

**Atmospheric Dispersion Modelling
Liaison Committee**

Annual Report 2003/2004

INCLUDING

**Modelling of atmospheric dispersion for releases
from fires**

AND

Review of past work funded by ADMLC

PREFACE

In 1977 a meeting of representatives of government departments, utilities and research organisations was held to discuss methods of calculation of atmospheric dispersion for radioactive releases. Those present agreed on the need for a review of recent developments in atmospheric dispersion modelling, and a Working Group was formed. Those present at the meeting formed an informal Steering Committee, that subsequently became the UK Atmospheric Dispersion Modelling Liaison Committee. That Committee operated for a number of years. Members of the Working Group worked voluntarily and produced a series of reports. A workshop on dispersion at low wind speeds was also held, but its proceedings were never published.

The Committee has been reorganised and has adopted terms of reference. The organisations represented on the Committee, and the terms of reference adopted, are given in this report. The organisations represented on the Committee pay a small annual subscription. The money thus raised is used to fund reviews on topics agreed by the Committee, and to support in part its secretariat, provided by NRPB. The new arrangements came into place for the start of the 1995/96 financial year. This report describes the ninth year in which the Committee has operated under the new arrangements, and during which it placed two contracts. These covered a review of atmospheric dispersion modelling for releases from fires and a review of the work previously funded by the committee. The technical specifications for the contracts are given in this report, and the contract reports are attached as annexes to this report. The Committee funded nineteen studies in previous years; they are described in its earlier annual reports.

The Committee intends to place further contracts in future years and would like to hear from those interested in tendering for such contracts. They should contact the Secretary:

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1 ORGANISATIONS REPRESENTED ON THE COMMITTEE

The organisations on the committee during the year covered by this report were:

Amersham plc

Atomic Weapons Establishment, Aldermaston

British Nuclear Fuels plc

BNFL Magnox Generation

Defence Science and Technology Laboratory

Department for Environment Food and Rural Affairs (DEFRA)

Environment and Heritage Service, Northern Ireland

Environment Agency

Food Standards Agency

Health and Safety Executive

Methodology and Standards Development Unit, Hazardous Installations Directorate

Nuclear Installations Inspectorate

Health Protection Agency

Meteorological Office

National Nuclear Corporation

National Radiological Protection Board

Nuclear Department, HMS Sultan

Rolls Royce Naval Marine

Scottish Environment Protection Agency

Shell Global Solutions

Westlakes Research Institute

The Chairman and Secretary are provided by NRPB.

2 TERMS OF REFERENCE

The terms of reference of the committee were revised at the start of the year covered by this report. The revised terms of reference are:

Areas of technical interest

1. ADMLC's main aim is to review current understanding of atmospheric dispersion and related phenomena for application primarily in authorization or licensing of discharges to atmosphere resulting from industrial, commercial or institutional sites. ADMLC is primarily concerned with dispersion from a particular regulated site or from discrete sources, and will not normally consider work in the following areas: traffic pollution, acid rain and ozone.
2. ADMLC is concerned both with releases under controlled conditions occurring at a constant rate over long periods, and with releases over shorter periods such as accidents or controlled situations where the release rate varies.
3. ADMLC is concerned with modelling dispersion at all scales, including on-site and within buildings.

Organisations and outputs

4. The Committee shall consist of representatives of Government Departments, Government Agencies and organisations with an interest in modelling dispersion of material for the situations identified above. Each organisation represented on the Committee shall pay an annual membership fee.
5. ADMLC believes that it can be most effective by limiting its membership to about 25 organisations. New organisations will only be admitted to membership of ADMLC if the majority of existing members agree to their membership.
6. ADMLC aims to review, collate, interpret and encourage research into applied dispersion modelling problems. It does not endorse particular brands or suppliers of commercial models. However, it is concerned to ensure that users for industrial applications are aware of what is available, how it can be applied to particular problems and of the uncertainties in the results.
7. The Committee will commission work on selected topics. These should be selected following discussion and provisional agreement at meetings of the Committee, followed by confirmation after the meeting. It will produce reports describing current knowledge on the topics. These may be reports from contractors chosen by the committee or may be based on the outcome of conferences or workshops organised on behalf of the committee. The money raised from membership fees will be used to fund contractors, organise workshops and report on their outcome, and any other matters which the Committee may decide.

3 WORK FUNDED DURING THE YEAR

3.1 Modelling of atmospheric dispersion for releases from fires

The Atmospheric Dispersion Modelling Liaison Committee wishes to fund work for a review of models for plume rise and for calculating the atmospheric dispersion of material released in a fire.

The contractor should review and compare different models for plume rise, and their validation. In particular, are the models validated for the height of the plume centre line, or the concentration at ground level.

