD} - X_m}{D_o} = 0.56(\frac{\Delta h}{D_o})^3(\frac{H + 2\Delta h}{\Delta h})^{\frac{3}{2}}\frac{U_e}{(g_o\prime D_o)^{\frac{1}{2}}}(\frac{U_o}{U_e})^{\frac{3}{2}}$$

The mean surface concentration at touchdown is given by (Meroney, 1982)

$$\frac{C_{TD}}{C_o}\frac{U_o D_o^2}{Q_o} \simeq 3.1(\frac{H + 2\Delta h}{\Delta h}) - 2.$$

The ground-level plume concentration then decays as $x^{-0.65}$ and then later as $x^{-1.7}$ (indicative of an equivalent ground-level source). Meroney (1982), referring to experiments by Kothari and Meroney (1979), shows similar results for elevated releases in a simulated atmospheric boundary layer rather than a uniform crossflow.

For more complicated situations (including the influences of initial momentum, atmospheric stability and inclination of the jet), there are several computational

models that have been developed e.g. Ooms et al (1974), Ooms and Duijm (1984) for atmospheric problems and many examples in a civil engineering context, see Fischer et al (1979).

## 5.4 Extension to Very Small Concentrations

### 5.4.1 Continuous Releases

A pragmatic approach is to plot concentration data from Figure 8, against $\frac{x}{(q_o/U_{ref})^{\frac{1}{2}}}$ for the required $(\frac{g_o{l'}^2 q_o}{U_{ref}^5})^{\frac{1}{5}}$ and extrapolate the data to smaller concentrations.

The correlation provided in Section 3.7.1 i.e.

$$x = A q_o^{0.4} g_o{l'}^{-0.2}$$

may be extrapolated to smaller concentrations in the absence of more specific information. The extrapolation is restricted, as in the original derivation, to values of $(\frac{g_o{l'}^2 q_o}{U_{ref}^5})^{\frac{1}{5}} \geq 1$.

Alternatively, we can use the criterion given in Section 3.5 to determine the position downwind beyond which a passive dispersion (with suitable source conditions) problem is relevant. The result of such a calculation is that when

$$\frac{x}{(q_o/U_{ref})^{\frac{1}{2}}} \geq (\frac{1}{0.15})^{\frac{9}{2}} (\frac{1}{2.5})^{\frac{3}{2}} \{(\frac{g_o{l'}^2 q_o}{U_{ref}^5})^{\frac{1}{5}}\}^{\frac{5}{2}},$$

the dispersion is effectively passive. This result *might* also provide a relevant estimate of the extent to which the dense gas correlations may be extrapolated.

### 5.4.2 Instantaneous Releases

As above, a simple extrapolation of the data, for concentrations down to 0.001, to smaller concentrations is recommended here for want of more specific information.

As a result of the small variation in non-dimensional downwind distance to a given concentration with the stability parameter, a useful practical simplification is possible. The interpolation formula given in Section 3.8.1 i.e.

$$x = B Q_o^{\frac{1}{4}} g_o{l'}^{-\frac{1}{4}} U_{ref}^{\frac{1}{2}}$$

for

$$2 \leq (\frac{g_o{l'} Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \leq 10$$

may be extrapolated to give estimates for smaller concentrations if more specific information is not available.

Again, we can use the criterion given in Section 3.5 to determine the position downwind beyond which a passive dispersion (with suitable source conditions) problem is relevant.

## 5.5 The Influence of Heat Transfer and Thermodynamic Effects

There are three specifically thermodynamic phenomena that must be considered if the release is at a temperature different to that of the environment. The relevant release temperature here is that in the plume after source effects, e.g. source momentum, have subsided and any released aerosol has evaporated to form a gaseous mixture.

The two phenomena are:

(i) the influence of heat transfer to the plume due to (a) sensible heat exchange between the plume and the ambient air as a result of the entrainment of ambient air; (b) heat transfer at the plume boundaries, in particular through the lower surface over which the plume is transported; (c) latent heat exchange due to condensation of the moisture content of entrained humid air and any subsequent reevaporation as the saturation conditions change with downstream distance, and

(ii) the non-linear variation of the temperature and density of a mixture of gases with mole fraction when the species have different molar specific heat capacities.

Heat transfer to the cloud or plume has two effects. The first is a consequence of our concentration being measured as molar or volume/volume concentration referred to a source concentration taken as unity. The volumetric addition of air, say $V_a$, at temperature $T_a$, will be the same in the non-isothermal problem as is incorporated in the isothermal correlations. The initial volume in the non-isothermal problem (for which the source temperature is $T_o$) is $V_o$ and the concentration, $C_{ni}$, will be $\frac{V_o}{V_o+V_a}$. The corresponding initial volume in the isothermal correlations (for which the source temperature is $T_a$) is $V_o\frac{T_a}{T_o}$ and the concentration, $C_i$, will be

$$\frac{V_o\frac{T_a}{T_o}}{V_o\frac{T_a}{T_o}+V_a}.$$

After rearranging, we obtain

$$C_{ni}=\frac{C_i}{C_i+(1-C_i)\frac{T_a}{T_a}}$$

or alternatively

$$C_i=\frac{C_{ni}}{C_{ni}+(1-C_{ni})\frac{T_a}{T_o}}$$

For example, for an LNG release, the source temperature will be 111°K. If the ambient temperature is 290°K, then for comparison with an experimental concentration of say 0.05, the concentration from the isothermal correlations must be taken as 0.02.

The second effect of heat transfer (for the usual case of a cold gas release) is that it will act to reduce the negative buoyancy and, as a consequence, reduce the horizontal dimensions that result from gravitational spreading. It is frequently assumed that heat transfer also acts to reduce the distance to a given concentration. Laboratory data (Andreiev et al, 1983) and field results (Puttock et al, 1982) over limited ranges of stability parameters and chemical types have encouraged this assumption, although the universality of the assumption is not proven. In contrast, our correlations indicate that if the sole result of heat transfer could be treated as a reduction in the negative buoyancy of the plume or cloud, then there are parameter ranges where an increase in distance to a specific concentration might be expected. However, it is not clear that such an assumption on the role of heat transfer is justified.

The above lack of clarity on the overall effect of heat transfer is a further reflection of the uncertainty concerning the relative dominance of the two competing effects of cloud density, that is to reduce the rate of mixing per unit area between the cloud or plume and the environment but to increase the area over which the mixing is taking place. Our correlations suggest that the relative dominance of the two effects varies with the stability parameter, although the variation as best as can be established from the data is comparable to the uncertainty range.

Although the influence of the two phenomena should be considered within the developing cloud or plume, we restrict ourselves to a global treatment appropriate to a workbook approach. Specifically, for each of the two phenomena, we recommend performing two calculations which will bracket the result which would be obtained from a proper treatment of the problem. A comparison of the two solutions allows the following decisions to be made:

(i) if the difference between the calculations is small, then the user assesses that the phenomenon is unimportant and may be neglected;

(ii) if the difference is neither large nor small (say a factor of two), then the most pessimistic of the two solutions is adopted;

(iii) if the difference is large (say more than a factor of two), then the most pessimistic may be selected, but further investigation may be worthwhile (e.g. use of a valid computational code) to provide a reasonable estimate.

Note that the 'difference' should be assessed in whatever form the user considers appropriate and is not necessarily the distance to a specific concentration.

The execution of the approach to each of the two phenomena is as follows:

(i) Heat Transfer

(a) Determine the source density difference and volume (or volume flow rate) and use these values with the correlations, using the modified measure of the concentration as given above.

(b) Take the source density difference and volume (or volume flow rate) as calculated in (a), assume heat addition at the source sufficient to bring this source material to ambient temperature, which clearly provides the limit to the effect of heat transfer. Use these revised values of density difference and volume (or volume flow rate) with the correlations, again using the modified concentration.

For gases with a molecular weight less than that of air (principally methane and ammonia) the procedure breaks down since calculation (b) renders the gas positively buoyant. No simple treatment for these cases is obvious. It may be noted that Havens and Spicer (1985) have performed calculations for LNG releases using the DEGADIS model and found that an assumption of no heat transfer (i.e. as in calculation (a) above) gives conservative answers, i.e. greater distances to a given concentration, compared to those obtained with heat transfer effects included.

(ii) Difference in Molar Specific Heat Capacities

(a) Determine the source density difference and volume (or volume flow rate) and use these values with the correlations.

(b) From the results of (a), determine the density difference at the concentration of interest and the volume (or volume flow rate) that satisfies mass continuity. Determine a revised source density difference, source temperature and source volume (or volume flow rate) based on mass conservation, pure species at the source, adiabatic mixing and a constant molar specific heat equal to that of the environment.

This effect is probably not significant for most materials of interest, with methane and hydrogen being relevant exceptions (Fay and Ranck, 1981).

# Chapter 6

# Examples in the Use of the Workbook

## 6.1 Introduction

In this chapter, the methods that have been presented will be called up in a number of ways to illustrate their application. The illustrations we select are intended primarily to serve as examples of the usage of the correlations in performing calculations on experimental or accidental releases and on hypothetical releases typical of a hazard analyst's portfolio of accidents. They also serve to confirm, in a restricted sense, the validity of the correlations. However, it needs to be emphasised that the validation of the correlations is implicit in their derivation since most of the extant data have been used. Any comparisons by us with the same data would essentially form a circular argument.

However, the treatment of experimental data is subject to some judgement and choice. Where an independent treatment of the data is available, it can provide useful verification that our exercise of judgement has at least been consistent with that of the independent assessor. In addition, we recognise that users will be interested in knowing how well the correlations are able to describe the results of large-scale field experiments, especially those involving releases of liquefied gas. Thus for both reasons we include some comparisons with experimental data, recognising the limited conclusions that can be drawn from such comparisons.

The coverage we can provide by way of illustration cannot be all-embracing. Nor can the user of the workbook expect to forego all exercise of judgement. However, this factor is inseparable from the practice of hazard analysis and the workbook will hopefully reduce, though not eliminate, the need insofar as the estimation of dispersion is concerned. The important point is that this judgement can be aided by sensitivity tests. As will be seen, these are easily performed and allow the user to come to an informed conclusion on the range of uncertainty resulting from the uncertainty in the judgemental factors.

A flow diagram is shown in Figure 15 which sets out the route that would be taken by the user of the workbook. The route is broken down into separate stages, with cross-references to relevant parts of the workbook, as follows:

Stage 1 The portfolio of potential accidents is compiled using a technique such as Hazard and Operability Study (Section 2.2)

Stage 2 The release conditions as required for use of the workbook methods are determined from the guidance and source references in Section 2.4 and the specification of requirements in Section 3.4.1.

Stage 3 The determination of the release type uses the criteria given in Section 3.6.

Stage 4 The classification of the release as passive or one for which dense gas treatment is appropriate is determined using the guidance in Section 3.5. If a passive release is deemed to be appropriate, the user refers to standard methods in the cited references.

Stage 5 The estimation of the magnitude of the effects produced by buildings, e.g. on the depth and depth-averaged concentration, draws on the information in Section 5.1 for those cases where the information is available. In other cases, recourse will be necessary to a properly validated code or to physical modelling. Where the effects can be estimated, these serve to redefine the source conditions for the basic correlations i.e. modified source concentration, density difference and volume (or volume flow rate). The location of the redefined source also needs to be estimated. The calculation loops back so that the criteria in stages 3 and 4 can be retested using the redefined source conditions.

Stage 6 The guidelines and cited references in Section 5.2 are used to determine whether topography is important and, if so, the corrections to be applied to estimates for dispersion in the absence of topographic effects. The corrections are stored for subsequent recall when the latter estimates have been prepared.

Stage 7 The dispersion calculation is performed using the correlations and formulae in Section 3.7 or 3.8 as appropriate to the release type determined in Stage 3. If the release is deemed to be transient, the estimate is the upper bound calculation as described in Section 3.9. At this stage, any heat transfer or thermodynamic effects are ignored in the calculations, except that the concentration must be modified as described in Section 5.5.

Stage 8 Any corrections for topographic effects are now applied.

Stage 9 Heat transfer or thermodynamic effects are assessed using the guidance in Section 5.5. If the effects are negligible or if a pessimistic estimate is acceptable, the calculation proceeds to Stage 10. If not, consideration needs to be given to use of a validated code which includes heat transfer and thermodynamic effects.

Stage 10 Finally, the information on the concentration distribution and the geometry of the plume/cloud is applied to assess damage effects as outlined in Section 2.5.

## 6.2 Comparisons with Experimental Results

### 6.2.1 The Correlation of Carpenter et al (1987)

The form of the relationship for the distance-concentration for an instantaneous release has recently been independently described by Carpenter et al (1987). In

analysing the results of several field and laboratory experiments, they found that the distance to the 0.02 concentration non-dimensionalised with $Q_o^{\frac{1}{3}}$ (or $V_o^{\frac{1}{3}}$ in their notation) was independent of the Richardson number defined as $\frac{g_o' V_o^{\frac{1}{3}}}{U_{ref}^2}$, where $U_{ref}$ is the windspeed at 10 m height. These are, of course, the same two parameters that form the basis of the correlation described in Section 3.8. Figure 1 from Carpenter et al's paper is reproduced as Figure 16. The experimental data points on the figure are those evaluated by Carpenter et al from published information and include results from Bradley and Carpenter (1983) and Dirkmaat (1981) not considered in the preparation of the workbook correlations. Also shown in Figure 16 is the curve represented by the correlation presented in Section 3.8 and Figure 11. The agreement between the two independent studies is gratifyingly good.

### 6.2.2 The Correlation of Hanna and Drivas (1987)

Hanna and Drivas (1987) fitted a curve to a collection of the Thorney Island maximum concentration versus distance data. The curve and the data are shown in Figure 17. The curve is given by the formula

$$\frac{C_m}{C_o} = \left(\frac{x}{Q_o^{\frac{1}{3}}}\right)^{-1.5}$$

in the workbook notation. Also shown in Figure 17 is the curve produced from the correlation in Figure 11 where a value of 2.2 has been used for $\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}}$, corresponding to typical parameter values for the trials of $g_o' = 10$ m/s$^2$, $Q_o = 2000$ m$^3$ and $U_{ref} = 5$ m/s.

### 6.2.3 Havens and Spicer (1985) Treatment of Thorney Island Data and Comparisons with DEGADIS Model Predictions

Another published source of information on the evaluation of experimental results is that of Havens and Spicer (1985). They evaluated data from 6 of the Thorney Island trials for purposes of comparison with the predictions of the DEGADIS model. Their comparisons between experimental data and DEGADIS predictions are reproduced in Figure 18a to f. Mercer (unpublished) has used the correlation of Section 3.8 and Figure 11 to provide the workbook estimates for the same set of trials and these are also shown in Figure 18. Again, the agreement is very good throughout.

### 6.2.4 Lyme Bay Trials and the Model Predictions of Wheatley et al (1988)

These trials are referred to in Appendix C.1.4. The results were not included in the database used to derive the workbook correlations. This was because the reported

concentrations were substantially below the range covered by the correlations. However, when account is taken of dilution at the source in the manner described by Wheatley et al (1988), the concentrations expressed as ratios to the source concentration fall within the range. The trials' results therefore provide a source of independent data as a check on the correlations. In addition, a further useful point is that Wheatley et al provide predictions from a number of dense gas dispersion models in widespread use.

The trials, which involved the release of pressurised liquefied chlorine over a duration of 15 minutes, are fully described in Wheatley et al (1988) and only the essential features will be described here. Four trials were performed, with conditions as given in Table 1.

| Trial* | III | IV | V | VI |
|---|---|---|---|---|
| Release rate of chlorine,kg/s | 3.60 | 7.71 | 11.5 | 7.02 |
| Windspeed at 10 m, m/s | 3.1 | 2.5 | 4.1 | 3.6 |
| Air temperature $°C$ | 10.4 | 11.4 | 12.8 | 12.9 |

* Trials I and II were preliminary

Table 1: Conditions in the Lyme Bay Trials, from Wheatley et al (1988)

The chlorine was stored as a liquid in cylinders under pressure at ambient temperature. On release, a two-phase flashing jet would have formed, entraining air in the process. Wheatley et al assumed that sufficient air was mixed with the chlorine at the source to vapourise all the chlorine and result in a mixture with a temperature equal to the boiling point of chlorine at atmospheric pressure i.e. -34$°C$. The resultant mass ratios of air to chlorine in the mixture are given by Wheatley et al as 5.58, 5.44, 5.25 and 5.24 for trials III to VI respectively. We accept the above assumption and derive the release conditions given in Table 2.

| Trial | III | IV | V | VI |
|---|---|---|---|---|
| Volume ratio of air to chlorine | 13.6 | 13.2 | 12.8 | 12.7 |
| Initial concentration of chlorine in air | 0.069 | 0.070 | 0.073 | 0.073 |
| $q_o$ m$^3$/s | 14.5 | 30.6 | 44.1 | 26.9 |

| | | |
|---|---|---|
| Notes: | Density of chlorine at -34°C | $= 3.59$ kg/m$^3$ |
| | Density of air at -34°C | $= 1.48$ kg/m$^3$ |
| | Volume Ratio | $= \frac{3.59}{1.48}$Mass Ratio |
| | | $= 2.43$ Mass Ratio |
| | Initial concentration | $= \frac{1}{VolumeRatio+1}$ |
| | Initial density ($\rho_o$) | $= 1.63$ kg/m$^3$ |
| | $g_o'$ | $= 3.1$ m/s$^2$ taking ambient temperature as 12°C. |

Table 2: Release Conditions for the Lyme Bay Trials

For Stage 3, the criterion for the release to be treated as continuous is that $\frac{U_{ref}T_o}{x} \geq 2.5$ (Section 3.6). Application of this criterion (taking $T_o = 900$ s) indicates that a continuous plume is obtained up to distances of 1100, 900, 1500 and 1300 m for trials III to VI respectively. These distances include most of the measurement range in the trials and therefore a continuous release condition is an appropriate assumption.

Proceeding to Stage 4, the relevant criterion for the release to be treated as passive is $(\frac{g_o'q_o}{U_{ref}^3}/D)^{\frac{1}{3}} \leq 0.15$ (Section 3.5). To estimate the source length scale, $D$, it seems reasonable to assume that the relevant dimension is the width of the jet of chlorine/air mixture when the mean velocity of the jet has become comparable to the windspeed. Hence $D$ will be approximately $(\frac{\pi U_{ref}}{4q_o})^{\frac{1}{2}}$ and the above criterion can be rewritten as $(\frac{g_o'q_o}{U_{ref}^{\frac{5}{2}}})^{\frac{1}{3}} \leq 0.15$. The values of this parameter are 0.89, 1.2, 0.85 and 0.87 for trials III to VI respectively. Hence, we conclude that a dense gas treatment is appropriate.

The releases were conducted at sea so that Stages 5 and 6 are not relevant.

For Stage 7, the workbook parameters are derived from the data in Table 2 and are shown in Table 3.

| Trial | III | IV | V | VI |
|---|---|---|---|---|
| $(\frac{g_o'^2q_o}{U_{ref}^5})^{\frac{1}{5}}$ | 0.86 | 1.24 | 0.82 | 0.85 |
| $(\frac{q_o}{U_{ref}})^{\frac{1}{2}}$ | 2.2 | 3.5 | 3.3 | 2.7 |

Table 3: Workbook Parameters for the Lyme Bay Trials

For each trial, the distances to given concentrations are obtained from Figure 8. Since these concentrations are referred to a source concentration of unity, they must be multiplied by the initial concentrations given in Table 2. Furthermore, since the releases were non-isothermal, the concentrations must be modified to allow for volumetric expansion, as explained in Section 5.5. For the release temperature of -34°C and the typical ambient temperature of 12°C, the modification requires the concentrations from the correlations to be multiplied by a factor of 1.19.

The atmospheric stability categories during the trials were estimated by Wheatley et al, using Pasquill's (1961) scheme, from the reported weather observations. Wheatley et al used these stability categories in preparing their predictions, although they acknowledged the doubtful applicability of Pasquill's scheme to conditions over the sea. For consistency, the workbook estimates have been corrected for the effects of stability using the recommendation in Section 4.2. In order to do this, the concentration versus distance relationship was obtained using the Pasquill-Gifford relationships (see Turner, 1970) at each stability category for the same volumetric release rate and windspeed as applied in the trials. The factor by which the distance to a given concentration deviated from that for D stability was found and the workbook estimates were then corrected by a factor corresponding to half this deviation. For category C, the correction reduces the workbook estimate of distance by a factor 0.78 and for category B by a factor 0.65.

The results are plotted in Figures 19a to d which are reproduced from Wheatley et al (1988). The workbook results tend to fall at the upper end of the range covered by the predictions.

The estimates in this case have had to use the workbook correlations in the area where they are least supported by experimental data - i.e. at low Richardson numbers and towards the passive limit. In deriving the correlations in this region, less weight was given to the limit derived from the Pasquill-Gifford scheme than to the dense gas dispersion results. The final values accepted for the non-dimensional distances to given concentrations at the passive limit were somewhat above the Pasquill-Gifford values, although still satisfying the 'within a factor of two' criterion adopted. The deviation would result in conservative answers (i.e. larger distances to a given concentration) than the Pasquill-Gifford scheme would provide on its own. The effect of a conservative choice is evident in the comparisons in Figures 19a to d, although it should be said that the concentrations measured in the trials could have been too low as a result of particular effects. These include rainout of chlorine into the sea at release, absorption of chlorine by the sea during dispersion and the effects of addition of chlorosulphonic smoke to the chlorine as a marker. For further details, the reader is referred to the report by Wheatley et al (1988). Of more relevance, perhaps, is that the workbook estimates are all within a factor of two of the predictions from codes which have themselves been extensively validated against experiment.

The question of the uncertainty in the correlations at the passive limit is discussed further in Chapter 7.

### 6.2.5 Burro Series LNG Experiments

We shall use the summarised data as presented by Ermak et al (1982) in their comparisons with predictions of several dense gas dispersion models. The relevant data are given in Table 4.

| Burro trial | 3 | 7 | 8 | 9 |
|---|---|---|---|---|
| Spill rate of liquid, $m^3$/min | 12 | 14 | 16 | 18 |
| Duration, s | 167 | 174 | 107 | 79 |
| Windspeed at 2 m, m/s | 5.4 | 8.4 | 1.8 | 5.7 |

Table 4: Conditions in the Burro Trials

To derive the workbook parameters, we note that the density of LNG is 425.6 kg/$m^3$ and of LNG vapour at the boiling point of -162°C is 1.76 kg/$m^3$ . As is usual for LNG releases, we assume that there is no initial mixing at the source. We calculate the reference windspeed at 10 m height using the logarithmic profile and taking a representative ground roughness of 1 cm. We take the ambient temperature to be 34°C throughout.

The derived data in workbook format are given in Table 5.

| Burro | 3 | 7 | 8 | 9 |
|---|---|---|---|---|
| $U_{ref}$, m/s | 7.0 | 10.9 | 2.3 | 7.4 |
| $q_o$ $m^3$/s | 48.6 | 56.7 | 64.8 | 72.9 |
| $(\frac{g_o{}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}}$ | 0.60 | 0.4 | 1.9 | 0.6 |
| $(\frac{q_o}{U_{ref}})^{\frac{1}{2}}$ | 2.6 | 2.3 | 5.3 | 3.1 |

Table 5: Workbook Parameters for the Burro Trials

Application of the criterion for passivity shows, not unexpectedly, that the trials must be treated as dense gas releases (assuming that a continuous release condition applies). In using the criterion, we have taken the diameter of the liquid pool as the source length scale and calculated it using the liquid regression rate of 4.2 x $10^{-4}$m/s given by Ermak et al (1982).

As to whether the releases are in fact continuous, the relevant criterion suggests that trials 8 and 9 become transient within the measurement range. We shall proceed as if all four trials were continuous and return to this question later.

The modification to the workbook concentrations to account for the non-isothermal nature of the releases (as described in Section 5.5) means that the

concentration corresponding to the LFL must be taken as 0.02, compared to the actual LFL of 0.05.

The distances to this concentration obtained from Figure 8 are compared in Table 6 with the corresponding results given by Ermak et al (1982) for the distances to the LFL.

| Burro | 3 | 7 | 8 | 9 |
|---|---|---|---|---|
| Workbook estimate, m | 470 | 370 | 560 | 560 |
| Experiment, m | 255 | 200 | 420 | 325 |
| Germeles-Drake model, m | 126 | 150 | 661 | 235 |
| SLAB model, m | 215 | 264 | 418 | 315 |
| FEM3 model, m | 190 | 210 | 630 | 330 |

Table 6: Comparison of Calculations with Experiment for the Burro Trials

Overall, the comparison shows that the workbook estimates are consistently conservative. This is most likely due to the influence of heat transfer in reducing the negative buoyancy. However, as explained in Section 5.5, it is not possible to apply the workbook recommendation to these LNG releases. If a conservative answer is not acceptable, recourse must be made to a properly validated code which includes a treatment for heat transfer effects.

Finally, the view taken in the workbook is that the distance to a given concentration for a transient release should be the smaller of the distances calculated for instantaneous and continuous assumptions. The calculation for trials 8 and 9 have therefore been repeated assuming they were instantaneous releases with $Q_o$ as the total amount of material released. The distances to the LFL are obtained as 330 m for trial 8 and 320 m for trial 9.

Since these are both less than the distances for the comparable continuous release, they should substitute for them in accordance with our recommendation. Two points should be remembered. Firstly, the workbook provides estimates that are not claimed to be better 'than a factor of two'. Secondly, the instantaneous correlation applies to releases of unit aspect ratio associated with substantial initial mixing, whereas in the Burro Series the releases were of pancake clouds of low aspect ratio. The influence of aspect ratio and the need for more information will be further remarked upon in Chapter 7.

### 6.2.6 Maplin Sands LNG and Refrigerated Liquefied Propane Trials

The full series of trials is described by Puttock et al (1982). We shall use the same set of trials selected by Puttock et al for comparison with the HEDAGAS model. In view of the similarity with the calculations in Section 6.2.5, we give only

a foreshortened description. The relevant information is summarised in Table 7.

| Material | Propane | | | LNG | | |
|---|---|---|---|---|---|---|
| Trial | 46 | 47 | 54 | 15 | 39 | 56 |
| Spill rate of liquid, $m^3$/min | 2.8 | 3.9 | 2.3 | 2.7 | 4.5 | 2.5 |
| Duration, s | 468 | 270 | 300 | 402 | 138 | 150 |
| Windspeed at 10 m, m/s | 7.9 | 5.2 | 3.6 | 3.9 | 4.5 | 4.8 |

Table 7: Conditions in the Maplin Sands Trials

We note that the density of liquefied propane is 553 kg/$m^3$ and of propane as a gas at the boiling point of -42°C is 2.32 kg/$m^3$. We take the ambient air temperature to be 20°C throughout. We again assume that there is no initial mixing at the source, since all the trials involved refrigerated liquids.

As with the earlier examples, the workbook concentrations must be modified for the non-isothermal nature of the releases, resulting in concentrations corresponding to the LFL of 0.02 for LNG (compared to an actual 0.05) and 0.017 for propane (compared to an actual 0.021). The distances to these concentrations as given by the workbook methods are compared in Table 8 to the experimental results and the HEGADAS model predictions for the distances to the LFL concentrations.

| Material | Trial | Workbook Estimate, m | Experiment, m | HEGADAS model, m |
|---|---|---|---|---|
| Propane | 46 | 240 | 245 ± 35 | 140 - 220 |
| | 47 | 320 | 340 ± 80 | 355 - 540 |
| | 54 | 280 | 400 ± 100 | 295 |
| LNG | 15 | 280 | 110 ± 30 | 235 |
| | 39 | 340 | 130 ± 20 | 200 - 390 |
| | 56 | 260 | 150 ± 30 | 235 - 320 |

Table 8: Comparison of Calculations with Experiment for the Maplin Sands Trials

The experimental distances were estimated (except for trial 54) by Puttock et al from the records of the maximum concentration at sensor positions rather than the long-time average concentration. This was intended to remove the effect of meandering of the plume. The ranges in the HEGADAS model predictions reflected the uncertainty in the ambient and source conditions.