The work relating to fires should address the capabilities of current models to describe the dispersion of material from a range of different types and intensities of fire, including

- a Fires in large buildings, such as warehouses, where only a small part of the building is affected by the fire and the building remains intact
- b Fires in buildings where a large part of the building suffers damage and material is released from most of one face or through a severely damaged roof. Any differences in the modelling for different building sizes, shapes and orientations to the wind should be identified.
- c A fire at a location unaffected by building effects; for example, an intense fire following an aircraft crash in the open countryside.

The review should include the following items:

- a The calculation of air concentration at ground level underneath a rising plume.
- b What models are available for the different aspects identified above.
- c The range of values for the buoyancy parameters to be used in calculations relating to fires of different intensities.
- d The likely particle size of material released into the atmosphere.
- e The calculation of air concentration at short distances from a burning building or transport accident involving a fire.

The study is not intended simply to be a review of available information but should, where possible, provide guidance to model users on the most appropriate approach for the situations considered.

The report on this work is published as [ADMLC/2003/1](#).

3.2 Review of previous work

ADMLC and the Working Group which preceded it have published a number of reports, starting with NRPB-R91. In some cases, similar topics have been

covered in more than one report. ADMLC requires the following work undertaking:

1. Prepare a summary of all work that has been carried out by ADMLC and the Steering Committee and Working Group from which it was formed. The work must cover all reports from NRPB-R91 to the work carried out for ADMLC in the 2002/03 financial year. This document is intended for use within ADMLC for the following purposes:
 - Identifying items in existing reports
 - Identifying gaps or overlaps where similar topics have been addressed in different ADMLC reports
 - Summarising previous work as a basis for identifying future needs of the Committee
2. The document should be limited to considering what is in the existing reports. It is not intended that this review will identify work since the reports were published which might be used to update the existing reports.
3. ADMLC has supported a number of contracts on items loosely related to meteorological data. A summary of the relationship between these reports, and the overall position on choice of met data for dispersion models is also required, as part of the review in item 1.
4. Identify ways in which items in existing reports can be easily located, such as a key-word index which could be incorporated in the report from item 1 if this were published on the ADMLC web site.
5. Copies of all existing reports should be placed on the ADMLC web site.

The report on this work is published as [ADMLC/2003/2](#)

A Review of Models for Dispersion Following Fires

D.J. Hall, A.M. Spanton. Envirobods Ltd.

ABSTRACT

This review examines the properties of buoyant plumes at short ranges associated with surface fires or fires within buildings that discharge through the building surfaces. The fire plume is the main source of exposure to fire products and its effective prediction is a critical feature of hazard assessment. Though there is a substantial literature on buoyant plumes in air pollution, these are mainly related to elevated point sources. However, fire plumes have specific properties which depart from this form: they are at the ground or on a building surface, they may occupy a significant surface area and they are usually associated with a surface obstacle of some sort (a building, process plant, a crashed or damaged vehicle or aircraft). These factors can markedly modify the plume dispersion and, especially, the plume rise in the near-field (a range of 1-2km).

This specific behaviour of fire plumes is described and simple models for accounting for it are reviewed and investigated. The review covers fire plumes in still air, the transition to wind driven dispersion, fire sources in open terrain and those arising both outside and inside buildings. In the latter case there is a complex interaction between the building ventilation processes, the development of the fire and the properties of the discharged fire plume. It also considers the lift-off phenomenon, the conditions for which a fire plume will rise clear of its surroundings (mitigating the exposure of those nearby at the ground). There is a discussion of the behaviour and dispersion of particles carried in fire plumes (a common feature of fires), of both fire plumes in urban areas and of the behaviour of short term (or 'puff') releases in relation to continuous plumes. The latter two subjects are considered only briefly due to the lack of information.

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This study was funded by the UK Atmospheric Dispersion Modelling Liaison Committee.

The views expressed in this report are those of the authors, and do not necessarily represent the views of ADMLC or of any of the organisations represented on it

EXECUTIVE SUMMARY

This review examines the properties of buoyant plumes at short ranges associated with surface fires or fires within buildings that discharge through the building surfaces. The fire plume is the main source of exposure to fire products and its effective prediction is a critical feature of hazard assessment. Though there is a substantial literature on buoyant plumes in air pollution, these are mainly related to elevated point sources. However, fire plumes have specific properties which depart from this form:

They are usually at the ground. Thus there is no initial plume height and the release is also subject to the pronounced wind shear at the ground.

They often occupy a significant surface area.

It is also common for surface fires to be associated with surface obstacles of some sort, possibly buildings, process plant, crashed vehicles or aircraft for example. Discharges are usually either flush with the obstacle surface or nearby on the ground and in both cases can be subject to the full downwash field of the obstacle. There can also be a secondary interaction between the downwash field of the obstacle and the buoyancy forces in the plume, so that both the fire plume and the wind flow pattern around the obstacle are modified. Conventional downwash estimates then become unreliable.