A further useful comparison is between the workbook estimates and predictions for the continuous propane spills in the Maplin Sands trials produced by Havens and Spicer (1985) using the DEGADIS model. These predictions were for the distances to the 0.05, 0.025 and 0.01 concentrations. The predictions have been plotted in Figure 20. Also shown are the correlation curves for 0.05, 0.02 and 0.01 concentrations. (The modifications to allow for the effect on the workbook concentrations of volume expansion are minor and are neglected in this particular comparison). The agreement between the two sets of predictions is seen to be very satisfactory.

## 6.3 An Illustration Based on the Potchefstroom Accident

This illustration is selected as an example of an accident that might feature in a hazard analyst's portfolio. The conditions taken are those that prevailed in an ammonia accident at Potchefstroom, South Africa in 1973 (Lonsdale, 1975). The windspeed at the time of the accident was uncertain and the workbook estimates are prepared for two windspeeds covering the likely range, illustrating the ease with which this sensitivity check can be carried out. The concentration distribution was not, of course, known but information on fatalities is available. The estimates of concentration and duration can therefore be compared with expectations of fatalities based on published toxicity data, although this is not the prime purpose of the exercise.

In the accident, 38 tons of pressurised liquefied ammonia escaped following the catastrophic failure of a storage vessel. The accident resulted in the deaths of 18 people. Lonsdale (1975) states: 'Although the air was apparently still at the time of the incident, within a few minutes a slight breeze arose and the gas cloud began moving toward a nearby township'. We shall perform our estimates for windspeeds of 1 and 2 m/s at 10 m height. Lonsdale gives the air temperature as about 19°C and relative humidity as 30 to 35%.

The initial conditions for the dispersion calculation can be found using the assumption that the vigorous expansion of the cloud causes air entrainment sufficient to evaporate all the liquefied ammonia giving an ammonia-air mixture at the boiling point of ammonia of -33°C. A simple heat balance, assuming for convenience that the air is dry, gives the mass ratio of air to ammonia in the final mixture as 26.4. This calculation uses the specific heat of dry air of 996 J/kg°C and the latent heat of vapourisation of ammonia of $1.37.10^6$ J/kg. The volume ratio of air to ammonia is found as 15.4 corresponding to an initial concentration of ammonia in air of 0.061 and an initial density ($\rho_o$) of the mixture of 1.434 kg/m$^3$. The total volume of the cloud ($Q_o$) is $7.25.10^4$m so that $Q_o^{\frac{1}{3}} = 41.7$ m. The stability parameter $(\frac{g_o Q_o^{\frac{1}{3}}}{U^2_{ref}})^{\frac{1}{2}}$ is therefore 8.8 for $U_{ref} = 1$ m/s and 4.4 for $U_{ref} = 2$ m/s. The distances downwind corresponding to the concentrations in Figure 11 are given in Table 9 together with the absolute concentrations obtained by multiplying by the

source concentration.

| Workbook Concentration | Absolute Concentration ppm | $U_{ref}$ = 1m/s $\frac{x}{Q_o^{\frac{1}{3}}}$ | x,m | $U_{ref}$ = 2m/s $\frac{x}{Q_o^{\frac{1}{3}}}$ | x,m |
|---|---|---|---|---|---|
| 0.10 | 6100 | 8 | 333 | 8 | 333 |
| 0.05 | 3050 | 10 | 417 | 10 | 417 |
| 0.02 | 1220 | 13 | 542 | 17 | 709 |
| 0.01 | 610 | 20 | 834 | 27 | 1125 |
| 0.005 | 305 | 28 | 1170 | 37 | 1540 |
| 0.002 | 122 | 40 | 1670 | 50 | 2090 |
| 0.001 | 61 | 60 | 2500 | 76 | 3170 |

Table 9: Concentration Distributions for Potchefstroom Accident

The concentrations in Table 9 are the maximum values of the short-term average concentrations and are therefore the short-term average concentrations at the time of arrival of the cloud at the given distances. In order to assess the toxicity effect, we need to know the concentration-time history at the point of interest. The manner in which this history is derived has been explained in Section 3.8.2 and we shall illustrate it for the first distance in the above table i.e. x = 333 m. (Note that the workbook correlations cannot give information on concentrations at positions nearer than this to the release point). In addition to the concentration at the arrival time, we also need to know the duration of the cloud presence at the point and (as a minimum) the concentration at the departure time.

The arrival and departure times, $t_a$ and $t_d$, are obtained as the roots of the equation (see Section 3.8.2)

$$(x - 0.4U_{ref}t)^2 = R_o^2 + 1.2(g_o{}'Q_o)^{\frac{1}{2}}t.$$

For $U_{ref}$ = 1 m/s, we find $t_a$ = 163s, $t_d$ = 4255s and hence a duration of 4092s. For U = 2 m/s, we find $t_a$ = 124s, $t_d$ = 1396s and hence a duration of 1272s.

The concentration at the departure time at x = 333 m is equal to the concentration obtained from the correlation for the distance reached by the front of the cloud at this time. This distance is obtained from the equation for the arrival time (see Section 3.8.2) i.e.

$$x = 0.4U_{ref}t_a + [R_o^2 + 1.2(g_o{}'Q_o)^{\frac{1}{2}}t_a]^{\frac{1}{2}}$$

where $t_a$ is set equal to the departure time at x = 333 m. The resulting distances are obtained as 3072 m for $U_{ref}$ = 1 m/s and 1902 m for $U_{ref}$ = 2 m/s. From

the correlation (or by inspection of Table 9), we find that the concentration is less than 0.001 (absolute concentration less than 61 ppm) for $U = 1$ m/s and is just over 0.002 (absolute concentration just over 122 ppm) for $U = 2$ m/s.

Thus in summary, the concentration at x = 333 m decreases from 6100 ppm to less than 61 ppm over a period of 4092s (68 mins) when $U_{ref} = 1$ m/s and decreases from 6100 ppm to just over 120 ppm over a period of 1272s (21 mins) when $U_{ref} = 2$ m/s.

The Potchefstroom accident did not result in any fatalities beyond x = 220 m and the remaining question is whether the results of the above calculations are consistent with this evidence, even making the worst-case assumption that an exposed individual would have remained at a fixed position for the full duration of cloud passage.

Information on the toxicity of ammonia is somewhat uncertain as is clear from a number of proposed relationships that are collected together in Figure 21 (from Engelhardt and Holliday, 1985). This plots the steady concentration that would result in a probability of death of 50% against the exposure time. The results of the calculations are superimposed on the figure as the range of concentration over the durations calculated for each assumed windspeed. No greater sophistication is needed to warrant the conclusion that the absence of fatalities is broadly consistent with the calculations viewed against all the proposed relationships. It may be noted that the uncertainty in knowledge of toxicity effects illustrated in Figure 21 means that no great demand is placed on the accuracy of the concentration-exposure time estimates.

## 6.4 Application of the Recommendation for Transient Releases

In Section 3.6 it was recommended that concentration estimates for a transient release should be the lower (but still conservative) of the estimates provided by continuous and instantaneous formulations. It may be useful to provide a specific illustration of how this recommendation should be applied.

In practice, the need to perform the estimates is likely to arise where the duration of the release is uncertain but the total quantity released can be specified with some confidence. This would be the case where a vessel suffers a failure which might range from the catastrophic (giving an instantaneous release) to a leak (giving a continuous release). Within a part of this range, the failure will result in what we have termed a 'transient' release. The total quantity released will be known and will be the contents of the vessel (or some lower estimate prepared using the guidance cited in Section 2.4). The problem becomes that of estimating the sensitivity of the concentration at any location of interest to the possible range of the release duration, $T_o$, for a release of this total quantity.

We take the following values of the release parameters for illustration:

Total quantity released 2000m$^3$ of gas

Reference windspeed ($U_{ref}$) 2m/s

Distance from release position (x) 200m
Initial reduced gravity ($g_o'$) 10m/s$^2$

For an instantaneous release, the workbook parameters are $\left(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2}\right)^{\frac{1}{2}} = 5.6$ and $\frac{x}{Q_o^{\frac{1}{3}}} = 15.9$ so that $C_m/C_o$ is obtained as 0.04 from Figure 11. As discussed in Section 3.6, one approach might be to accept this estimate irrespective of the actual release duration $T_o$ but this will inevitably result in unduly conservative estimates at large values of $T_o$.

For a continuous release, we proceed by estimating the concentration as a function of $T_o$, using a release rate, $q_o$, of $2000/T_o$ m$^3$/s and the correlation in Figure 8. At low values of $T_o$ this method will provide unduly conservative estimates of the concentration.

The results obtained from the above calculations are plotted in Figure 22. Also shown are the limits for an instantaneous and continuous release according to the recommendations in Section 3.6, i.e.

For an instantaneous release $\frac{U_{ref} T_o}{x} < 0.6$ or $T_o < 60$s

For a continuous release $\frac{U_{ref} T_o}{x} > 2.5$ or $T_o > 250$s

The recommended estimate is identified in the figure as the lower of the estimates for an instantaneous or a continuous release for any release duration. The actual variation of concentration with duration will follow a smooth curve somewhat similar to that indicated in the figure.

# Chapter 7

# Limitations of the Workbook and Identification of Research Needs

## 7.1 Introduction

It is difficult to separate out limitations that are peculiar to this Workbook from those that apply to all models at the present time. This chapter, in considering the limitations of the Workbook, is also used to provide pointers for future research priorities. Where it is possible for specific limitations to be overcome by other methods currently available, this is noted.

Substantial progress has been made in recent years towards resolving the many issues identified in the opening chapters. The first priority was for reliable data with which to validate and improve mathematical and physical models of dispersion. As a result of several large-scale field trials, notably those at China Lake, Maplin Sands and Thorney Island, there now exists a very extensive database on the basic case of dispersion of dense gases over a flat surface. The main priorities for further research are in peripheral topics, many of which have already been mentioned in the course of the Workbook. In keeping with the separation into formation and dispersion phases that we have adopted, the discussion of research priorities will be similarly separated.

## 7.2 Formation Phase

Theoretical analysis of pool spreading has made good progress but there is surprisingly little supporting experimental information available on this basic fluid mechanics problem. The paper by Webber and Brighton (1984) highlights the variety of phenomena predicted by theory and the scope for physically instructive experimentation.

There is an urgent need for experimental information on sudden releases of pressurised liquefied gases and especially for fundamental measurements of the evolution of the expanding two-phase cloud. Useful laboratory-scale work has been carried out by Bettis and Moodie (1987) but possible scaling effects suggested by

Jagger and Kaiser (1981), require investigation at large scale. This is a problem of considerable experimental difficulty and rapid progress cannot be expected. Of particular interest is the case where a jet emission occurs at a height above ground level. Laboratory experiments on the bending over of a dense gas jet by the wind and its return to ground level, as illustrated in Figure 14, have recently been reported by Xiao-yun et al (1986). Good agreement with the predictions of the model of Ooms et al (1974) was found. However, the measurements did not extend to the spreading of the jet over the ground and its subsequent dispersion by the wind. There is also a need for similar experiments on two-phase jets. There is a large range of possible experimental configurations in terms of jet inclination, initial conditions, atmospheric conditions and the scale of release, and much work remains to be done.

A feature of experimental work on dense gas dispersion is that each experimental programme adopts its own design of source geometry. Systematic differences between the results of different experiments have been observed in the course of our analysis and it is suspected that source effects may be the cause. Although these effects might be expected to be unimportant at the distances required for safe dispersion of highly toxic gases, nonetheless they may be important in some circumstances (and they certainly are important for flammable gases where the dilution to a safe concentration is of the order of $10^2$). For example, there are puzzling and substantial differences between behaviour as observed in the continuous release experiments conducted during the Thorney Island programme and in the ammonia release experiments reported by Koopman et al (1984). In the former, the release was in the form of a gas with negligible initial momentum and in the latter as a flashing two-phase jet with high momentum. Recent wind tunnel experiments by Krogstad and Pettersen (1986) showed that source effects had a strong influence on plume behaviour. In the case of fixed volume releases, there has been no systematic investigation of initial aspect ratio effects, a subject on which we have been able to give little guidance. There is an urgent need for research to clarify the influence of source conditions.

In practice, the source will in many cases be surrounded by buildings, pipe racks, etc. The effects of release into a building wake have been extensively studied for passive releases but little comparable work has been done for dense gases. Brighton (1986) has speculated on how the approach to the passive case might be adapted to dense gases, whilst the topic is discussed in the review by Britter (1982). Some of the results of experiments in which a building is located near the source (Krogstad and Pettersen, 1986, McQuaid and Roebuck, 1985) will be relevant.

A release of dense gas may occur within a building, for example within a process building in a chemical plant. The gas is then released to the atmosphere through openings in the building. The effect of this source configuration has been considered by Brighton (1986). The application of a 3D model to dispersion in the presence of an obstruction has been published by Deaves (1985). However, there is a need for simple guidance on plausible assumptions for the source conditions to use with the simpler types of dispersion model. It is of course desirable that

this guidance should be supported by experimental evidence.

## 7.3 Workbook Correlations

The workbook correlations are intended to provide both a framework for the comparison of various experimental and modelling activities in addition to their direct use for estimating dispersion. It is hoped that further data will become available to confirm or refine the correlations presented. With this in mind, we present the following observations derived from our very extensive examination of the existing data.

### 7.3.1 The correlations for a continuous release

The correlations provided are an assessment of laboratory and field data from various sources. Most sources provide data for only a limited range of the independent parameters and, as a result, the correlations have been pieced together from different experimental sets. An assessment of the generality of the correlations would be assisted by a data set, preferably in the field, which covered the complete practical range of the independent variables. The wide variation between the results from individual researchers obviously casts some doubt on the correlations derived from these results. The variation between researchers requires explanation and a consequent screening of the results.

There is some difficulty with the correlation towards the passive limit. Much of the available data indicates that the correlations should have maxima. However, the results from Stretch (1986) and Britter and Snyder (1988) show little evidence of pronounced maxima. The full-scale results produce pronounced maxima (determined by the Maplin Sands results) between the Thorney Island results and a passive estimate from conventional correlations. The method of analysis of the Maplin Sands experiments, see Puttock et al (1982), with a limited array of measuring stations may have led to an overestimate of the maximum of the long time average concentration in the plume. However, this is unlikely to produce, of itself, the magnitude of the maxima exhibited by the correlations. As a consequence, and erring on the side of conservatism, the correlations have been drawn such that the values at the passive limit are a little higher than estimates from conventional passive correlations.

### 7.3.2 The correlations for an instantaneous release

The principal limitation of these correlations is that they have been deduced from experiments with near-unity aspect ratio releases. There is little information available for instantaneous low aspect ratio sources.

Puttock and Colenbrander (1985) compared the results of Thorney Island trial 7, which had an aspect ratio near unity, with those of Maplin Sands 63, which was an instantaneous propane spill with small aspect ratio. These had quite similar concentrations at 100m from the source — in terms of absolute concentration,

concentration variation with height and arrival and departure times. This may be fortuitous as different physical mechanisms of dilution and transport are relevant in the two cases, see Britter (1988). For want of extensive information on other aspect ratio releases there is little alternative other than to assume that the correlations apply to any aspect ratio.

A further limitation that must be borne in mind is that the release mode is not that to be expected in many accidental releases, in which the initial cloud will acquire momentum in the wind direction as a result of initial mixing due to source momentum. This was absent in the Thorney Island experiments and substantial dilution of the cloud was effected by a mechanism discussed in some detail by Rottman et al (1985). An alternative set of correlations has been provided (see Appendix E) which is more relevant when source momentum produces substantial initial cloud dilution. However, there is no specific validation of these correlations.

## 7.4 Concentration Distribution Within the Cloud or Plume

The workbook has provided no information concerning the vertical and horizontal profiles of concentration within the cloud or plume and has, by neglect, implied that the concentrations are uniform. This was long thought to be a reasonable assumption with the horizontal gravity spreading ensuring that horizontal concentration gradients were large only near the edge of the cloud or plume. The variation of concentration in the vertical was also thought to be fairly uniform within the cloud and topped with sharp density discontinuity.

The Thorney Island experiments have shown that the former assumption is a reasonable one, particularly when the cloud or plume is dominated by the density driven flow close to the source. Further from the source the edges become more diffuse. Britter and Snyder (1987) have suggested that $(g_m{}'h)^{\frac{1}{2}} \leq u_*$ is an approximate criterion for the development of diffuse edges in a plume where $g_m{}'$ is the reduced gravity corresponding to the maximum concentration and $h$ is a measure of the plume depth.

A similar criterion might be considered for an instantaneous release. However, several divergent features of the two release modes make the problem substantially more difficult. The diffuse edges of the plume are partly the result of a meandering plume and also true plume dilution.

For the instantaneous release the meandering element is equivalent to selecting members of an ensemble. Thus some consideration must be given as to whether variations in position between members of an ensemble are relevant (probably not) or whether the variation that matters is that between members of an ensemble when their centres of mass overlay. However, over-riding these concerns is the importance of the mechanisms of longitudinal dispersion in producing a longitudinal concentration profile for instantaneous releases.

Unfortunately, experiments in the laboratory or field on transient problems are very time-consuming, requiring spatial and temporal information.

It is clear from experiments in the laboratory (Britter and Snyder, 1987) and in the field (Van Ulden, 1987) that the vertical profiles of concentration are not uniform. In passive diffusion models a Gaussian or normal distribution is frequently assumed although a more correct form is thought to be $exp\{-z^n\}$ with $n$ approximately 1.5 ($n = 2$ corresponds to the Gaussian or normal distribution, and $n = \infty$ corresponds to the uniform distribution). The experiments of Britter and Snyder (1987) require an even smaller exponent of unity in regions where the plume density is significant.

This discussion of the vertical profile of concentration is not, directly, of great concern, its principal effect being to change slightly the 'depth' of the plume. There is however, a secondary aspect that can be of consequence. The observations suggest a very rapid change of concentration close to the surface (unlike the Gaussian distribution which has no variation close to the surface) and the specification of the 'ground level concentration' may be quite critical in assessing experimental results. It is probable that much of the scatter in the laboratory and field experiments used in this Workbook results from an uncertainty in specifying the 'ground level concentrations'. Further, for example, if a full scale release produces concentrations at a height of say, 1m, which are half that at ground level, the question arises as to whether the ground level concentrations are in fact relevant to an assessment of the hazard from a toxic gas.

## 7.5 Concentration Fluctuations

The Workbook has provided information for mean and ensemble concentrations with only limited reference to fluctuations about this mean. However, as discussed in Section 2.5, the fluctuations in concentration may be very relevant to the assessment of risk from the release of hazardous materials.

Unfortunately there is still uncertainty about the correct description and quantification of concentration fluctuations for continuous plumes of neutrally buoyant material, quite apart from the influence of surface roughness and atmospheric stability. Consequently the description of concentration fluctuations in dense gas releases, and particularly the transient or instantaneous releases, is very rudimentary.

Hanna and Drivas (1987) provide a recent summary of some relevant studies.

There are however, some aspects of the treatment of dense gases which are different but, possibly, simpler than the corresponding passive release. The partially deterministic nature of the dense gas release is likely to produce smaller fluctuations in concentration than the equivalent passive release. Further the plume or cloud remains adjacent to the surface and it is the concentration near the surface that is particularly of interest. Laboratory work on passive releases e.g., Fackrell and Robins (1982) shows that ground level releases and ground level measurements both lead to reductions in the level of concentration fluctuations.

Broadly the subject considers the determination of a mean or ensemble concentration and the fluctuations or variations about these, together with the probability

density function of the fluctuations. Much of the problem concerns the averaging time over which the concentrations are quantified.

The continuous release is the least complicated problem. For continuous plumes the Workbook has provided information on the long-time mean concentration (assumed to be averaged over 10 minutes at full-scale) together with estimates of the peak of short-time average (of order 1 second at full-scale) concentrations.

The Workbook recommendations might be reinterpreted in terms of the ratio of the intensity of concentration fluctuation $c\prime$ to the mean concentration which has the value between 0.2 and 0.3 for dense plumes. The comparable ratio for passive plumes is the laboratory is about 0.35, Fackrell and Robins (1982). These values refer specifically to ground level concentrations on the plume centreline and they should be compared with the values reported by Hanna (1984) of 1.5 for plume centreline results for a smoke plume released in the atmospheric boundary layer. This difference, although qualitatively expected, is so substantial as to require further attention and explanation.

Hanna (1988) provides a useful formula describing the influence of the averaging time used for the fluctuations on the measured $c\prime$, that is

$$\frac{C\prime(T)}{C\prime(O)} = \{2(\frac{T_I}{T})(1 - \frac{T_I}{T}(1 - exp(-\frac{T}{T_I})))\}^{\frac{1}{2}}$$

where $T_I$ is the integral time scale of the concentration fluctuations, $T$ is the averaging time of the fluctuations, and $C\prime(T)$ and $C\prime(O)$ are the concentration fluctuations measured with averaging time $T$ and $O$ respectively.

For example if, as Hanna (1988) suggests, $T_I$ could be about 10 seconds in the surface layer of the atmospheric boundary layer then the ratio

$$\frac{C\prime(1sec)}{C\prime(o)} = 0.98$$

i.e. a one-second averaging measurement will capture 98% of the fluctuations. With an averaging time of 10 seconds (corresponding to spatial scales of several 10's of metres) the ratio $\frac{C\prime(10s)}{C\prime(O)}$ is reduced to 0.86 and for 100 seconds to 0.42.

Further analysis requires specification of the probability density function of the concentration fluctuations. The consensus (see Hanna and Drivas (1987), is that the p.d.f. for passive, elevated, plumes is non-Gaussian, possibly exponential. This appears to be a good representation of intermittent plumes. This distribution does produce $C\prime/\bar{C}$ equal to unity. It is suggested here that for ground level sources and receptors on the plume centre-line and, particularly, for dense gas dispersion experiments, in which the plume cannot be described as intermittent, that the exponential p.d.f. may not be appropriate and the Gaussian p.d.f. should be reconsidered.

Instantaneous (or transient) releases have a greater importance in chemical accident studies than in conventional pollution problems. This release mode gives rise to the practical difficulty that predictions from all available models average behaviour over an ensemble of releases. The user will be uncertain as to the variability between different realisations of the ensemble and thus of the confidence

bounds he can place on the predictions (or whatever other measure he may use to reflect the non-deterministic nature of the predictions). The topic has been considered by Chatwin (1982), Carn and Chatwin (1985) and Carn(1987) from the point of view of adopting a rigorous probabilistic approach to the problem.

Comprehensive experimental information is lacking although some indication is given in small-scale experiments by Hall et al (1982) that substantial differences (of an order of magnitude) in concentration at a given location can occur for repetitive experiments conducted under the same nominal conditions. Meroney and Lohmeyer (1982) provide data that show rather less variability. The large-scale experiments at Thorney Island also showed rather less variability than the laboratory experiments of Hall et al (1982).

The Workbook has only provided information on instantaneous releases (of unit aspect ratio) and provided a correlation for the ensemble of the maximum of short-time averaged concentrations together with an estimate of the variability about that ensemble average. Assuming a Gaussian distribution of the variability a ratio of $C\prime$ of the ensemble to the mean of the ensemble between 0.1 and 0.15 can be estimated. This is substantially smaller than the results from Hall et all (1982) but not a great deal smaller than the results from Meroney and Lohmeyer (1982), particularly those using the largest release volume and for measurements well removed from the source position.

Of course the variability of the concentration at a fixed point in space is unlikely to be the measure of variability that is actually required. A measure which removes the gross movement of the cloud (equivalent to the meandering component of plume structure) is more appropriate but is not currently available. The variability of this latter measure will, undoubtedly, be less than the variability of the concentration at a fixed point in space.

The data from Meroney and Lohmeyer (1982) also emphasize the important, but hitherto ignored point, that the variability of measurements at a fixed position, particularly close to the source, will be a function of the source size. The smaller the source size (compared to the length scale of turbulence) the more apparent is the gross movement of the cloud and the larger the ratio of the variability to the ensemble mean. In general the source size will have substantially greater effect on the variability about the mean than on the mean itself. A similar statement is applicable to continuous plumes.

For transient releases (particularly instantaneous ones) much of the variability due to the 'meandering' component will be produced by the variation in the velocity felt by the advected cloud. This effect should be considered during the interpretation of experiments when the advection time between source and receptor is small compared with the standard averaging time of the mean velocity, that is 10 minutes in full scale.

The question of variability is part of the general problem of uncertainty in dispersion estimates. This has been the subject of a recent symposium, of which a summary is given by Carson (1986). In general, there is little firm guidance that can yet be given to the user of the Workbook.

Although not directly the subject of this Workbook the user who finds that he

must use a model is well advised to question what are the averaging times used in the model; this is rarely stated specifically.

## 7.6 Advection Speeds

The Workbook has recommended an advection speed for instantaneous releases of 0.4 times the ambient velocity at a height of 10m. This recommendation may be reconsidered in the light of further experimental information that may be forthcoming, though there seems little point in greater refinement here, given the essential simplicity of the description. Appreciation of the mechanism of longitudinal dispersion (due to the variation of the mean velocity with height) and its appropriate incorporation is probably of more consequence.

## 7.7 Buildings and Building Complexes

The effect of obstructions away from the vicinity of the source is a clear research priority. The emphasis needs to be on the development of simple models, probably limited to some standard types of obstruction. However, it seems likely that for some purposes (e.g., building complexes) it will be necessary to resort to physical modelling. Physical modelling techniques for the study of the dispersion of dense gases are still being developed. Appendix F addresses the general approach, applicability and limitations of physical modelling. The recent availability of large-scale data will assist the establishment of scaling behaviour and comparative studies have already started (e.g., Davies and Inman, 1987).

## 7.8 Slopes, Valleys and Topographic Features

Under light wind conditions, dense gas flows are very sensitive to variations in height of the underlying surface. Given the diversity of problems that could be met it is unlikely that simple correlations will be available that include topographic effects. Physical modelling is the most obvious technique to apply but there is a limit to the scale reduction that will provide a correct model. As topographic features are likely to extend over a larger region than buildings etc. the correct physical modelling of the influences of topographic features will be more restrictive than for a study of the influences of buildings etc.

# Appendix A

# Criteria for Effectively Passive Behaviour

## A.1 Continuous Releases

For the continuous release from an area source of typical horizontal dimension $D$, Britter (1980) proposed that the plume was passive from the source provided

$$(\frac{g_o' q_o}{U_{ref}^3})/D < 10^{-3}$$

A further consideration of his data suggests that the criterion can be relaxed to

$$(\frac{g_o' q_o}{U_{ref}^3})/D < 3 \times 10^{-3}$$

or

$$U_{ref}/(\frac{g_o' q_o}{D})^{\frac{1}{3}} > 7$$

The definition of the reference velocity was particular to the experiment of Britter (1980) and its extension to the atmospheric boundary layer is uncertain. However, the criterion may be rewritten as

$$u_*/(\frac{g_o' q_o}{D})^{\frac{1}{3}} > 0.35$$

which may be reinterpreted as

$$U_{ref}/(\frac{g_o' q_o}{D})^{\frac{1}{3}} > 6$$

where the conversion has been made for a neutrally stratified atmospheric boundary layer with a roughness length $z_o = 1$ cm.

The flume data of Cheah et al (1984) and wind tunnel results of Stretch (1986), both using rough surface boundary layers, support this criterion, again with some uncertainty in interpreting $U_{ref}$.

Experiments with a two-dimensional line source of dense fluid by McQuaid (1976) and Stretch (1986) produce a similar criterion for the neglect of density effects on vertical turbulent diffusion.

The physical model studies performed by Meroney and Neff (1982) of the China Lake field trials do not contradict this criterion: Run 20, which appeared passive, had

$$U_{ref}/(\frac{g_o{}'q_o}{D})^{\frac{1}{3}} \simeq 8$$

or

$$u_*/(\frac{g_o{}'q_o}{D})^{\frac{1}{3}} \simeq 0.65$$

Thus we recommend the following criterion for demarcating passive from active plumes when the source momentum is unimportant

$$U_{ref}/(\frac{g_o{}'q_o}{D})^{\frac{1}{3}} > 6$$

or

$$((\frac{g_o{}'q_o}{U_{ref}^3})/D)^{\frac{1}{3}} \leq 0.15$$

where $U_{ref}$ is measured at 10m height or

$$u_*/(\frac{g_o{}'q_o}{D})^{\frac{1}{3}} > 0.35$$

## A.2 Instantaneous Releases

We have argued that $(g_o{}'Q_o{}^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}}$ and the initial geometry (aspect ratio) characterises the subsequent flow completely. For what values of $(g_o{}'Q_o{}^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}}$ might the flow be treated as passive from the source?