These differences from elevated point sources are sufficient to markedly modify fire plume dispersion from the conventional behaviour and some account should be taken of them. For example, the shape and size of the source modifies the plume behaviour and can profoundly affect its buoyant rise. There is a limited but useful body of research data that explores some of this behaviour and a number of simple fire plume models and empirical rules derived from this data that can be used, partly at least, to account for some of the variations in plume behaviour.

The application of fire plume modelling in practice is presently somewhat variable. There is no standard software or methodology generally available for dealing with fire plumes (some exist, but are not publicly available) and, as a result, the application of different models and methods is largely ad-hoc. Some calculations use conventional dispersion models with little reference to specific fire plume properties. In general these conventional models do not account very well for fire plume behaviour, though some attempts have been made to adapt them. The application of the limited variety of simple fire plume models and empirical rules is not standardised. Similarly (with one exception), there is no organised archive of the existing limited experimental database that can be used for common validation purposes. Nor are there any agreed standard test cases for fire plume model intercomparison, which should include specific conditions known to affect fire plume behaviour.

The present review examines the main physical processes affecting fire plume dispersion from the ground or arising from or within buildings, based on the existing experimental database. It:

Discusses the scaling of plume rise and dispersion from buoyant sources at the ground, especially with regard to source size and shape, interactions with building wakes and discharges from buildings progressively damaged by the development of fires.

Reviews the existing literature, particularly with regard to criteria for plume behaviour.

Describes the main characteristics of fire plumes and fire plume interaction with the ground and with buildings.

Investigates current simple near-field dispersion models and, where practicable, compares them.

Considers whether modifications to model inputs or other parameters in the major conventional models might provide better dispersion estimates.

Recommends best modelling practice.

Discusses the discharge of particles in fire plumes and recommends modelling procedures where practicable.

Recommends desired improvements to models and to the experimental database.

The review is restricted to short range dispersion, within a range of about 1-2km, where the specific properties of fire plumes most affect their dispersion. It mainly concentrates on models and methodologies which are accessible to the general user, either by application at about spreadsheet level or where (as in the case of the conventional dispersion models) the software is widely available. Some more sophisticated fire models are discussed, but only briefly where the software is not generally accessible. CFD modelling is not considered here. Though there is wide use of CFD in fire research, this is heavily oriented towards internal flows rather than external dispersion. Further it is a specialised application in its own right and its use in dispersion modelling has been considered previously for ADMLC.

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NOTATION

c	Contaminant concentration.
C_p	Specific heat of air at constant pressure.
d	Surface displacement of the flow in Equation (1).
d_a	Particle aerodynamic diameter.
D	Diameter of circular pool fire.
D_s	Particle stop distance.
F	Total Flux of buoyancy from a fire source. Equation (8).
F_w	Flux of buoyancy per unit width across the wind from a fire source. Equation (45).
g	Gravitational acceleration.
h	Plume height.
h_B	Plume height due to buoyancy.
h_M	Plume height due to momentum.
H	Building height.
ΔH_c	Heat of combustion of fuel vapour, Equation (42).
K	Dimensionless concentration, usually $cU_{ref}L^2/q$.
l	Fire source length, Equations (33) ff.
L	A characteristic length scale for the buoyant discharge.
L_f	Flame Height, Equations (26) ff.
L_{MO}	Monin-Obukhov length scale.
L_p	Meroney's 'Lift-Off' parameter, Equation (61).
M	Momentum flux, Equation (16).
P	Ratio of concentrations at the ground due to the buoyant and non-buoyant plume, from Poreh and Cermak(1986), Equation (63).
q	Mass emission rate of contaminant.
Q	Heat release into plume, excluding radiation and other losses.
Q_T	Total heat release from combustion, including radiated component.
Q_T^*	Dimensionless heat release based on Q_T , Equation (28).

t	Time.
t_D	Dimensionless release time, Equation (72).
T	Temperature, usually K.
T_a	Ambient temperature, usually K.
ΔT_m	Maximum temperature difference on fire plume axis, K.
U	Wind speed.
U_r	Radial inflow velocity at base of pool fire. Equation (68).
U_{ref}	Reference wind speed at a height z_{ref} .
u^*	Friction velocity.
u	Mean wind speed.
u_m	Maximum vertical velocity, in cross section of a fire plume in still air.
v_f	Particle falling speed.
V	Plume source volume flow rate, Equation (4). Also plume velocity/wind speed ratio in transitional plume. Equation (42).
V'	Dimensionless velocity ratio in transitional fire plume; Equation (42).
w	Source or fire width.
w_s	Gas discharge velocity from source.
W	Building width.
x	Along-wind distance (vertical distance in some still air fire plume models).
x_{eff}, x_n, x_t, x_1	Plume distances arising in Carter's plume rise model. Equations (50) ff.
y	Across-wind horizontal distance.
z	Height above the ground.
z_0	Aerodynamic roughness length. Also height of virtual origin in still air fire plume.
z_c	Height of plume centreline above ground.
α	Slope of particle falling trajectory in a uniform wind. Equation (70).
Γ	Atmospheric potential temperature gradient. Nominally $0.98^\circ\text{C } 100\text{m}^{-1}$.
θ	Angle of transitional fire plume (from still air to wind driven) from the vertical. Equations (40) ff.
κ	Von Karman's constant, taken here as 0.4.