The following points are made with reference to an initial aspect ratio of near unity, although some variation, $0.7 \rightarrow 1.3$, say, might not lead to significantly different conclusions.

(i) When $U_{ref} >> (g_o{}'Q_o{}^{\frac{1}{3}})^{\frac{1}{2}}$ e.g. $(g_o{}'Q_o{}^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}} < 0.1$, the initial buoyancy driven flow is very small compared with the advecting flow (the wind speed $U_{ref}$).

(ii) Puttock et al (1982) put $(g_o{}'Q_o{}^{\frac{1}{3}}/u_*^2) < 10$ as a criterion for effectively passive behaviour. That is $(g_o{}'Q_o{}^{\frac{1}{3}}/u_*^2)^{\frac{1}{2}} < 3$, or $(g_o{}'Q_o{}^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}} < 0.2$, where $U_{ref}$ refers to the wind speed at 10m height and a typical value of $u_*/U_{ref}$ has been used.

(iii) Rottman et al (1985) argue that a cloud acceleration time is

$$t_a = \frac{5(\frac{1}{2}Q_o^{\frac{1}{3}}}{U_{ref}}$$

and the time taken for the cloud to collapse due to buoyancy is

$$t_b = \frac{5(\frac{1}{2}Q_o^{\frac{1}{3}})}{(g_o' Q_o^{\frac{1}{3}})^{\frac{1}{2}}}$$

If we argue that effectively passive behaviour occurs when $t_b >> t_a$, say $t_b > 5t_a$, then

$$(g_o' Q_o^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}} < 0.2.$$

(iv) Figure 19 of Meroney and Lohmeyer (1982) gives an indication of maximum upwind and cross-wind extent of the release near the source. These results show no lateral spreading near the source when

$(g_o' Q_o^{\frac{1}{3}}/u_*^2)^{\frac{1}{2}} < 10$, which may be rearranged to give

$(g_o' Q_o^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}} < 0.5.$

However, we note from Britter (1980) for continuous releases that there is significant difference in downstream development between a flow with no lateral spreading at the source and a flow with no buoyancy effects.

(v) Calculations by Rottman and Simpson (1984) on the collapse of a two-dimensional cross-wind cloud in the shape of a semi-cylinder of radius $h_o$ with its diameter on the ground plane, show that buoyancy forces are irrelevant when $(g_o' h_o/U_o^2) < 1$, where $U_o$ is a *uniform* wind velocity.

A smaller critical value of the parameter is required to ensure that there is no lateral spreading for the comparable three dimensional problem (with $Q_o^{\frac{1}{3}}$ replacing $h_o$).

(vi) Unpublished visualisation experiments by Britter suggest that the relevant criterion for the neglect of density effects is $(g_o' Q_o^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}} < 0.3$.

(vii) In analysing a field trial from Porton Down, Hall et al (1982) state that Run 21, for which $(g_o' Q_o^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}} = 0.68$, showed significant dense gas effects both in the field and in the subsequent physical model.

In summary then we recommend that the flow and dispersion will be effectively independent of buoyancy effects when

$$(g_o' Q_o^{\frac{1}{3}}/U_{ref}^2)^{\frac{1}{2}} < 0.2.$$

or

$$(g_o' Q_o^{\frac{1}{3}} / u_*^2)^{\frac{1}{2}} < 3,$$

where $U_{ref}$ is the wind velocity at 10m height.

This result is for instantaneous releases of near-unit aspect ratio. There appears to be little data available for a similar criterion for instantaneous releases with very small aspect ratio.

# Appendix B

# Criteria for Distinguishing Instantaneous and Continuous Releases

Hall (1977)considered variable durations of release, $T_o$, at constant release rates. For the restricted parameter range of flows and considering specifically the distance to the 0.02 concentration contour he found that $\frac{u_* T_o}{x} > 1$ provided an effectively continuous release. That is, the concentration at the position $x$ downstream was not different from that for $\frac{u_* T_o}{x} \to \infty$ at the same constant release rate.

The data from the Thorney Island continuous release trials clearly show a progression from continuous conditions near the source, where the concentration was constant for a substantial period, to instantaneous conditions in the far field, where the concentration rose to a maximum and then decreased. The data thus allow judgement, admittedly speculative, to be made of the point at which a constant concentration was just discernible i.e., the conditions were 'marginally continuous'. This interpretation of the data suggests that a marginally continuous plume results when

$$\frac{U_{ref} T_o}{x} \geq 2.5$$

or

$$\frac{u_* T_o}{x} \geq 0.15$$

In accordance with the view that averaging time is unimportant in defining the mean concentration in a steady continuous plume, we accept the specification of 'marginally' continuous as conforming to 'effectively' continuous.

Analysis of the Burro and Coyote trials by Morgan et al (1984) led to the conjecture that the time over which effectively continuous behaviour is observed at a distance $x$ could be given by

$$T = T_o - \frac{Cx}{U_{ref}}$$

where $C$ is a constant with the range 0.25 — 0.5.

This leads to a marginally continuous release, that is $T = 0$, when

$$\frac{U_{ref}T_o}{x} > 0.25 - 0.5$$

This is in distinct disagreement with the results from the Thorney Island tests and the wind tunnel experiments.

The Burro and Coyote trials were with liquefied natural gas, and as a result, many neglected processes (e.g. surface heat transfer) may have complicated the interpretation. In addition many of the concentration-time plots within Morgan et al (1984) do not support such a low value of $C$.

The laboratory data of Hall (1977) may have suffered from the general difficulties associated with the physical modelling of dense gas dispersion (see Appendix F).

It is also likely that a criterion for the demarcation of effectively continuous and effectively instantaneous releases will need to account for the influence of buoyancy.

This area of interest remains uncertain but with the limited data available we recommend, weighting the Thorney Island data more strongly than the laboratory data, that is

$$\frac{u_*T_o}{x} > 0.15$$

or

$$\frac{U_{ref}T_o}{x} > 2.5$$

then an effectively continuous plume may be assumed.

An instantaneous treatment will be applicable for some considerably smaller value of $\frac{u_*T_o}{x}$ or $\frac{U_{ref}T_o}{x}$. In the absence of experimental data, it is suggested that this numerical value should be $\frac{1}{4}$ of that above which the continuous treatment is applicable. It may be noted that such an approach is consistent with the view that a release is instantaneous if the release time is small compared with the time taken to reach the position of interest. Thus we recommend

$$\frac{U_{ref}T_o}{x} < 0.6$$

or

$$\frac{u_*T_o}{x} < 0.04$$

Finally, the criterion provided by Puttock et al (1982) that

$$T_o U_{ref}^2 / (\frac{g_o' Q_o}{\pi})^{\frac{1}{2}}$$

should be less than 10 for the release to be treated as instantaneous is difficult to interpret in our terms as it omits reference to the position, $x$, under consideration.

# Appendix C

# Correlations for Continuous Releases

## C.1 Field Trials

In this section we consider only large-scale field trials which are

1. continuous releases;
2. with no or negligible heat transfer;
3. with no terrain influence;
4. with no or negligible forced mixing with the ambient at the source; and
5. with no chemical reaction or phase change.

### C.1.1 Thorney Island Trials

Three nominally continuous releases (release times of approximately 400 seconds) were included in the program organised by the U.K. Health and Safety Executive at Thorney Island (McQuaid, 1987).

The releases were at a rate of about $q_o = 4m^3/s$, density ratios $\rho_o/\rho_a$ near 2 and reference wind speeds at 10 m height of 1.5 to 3.2 m/s. The experimental conditions are summarised below.

| RUN | 45 | 46 | 47 |
|---|---|---|---|
| $q_o m^3/s$ | 4.33 | 4.33 | 4.17 |
| $U_{ref}$ m/s | 2.1 | 3.2 | 1.5 |
| $\rho_o/\rho_a$ | 2.0 | 2.0 | 2.05 |
| $(\frac{g_o{l'}^2 q_o}{U_{ref}^5})^{\frac{1}{5}}$ | 1.59 | 1.04 | 2.25 |
| Inferred Pasquill Stability | E/F | D | F |

Quantitative data and visual observations show wide, shallow plumes. Time traces of the concentration with a 0.6 second averaging are available. However the long-time averages (of about 100 seconds) at a nominal-ground level position of z = 0.4 m have been used to estimate distances to specific concentrations. These have been plotted in Figures 23a to f.

Although it is inappropriate here to attempt any extensive analysis of data the following observations are immediately relevant:-

(i) Considering only data at the nominal ground-level position, z = 0.4 m, and near the plume centreline, the maximum of the 0.6 second averaged data over the duration of the experiment is only about 1.4 times the long-time average. This suggests a quite small ratio of root-mean-square concentration fluctuations to mean concentration near the ground. This result is indicative of limited penetration of the plume by external turbulence. At greater elevations e.g. z = 1.4 m, the ratio of the maximum of the short-time averaged to the long-time averaged concentration is substantially greater (Mercer and Davies, 1987). However, the long-time averaged concentration at z = 1.4 m is much smaller than that at z = 0.4 m. At sensor positions removed from the centreline and near the upper edge of the plume the concentration maxima are far more sensitive to the averaging time.

(ii) The nominally continuous releases were, in fact, over about 400 seconds. Sensors close to the release point show concentration histories that rise from zero, maintain an approximately constant level for times comparable to the release time and then reduce to small values. The concentration history for sensors further from the source have a reduced (in time) and difficult to define 'constant level'. At positions far downwind a transient source is more appropriate than an effectively continuous one and a criterion for defining the onset of this stage is given in Appendix B. The data used in the correlations are taken from the plume development within the continuous regime as therein defined.

(iii) Further to (ii) we note that a long time is required for the development of the concentration pattern. For example, using run 045, if an advection time is defined in terms of the time of arrival of the maximum concentration, then an advection velocity of 0.15 to 0.2 times $U_{ref}$ is observed. This corresponds to 0.25 to 0.3 of $U_1$ (the mean velocity at the more appropriate height of 1 m). The first traces of released material travel considerably faster (at about $U_1$ m/s). Of course, an advection velocity characterising the bulk transport of material will fall between these two limits.

(iv) Analysis of run 045 produces a plume which, at x = 220 m, is 150 m wide, about 3m deep and a bulk advection velocity of about 1 m/s i.e. 0.4 $U_{ref}$, or 0.65 $U_1$.

Using

$$L_H = C\left(\frac{g_o' q_o}{U_{ref}^3}\right)^{\frac{1}{3}} x^{\frac{2}{3}}$$

produces a coefficient C = 2.7. If $U_{ref}$ is replaced by $U_1$, then C = 1.8.

### C.1.2 Maplin Sands Trials

Several continuous spills of liquid propane were made on to a calm sea surface and the intent was to have no vertical momentum at the source (Puttock et al, 1982).

Concentration measurements were based on a 3 second moving average. Changing to a 0.3 second moving average increases the maxima by 7% while a 10 second moving average reduces the maxima by 3%. The 3 second moving average data from the lowest level sensors (0.6-0.9m) were used to estimate distances from the source to specific maximum concentrations. The use of sensors at about 1.3 m would not change results suggesting that the lowest level sensor is also a good estimate of the 'ground-level' concentrations.

Some surface heat transfer to the cloud is apparent but it is unlikely that the results were significantly affected. Volume flow rates of gaseous propane were between 10 and 25 $m^3/s$ in winds (at 10 m height) between 4 and 8 m/s. The density of gaseous propane at $15°C$ has been used to determine these fluxes. This is more appropriate for the concentrations of interest than the source volume flux at the boiling point of propane. The data are included in Figures 23a to e.

### C.1.3 HSE $CO_2$ Trials

Data from the HSE tests with $CO_2$ (Moodie, 1985) are included on the graph for 0.02 concentration (Figure 23c) but the design of the experiment was such that the initial plume dilution at the source was probably considerable.

### C.1.4 Lyme Bay Chlorine Trials

These trials were carried out at sea and each trial involved the release of up to 8 tonnes of chlorine over a period up to 30 minutes. The plume was tracked by four submarines equipped with dosage sensors. The trials, which were carried out in 1927, have been described by Wheatley et al (1988). Unfortunately, little usable data in the form required by the workbook were obtained from these trials. Further consideration, after the workbook correlations had been derived, showed that useful insight could be obtained from the trials' data. They have therefore been adopted for ex-post evaluation, as described in Section 6.2.4.

### C.1.5 The Battelle Correlation

A series of spills of liquified natural gas (LNG) into a diked area was carried out by Duffy et al (1974). The source strength increased rapidly as the LNG spread over the dike floor, then remained constant for about one minute before decreasing rapidly as the dike floor cooled. Continuous records of concentration was obtained at locations up to 293 m from the dike. The correlation of results by Duffy et al

has been reworked, after several assumptions, by Meroney (1982) into a suitable form for comparison:-

$$\frac{CU_{ref}l_b^2}{q_o} = 130(\frac{x}{l_b})^2$$

This was obtained for the downwind distance of a 0.05 concentration contour for LNG which is equivalent (see Section 5.5) to a 0.02 concentration for an isothermal release, i.e.

$$\frac{x_2}{(\frac{q_o}{U_{ref}})^{\frac{1}{2}}} \simeq 51$$

and this has been included in Figure 23c.

### C.1.6 LNG Trials (Lawrence Livermore Laboratory)

Further large scale experiments are available with the continuous release LNG experiments reported by Lawrence Livermore Laboratory in various papers. Heat transfer to the gas plume from the underlying surface would be expected in these experiments. However, the heat transfer will be markedly less than that for a release over a liquid surface and, as these experiments have been well documented, we have included the results in our analysis.

Results from the Burro series in Ermak et al (1982) are based on 10 second averages. Data for Burro 3, 7, 8 and 9 have been included on the graph for 0.02 concentration (Fig. 23c) where again a 0.05 LNG concentration is taken to correspond to a 0.02 concentration for an isothermal release (see Section 5.5).

Data for some of the Coyote series trials are also included in Figure 23c.

These data have been plotted with $U_{ref}$ obtained at a reference height of 10 m. Furthermore it is unlikely that the releases were of sufficient duration to ensure that the measurements were for an 'effectively continuous' source. The transient nature of the release will mean that the measured concentrations are reduced below those for an effectively continuous release.

Morgan et al (1984) use a pragmatic approach in analysing the Burro and Coyote trials by correlating the distance to the 0.05 concentration contour (or the equivalent 0.02 for an isothermal release) with source flow rate, wind speed at 2 m height and a measure of atmospheric stability. The variable $(g_o l^2 q_o)^{\frac{1}{5}}/U_2$ varies from about 0.4 to 1 except Burro 8 for which the parameter is 1.9.

Morgan et al put $x_2 = Aq_o{}^{\alpha}U_2{}^{\beta}\phi_2{}^{\gamma}$ where $x_2$ is the distance to the 0.02 concentration contour and $\phi_2$ is a measure of atmospheric stability. $q_o$ varies from 11.3 $m^3$/min to 18.4 $m^3$/min (of liquid), $U_2$ from 1.8 to 9.7 m/s, and $\phi_2$ from 0.68 to 1.61.

All data provide $\alpha = 0.07 \pm 0.22$

$\beta = -0.21 \pm 0.09$

and $\gamma = 0.57 \pm 0.18$

Application of a numerical model (SLAB) to the conditions of the Burro and Coyote trials provides

Application of a numerical model (SLAB) to the conditions of the Burro and Coyote trials provides

$$\alpha = 0.33$$
$$\beta = 0.2$$
and $$\beta = 0.6$$

Putting aside the dependence on atmospheric stability $\phi_2$ and seeking a correlation between $x_2/(\frac{q_o}{U_{ref}})^{\frac{1}{2}}$ and $\{(g_o{'}^2 q_o)^{\frac{1}{5}}/U_{ref}\}^m$ leads to an exponent m between -0.2 and -3.3 based on the field experiments and between -0.7 and -0.85 based on the model results. Direct plotting of the data on Figure 23c, ignoring any dependence on atmospheric stability, produces encouraging collapse of the data consistent with a small negative exponent. However, all the data fall within the small range $x_2/(\frac{q_o}{U_{ref}})^{\frac{1}{2}} = 75 \pm 15$, that is an exponent of zero. The smaller non-dimensional distances observed in the Burro and Coyote series LNG experiments than for the Thorney Island and Maplin Sands tests may be a result of more significant heat transfer effects in the LNG tests. Morgan (1984), using a model simulation of Burro 9, found a 60% increase in non-dimensional distance when heat transfer was removed from the model.

## C.2 Laboratory Studies

Extensive laboratory investigations into the dispersion of dense gases have been undertaken by

1. R. N. Meroney and colleagues at Colorado State University
2. D. J. Hall and colleagues at the Warren Spring Laboratory.

Appendix F summarises the requirements for adequate physical modelling of the dispersion of dense gases. In essence laboratory experiments are at different Reynolds numbers (non-dimensional viscosity) and Peclet numbers (non-dimensional mass diffusivity) to the full-scale situation they are intended to simulate. The importance of not maintaining the Reynolds and Peclet number is poorly understood (Puttock, 1985).

The 1982 report by Neff and Meroney is an extensive study on the continuous release of dense gases. Plumes with source specific gravities of 1.38, 2.59 and 4.18 were studied with various source flow rates and reference velocities. A combination of vortex generators, fence and roughness elements were used to model a boundary layer with a roughness length $z_o$ of $10^{-2}$ cm. The reference velocity $U_H$ was measured at a height of 2.1 cm. The roughness elements were placed over the first 6 m of the tunnel. A 0.15 m diameter source, flush with the surface was placed 3 m downstream from the end of the roughness elements.

All the data may be presented to a fair degree of accuracy as one correlation which may be written as

where $x_c$ is the downstream distance to the concentration C. The correlation is from data over the range

$$0.6 \leq (\frac{g_o{}'^2 q_o}{U_H^5})^{\frac{1}{5}} \leq 2.7$$

Limited data are available in Meroney and Neff (1982) for 0.05 and 0.1 concentration contours at smaller values of $(\frac{g_o{}'^2 q_o}{U_H^5})^{\frac{1}{5}}$ and these are included in Figures 24a and b.

Earlier data from Meroney et al(1977) are also included in Figures 24a to f.

Data are also presented by Neff and Meroney (1981) for a passive release with $g_o{}' = 0$ and these are plotted on the axis for $(\frac{g_o{}'^2 q_o}{U_H^5})^{\frac{1}{5}} = 0.1$ in Figures 24a to f.

The importance of molecular diffusion in diluting the plume when the turbulence is weak and the density stratification is strong has only recently been recognised. It is now thought that some of the experiments in laboratory wind tunnels may have been influenced by molecular mass diffusion. There is uncertainty about the relevant parameter and its magnitude to ensure that molecular mass diffusion can be neglected. Puttock (1985) quotes a reanalysis of wind tunnel work that proposes the criterion

$$\frac{U^3}{g_o{}'\mathcal{D}} \geq 1500$$

for the neglect of molecular diffusion where U is the mean velocity 10 cm above the wind tunnel floor and $\mathcal{D}$ is the mass diffusivity. Meroney (1986) presents data suggesting a similar criterion.

It is difficult, in wind tunnel experiments, to satisfy this criterion and operate at large values of the parameter $(\frac{g_o{}'^2 q_o}{U_H^5})^{\frac{1}{5}}$. This casts doubt on the previous wind tunnel experiments with $(\frac{g_o{}'^2 q_o}{U_H^5})^{\frac{1}{5}} \geq 1.5$ and these should be treated with caution.

The arbitrariness of the reference velocity in the criterion for the neglect of molecular diffusion is unsatisfactory and a criterion using a friction velocity $u_*$ may be more useful. The data suggest $u_*/(g_o{}'\mathcal{D})^{\frac{1}{3}} \geq 0.6$.

Further wind tunnel data from various sources i.e., Hall (1979), Hall and Waters (1985), Janssen (1981), Stretch (1986) have been plotted where appropriate.

Inspection of the data from Neff and Meroney (1981) shows that the correlation in the form of the equation for $x_c$ given above is not applicable at the small concentrations of 0.005 and 0.002. Individual data points are included in addition to the correlation in Figures 24a to f.

Extensive water tunnel results are available from Cheah et al (1984) in a simulated turbulent boundary layer with a boundary layer depth of 25 cm and a roughness length $z_o$ of 8 x $10^{-3}$ cm in one series of experiments and $z_o$ of 10 x $10^{-3}$ cm in another. Specific gravities of 1.042, 1.094 and 1.202 were used with flush sources of diameter 5 cm and 10 cm. In these experiments the floor roughness elements extended over the complete surface area.

cm in another. Specific gravities of 1.042, 1.094 and 1.202 were used with flush sources of diameter 5 cm and 10 cm. In these experiments the floor roughness elements extended over the complete surface area.

Similar, unpublished, results by Britter but with a smooth surface are broadly consistent with those of Cheah et al but show higher concentrations. These data have been included in Figures 24a to f to support Cheah's results, but the smooth wall precludes strict comparison. It would be unwise to deduce, from this comparison, any influence of surface roughness on plume dilution. The observations are more likely to be the result of surface roughness influence on transition of a near-laminar plume. Experimental results for the distances to the 0.01 and 0.02 concentrations are consistent with the wind tunnel data.

The correlations for 0.1 and 0.05 concentrations (Figures 24a and b) show that there is a significant discrepancy between the wind tunnel and water flume results. The very small molecular diffusivity of salt in water ensures that molecular diffusion is negligible in the water flume results. Inspection of both Cheah et al's results and those of Britter show that the plume effectively laminarises near the source and then undergoes transition to a turbulent plume further downstream. Laminarisation and subsequent transition suggests that molecular viscosity will be relevant.

As the Reynolds numbers of the wind tunnel and water flume results are similar the different plume behaviour is surprising and unexplained. A further complication is that near-source mixing and dilution will increase the plume thickness and Reynolds number. Thus the near-source behaviour may be very sensitive to a small amount of near-source mixing.

# Appendix D

# Correlations for Instantaneous Releases of Near-Unit Aspect Ratio

## D.1 Field Trials

Large-scale field trials of instantaneous releases that are well-documented are confined to the experiments at Porton Down (Picknett, 1981) and those at Thorney Island (McQuaid and Roebuck, 1985). Of these the Thorney Island trials are at larger scale and are the more comprehensive. The tests were over a surface with $z_o = 5 \times 10^{-3}$m and had a nominal fixed initial volume of 2000 $m^3$. The density difference, ambient velocity and atmospheric stability were relevant variables. The data are considered below without reference to atmospheric stability and using a reference mean velocity at z = 10 m. Typical Reynolds numbers for the experiments were

$$\frac{U_{ref} Q_o^{\frac{1}{3}}}{\nu} \simeq 4 \times 10^6$$

Data from the nominally ground-level sensors (at z = 0.4 m) based on a 0.6 second averaging time are used in the following analysis.

For each experimental run the maximum, $C_m$, in the concentration time curves C(t) were obtained. The spatial distribution of $C_m$ was used to estimate the maximum distances to given concentrations and these are plotted in Figures 25a to e. Data for 0.005, 0.01 and 0.05 are taken from Gotaas (1985) while data for 0.002 and 0.02 are from the authors' analysis. The authors' analysis of data for 0.05 are consistent with that from Gotaas (1985). Similarly analysed results are available in McQuaid and Roebuck (1985) where, in addition, it may be estimated that $x_{10}/Q_o^{\frac{1}{3}}$ ranges from 4 to 8 with any trends masked by the scatter of data.

Longer averaging times (of 10 to 20 seconds) have little influence on the data from the ground-level sensors.

The data show little trend of $\frac{x}{Q_o^{\frac{1}{3}}}$ with $(\frac{g_o/Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}$ in the range

$$1 \leq (\frac{g_o/Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \leq 5$$

All the data in this range have been averaged and the mean value together with $\pm$ one standard deviation plotted in Figure 26. Extrapolation of the data to 0.1 and 0.001 concentration is appropriate giving mean values of $\frac{x}{Q_o^{\frac{1}{3}}}$ of 6 and 80 respectively. Extrapolation to even lower concentration is uncertain but tempting. A tentative extrapolation gives $\frac{x}{Q_o^{\frac{1}{3}}} = 200$ for a 0.0001 concentration.

The data further suggest that a correlation

$$\frac{C_m}{C_o} = 10(\frac{x}{Q_o^{\frac{1}{3}}})^{-2}$$

will encompass the concentration data at any position downstream.

It has been suggested (Davies, 1985) that laboratory and Thorney Island data for an initial relative density ratio of 3.2 both show that there is a dependence upon $\Delta\rho/\rho_a$ as well as the parameter

$$(\frac{g_o/Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}.$$

Use of the latter parameter alone has relied on the Boussinesq approximation which is valid in the limit as $\Delta\rho/\rho_a \rightarrow 0$. Inspection of the full scale data indicates that

$$(\frac{g_o/Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}}.$$

alone is an adequate parameterisation when $\Delta\rho/\rho_a \leq 1.0$, a surprisingly large criterion.

It is difficult to envisage an instantaneous release in which there is not sufficient dilution at the source to reduce the effective initial relative density difference below unity. A problem may arise, however, when a laboratory model is undertaken with an enhanced $\Delta\rho/\rho_a$.

## D.2 Laboratory Studies

Extensive data on this problem are presented in Meroney and Lohmeyer (1982). The experiments were conducted in a wind tunnel with $z_o \simeq 2.4 \times 10^{-5}$m and $\frac{u_*}{U_{ref}} = 0.048$. Released volumes were in the range $35 \leq Q_o cm^3 \leq 450$. The quoted frequency response of the concentration measuring system was 150 Hz and a spatial resolution estimated to be between 1 and 2 mm. However the data were

recorded on a chart recorder before analysis and the frequency response of the chart recorder was not quoted but is unlikely to be better than 10 Hz.

The distances to specific concentrations estimated from the data presented in Meroney and Lohmeyer (1982) are plotted in Figures 27a to g.

Hall et al (1982) and Hall and Waters (1985) present results for a similar experiment and data for the distance to 0.02 concentrations are included in Figure 27c. The quoted frequency response of the concentration probe used by Hall et al was 20 Hz and a spatial resolution of a few millimetres. Further data for concentrations of 0.1 and 0.01 have been extracted from the papers.

There is a broad consensus regarding the limit of

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \rightarrow \infty,$$

that is, no wind conditions. Wind tunnel experiments from Meroney and Lohmeyer (1982), Hall and Waters (1985) and Spicer and Havens (1985) and water flume experiments of Hansen (1981) show similar dilutions down to concentrations of 0.01 as a result of buoyancy generated motion. Meroney and Lohmeyer (1982) present data down to lower concentrations but these show further dilution at a rate greater than $x^{-2}$. Such an exponent is inadmissable on energy grounds because combining this result and the growth of cloud radius with time requires the height of the centre of gravity of the cloud to increase with time. Either

1. viscous effects influenced the experiment
2. molecular mass diffusion was significant or
3. the measurement of low concentrations was inaccurate.

Extrapolation of data to concentrations below 0.01 has been included in Figures 27e to g based on the correlation

$$\frac{C_m}{C_o} = 20(\frac{x}{Q_o^{\frac{1}{3}}})^{-2}$$

for

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \rightarrow \infty.$$

No systematic dependence on density difference is apparent in the data which include results with $\Delta\rho/\rho_a$ up to about 3.5.

# Appendix E

# Passive Limit Results

## E.1 Continuous Releases

Under certain conditions outlined in Appendix A the density of the release is not relevant and the problem may be treated as a conventional dispersion problem from the source. It is useful if these cases may be included on the distance-concentration plots, Figures 8 and 11, for completeness.

However, it is not straightforward to transpose these results to a criterion based on the stability parameter $(\frac{g_o{}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}}$ on which the non-dimensional distance to a given concentration depends. If $(\frac{g_o{}' q_o}{U_{ref}^3 D})$ is the relevant parameter then it is apparent that density effects are always important for a hypothetical point source. That is, any source flow from a point will be density dominated out to some distance after which the dispersion is effectively passive. A useful estimate may be obtained by rewriting

$$(\frac{g_o{}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}} = (\frac{g_o{}' q_o}{U_{ref}^3 D})^{\frac{2}{5}} (\frac{q_o}{U_{ref} D^2})^{-\frac{1}{5}}$$

and realising that, for our previous constraint, source momentum effects are small (say $(\frac{q_o}{U_{ref} D^2}) < 0.1$) an equivalent passive limit of

$$(\frac{g_o{}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}} \leq 0.2$$

is produced. This has been included on the relevant concentration-distance curves.

An alternative approach is to base the criterion on the requirement that the flow be effectively passive further than a multiple of the length scale $(\frac{q_o}{U_{ref}})^{\frac{1}{2}}$ from the source. Using $10(\frac{q_o}{U_{ref}})^{\frac{1}{2}}$ the criterion

$$(\frac{g_o{}'^2 q_o}{U_{ref}^5})^{\frac{1}{5}} = 0.2$$

is also obtained.

Laboratory data of maximum ground-level concentrations for dispersion in neutrally stratified turbulent boundary layers with smooth or rough surfaces are commonly plotted as

$$C\frac{U_{ref}H^2}{q_o} = A(\frac{x}{H})^{\alpha}$$

where H is a reference length scale and $\alpha$ is typically -1.5. However, if interest is limited to downwind distances of a few kilometres at full-scale it is possible to approximate the results with

$$C\frac{U_{ref}x^2}{q_o} = \text{a constant}$$

The use of a reference velocity consistent with a 10 m height at full-scale produces a constant between 100 and 250 dependent upon author and, in particular, the surface roughness. The lower value is typical for a surface roughness length of order 10 cm at full scale. Results from Neff and Meroney (1981) are included in Figures 24a to f and these are broadly consistent with a constant of 100.

A similar approximation to the guide presented by Turner (1970) for passive dispersion under D category (Pasquill-Gifford) stability produces a constant of 140 while the constant is 560 for F stability. These results are included in Figures 23a to f, and provide a useful extrapolation of the density-influenced data.

These estimates, it must be stressed, are provided for completeness and, if the release has been deemed passive, the user of the workbook is advised to consult the more extensive literature currently available (Turner, 1970; Clarke, 1979) on the dispersion of passive pollutants. However it is important to note that much of the literature available is for nominal point sources and the application to sources of area $D^2$ only becomes relevant after about 10D downwind.

## E.2 Instantaneous Releases

There is little data for the limit

$$(\frac{g_o' Q_o^{\frac{1}{3}}}{U_{ref}^2})^{\frac{1}{2}} \rightarrow 0$$

when the release behaves as if it was not influenced by buoyancy.

Figure 28 shows the variation with downwind distance of the maximum ground-level concentration in passive clouds obtained using conventional Gaussian arguments and dispersion coefficients from Beals (1971). The use of dispersion coefficients for plumes from Turner (1970) and those for clouds from Slade (1968) quoted in Turner lead to similar results.

The data as plotted here are only valid out to x = 2000 m for D (i.e. neutral) atmospheric stability. An analysis based on Lagrangian similarity theory (from Yang and Meroney, 1972) also provides similar results.

Further data on passive clouds are provided by the laboratory experiments of Meroney and Lohmeyer (1982). A release volume of $Q_o = 35cm^3$ was used in two flows with reference velocities of 0.2 and 0.6 m/s. The results, plotted on Figure 28, show no dependence upon the flow velocity and are at variance with the data from Beals (1971) etc.

The principal difference between the results is the rapid dilution in the near field observed by Meroney and Lohmeyer (1982). This initial rapid dilution is expected for releases of large volume where the cloud is accelerated by mixing between the cloud and the ambient flow. Analysis by Rottman et al (1985) is consistent with a dilution to $\frac{C_m}{C_o} = 0.1$ by $\frac{x}{Q_o^{\frac{1}{3}}} = 3$. A similar estimate may be made from the photographs of experiments at Porton Down (particularly experiment 27A) reproduced in Hall et al (1982).

Trial 4 from Thorney Island (see McQuaid and Roebuck, 1985) was a passive release. Only limited experimental measurements were made but the visual observations were consistent with a dilution by a factor of 10 at $\frac{x}{Q_o^{\frac{1}{3}}} = 3$ to 4. An estimate of the distance to a concentration of 0.005, although difficult, is that $\frac{x}{Q_o^{\frac{1}{3}}} \simeq 40$.

The data of Meroney and Lohmeyer (1982) are complicated by the observation that the cloud fills much of the boundary layer depth when the concentration is reduced to 0.01 of the source concentration. Nevertheless for want of more definitive data we shall adopt that from Meroney and Lohmeyer (1982).

An important caveat is that if the release is a rapidly expanding and diluting cloud during formation then the transfer of momentum from the ambient flow will already have taken place and no further dilution can be anticipated as a result of cloud acceleration. Subsequent dilution of the cloud is anticipated to be that deduced from dispersion parameters presented by Beals (1971) and Turner (1970) as plotted in Figure 28. Figure 29 is a suggested modification of Figure 11 if there has already been significant dilution of the cloud and consequent cloud acceleration. The basis of the modification has been to assume that the correlations are unaffected where buoyancy is dominant and to smoothly extrapolate these correlations to the passive limit from the Beals/Turner curve in Figure 28.

# Appendix F

# Physical Modelling

## F.1 Introduction

In many situations, particularly those involving complex topography or flow and dispersion near regions of flow separation, physical modelling is the appropriate means of solution. The conduct of physical modelling studies requires care and experience. Snyder (1981) produced a useful guide to the physical modelling of neutrally or positively buoyant emissions while Meroney (1986) has considered further requirements for the physical modelling of dense gas releases. The following discussion is taken from Britter (1987) and is a brief account of the modelling procedure for the dispersion of dense gases in which the density difference is produced by a difference in molecular weight alone.

Model testing is based upon the equality of dimensionless variables in the full scale and the model. The dimensionless variables may be obtained by

(i) non-dimensionalizing the equations describing the flow or,

(ii) listing the relevant variables involved and forming them into dimensionless groups or,

(iii) comparison of various physical effects, e.g. forces and thereby forming dimensionless variables.

As an example of (ii) consider the following.

A problem is fully specified by the set of independent variables and we observe the dependent variables for a given set of independent variables. The functional relationship between dependent and independent variables cannot be influenced by the units with which we choose to measure them. Consequently a problem is fully specified by the set of dimensionless variables that may be formed from the independent variables. If there are $n$ relevant dimensions in the physical problem then there are $n$ fewer **dimensionless** independent variables than there are independent variables.

In practice it is rarely possible to model all the dimensionless independent variables. Even when the most relevant are retained, constraints based on usable

working fluids, size and cost of modelling facility and available instrumentation require a compromise and often lead to 'distorted modelling'.

Physical modelling (e.g. wind tunnels, water flumes) of dispersion problems conveniently splits into two parts:-

(a) modelling the fluid flow in which the dispersion is to take place, the atmospheric boundary layer, say, and

(b) modelling the pollutant release within that flow.

## F.2 Modelling of the Atmospheric Boundary Layer

The report by Snyder (1981) has considered, in some detail, guidelines for fluid modelling with a view towards atmospheric dispersion modelling. To ensure dynamical similarity between model and full-scale flows which are steady, the fundamental equations of motion require that:-

| | |
|---|---|
| the Reynolds number | $(\rho\frac{UL}{\mu})$ |
| the Rossby number | $(\frac{U}{fL})$ |
| the Richardson number | $\{(g\frac{\Delta\rho}{\rho}L)/U^2\}$, see Batchelor (1953) |

be equal at model and full scale. The independent variables are:-

| | |
|---|---|
| characteristic velocity | U |
| characteristic length | L |
| characteristic potential density (or temperature) difference due to atmospheric stability /instability | $\frac{\Delta\rho}{\rho}(=-\frac{\Delta T}{T})$ |
| fluid properties | $\rho$, $\mu$ |
| Coriolis parameter | f |
| and acceleration due to gravity | g |

The observant reader will note that we have 7 variables, 3 dimensions but only 3 dimensionless variables. The explanation is that in atmospheric flows $\frac{\Delta\rho}{\rho}$ is small and its effect on the inertia of the flow is small. But $\frac{\Delta\rho}{\rho}$ is not negligible when appearing in a buoyancy term and there it is always coupled with g. Thus a Boussinesq approximation has, correctly, been made.

The Prandtl number $(=\frac{\nu}{\kappa})$, the ratio of kinematic viscosity to thermal diffusivity, must also be the same in model and full-scale if non-neutral temperature stratification is being modelled. As both full-scale and model working fluids are typically air, this requirement is often automatically met.

In addition the boundary conditions require modelling, that is correct geometrical scaling of topography, buildings, trees, etc. and any imposed surface temperature distribution.

It is indicative of the 'art' of physical modelling that, in general, none or possibly only one, of the above dimensionless parameters is correctly modelled.

Rossby number modelling is unlikely to be obtainable in laboratory facilities and one is left to argue about what is the largest region modellable or the minimum Rossby number allowable for the neglect of the effects of rotation. It is suggested that a Rossby number of order 10 would allow neglect of rotational effects whereas

the neglect of a Rossby number of order unity would require justification, Snyder (1981).

The correct modelling of Reynolds number is obviously not possible. However, many properties of turbulent flows (and we are concerned with turbulent flows in the full-scale) are independent of Reynolds number provided the Reynolds number is large. The smallest scales of turbulence will not be reproduced in the model; the largest scales reduce with the model scale whereas the smallest scales only reduce as the $\frac{1}{4}$-power of the model scale, Snyder (1981).

At 10m above the surface in the neutrally stratified boundary layer with $u_* = 0.5$ m/s, the smallest scale of turbulence is 0.5mm. In a 1:1000 scale model the smallest scale of turbulence, the Kolmogorov micro-scale, is typically 0.1mm corresponding to 10cm in full scale. In practice, this is significant only if spatial detail down to 10cm is required; usually 1m is adequate.

Not satisfying the Reynolds number scaling in the model essentially implies the neglect of viscosity. However, as we are generally dealing with 'rough wall' turbulent boundary layers, the product of the friction velocity $u_*$ and the roughness length $z_o$ i.e. $(u_* z_o)$, adopts the role $\nu$. That is, the relevant Reynolds number to model is $\frac{UL}{u_* z_o}$ rather than $\frac{UL}{\nu}$.

Thus the emphasis changes from trying to model the Reynolds number to modelling $\frac{u_*}{U}$ and $\frac{z_o}{L}$. In many physical modelling facilities the boundary layer development is accelerated and adjusted until $\frac{u_*}{U}$, $\frac{z_o}{L}$ together with various other turbulence statistics and length scale ratios are correctly modelled.

The roughness length $z_o$ is a gross characterisation of the drag force resulting from separation about individual surface structures. Obviously $z_o$ will depend on both size and spacing of the surface structures and in typical simulations is about 0.1 of the roughness element height k for sharp edged roughness or about 0.03k for randomly distributed smooth roughness elements. The former ratio is not dissimilar to full-scale values, e.g. Simiu and Scanlon (1978). It should also be borne in mind that $u_*$ and $z_o$ are interdependent.

To ensure that the flow is fully aerodynamically rough in the model the size of the roughness element must be large compared with any viscous sublayer. Schlichting (1955), quoting Nikuradse's sand grain measurements, requires $\frac{u_* k}{\nu} > 70$ for the flow to be independent of the Reynolds number. Brutsaert, in Plate (1983) p.334, requires $\frac{u_* z_o}{\nu} > 2$, and suggests that $z_o \simeq 0.1$ k typically. The Nikuradse measurements with sand grains had $z_o \simeq 0.03$k and so are consistent with $\frac{u_* z_o}{\nu} > 2$. However Plate, in Plate (1983) p.578 uses $\frac{u_* z_o}{\nu} > 5$. To ensure Reynolds number independence, Snyder (1981) puts $\frac{u_* k}{\nu} > 100$ if possible but $\frac{u_* k}{\nu}$ must always be greater than 20.

A working consensus would be that $\frac{u_* k}{\nu} > 50$ or $\frac{u_* z_o}{\nu} > 5$ **will** provide Reynolds number independence but that $\frac{u_* k}{\nu} > 20$, $\frac{u_* z_o}{\nu} > 2$ **may** be satisfactory, particularly for sharp-edged roughness elements. Of course what is important is that the modelled mean and turbulent velocity profiles are similar to their full-scale counterparts over the region of interest and this comparison must override any arguments based on $\frac{u_* z_o}{\nu}$. Mulhearn (1977) and Raupach et al (1980) point out the considerable spatial inhomogeneity in the flow field due to the roughness elements

and their spacing; this inhomogeneity in the mean and turbulent fields exists for a height of (k + 1.5 S) from the surface for roughness elements of height k and spacing S.

When large scale reductions are used it may not be easy to satisfy the requirement that $\frac{z_o}{L}$ is constant and k $> 50\frac{\nu}{u_*}$ unless quite large roughness elements are used spread rather sparsely. Thus k, S and (k + 1.5 S) are large. This arrangement may be in conflict with any requirement of homogeneous flow within a regime of interest close to the model surface.

Flow over some surfaces (snow, sand or water for flow velocities less than a few metres per second) may be aerodynamically smooth at full scale. An equivalent roughness length for flow over a smooth wall is approximately $0.1\frac{\nu}{u_*}$.

Strictly, modelling of the Reynolds number $\frac{UL}{\nu}$ is required and is not possible. In practice the boundary layer is adjusted until acceptable mean and turbulence profiles are obtained at the correct scale.

The mean profiles are typically logarithmic, at least near the surface in neutral flows. However they are often well represented by power laws and, thus, the scale is somewhat arbitrary and the mean velocity profile adequately modelled. Obtaining small $\frac{u_*}{U}$ at the model scale presents the major difficulty.

## F.3 Modelling of Releases at Ambient Density

The introduction of the pollutant source introduces more independent variables and a corresponding number of dimensionless independent variables.

We restrict attention to pollutants that have the same density, temperature, kinematic viscosity and molecular diffusivity as the environment i.e. the pollutant behaves as a marker in air. That is $\rho_s = \rho_a$, $T_s = T_a$, $\nu_s = \nu_a$, and $D_s = D_a$ where the subscript s refers to source fluid and a to ambient fluid.

In addition to correct geometrical scaling of the source the following additional independent non-dimensional variables require modelling.

(a) If the source is an instantaneous release of volume $Q_o$ then $Q_o/L^3$ must be modelled.

(b) If the source has a constant volume flow rate $q_o$ then $q_o/UL^2$ must be modelled.

(c) If, in general, the release rate is time dependent then the variable $q_o(t)$ becomes $q_o(tU/L)/UL^2$, i.e. $q_o$ is a function of (tU/L) and must be scaled with $UL^2$.

For whichever case is applicable the concentration C as a ratio of the source concentration $C_o$ is given by

$$\frac{C}{C_o} = f(\tfrac{x}{L}, \tfrac{y}{L}, \tfrac{z}{L}, \tfrac{tU}{L})$$

For case (b) when the source is steady

$$\frac{C}{C_o} = f(\frac{x}{L}, \frac{y}{L}, \frac{z}{L})$$

and the non-dimensional concentration $C/C_o$ is the same at the same geometrical position in model and full scale.

Cases (a) and (c) will lead to an unsteady, that is time-dependent, concentration field. An unsteady concentration field also arises if case (b) is

$q_o = 0$ for $t < 0$

$q_o =$ constant for $t \geq 0$.

Whenever the concentration field is unsteady, the time dependence in both model and full-scale is the same whenever the times are non-dimensionalised as $tU/L$.

A further point to be made here is that modifications are often made to the model to ensure that a turbulent release in full scale is also turbulent in the model such as the promotion of turbulence inside a small, modelled chimney.

## F.4 Modelling of Different Density Source

If $\rho_s \neq \rho_a$ then two further dimensionless independent variables are required, namely $\rho_s/\rho_a$ and $U^2/gL$. The acceleration due to gravity g was not previously relevant but the variable densities make the inclusion of g necessary. Molecular, i.e. Schmidt and Reynolds number, effects are dealt with later in this section.

The Schmidt and Reynolds numbers aside, there are three dimensionless parameters to be modelled i.e.

$$\frac{\rho_o}{\rho_a}, \frac{U^2}{gL}, \frac{Q_o}{L^3} \text{ or } \frac{q_o}{UL^2} \text{ or } \frac{q_o(\frac{tu}{L})}{UL^2}$$

These three are, of course, not unique. Any three independent variables formed from them are also adequate.

If the concentration field is unsteady then time must be non-dimensionalised as tU/L (or $t(\frac{g}{L})^{\frac{1}{2}}$ which is equivalent as $U^2/gL$ is the same in model and full scale).

In the absence of a mean wind the dimensionless parameters are

$$\frac{\rho_o}{\rho_a}, \frac{Q_o}{L^3} \text{ or } \frac{q_o}{(gL^5)^{\frac{1}{2}}} \text{ or } \frac{q_o(\frac{tg^{\frac{1}{2}}}{L^{\frac{1}{2}}})}{(gL^5)^{\frac{1}{2}}}$$

and time will be such that $t(g/L)^{\frac{1}{2}}$ is the same in model and full-scale.

The limit of zero wind might be extended to cases where the wind is small compared with buoyancy-induced velocities (e.g. see Britter 1979).

For reasons associated with operating modelling facilities it is sometimes the case that all variables cannot be easily modelled and fewer variables may be selected. This is referred to as distorted modelling.

When modelling **positively** buoyant plumes the geometric scale is often distorted allowing a larger model chimney stack than is geometrically correct. Snyder (1981) noted that 14 different variables have been used at some time by 6 major

modelling facilities. General conclusions are difficult but if distorted modelling is required then there is most support for geometric scaling and for selecting the following two variables $\frac{U^2}{g(\frac{\rho_o}{\rho_a}-1)L}$ and $\frac{\rho_o q_o^2}{\rho_a U^2 L^4}$, i.e. a densimetric Froude number and a source momentum ratio. Distorted modelling for **positively** buoyant plumes has been discussed most coherently by Isyumov and Tanaka (1979).

By way of explanation the replacement of $\frac{U^2}{gL}$ and $\frac{\rho_o}{\rho_a}$ with $\frac{U^2}{g(\frac{\rho_o}{\rho_a}-1)L}$ is the Boussinesq approximation. The approximation has a long and useful history and its applicability is more correct when the density differences are a small fraction of the density.

There is less experience with distorted modelling of **negatively** buoyant plumes and its appropriateness is still uncertain. If distorted modelling is required then the same two variables would seem to be the most relevant.

Hall et al (1982) highlight the difficulty encountered in modelling the Froude number $U^2/gL$. This often leads to unacceptably low wind-tunnel speeds (on both Reynolds number and tunnel steadiness grounds). When necessary this difficulty is overcome by invoking a Boussinesq approximation to distort the modelling.

This reduces the independent dimensionless variables to

$$\frac{U^2}{g(\frac{\rho_o}{\rho_a}-1)L}$$

$$\frac{\rho_o q_o^2}{\rho_a U^2 L^4}$$

allowing considerable flexibility in the modelling.

If the ratio of efflux velocity to ambient velocity is much less than unity then the source momentum may be neglected and $q_o/UL^2$ is the relevant variable in place of

$$\frac{\rho_o q_o^2}{\rho_a U^2 L^4}$$

An alternative approach based on modelling mass fluxes,

$$\frac{\rho_o q_o}{\rho_a U L^2}$$

would not be geometrically correct near the source.

In the absence of a mean wind the distorted modelling requires that time is non-dimensionalised as

$$\{\frac{g(\frac{\rho_o}{\rho_a}-1)}{L}\}^{\frac{1}{2}} t$$

in model and full-scale.

A more radical distortion, valid only in the far field after considerable plume dilution, may be considered. After considerable plume dilution the plume consists principally of entrained ambient fluid and its size will not be dependent upon $q_o$ alone. The relevant variable will be the buoyancy flux of the plume $gq_o(\frac{\rho_o}{\rho_a}-1)$

(Turner, 1973) which is conserved during mixing of an isothermal plume. Thus, in the far field, the only relevant dimensionless group is the flux Froude number

$$\frac{U^3 L}{g q_o (\frac{\rho_o}{\rho_a} - 1)}$$

Modelling of this variable alone allows distortion of $q_o/UL^2$ but care must be taken in interpreting the model concentration field under this distortion. Meroney gives

$$C_f = C_m \{C_m + (1 - C_m) \frac{(q_o/UL^2)_m}{(q_o/UL^2)_f}\}^{-1}$$

where C is the mole fraction of the source material and the subscript m refers to model and f to full scale. In the far field this becomes

$$C_f = C_m \{\frac{(q_o/UL^2)_m}{(q_o/UL^2)_f}\}$$

If the effects of molecular diffusion of the pollutant in the ambient fluid are considered important (e.g. in correctly modelling the fine-scale structure of the concentration field) then both the Reynolds number $\frac{UL}{\nu}$ and the Schmidt number $S_c = \nu/\mathcal{D}$ also require modelling. In F.2 above the impossibility of modelling the Reynolds number correctly and the consequent loss of the fine structure of the turbulence was described. This leads to a loss of the fine structure of the concentration field. If, in addition, the Schmidt number is smaller in the model than at full-scale then more of the fine-scale concentration field is lost. Note that a large Schmidt number in the model cannot recover correct concentration fine-scale structure lost by the incorrect Reynolds number modelling.

If the fine-scale structure of the concentration field is required then the Schmidt number should be correctly modelled and the Reynolds number made as large as possible.

Two further points may be made here in the context of the dispersion of dense gases.

(a) The Peclet number

$$\frac{UL}{\mathcal{D}} = \frac{UL}{\nu} \cdot \frac{\nu}{\mathcal{D}} = Re.Sc$$

should be as large as possible in the model to ensure that the vertical growth of a dense cloud as a result of molecular diffusion is always negligible compared with the vertical growth due to turbulent mixing.

(b) There is also evidence (Turner, 1973) that a large turbulent Peclet number is required in the model to ensure that mixing across density interfaces is correctly modelled. The Peclet number should be based on the turbulent length and velocity scales near the interface. The quantification of this effect requires further study.

In F.2 it was argued that modelling the turbulent atmospheric boundary layer could be undertaken, by the justified neglect of the Reynolds number (based on the boundary layer scale), provided the flow was turbulent in both model and at full-scale. A similar argument is required for the pollutant plume. Otherwise the Reynolds number must be correctly modelled and this is virtually impossible.

For positively buoyant plumes neglect of Reynolds number is permissible provided that the flow from the source is turbulent. This is often ensured by placing a turbulent trip in the source.

For negatively buoyant plumes the Reynolds number based on the plume thickness may become relevant. There is little information available to provide guidance on this point. Hall et al (1982) note that criteria for the neglect of the plume Reynolds number are less precise when dealing with dense gas dispersion than with more routine dispersion studies. This is a result of the sensitivity of laminar - turbulent transition to the Reynolds number and stable density gradient.

Meroney notes that the plume Reynolds number should be above some unstated minimum value. The plume thickness, however, is a dependent and not independent variable so a minimum plume Reynolds number can only be checked after simulation rather than prescribed beforehand. When the wind speed is zero (or small compared with buoyancy-driven velocities), Simpson and Britter (1979) concluded that the Reynolds number based on the velocity of advance and the depth of the leading edge of the plume must be greater than 500 to allow neglect of viscous effects in determining the velocity of advance of the plume edge.

## F.5 Modelling Practicalities

There follow short notes on some modelling practicalities that will influence an experimental study.

(i) Dense gas plumes are wide and shallow; the finite width of the modelling facility is often an important constraint.

(ii) Very small scale models introduce difficulties related to spatial resolution.

(iii) It is very difficult to achieve a steady low velocity in a wind tunnel and extensive measurements of the velocity field are essential during an experiment to confirm that the derived properties are being attained. Snyder (1981) recommends 1.0 m/s as a practical lower limit.

(iv) It is often argued that a minimum Reynolds number is required to ensure correct wake flows. A value of $10^4$ will be adequate for a sharp edged body in uniform flow with no turbulence. This might be reduced to 1 - 3 x $10^3$ for sharp edged body in turbulent shear flow. Smooth structures require more caution.

(v) It is increasingly being recognized that the small vertical extent of dense plumes may be comparable to the viscous sublayers over smooth walls. Care

must be taken to ensure that the model plume is much larger than the viscous sublayer thickness, that is, much greater than $10\frac{\nu}{u_*}$. Violation of this criterion will lead to laminar like plumes in the model with reduced plume dilution.

Similarly for rough wall flows the plume may be comparable to the size of the roughness elements. Turbulence is not modelled correctly within roughness elements and therefore a preliminary requirement is that the plume depth should be much greater than 10 $z_o$, say. Although the turbulence within the roughness is not modelled, some averaged turbulence quantities will be approximately correct. Thus the requirement that the plume depth be much greater than 10 $z_o$ is preferred but may not be essential. A plume depth less than 10 $z_o$ would be less than satisfactory.

(vi) Recently criteria to determine the importance of molecular diffusion have appeared. Meroney (1986) suggests $\frac{U^3}{g_o' D} > 1500$ or $\frac{u_*^3}{g_o' D} > 0.2$ as satisfactory criteria. However, these must still be regarded as tentative.