- ρ_a Density of ambient air.
- ρ_c Density of fuel vapour; Equation (42).
- ρ_g Density of discharged gas plume.
- $\Delta\rho$ $\rho_g - \rho_a$
- σ_u Standard deviation of the mean wind speed distribution across a fire plume in still air; Equations (22) and (23).
- σ_T Standard deviation of the distribution of the mean temperature difference above ambient across a fire plume in still air; Equation (24).

1 INTRODUCTION

There has been a long interest in ground-based and building fires, and the behaviour of the resultant fire plume. This interest has ranged from quite small (sub MW) conflagrations to the fire storms resulting from the urban bombing of the second world war (Long(1967), Nielsen(1965)).

The importance of the fire plume lies in its being the main source of exposure to the fire products beyond the immediate vicinity of the fire. Due both to the materials combusted and to the relative inefficiency of the combustion process, the plume may contain a wide variety of toxic gaseous and particulate materials, both as raw materials in the fire and partial or complete products of combustion. These latter can include aldehydes, cyanides, hydrogen chloride, dioxins and other carcinogenic partial products of combustion.

Interest in fires and fire plumes has largely divided between the fire and dispersion communities, in the latter group mainly from those concerned with accident and hazard assessment. There seems to have been limited interaction between these groups. The fire community has tended to be more interested in fire development, burning rates and the production of toxic components of the combustion. Interest in the dispersion process has mainly been limited to building ventilation. Little consideration has been given to meteorological parameters such as wind speed and most fire plume models are of the 'still air' type. The dispersion community has tended to consider the fire plume alone dispersing in a wind, treating the fire as a source term defining the plume's initial characteristics of size, momentum and buoyancy, from which external dispersion estimates can then be made. This dichotomy is unfortunate as the two groups have overlapping interests and their separate efforts have been weakened as a result.

By far the largest literature on buoyant plume dispersion is that related to controlled emission stacks, which with some exceptions (mainly related to building downwash from low stacks) can be regarded as elevated point sources. However, there are several specific features of fire plumes which may affect their dispersion. These are:

They are usually at the ground. Thus there is no initial plume height and the release is also subject to the pronounced wind shear at the ground.

They often occupy a significant surface area. The shape and size of the source modifies the plume behaviour and can affect its buoyant rise.

It is also common for surface fires to be associated with surface obstacles of some sort, possibly buildings, process plant, crashed vehicles or aircraft for example. Discharges are usually either flush with the obstacle surface or nearby on the ground and in both cases can be subject to the full downwash field of the obstacle. There can also be a secondary interaction between the downwash field of the obstacle and the buoyancy forces in the plume, so that both the fire plume and the wind flow pattern around the

obstacle are modified and conventional downwash estimates then become unreliable.

At short ranges, typically within about 1-2km distance, the fire plume can range between elevated and ground based depending on the conditions, especially of fire size, heat release and wind speed. Here, these additional characteristics of fire plumes become more significant. Where the fire source is relatively small, has a high buoyancy or the dispersion calculation is over a sufficiently long range, these features of surface fires lose their importance and the conventional plume rise and dispersion models can reasonably be used directly. In practice, most fires pass through a cycle of growth and decay during at least part of which these additional conditions will apply. At the extremes of the fire's life history the heat release is usually limited, so that buoyant fire plumes with low heat release dispersing on or near the surface can be expected at some stage in nearly all fires. In some of the more spectacular cases of large warehouse fires, this latter stage of the fire has persisted for days or weeks.

Most conventional numerical dispersion models have tended to ignore these near field characteristics of ground-based buoyant plumes, even though the effects of basic parameters such as source area and shape and of interactions with buildings can have profound effects on the resultant plume rise. The major dispersion models in common use, for example R91, ISC, AERMOD, ADMS and CALPUFF, incorporate plume rise, area sources and building interactions, but not generally in combination. Similarly, the addition of plume buoyancy to area sources in the models does not include the effects of source size and shape on the plume rise. Neither is there treatment of further secondary interaction of flush buoyant releases from building surfaces with the building wake. The US EPA dispersion model web site contains no model that deals with these effects specific to fire plumes. Only the ADMS model has a recursive plume rise model that deals to some extent with these problems and data comparisons have shown some success; this is discussed later. Similarly, the fire research model databases 'firemodelsurvey.com' (by the 'Combustion Science and Engineering' journal) and the US NIST fire research database list large numbers of fire models, nearly all concerned with internal fire development, the effects of ventilation or other aspects of fires and fire control. Friedman(1992) listed sixty-two fire models, none of which was concerned with external dispersion.