# Appendix G

# References


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# Appendix H

# Figures



Contents

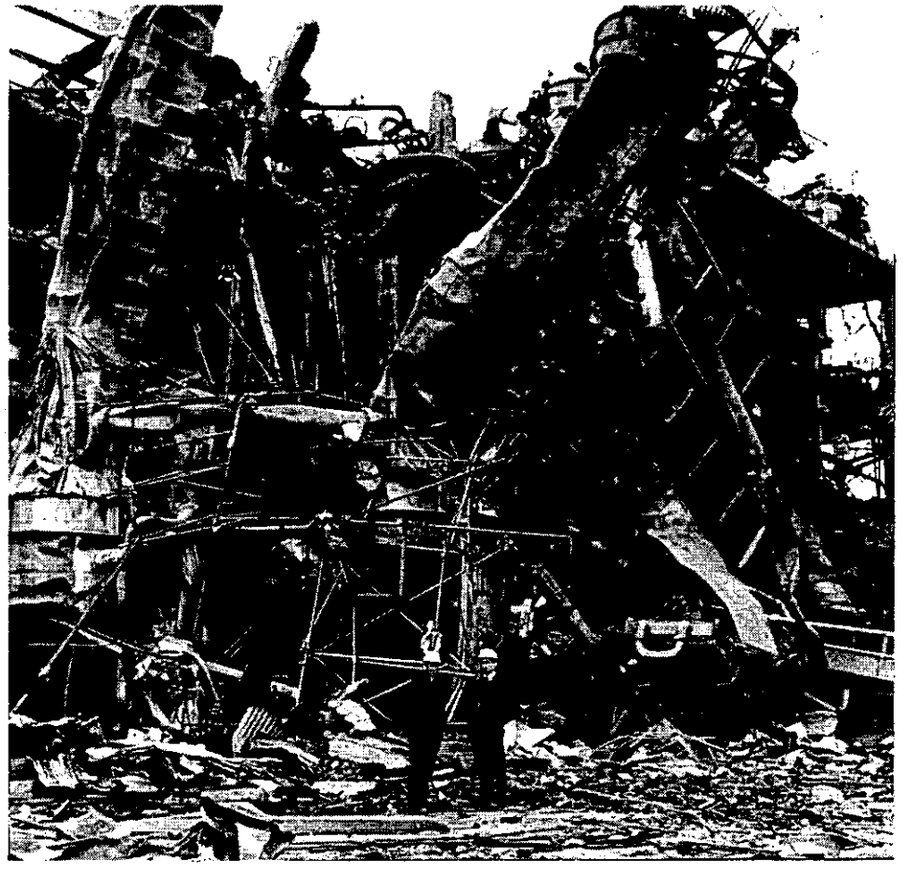
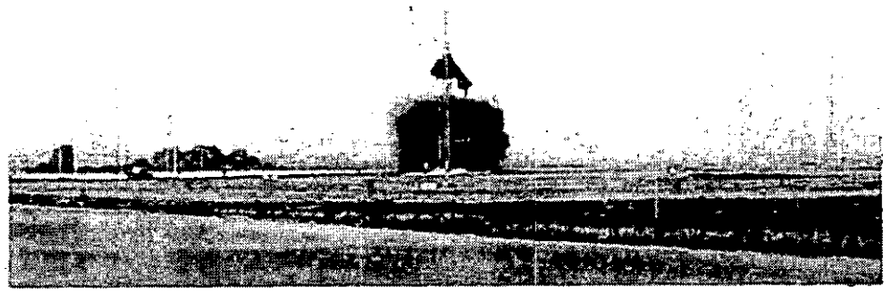


**Figure 1** The aftermath of the explosion at Flixborough UK, June 1974.



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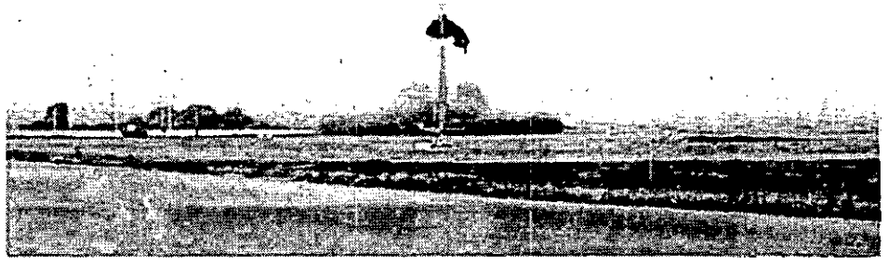

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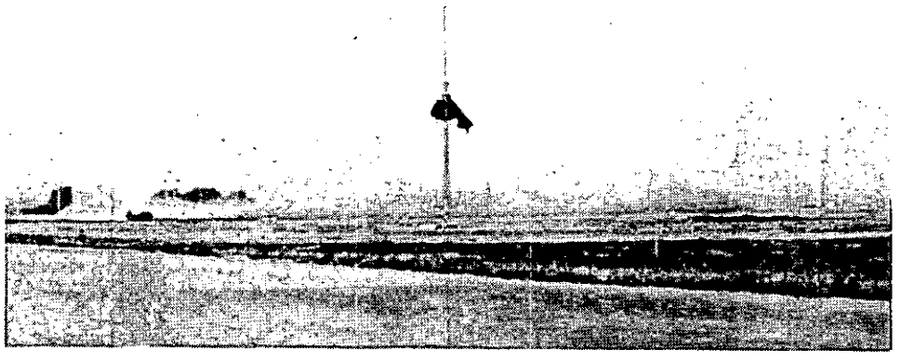
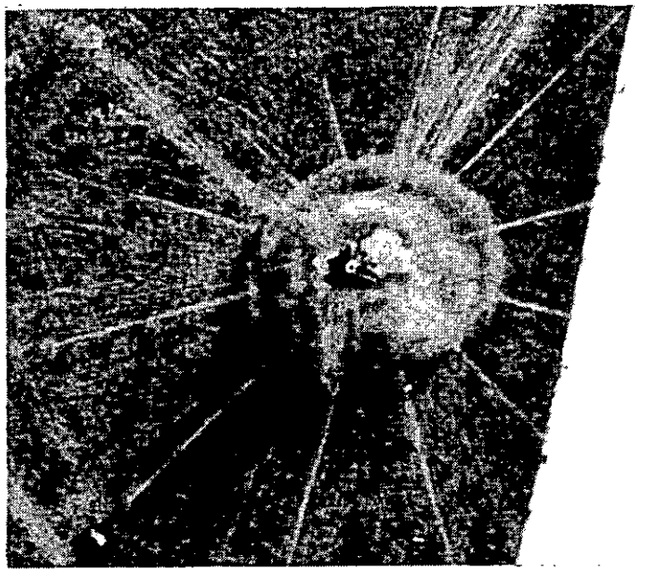


(c)

**Figure 2** Side views of the cloud in Thorney Island trial number 8 at release (a), after 3 secs (b) and after a further 24 secs (c).



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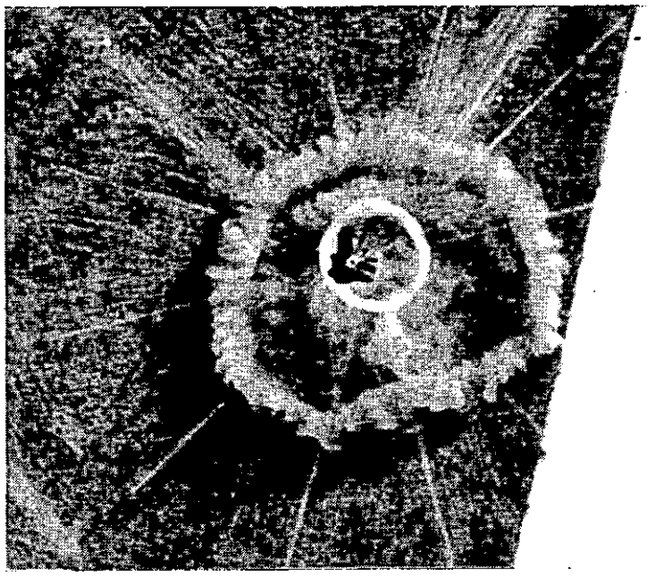

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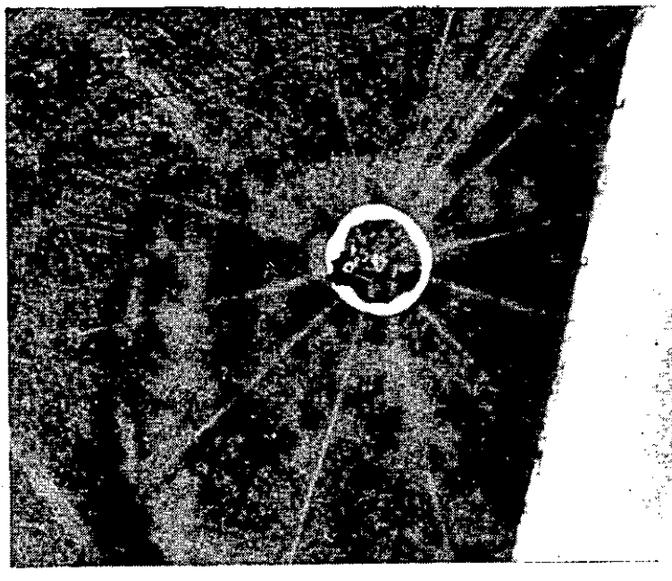

(c)

**Figure 3** Overhead views of the cloud in Thorney Island trial number 8 at about 3 secs after release (a), after a further 2.5 secs (b) and after a further 10 secs (c).

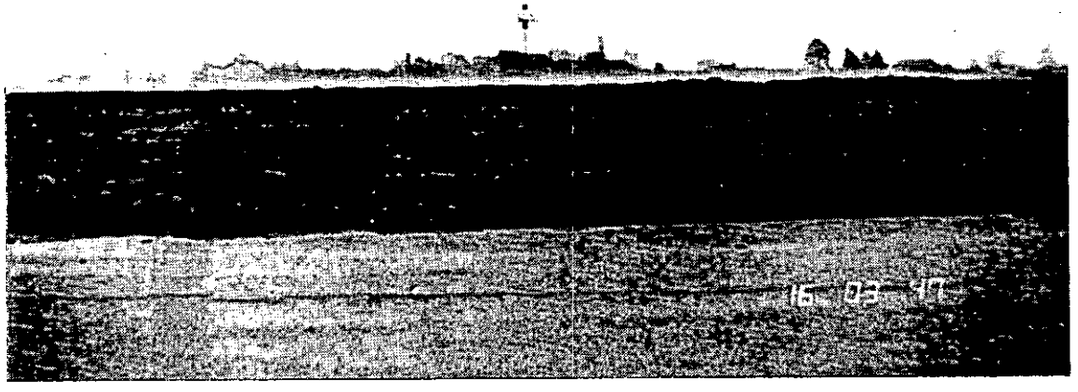

**Figure 4** Side view of the cloud in Thorney Island trial number 34 at about 100 secs after release.

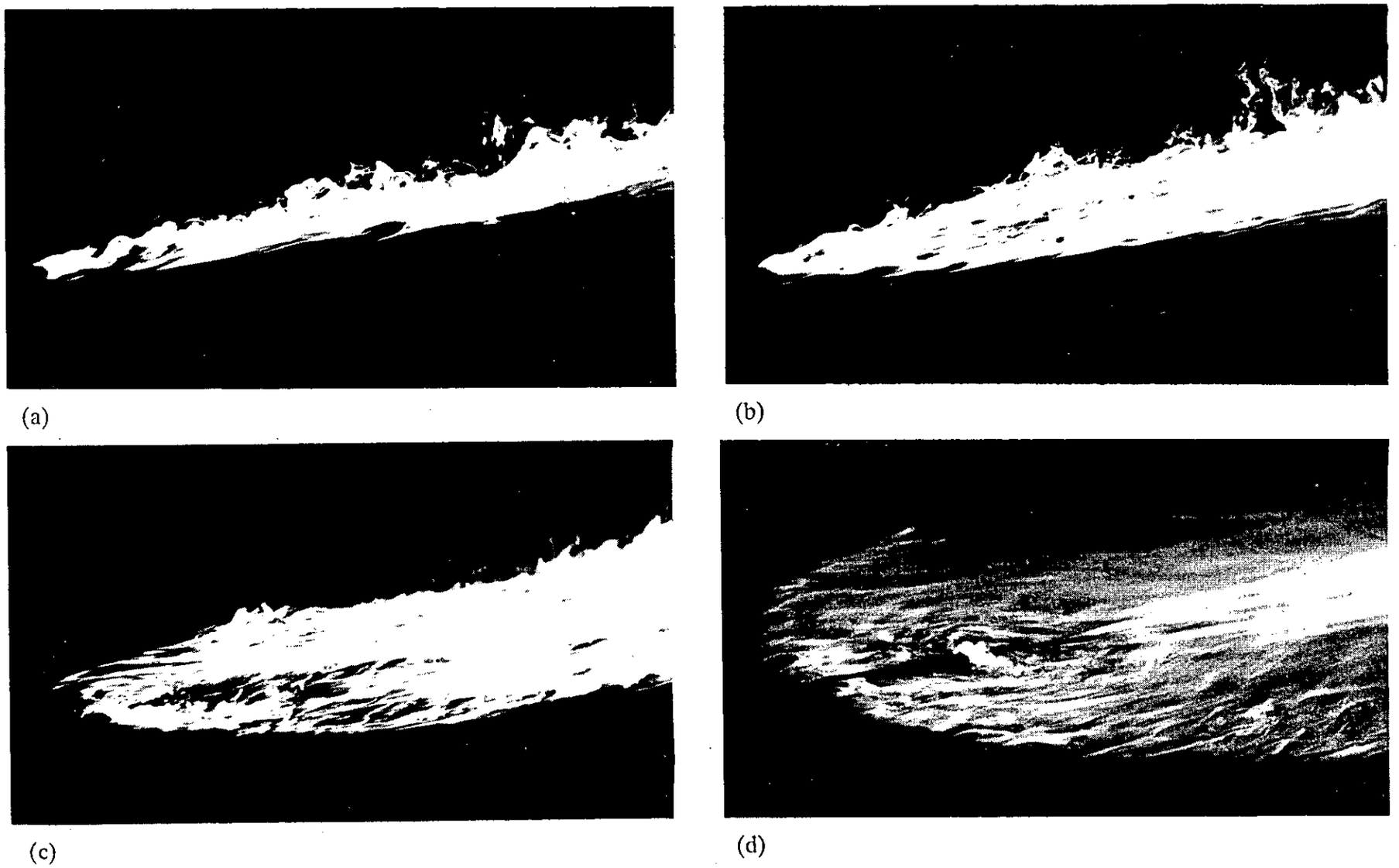


**Figure 5** Photographs from the wind tunnel model of a continuous dense gas release by Hall (1987). Figure (a) is a neutrally-buoyant release and Figures (b), (c) and (d) successively larger dense-gas effects.

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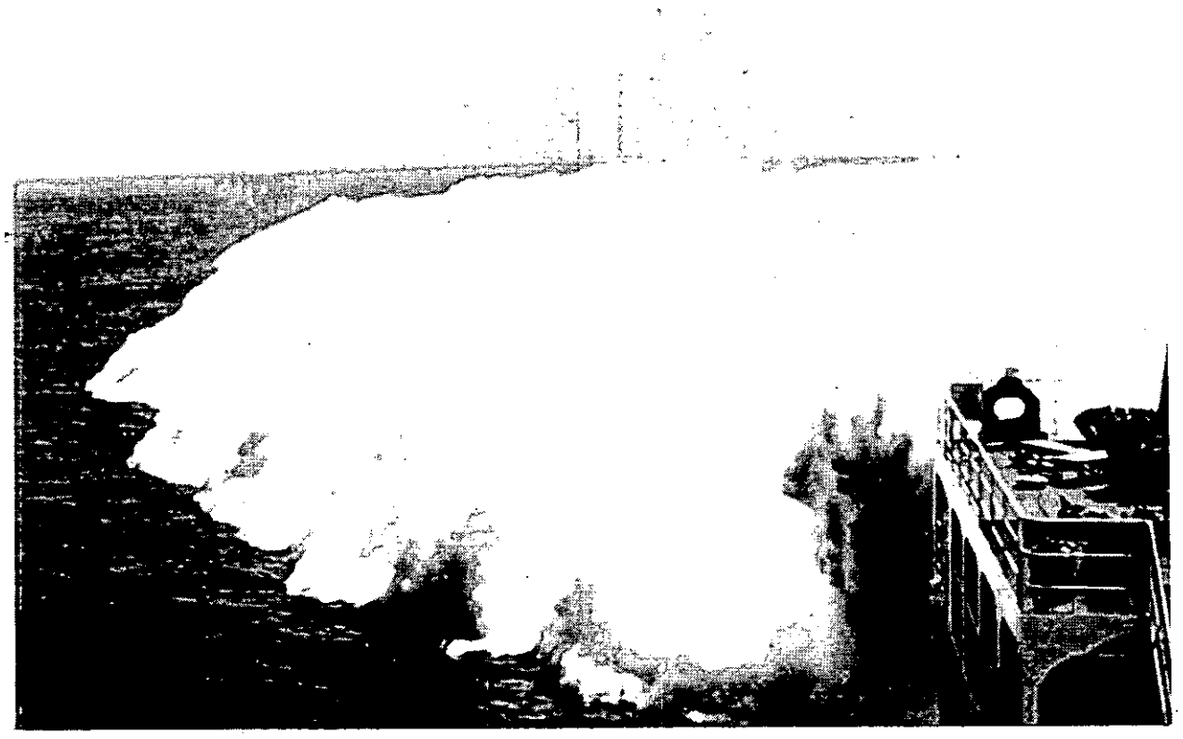

**Figure 6** The cloud from a discharge of liquefied natural gas from a tanker.

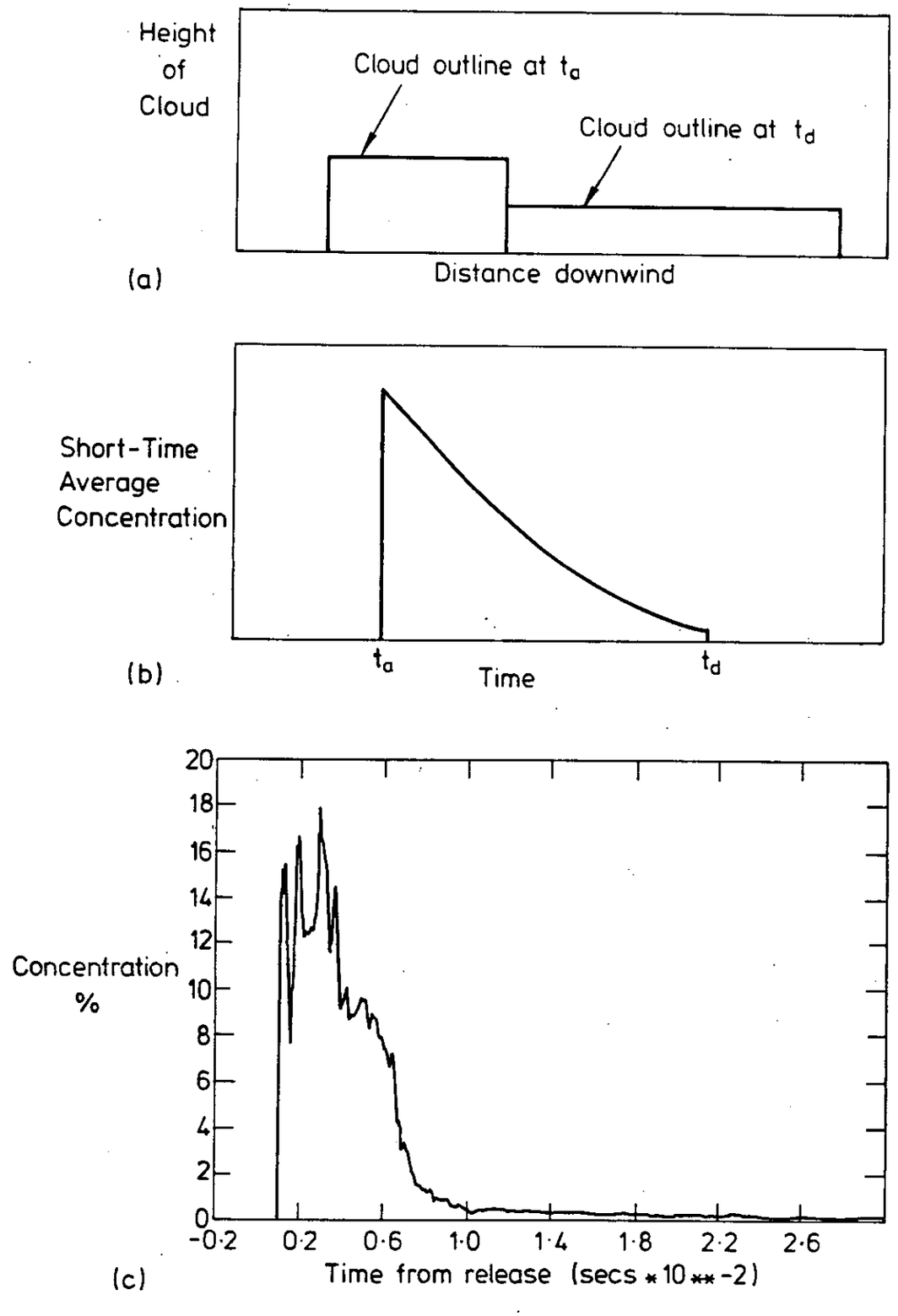


**Figure 7** The representation of the cloud from an instantaneous release and an illustrative record from the Thorney Island trials.

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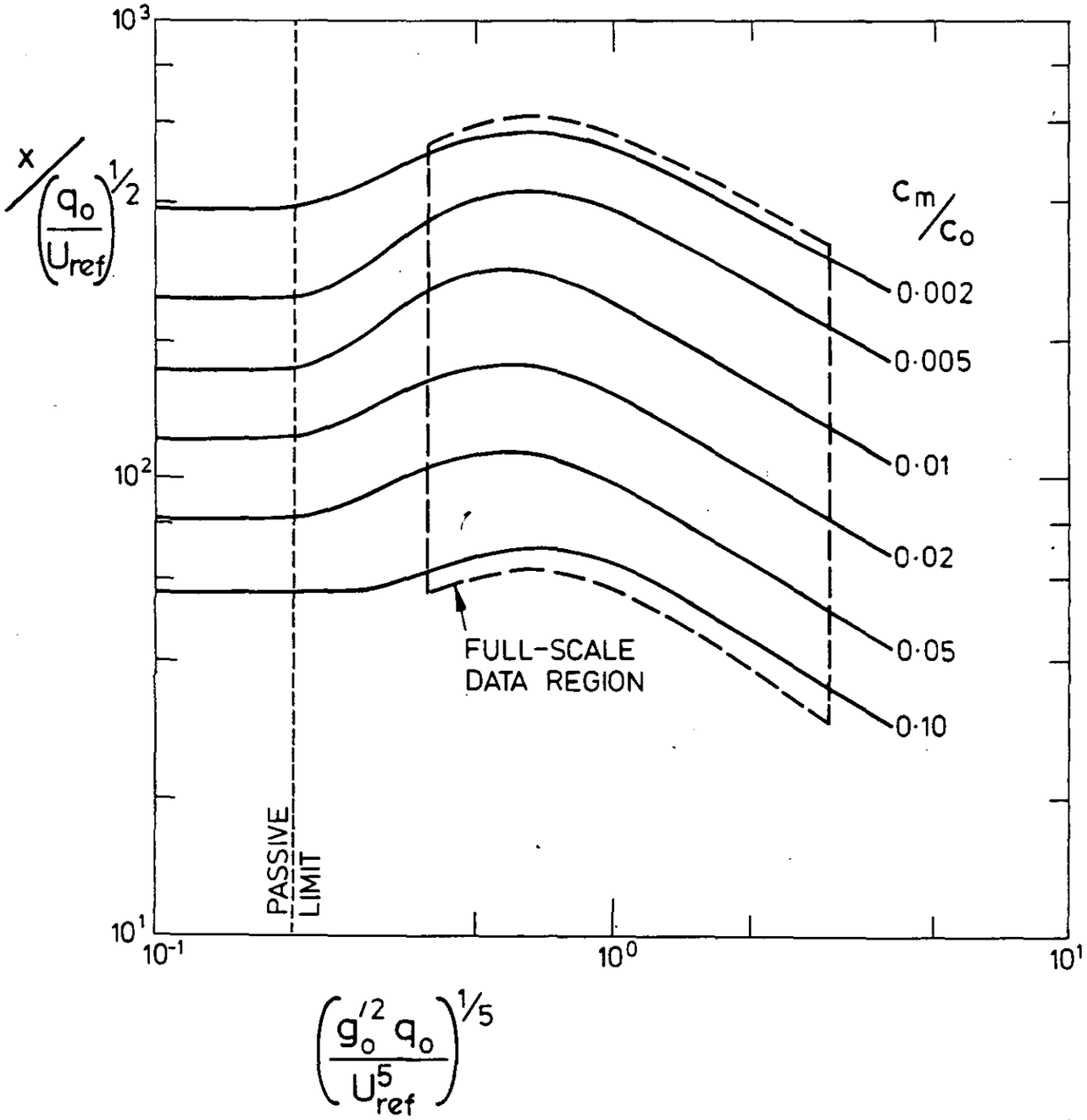


**Figure 8** Correlation for continuous releases.

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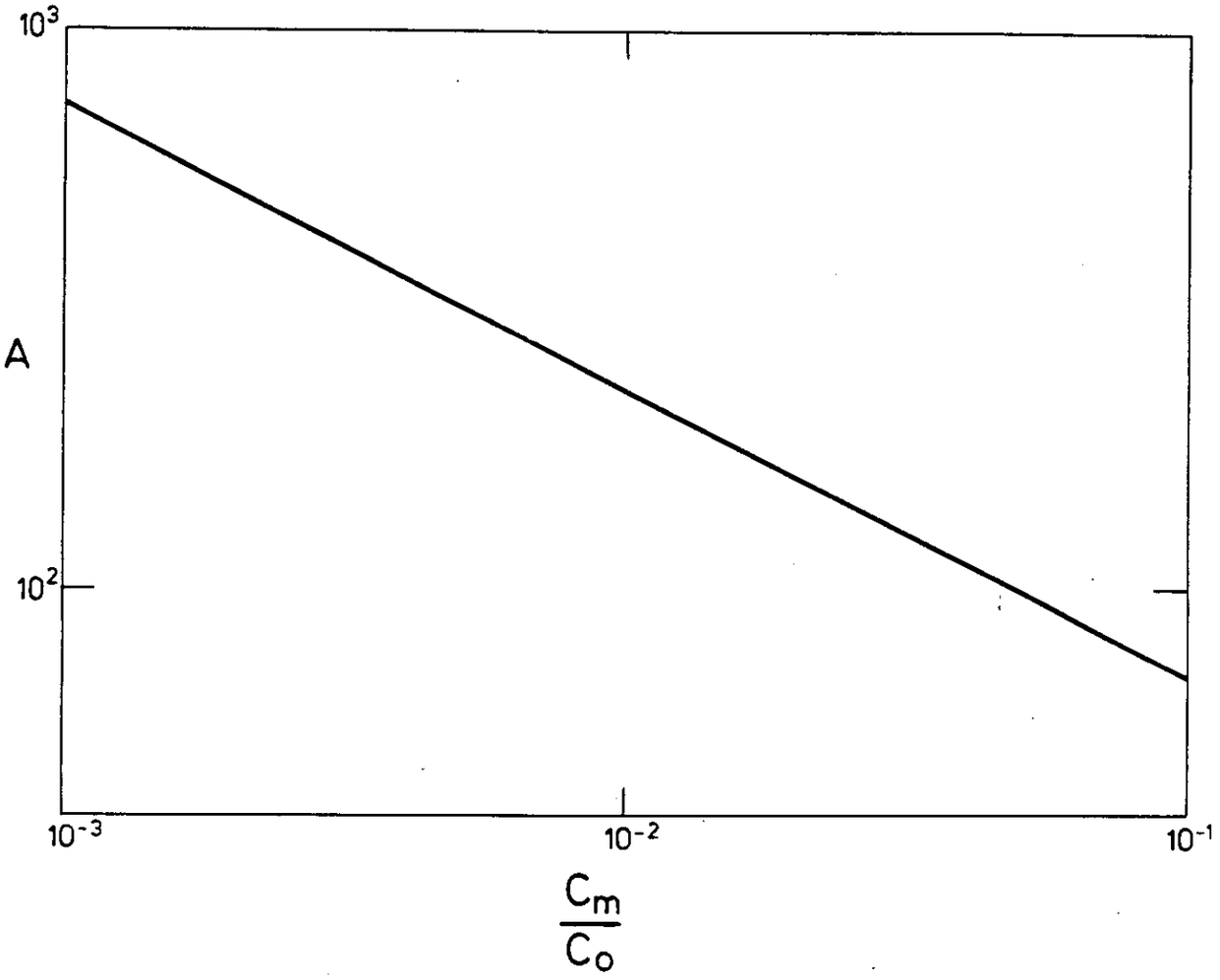


**Figure 9** The variation of the parameter A with concentration.

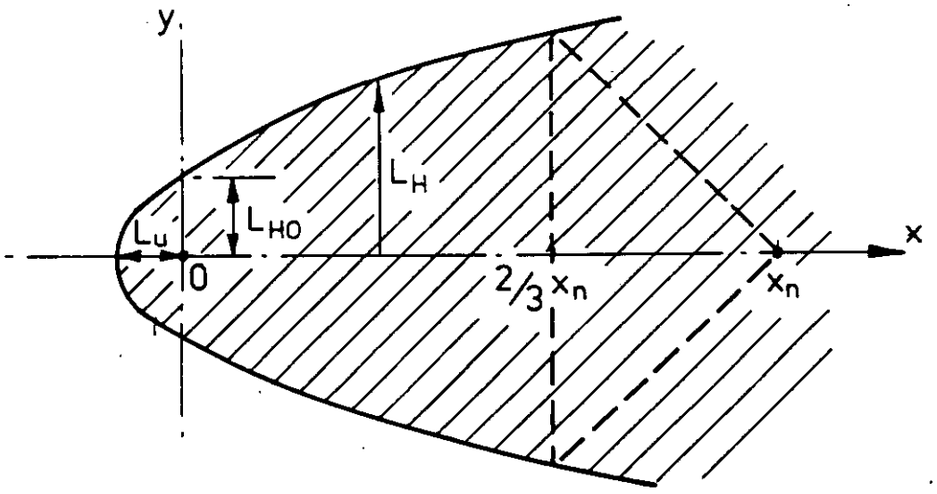


**Figure 10** The representation of the area covered by a concentration contour.

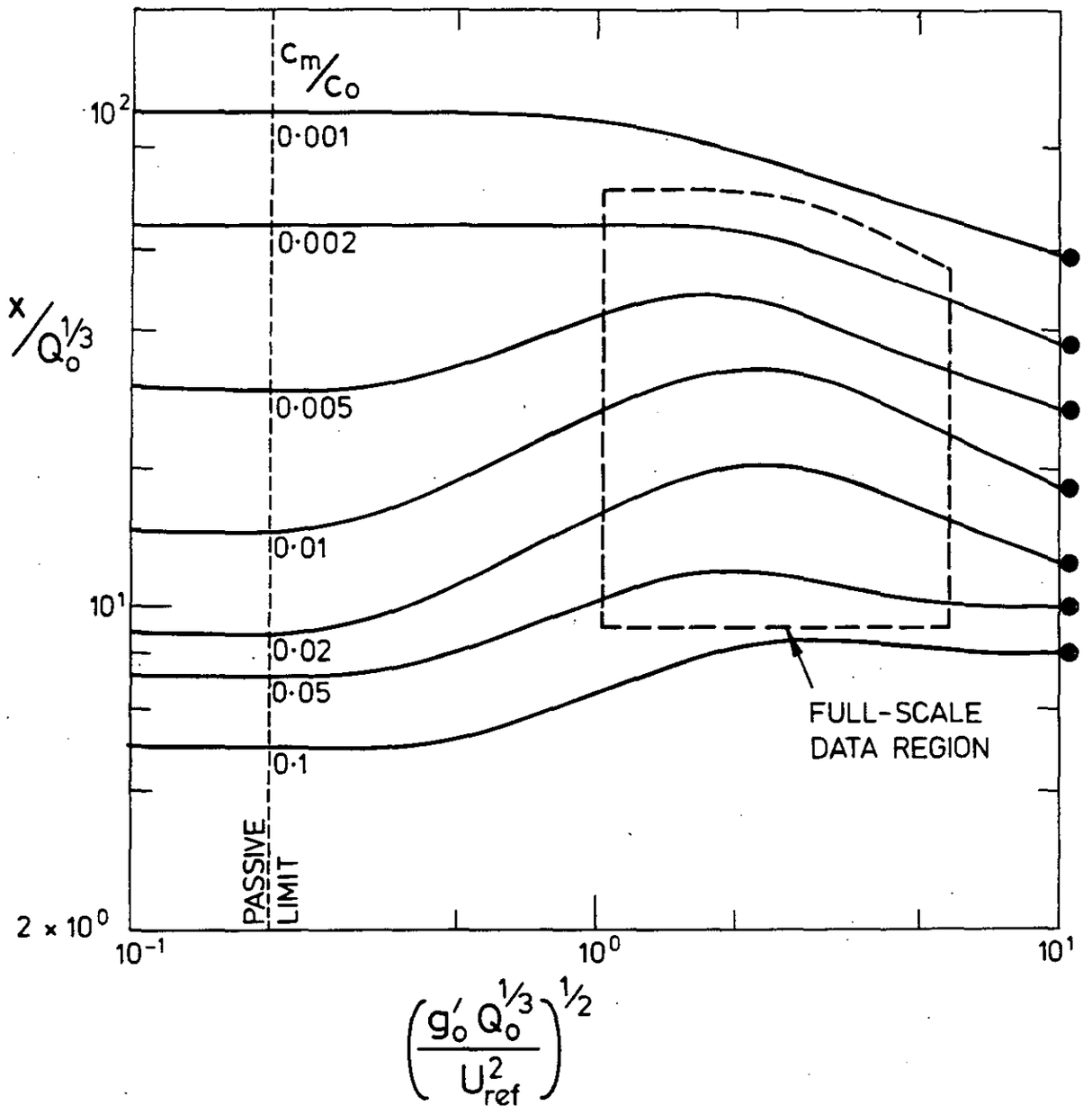


**Figure 11** Correlation for instantaneous releases.

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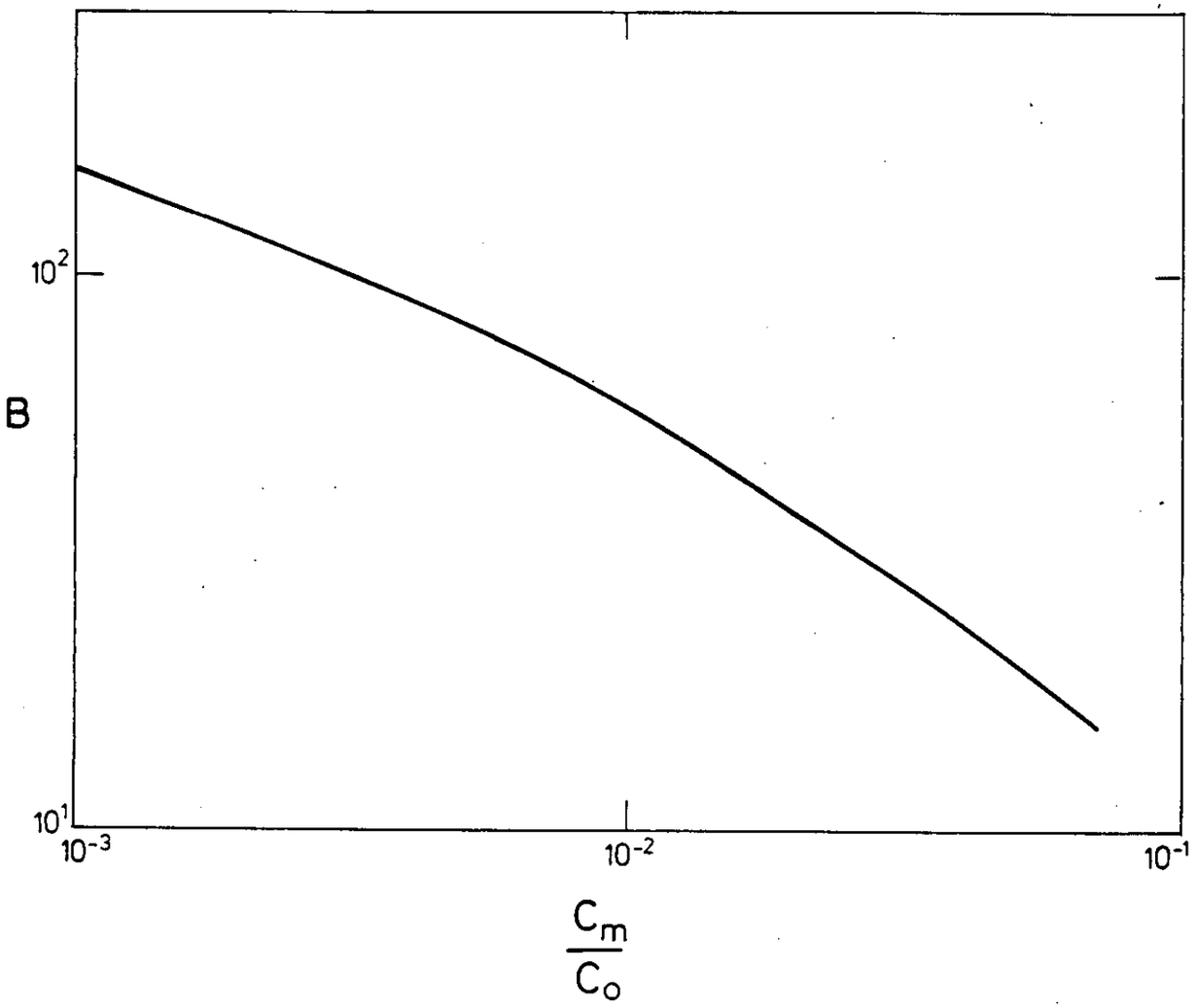


**Figure 12** The variation of the parameter B with concentration.

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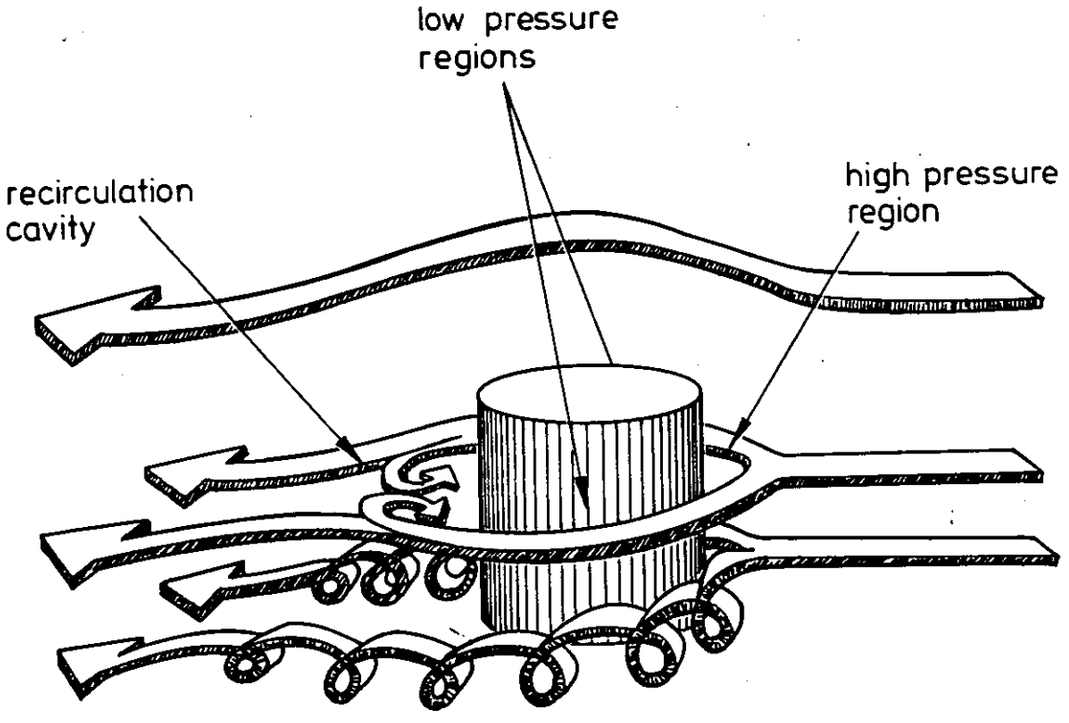


**Figure 13** Flow around a bluff body showing the generation of a recirculation cavity and a horseshoe vortex. (From Rottman et al, 1985)

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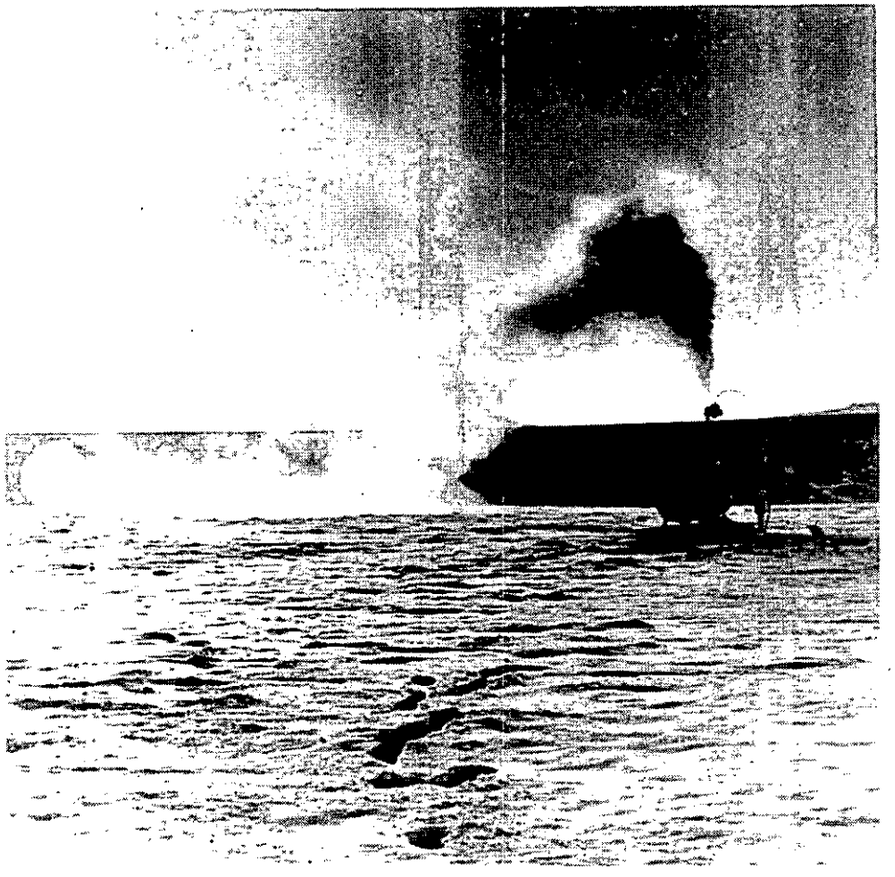

**Figure 14** Bending-over and descent of a vertical jet of dense gas in a cross flow.

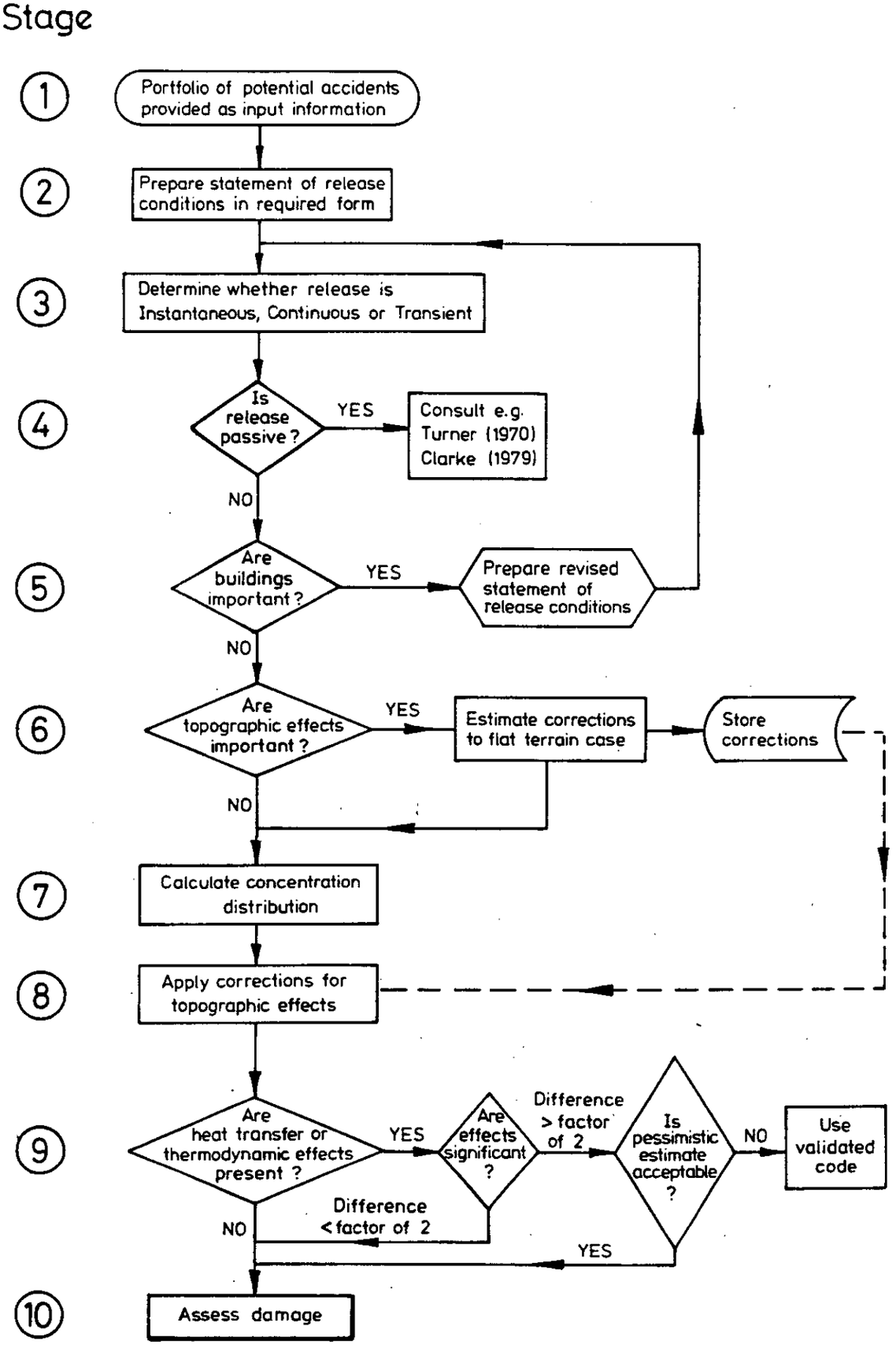


**Figure 15** Flow diagram for assessment of damage from an accident.

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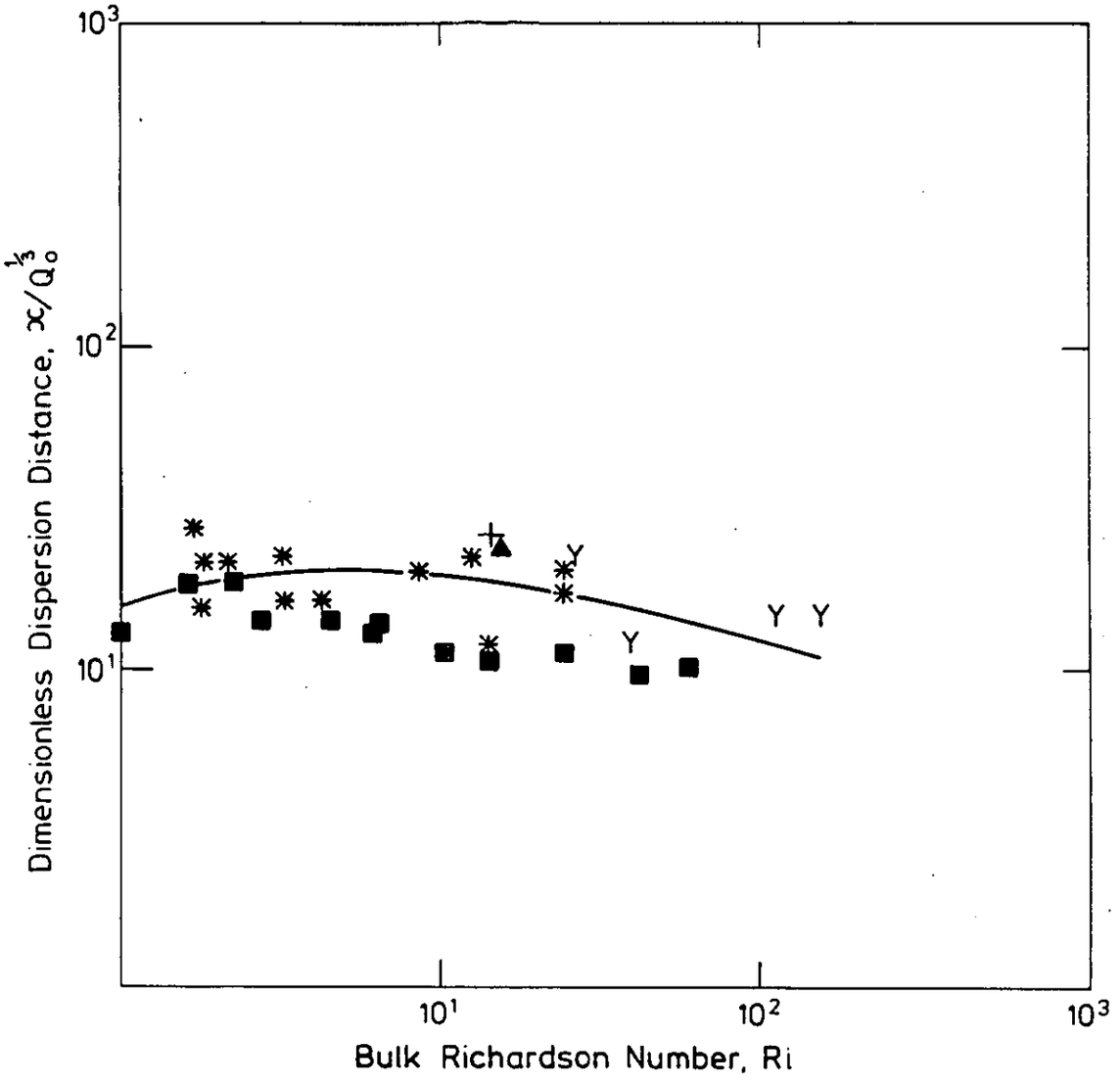


**Figure 16** Comparison of results quoted by Carpenter et al, 1987 (symbols) and workbook correlation (—-).

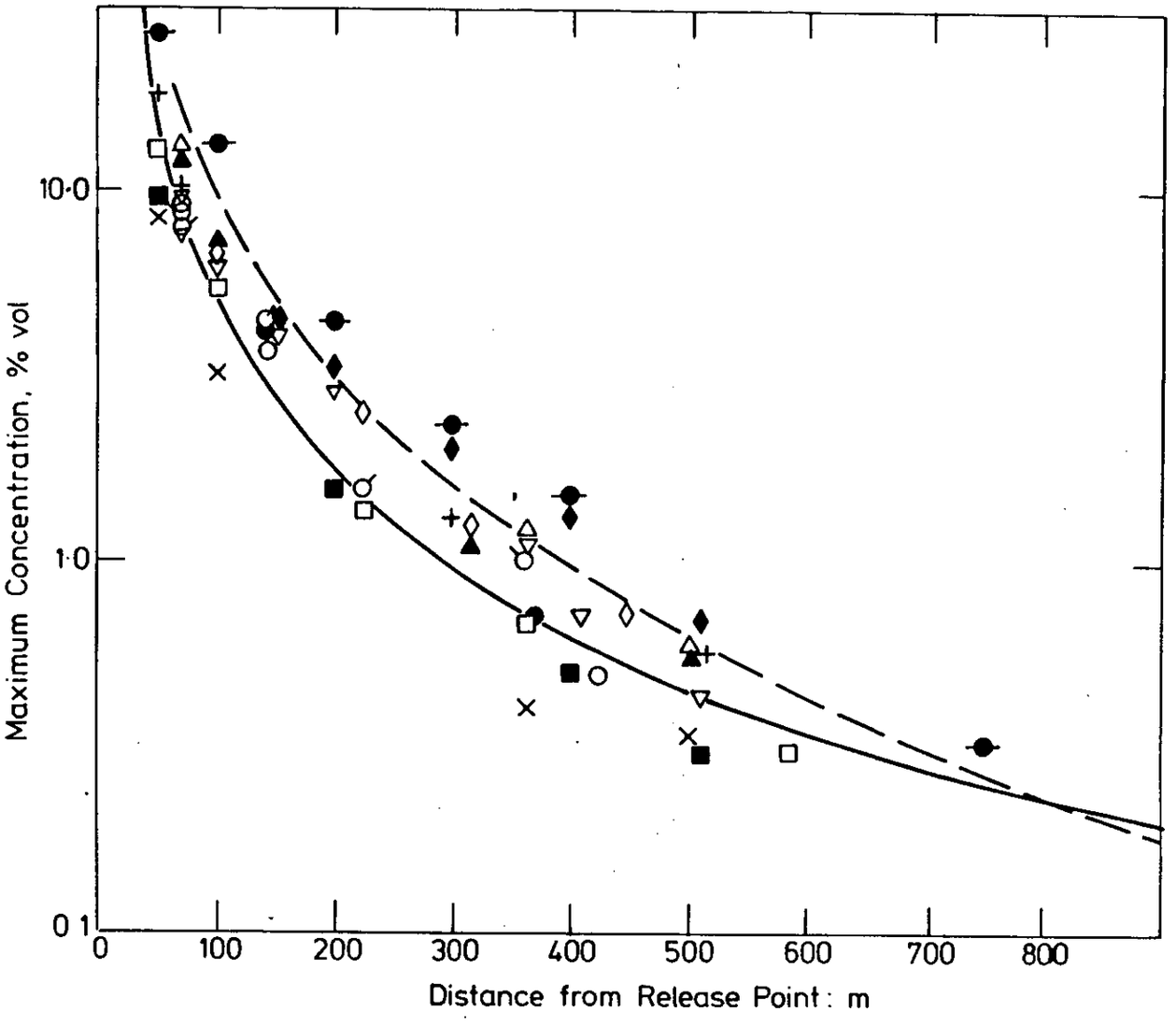


**Figure 17** Comparison of workbook correlation ( - - - ) with Thorney Island trials' data (symbols) and a correlation suggested by Hanna and Drivas, 1987 (——).

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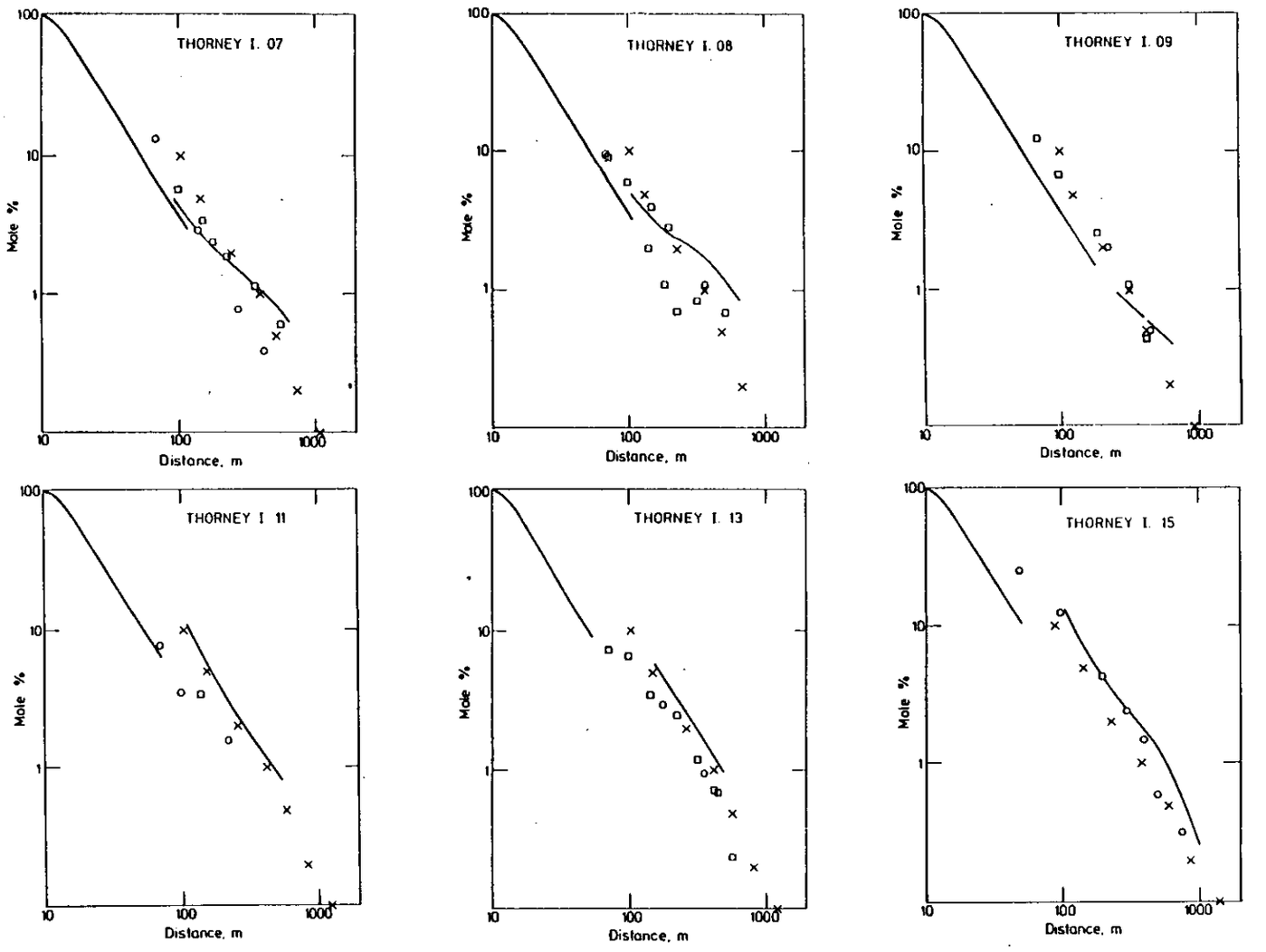


**Figure 18** Comparison with Thorney Island trials' data and predictions using the DEGADIS model by Havens and Spicer (1985). The o (centreline) and □ (near centreline) are measurements. The solid lines are DEGADIS predictions and the × are workbook estimates.