There has been a major use of CFD models in fire research, often quite successfully. CFD modelling has proved especially valuable in internal dispersion and fire spread calculations. However, this usage has been most heavily concerned with these specific problems. The use of CFD models in external dispersion calculations of fire plumes has in general been limited, especially where obstacles are involved. Many such studies are for commercial purposes and do not readily appear in the public domain, so it is difficult to assess their popularity and value. One concern over the application of CFD to external flows is what appears to be a limited validation database. The NIST fire research model database lists only two models of this type dealing with external flow and dispersion. The first of these is a long range LES fire plume model, ALOFT (McGrattan et al(1996, 1997)), which is mainly intended to deal with complex

terrain and has grid scale of order 500m to 1km, so that it will not deal with the near field. The second is the NIST Fire Dynamics Simulator ('FDS', including 'Smokeview'), which is a general purpose CFD fire modelling programme. This is mainly concerned with internal fire development, but will also calculate external flows; like other CFD models it is slow running and computationally intensive. Their relatively long calculation times also make their use difficult for the large numbers of calculations that are often needed in routine risk assessment. There is some discussion of this by Robins(1997), who notes one CFD comparison with experiments by Cowan(1996). Some pool fire CFD dispersion calculations are discussed by Sinai(1994). CFD dispersion modelling was also reviewed for the NRPB by Hall(1997), which includes only one reference to fire plume modelling, by Christolis et al(1995).

Small scale physical modelling, using wind or water tunnels, remains very effective in investigating external dispersion behaviour at short ranges, especially when involving complex plume interactions with obstacles and the ground. Much of the existing systematic experimental database on fire plume dispersion comes from this source. There have been small scale experiments on fire plume behaviour by Meroney(1979), by Poreh (for example, (Poreh and Cermak(1986, 1988b), Poreh et al(1986) and by Hall (for example (Hall and Waters(1986), Hall et al(1993, 1995), Hall and Walker (2000)). Well quantified data on fire plumes in the field are rare, but Yates(1996) has produced a significant field data set for pool fire plumes.

There are also a number of simple plume rise models for fire plumes and empirical rules related to plume behaviour at the ground (such as 'lift-off', the condition for which the plume rises clear of the ground) and to fire plume/building interactions, as for example in the FIREPEST model (Maddison et al(1996)). These are partly derived from the experimental database, though some pre-date much of this. Fisher et al(2001) discuss some of the simpler pool fire models, which deal to some degree with the effects of the source size on the plume rise. However, these models do not account for interaction with buildings or other obstacles. Nor, in general, are they incorporated into useable software. Fisher et al also note in their discussion the very limited amount of experimental data, especially field measurements, against which fire dispersion models can be validated, which causes difficulty with reliable plume rise and dispersion calculations.

There have been a number of projects over the last ten years, which have contributed to the research database on fires and fire plumes from the ground. The EC 'Industrial Fires' project (Cole and Wicks(1993, 1994)) produced useful experimental and theoretical work on fire plumes. A following 'BUOYANT' research project ((Kukkonen et al(1997), Nikmo et al(1996), Webber et al(1997)) investigated the behaviour of very buoyant plumes at large scales. The EC URAHFREP project (Porter and Nussey(2001)) was mainly concerned with accidental escapes of anhydrous hydrogen fluoride. However, there was a direct concern with the development of buoyancy in ground-based hydrogen fluoride plumes and its effects. As a result, the project produced both

theoretical and experimental work on plume rise from the ground with a more general application.

There have been several improved numerical treatments of fire plumes, for example by Webber et al(1997), Fannelop and Webber(2003), Nikmo et al(1997), Tickle(2000) and by Slawson et al(1990), though they are not immediately useable in risk assessments and coded versions are not readily available. However, they do provide useful guidance on potential model development.

For those engaged in fire plume dispersion calculations for risk assessment, the present state of fire plume modelling poses some difficulties. Many hazard assessments require rapid scoping calculations and broad estimates of short and long range levels of ground level contamination, which cannot be readily made with complex models either due to their computational demands or to the lack of accessibility to suitable software. Further, the option of developing fire plume specific models of any sophistication is uneconomic for most individual users. Similarly, there seem to be no validated standard software packages dealing adequately with fire plumes. The general user is then faced with two main options.

The first is the use of simple fire specific models such as those reviewed by Fisher et al(2001), together with empirical factors related to obstacle interactions and 'lift-off'. The second lies with the use of the conventional dispersion models. Though these latter generally show many deficiencies in application to fire plumes, they have the advantage of being packaged for easy use. One possibility is to investigate whether the data inputs to the standard dispersion models might be modified to provide better estimates of fire plume behaviour. An example of this technique applied to the ADMS model is given in Carruthers et al(1999).

The present review is mainly concerned with near-field behaviour of fire plumes and their dispersion, which occur typically within 1-2km of the source. It deals with the physical principles of fire plume dispersion and with the use of simple models and empirical rules for assessing fire plume behaviour and dispersion. The models described and used here are those that are either pre-packaged or which can be applied at approximately spreadsheet level. It is within this 1-2km range that the specific properties of fire plumes can markedly alter dispersion behaviour. Beyond this distance the effects of fire plume behaviour are not usually different from those of other buoyant plumes. Most aspects of long range fire plume modelling can then be dealt with using the conventional dispersion models. The review:

Examines the scaling of plume rise and dispersion from buoyant sources at the ground, especially with regard to source size and shape, interactions with building wakes and discharges from buildings progressively damaged by the developments of fires.

Reviews the existing literature, particularly with regard to criteria for plume behaviour.

Describes the main characteristics of fire plumes and fire plume interaction with the ground and with buildings.

Investigates current simple near-field dispersion models and, where practicable, compares them.

Considers whether modifications to model inputs or other parameters in the major conventional models might provide better dispersion estimates.

Recommends best modelling practice.

Discusses the discharge of particles in fire plumes and recommends modelling procedures where practicable.

Recommends desired improvements to models and to the experimental database.

The review does not cover complex models, including CFD, or long range modelling. Both pose specialised problems of their own and would require a separate review. CFD modelling has been reviewed recently for ADMLC by Hall(1997) and by Robins(1997) in relation to the rise of buoyant plumes from building wakes. This latter includes some plume modelling by Cowan(1996).

2 FIRE PLUME SCALING

The range of scaling parameters for buoyant plumes at the ground is limited and the work discussed here generally contains many similar features and uses broadly the same scaling parameters. It is therefore convenient to discuss the essential features of this type of plume scaling first. There are two features of the flow to be scaled, the atmospheric boundary layer within which the plume disperses and the buoyant discharge itself.

Since we are dealing with plumes at or near the ground, it is adequate to define the atmospheric boundary layer approach flow in terms of its surface conditions and surface layer scaling generally applies. In principle these are the roughness length, z_0 , and the friction velocity, u_* , appearing in the usual rough-wall mean velocity profile equation for neutral stratification,

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left(\frac{z-d}{z_0} \right), \quad (1)$$

where u is the mean velocity,
 d is the surface displacement of the flow and
 κ is Von Karman's constant, taken here as 0.4.

For rural levels of surface roughness the value of d is usually small and ignored, though it becomes more significant at urban roughness scales (Macdonald et al(1998)). Though the wind profile is modified by atmospheric stratification, the

effects are usually relatively slight near the ground and except in extreme conditions can often be ignored in typical risk assessment calculations. If a correction for stratification is preferred, further details can be found in Underwood(2001), who also offers values of d for some surfaces.

Values of u_* and z_0 (in combination with the Monin-Obukhov length scale, L_{MO}) are commonly used as defining parameters of the atmospheric boundary layer as they define the rest of the profile. However, it is often more convenient to use a reference velocity U_{ref} at a height z_{ref} . In some cases this also gives better data correlations if the effects of surface roughness on the plume behaviour are relatively weak. This is discussed further below.

There are two possible effects of atmospheric stability on buoyant plumes. These are, firstly, any direct relationship between the buoyancy in the plume and that locally in the atmosphere around it. Secondly, the atmospheric stability directly alters rates of plume dispersion, which control the total plume mass on which the buoyancy force acts. Generally, in a plume with sufficient buoyancy to rise rapidly at short ranges near the ground, the local atmospheric buoyancy forces are small compared with those in the plume and would have little effect on plume rise. Further, buoyant plumes generate their own internal convection and mixing, so that the dispersion is not solely controlled by the atmospheric turbulence and the significance of stratification at short ranges is further diminished. The effects of stratification at longer ranges are more significant and conventional plume rise calculations are usually modified to account for this (see, for example Jones(1983)). In the present review, there is almost no reference to atmospheric stability. Apart from some specific conditions such as limits to plume rise, there seems to be a nearly universal presumption of neutral stability.

A buoyant source may be solely a source of heat, Q , or a discharging volume of buoyant gas at a volume discharge rate, V , with density, ρ_g , lower than the ambient density ρ_a . In the latter case there will be a discharge velocity, w , associated with the discharge. If the buoyant source is of finite size it will have its own dimensions, for example a diameter, D , or a width across the wind, w .

A full scaling of the buoyant part of the discharge requires accounting separately for three dimensionless parameters. These are, either

$$\frac{\rho_g}{\rho_a}, \text{ or}$$

$$\frac{\rho_g - \rho_a}{\rho_a} \left[= \frac{\Delta\rho}{\rho_a} \right], \text{ the plume source/ambient density ratio,} \quad (2)$$

$$\frac{U_{ref}}{\sqrt{gL}} \text{ , a Froude number for the flow and} \quad (3)$$

$$\frac{V}{U_{ref}L^2} \text{ , a dimensionless discharge rate for the source.} \quad (4)$$

L is here a characteristic length scale for the discharge.