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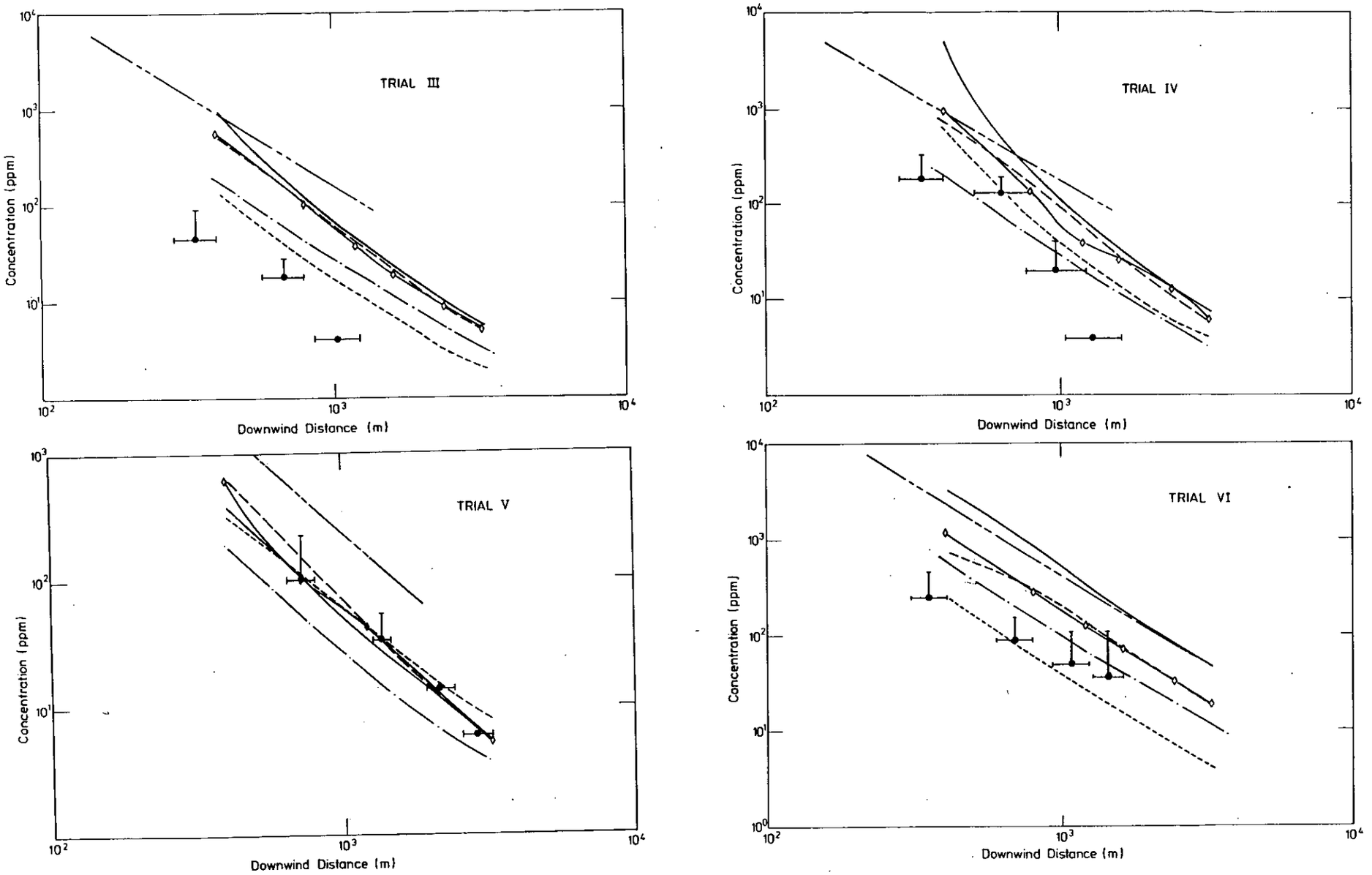


**Figure 19** Comparison of workbook estimates (— - - —) with data from Lyme Bay trials (•) and predictions derived by Wheatley et al (1988). For details of models, see Wheatley et al (1988).

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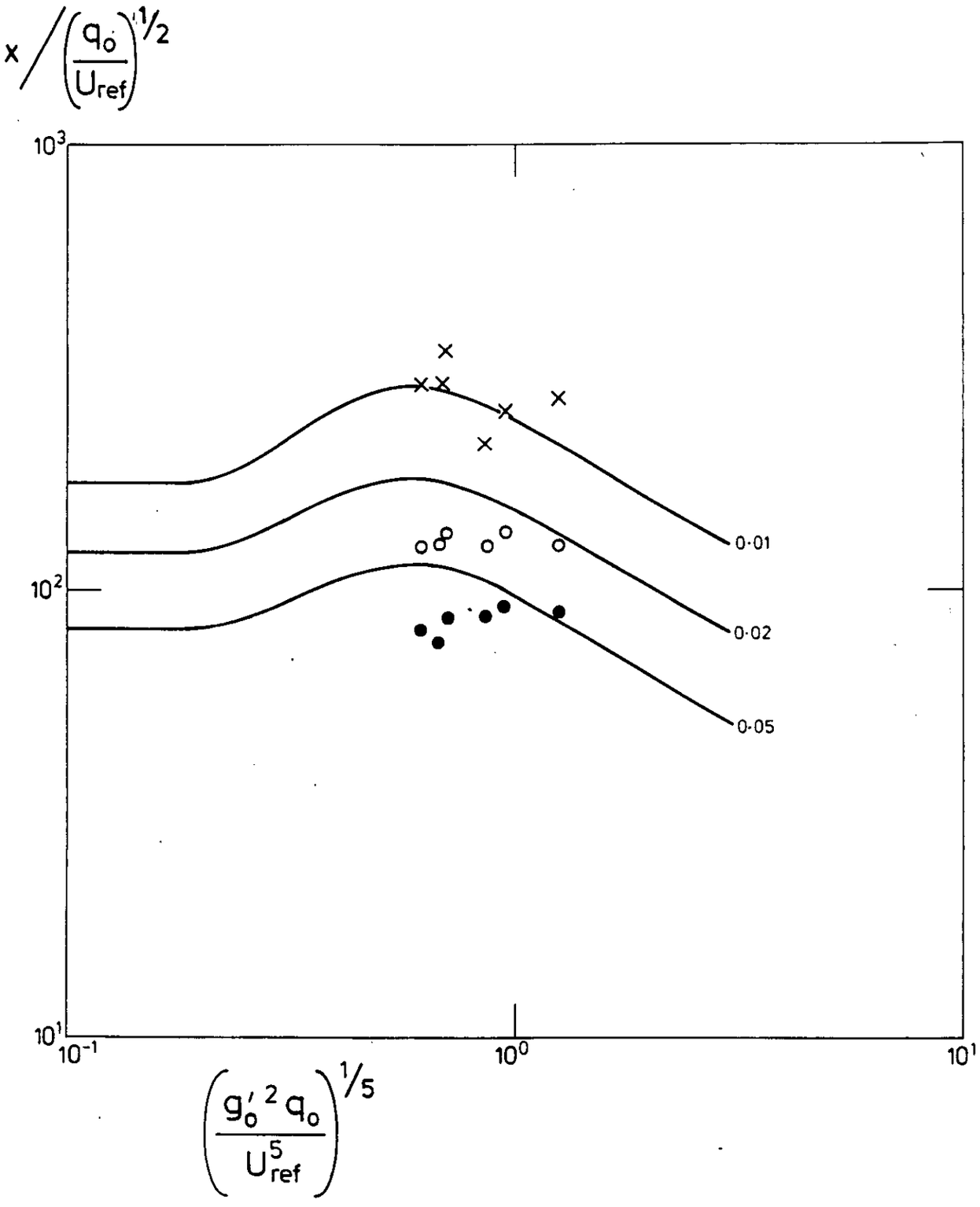


**Figure 20** Comparison of workbook correlations (—) with predictions using the DEGADIS model by Havens and Spicer (1985) for the Maplin Sands continuous propane spills. (× 0.01; ○ 0.025; • 0.05).

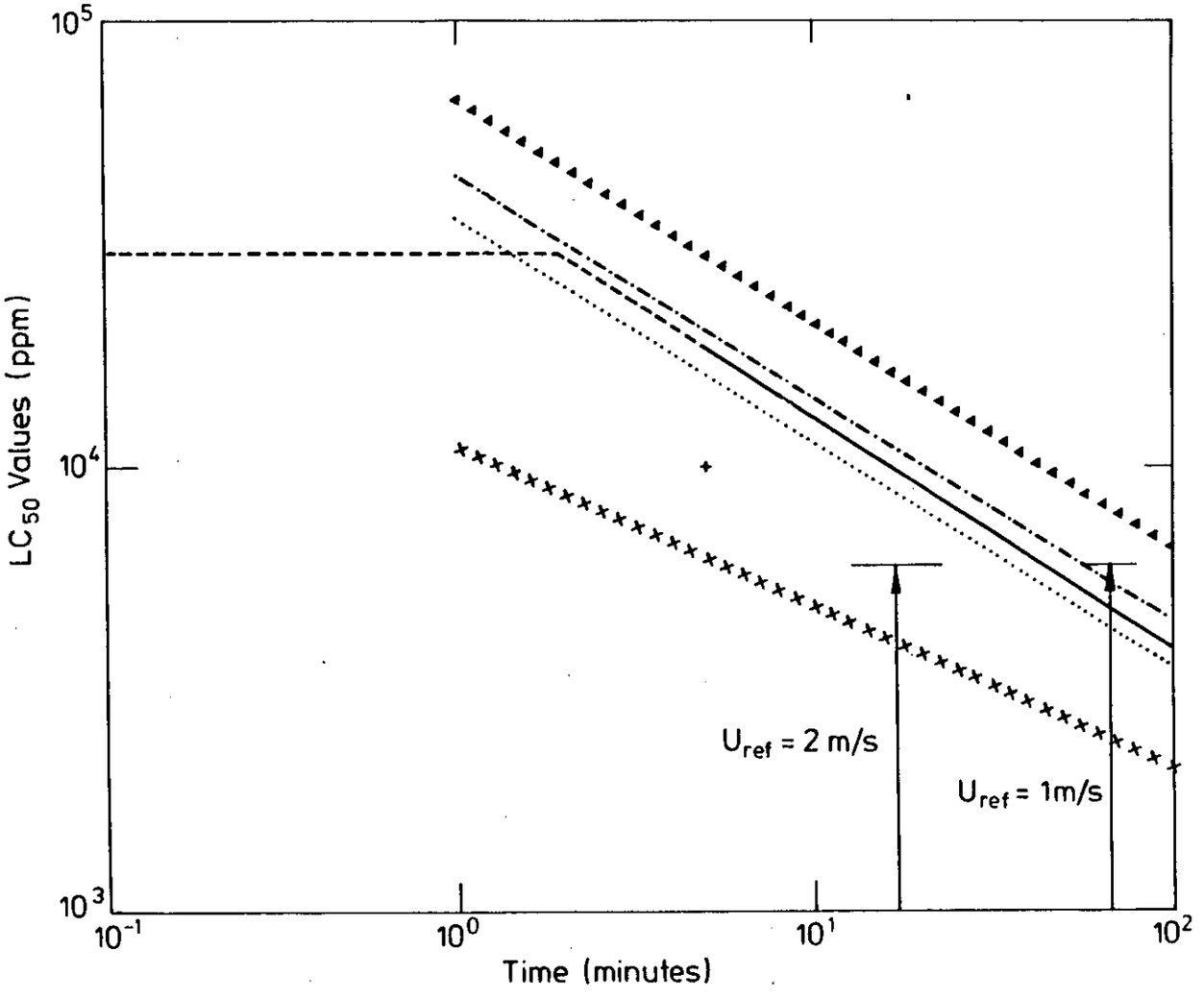


**Figure 21** Comparison of workbook estimates of the concentration range at x = 333m from the release point in the Potchefstroom accident with proposed toxicity relationships for ammonia, (from Engelhardt and Holliday, 1985).

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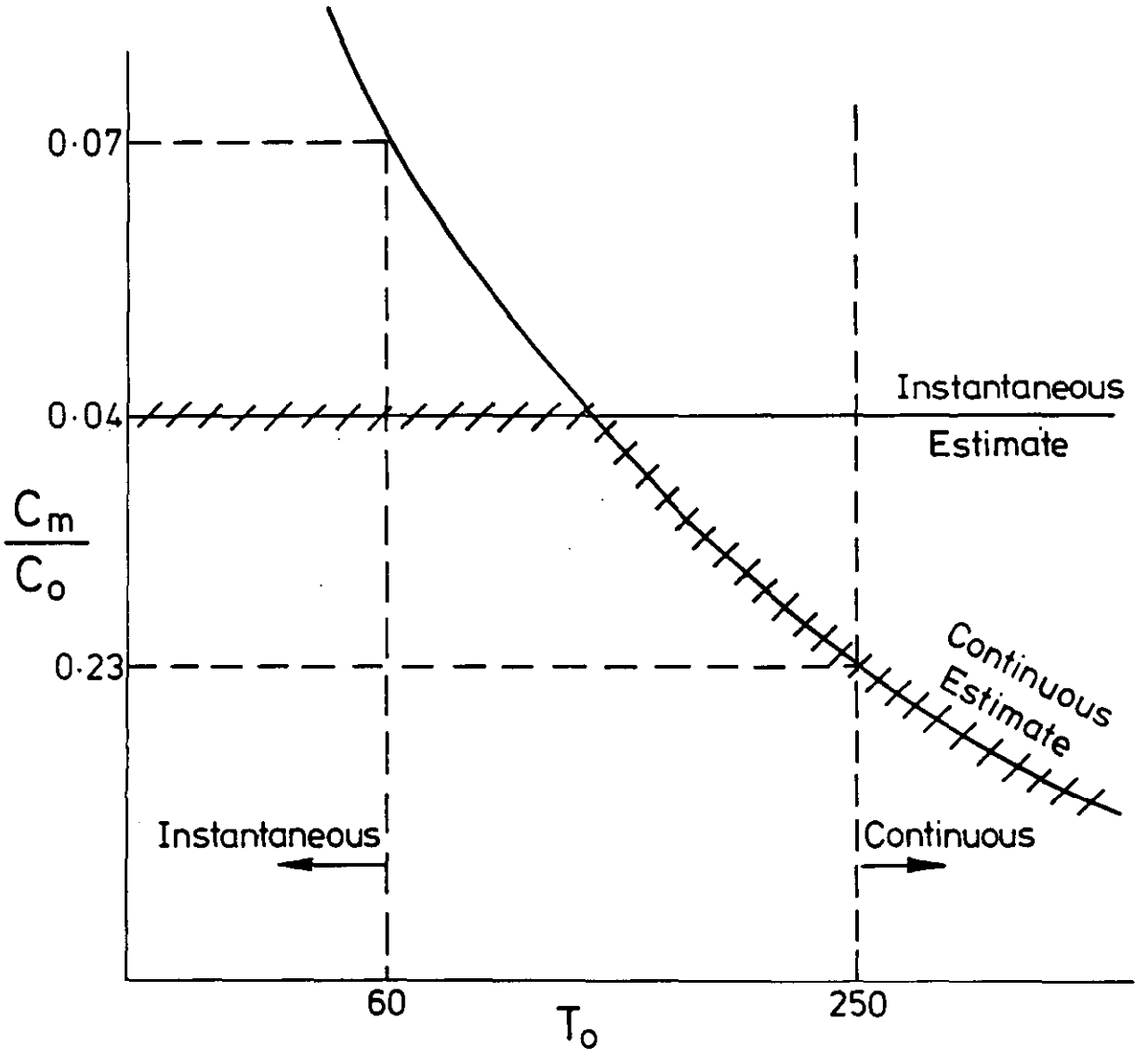



**Figure 22** The recommended treatment for transient releases, illustrated as the hatched portions of the curves.

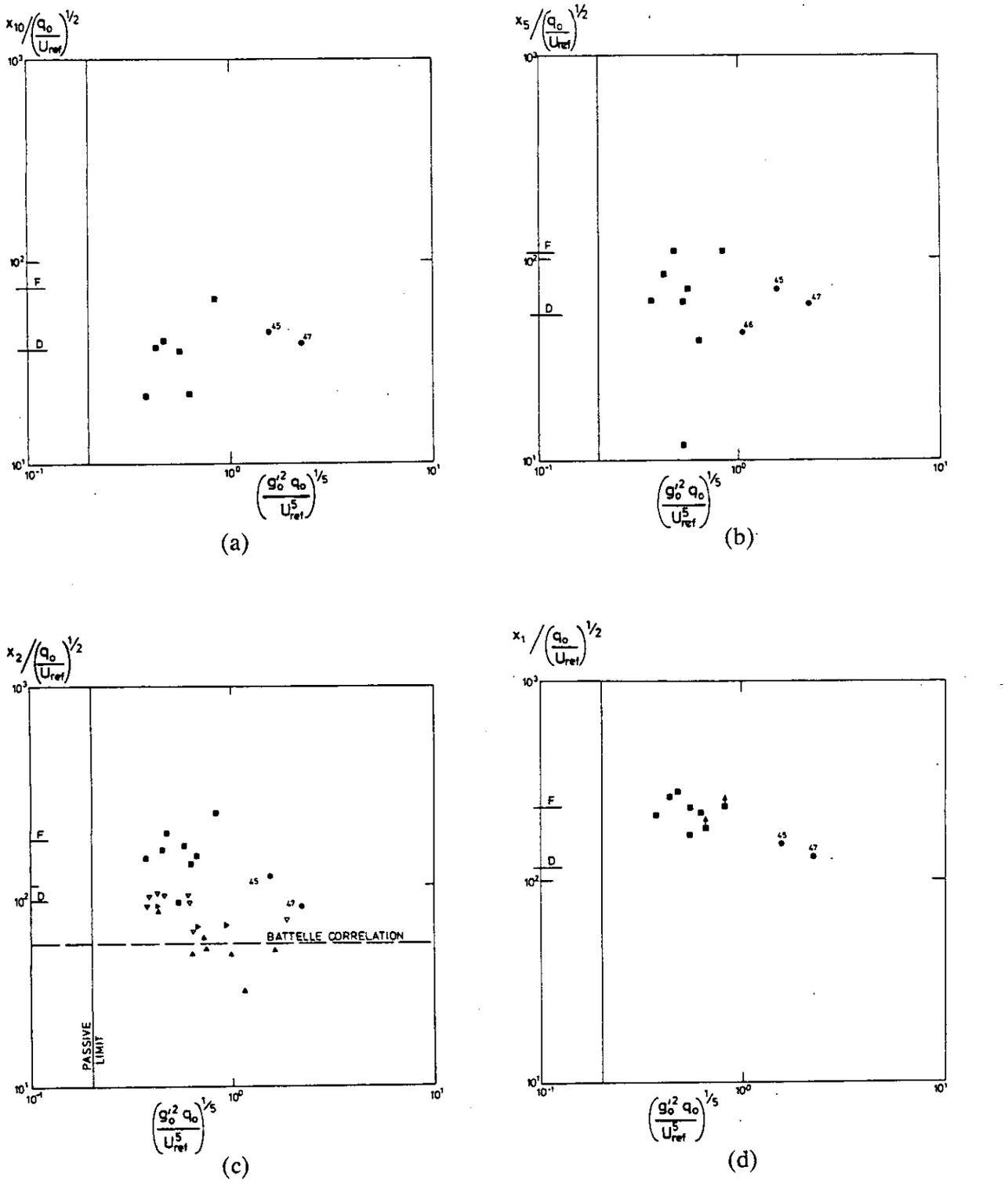



**Figure 23** Experimental results for the downwind distance to a given concentration for continuous releases – large scale data from ■ , Maplin Sands propane tests; ● , Thorney Island freon tests; ▲ , H.S.E. Carbon dioxide tests; ▽ ,Burro series L.N.G. tests and ▶ Coyote series L.N.G. tests.

$\frac{C_m}{C_o}$ = (a) 0.1 (b) 0.05 (c) 0.02 (d) 0.01

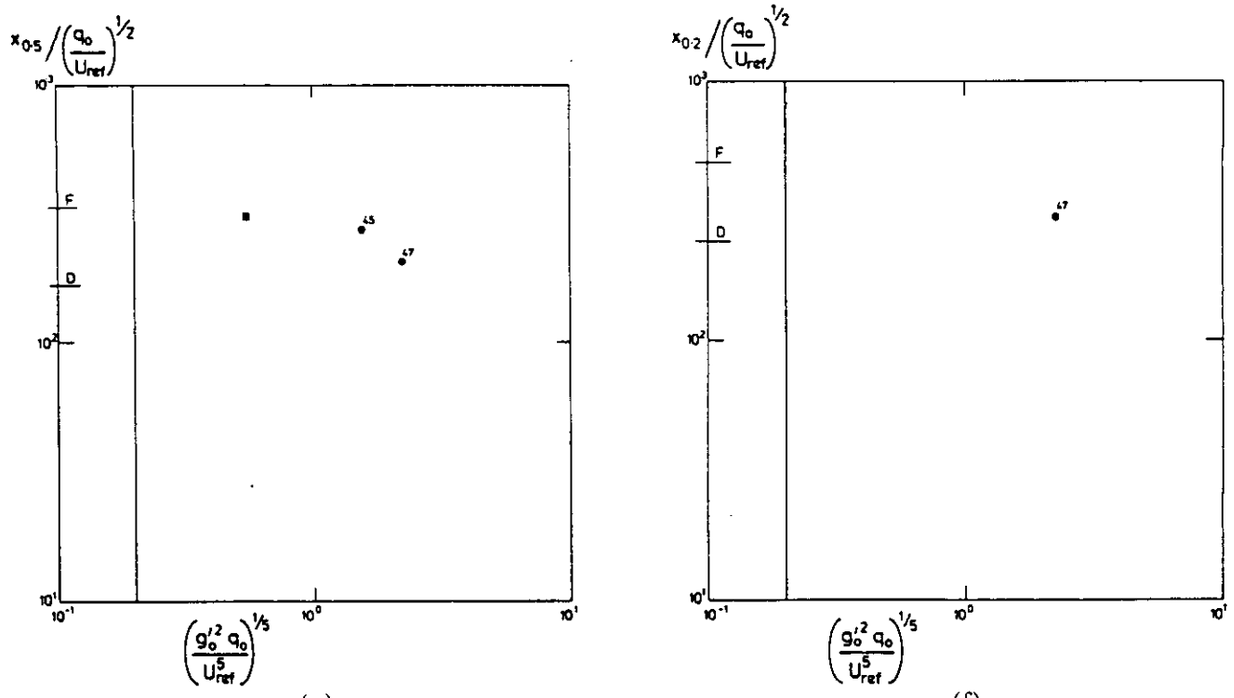



**Figure 23** Experimental results for the downwind distance to a given concentration for continuous releases – large scale data from ■ , Maplin Sands propane tests; ● , Thorney Island freon tests; ▲ , H.S.E. Carbon dioxide tests; ▽ ,Burro series L.N.G. tests and ▶ Coyote series L.N.G. tests.

$\frac{C_m}{C_o}$ = (e) 0.005 (f) 0.002.

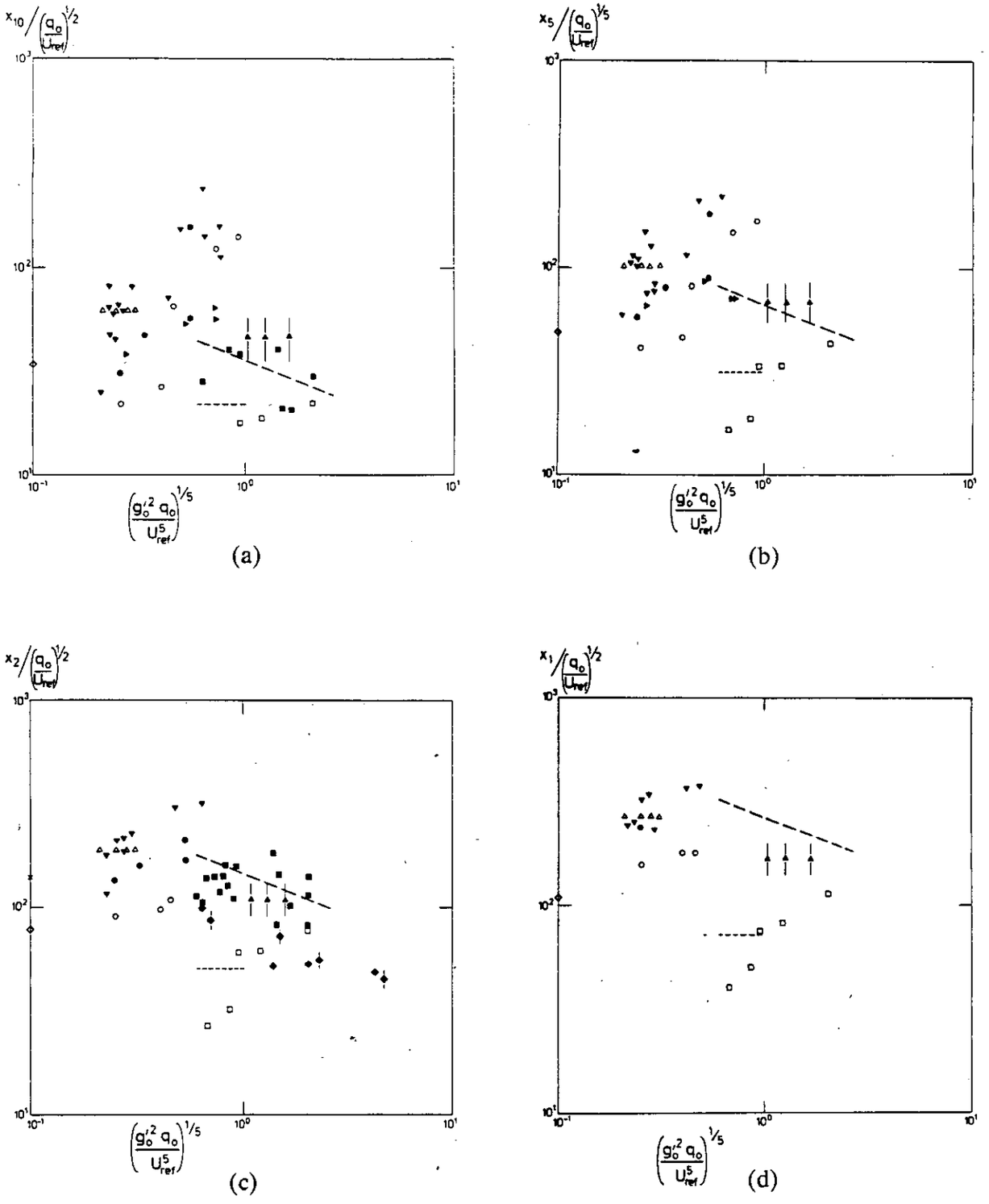



**Figure 24** Experimental results for the downwind distance to a given concentration for continuous releases – laboratory data. Data from Hall et al (1974), ▲ ; Hall (1979), □ ; Britter (unpublished), ▼ ; Stretch (1986), △ ; Cheah et al (1984), ,○ ● ; Janssen (1981), ♦ ; Meroney (1977) – – – -; Meroney and Neff (1982), ▶ ; Neff and Meroney (1981), ◇ , ■ ,—— ——·