If density differences between the dispersing plume and ambient levels are small (less than 10%, say) then the Boussinesq approximation can be applied (Turner(1973)). This is invariably the case for plumes away from the source and the approximation often seems to apply reasonably well with relatively large density differences. This allows a simplification in scaling by using a single merged parameter of the source density ratio and the Froude Number, the Richardson Number. The scaling can then be defined by,

$$\frac{g \Delta \rho}{\rho_a} \frac{L}{U_{ref}^2}, \text{ the Richardson number and} \quad (5)$$

$$\frac{V}{U_{ref} L^2}, \text{ a dimensionless discharge rate for the source.} \quad (6)$$

If the volume discharge rate of the source, V, is not sufficiently large to distort the flow pattern, a further simplification can be applied, merging the Richardson Number and dimensionless discharge rate to form a single 'buoyancy flux parameter'. The buoyancy scaling can then be defined solely by,

$$\frac{F}{U_{ref}^3 L}, \text{ the dimensionless buoyancy flux parameter, where,} \quad (7)$$

$$F = g \frac{\Delta \rho}{\rho_a} \frac{V}{\pi} \text{ is the buoyancy flux.} \quad (8)$$

The inclusion of the constant π in the buoyancy flux, Equation (8), follows the original analysis by Briggs(1969) for buoyant stack discharges. His buoyancy terms for plume rise are essentially the same as Equations (7) and (8).

The buoyancy flux is given in Equation (8) as a volume flow of gas of reduced density. However, it can also be expressed as a directly equivalent heat release, which is more convenient for many applications. Hall et al(1995) gave this, for discharges containing air or conventional combustion gases, as

$$F = 8.9Q, \quad (9)$$

where F (which has dimensions) is in SI units and Q is in MW. Fisher et al(2001) give a similar estimate, with an equivalent factor of 8.56, and some fire plume research papers give a similar conversion factor. The heat release, Q, mainly used here is that for the fraction of the combustion energy that directly heats the plume. In fires, Q is a variable fraction (possibly less than half) of the total combustion heat theoretically available, Q_T , the remainder being mostly lost in radiation and incomplete combustion.

The dimensionless buoyancy flux, either as in Equation (7) or in multifarious variants (including the Monin-Obukhov length scale, L_{MO}) is ubiquitous in work on buoyant flows. The majority of plume buoyancy experiments and related

plume rise models have used the dimensionless buoyancy flux parameter for scaling. The Richardson number, Equation (5), is also in common use and has been used by Briggs and others as an indicator of plume 'lift-off', discussed in Section 6. The main distinction between applications of the two buoyancy parameters is that the dimensionless buoyancy flux is a dimensionless source term, which defines the subsequent plume pattern, the Richardson number is a local plume property, which defines the state (and properties) of the plume at a particular point.

Where there are any flows generated by the buoyancy in the discharge, as for example with the strong convective flows that occur in fires (which are essentially heat releases with a buoyancy flux as in Equation (9)), these are scaled directly by the buoyancy parameters and no further scaling parameter is required to describe the flow. However, the momentum of any additional discharge associated with the buoyant discharge has its own scaling. Full scaling of any source discharge momentum requires accounting separately for three parameters. These are,

$$\text{either } \frac{\rho_g}{\rho_a}$$

$$\text{or } \frac{\rho_g - \rho_a}{\rho_a} \left[= \frac{\Delta\rho}{\rho_a} \right], \text{ the plume source/ambient density ratio,} \quad (10)$$

$$\frac{V}{U_{\text{ref}} L^2}, \text{ a dimensionless volume discharge rate for the source and} \quad (11)$$

$$\frac{w_s}{U_{\text{ref}}}, \text{ the source/wind speed velocity ratio.} \quad (12)$$

The similarity with scaling the buoyant part of the discharge will be apparent. Following the same arguments, if the source density ratio is not large (which is usually the case beyond short distances from the source, typically 5-10 source dimensions) the effects of the discharge velocity and source density can be merged. The momentum scaling can then be defined by,

$$V \frac{\rho_g}{\rho_a} \cdot \frac{1}{U_{\text{ref}} L^2}, \text{ a dimensionless relative mass discharge and} \quad (13)$$

$$\frac{w_s}{U_{\text{ref}}} \text{ as before.} \quad (14)$$

Similarly, if the volume of the discharge is not sufficient to distort the local flow pattern, the velocity ratio and dimensionless mass discharge can be merged to give a single dimensionless discharge momentum scaling parameter

$$\frac{M}{U_{\text{ref}}^2 L^2}, \text{ where } M \text{ is the discharge momentum, defined as,} \quad (15)$$

$$M = V \frac{\rho_g}{\rho_a} w_s. \quad (16)$$

Equation (15) is again the basic form of the momentum term used by Briggs ((Briggs(1969), Jones(1983)) for the momentum component of plume rise.