$\frac{C_m}{C_o}$ = (a) 0.1 (b) 0.05 (c) 0.02 (d) 0.01

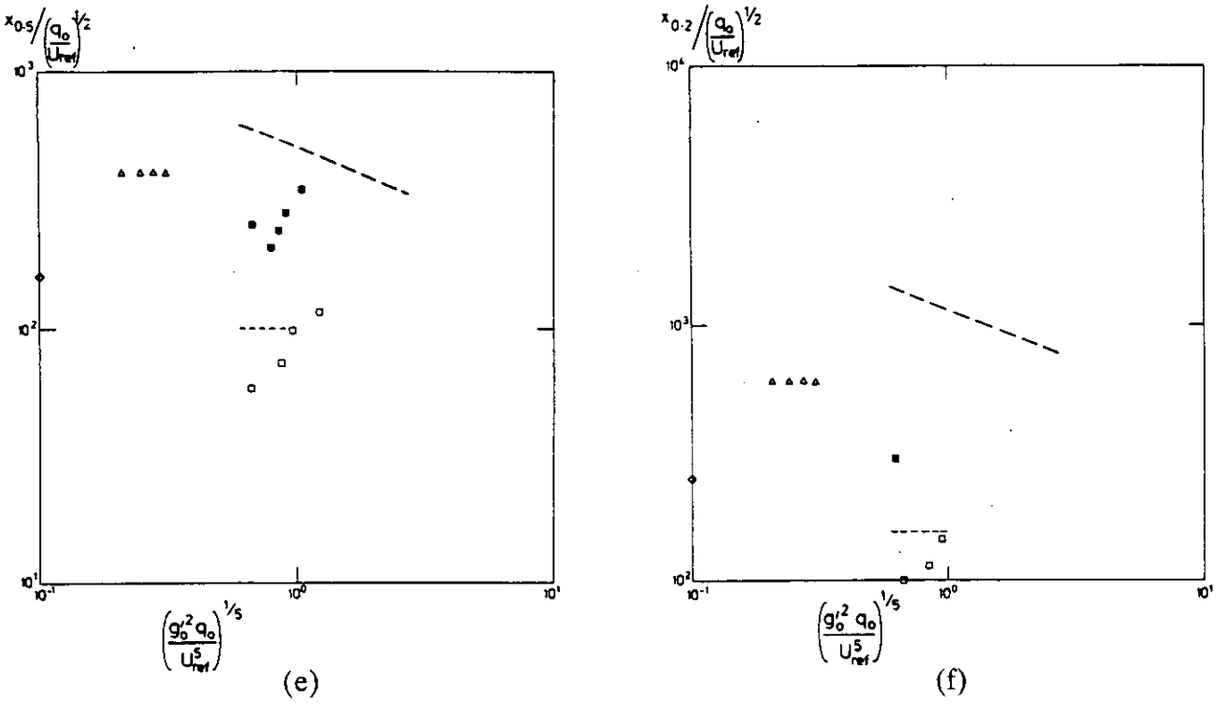



**Figure 24** Experimental results for the downwind distance to a given concentration for continuous releases – laboratory data. Data from Hall et al (1974), ▲ ; Hall (1979), □ ; Britter (unpublished), ▼ ; Stretch (1986), △ ; Cheah et al (1984), ,○ ●; Janssen (1981), ♦ ; Meroney (1977) - - - -; Meroney and Neff (1982), ▶ ; Neff and Meroney (1981), ◊ , ■ ,—— ——

$$\frac{C_m}{C_o} = \text{(e) } 0.005 \text{ (f) } 0.002$$

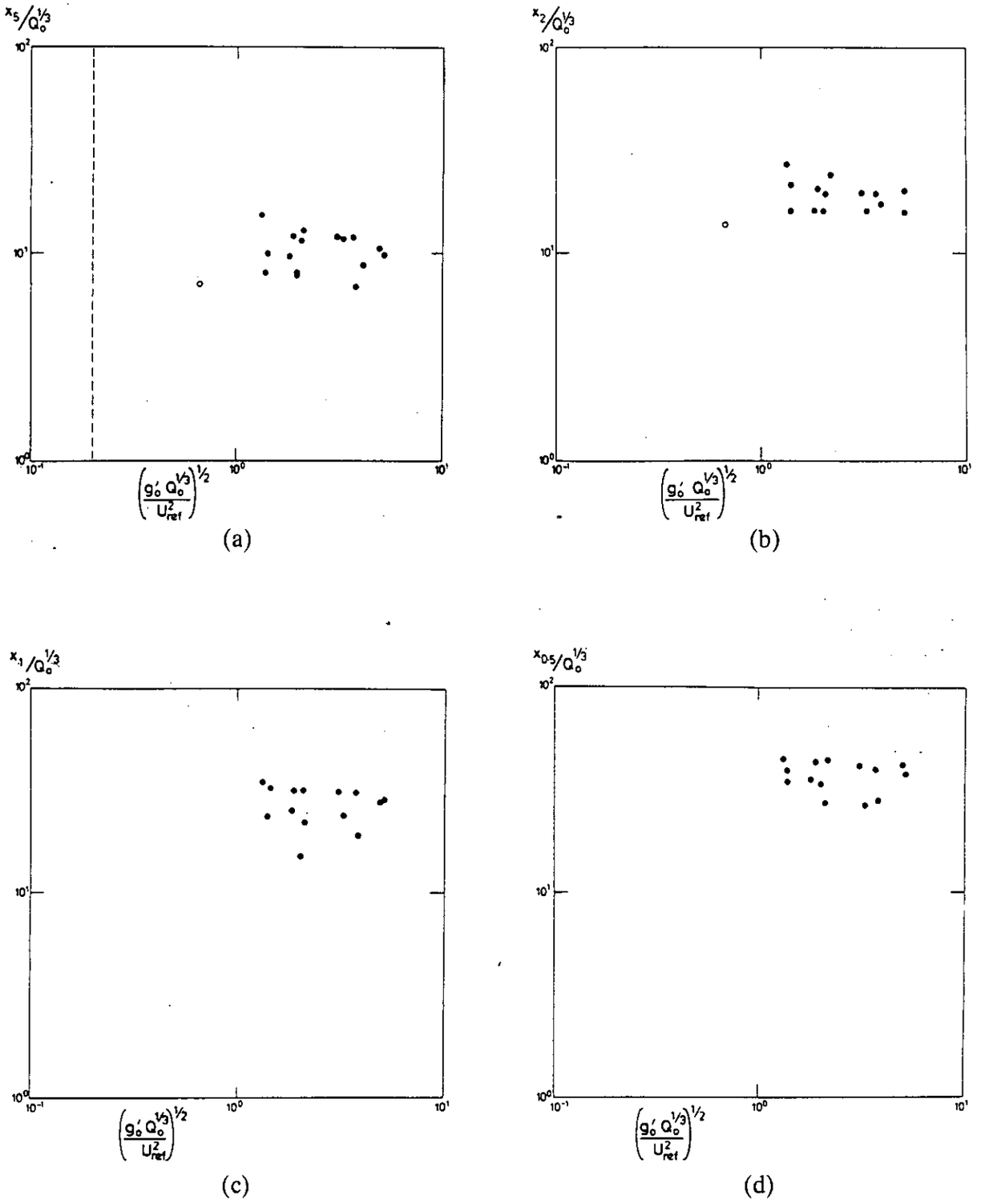
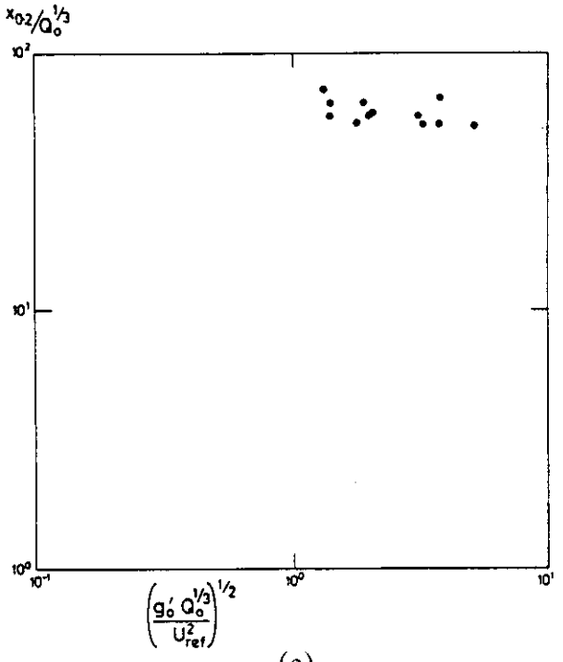



**Figure 25** Experimental results for the downwind distance to a given concentration for instantaneous releases – large scale data. Date from Thorney Island tests, ● , Porton Down test ○ .

$\frac{C_m}{C_o}$ = (a) 0.05 (b) 0.02 (c) 0.01 (d) 0.005




(e)

**Figure 25** Experimental results for the downwind distance to a given concentration for instantaneous releases – large scale data. Date from Thorney Island tests, ● , Porton Down test O .

$$\frac{C_m}{C_o} = \text{(e) } 0.002.$$

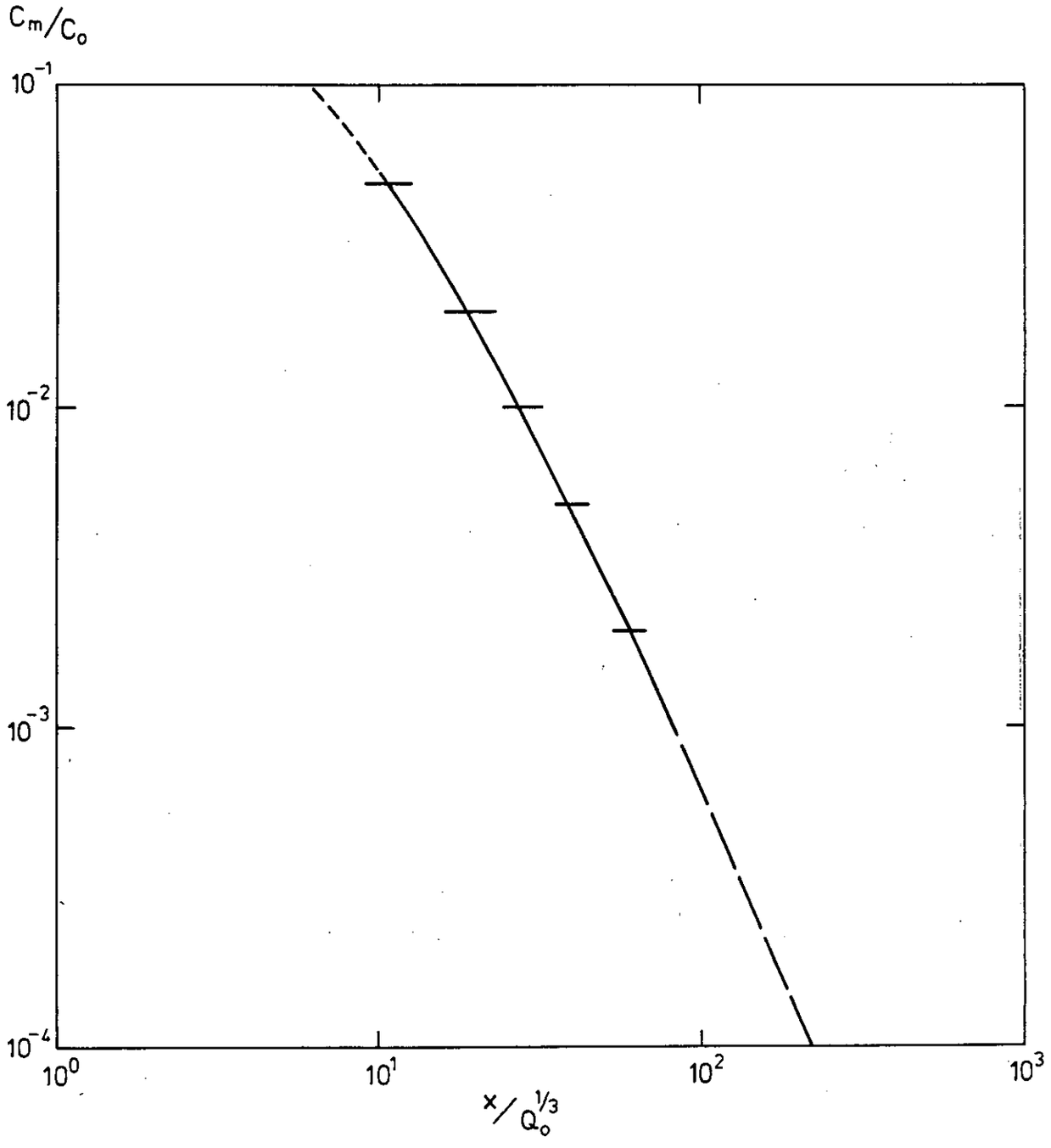



**Figure 26** Averaged large scale data for instantaneous releases within the quoted range of stability parameter (see text).

Contents

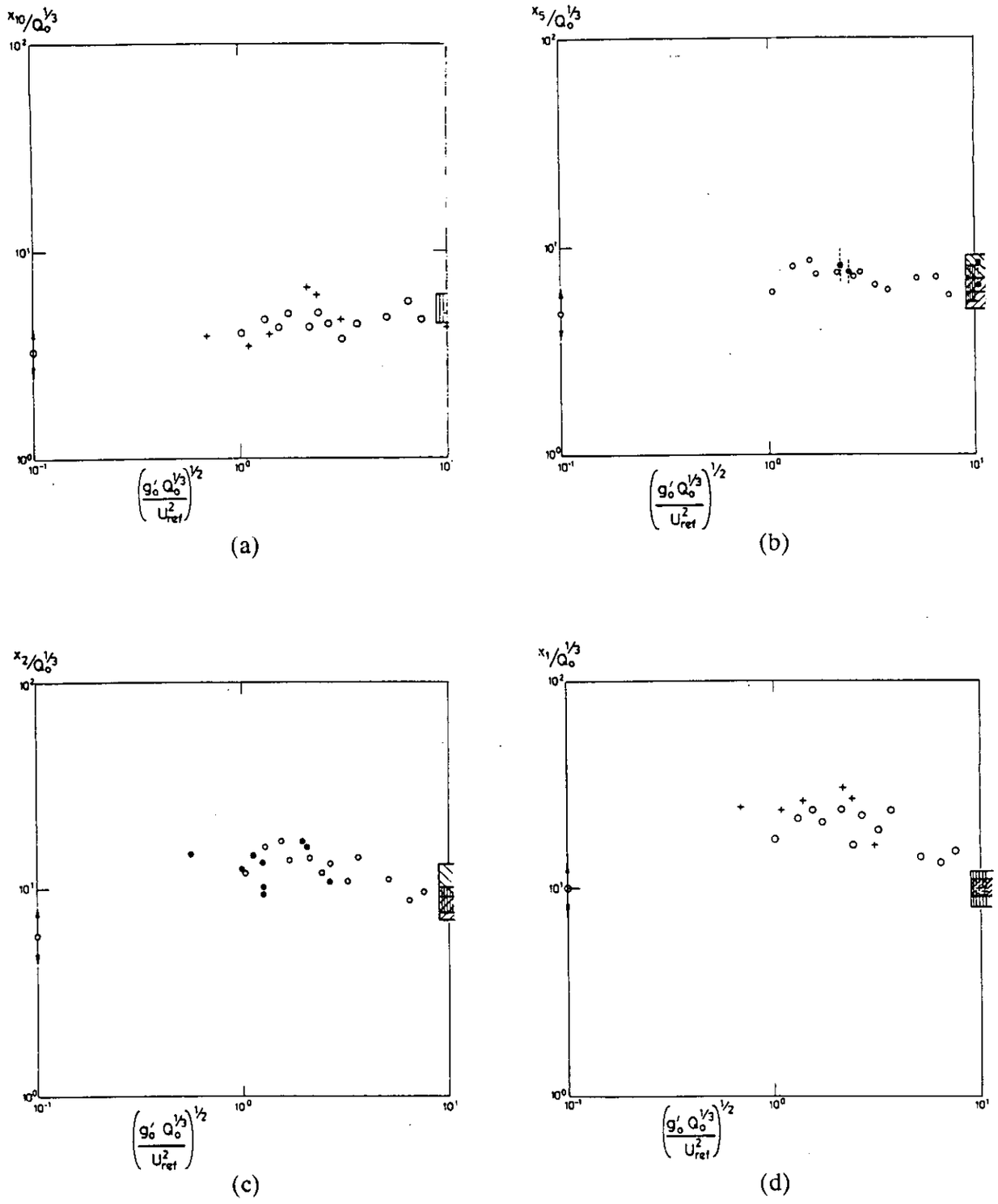
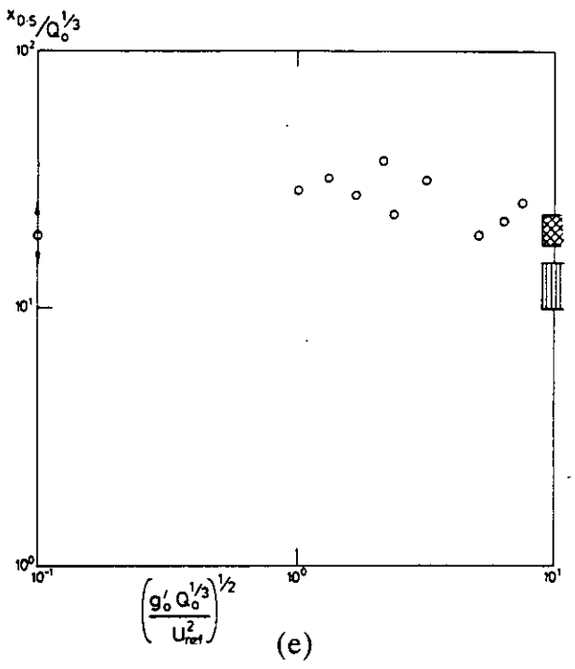
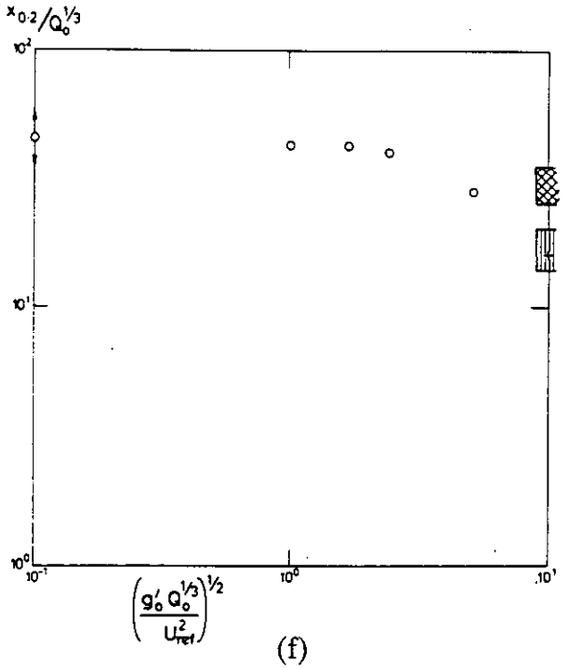



**Figure 27** Experimental results for the downwind distance to a given concentration for instantaneous releases – laboratory data. Data from Meroney and Lohmeyer (1982), O , ▥ ; deduced from Meroney and Lohmeyer data in calm conditions but satisfying energy conservation ▩ ; Hansen (1981), ⋮● ; Havens and Spicer (1985), ▨ ; Hall et al (1982), Hall and Waters (1985), + , ● , ▨ .

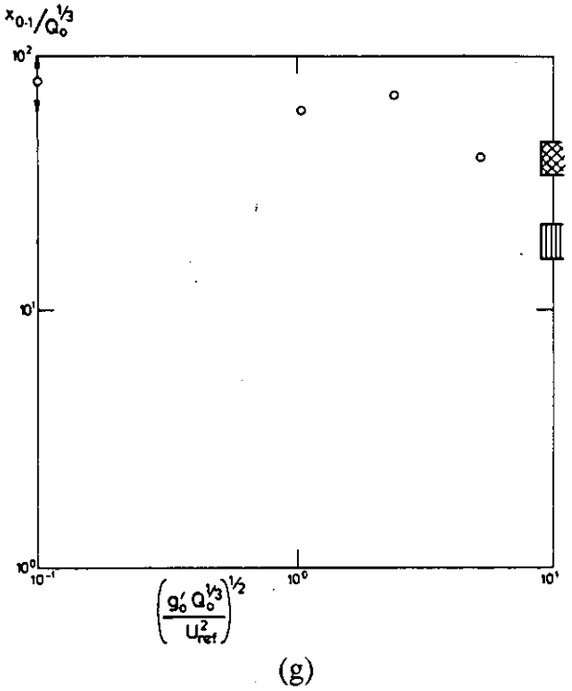
$\frac{C_m}{C_o}$ = (a) 0.1 (b) 0.05 (c) 0.02 (d) 0.01




(e)




(f)




(g)

**Figure 27** Experimental results for the downwind distance to a given concentration for instantaneous releases – laboratory data. Data from Meroney and Lohmeyer (1982), o , ▥ ; deduced from Meroney and Lohmeyer data in calm conditions but satisfying energy conservation ▩ ; Hansen (1981), ● ; Havens and Spicer (1985), ▨ ; Hall et al (1982), Hall and Waters (1985), +, ●, ▨.

$\frac{C_m}{C_o}$ = (e) 0.005 (f) 0.002 (g) 0.001.

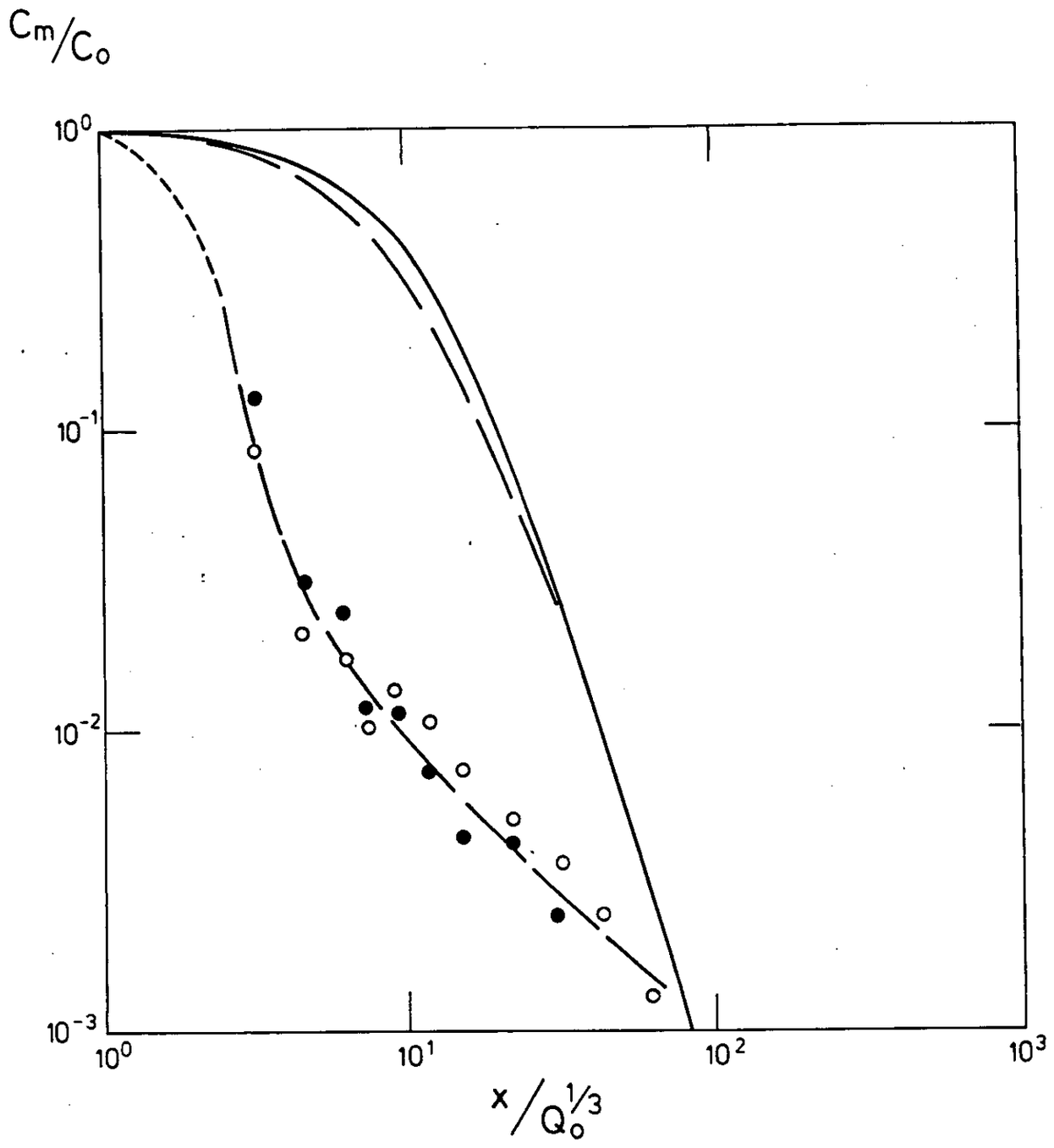



**Figure 28** $C_m/C_o$ versus $(x/Q_o)^{\frac{1}{3}}$ for instantaneous passive releases. Estimate from Beals (1971), Turner (1970) ———, from Lagrangian similarity arguments — ——— . Data from Meroney and Lohmeyer (1982); different symbols indicate different release volumes, ——— ——— . . . . . is possible interpolation for laboratory experiments.

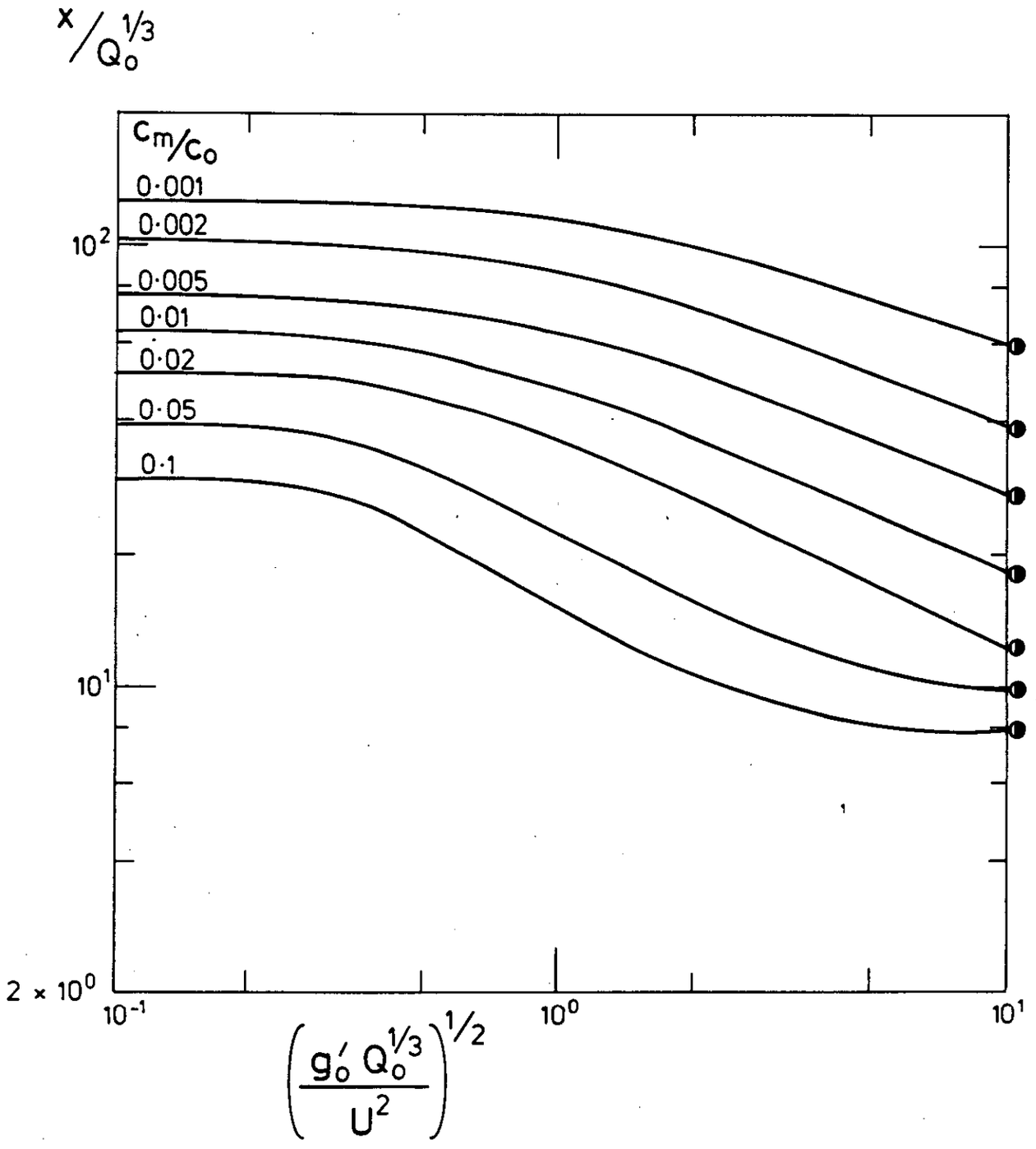



**Figure 29** Suggested modification of Fig. 11 if initial dilution already accounted for.

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