The majority of the work discussed here has been analysed in terms of the dimensionless buoyancy and momentum fluxes (Equations (7) and (15)), in some form or with some use of Richardson's number, (Equation (5)). It will be appreciated from the above discussion that the use of these dimensionless parameters alone does involve some degree of approximation, especially near the source. However, in most cases the effect of the other parameters is small, especially with discharge momentum. In practice, most data on buoyant rise from the ground is from small-scale experiments in wind and water tunnels. The physical constraints of such modelling usually make it impracticable to base experiments on anything other than the dimensionless buoyancy and momentum fluxes or the Richardson number.

There is a need for reference length scales and wind speeds for estimating the dimensionless buoyancy and momentum fluxes. Where the fire plume is associated with a surface obstacle of significant size, a building or chemical plant fire for example, it is rational to use a length scale related to the obstacle dimensions (usually the height) and a wind speed at this height. For surface fires in largely unobstructed terrain, the choice is less clear cut. The length scale can be rationally attributed to the fire source size. If this is irregular, from present experimental data, discussed later, it is probably better to use the width of the fire source across the wind. In open terrain, though the friction velocity u_* would seem a rational choice, it must then be related to a surface roughness in order to define the wind speed. There is some evidence that a reference wind speed at a height related to the source size gives better data correlations, as Fisher et al(2001) note. This may be partly because there seems to be only a weak coupling of plume rise with surface roughness when the roughness is relatively small. The literature contains little evidence of surface roughness effects on plume rise. Most practical assessments prefer a wind speed at a reference height and this has been used in most of the experimental data discussed here.

Figure 1 shows a plot of the variation in wind speed and plume heat release for a range of values of the dimensionless buoyancy flux and a source with a characteristic length scale, L , and a wind speed reference height, z_{ref} , both of 10m. Each line on the plot is for a fixed value of the dimensionless buoyancy flux, $F/U_{ref}^3 L$ (Equation (7)), and thus for a similar form of plume behaviour over the range of wind speed and heat release indicated. The plot can easily be redrawn or scaled for different characteristic length scales. From previous studies, to be discussed later, the lowest value of the dimensionless buoyancy flux for significant plume buoyancy effects is around 0.001, below which plumes behave as if neutrally buoyant. Values above 10-30 usually indicate strongly rising plumes, even in the presence of obstacle wakes, approaching the still air condition.

It will be noted that the Richardson number (Equation (5)) the dimensionless momentum flux (Equation(15)) and, especially, the dimensionless buoyancy flux (Equation (7)) are very sensitive to wind speed, so that the rapid rise of buoyant plumes from the ground is largely a low wind speed phenomenon unless the heat release is considerable.

3 DISPERSION FROM SURFACE BASED FIRES IN OPEN TERRAIN

3.1 Fire Plumes in Still Air.

The vertically rising plume from a buoyant ground source in still air has been a subject of continuing interest in a variety of applications. In the case of fires it is a condition that has been of more interest in the fire community than for dispersion modelling, as it does not give rise to ground level concentrations in the near field. However, the occurrence of this condition sets a useful lower bound for applying dispersion models.

A diagram of the main features of a simple still air fire plume is shown in Figure 2. The salient features of the process are:

There is an inflow of air at the surface which accelerates over the combustion area to produce a 'neck', smaller than the combustion area, with the maximum plume velocity just on or over the top of the flames.

The resultant plume above the neck is self-similar at all heights.

The distributions of excess temperature and contaminant concentration from the fire are Gaussian across the plume.

The plume has a linear spread, with a half angle of about 15° (to a half-width of 2σ) for axi-symmetric plumes.

The linear, self-similar part of the plume has a virtual origin at or below the neck and possibly below the ground.

The fire, and therefore the buoyancy source, usually shows some flame instability, sometimes with a quasi-regular oscillatory behaviour, which is observable in the plume structure.

There are useful reviews of fire plume behaviour in still air by Gupta(1993) and by Zukoski(1995), with more recent work on unifying fire plume data by Quintiere and Grove(1998a,b). Gupta analysed a number of still air plume rise models, both theoretical and experimental, and noted their essential basic similarity. They could all be reduced to common characteristic equations, for which the empirical constants did not vary greatly between models.

From this Gupta derived a set of basic formulae for the plume properties. There have been two solutions of interest, for point or circular area source fires and line source fires. For these Gupta derived the formulae below. The constants are averages of Gupta's range of values quoted from different sources; in practice they do not vary greatly.

For axi-symmetric plumes from circular sources, the maximum vertical velocity, u_m (in m s^{-1}), and the maximum temperature difference, ΔT_m (in K), in the plume cross section (effectively the maxima of the lateral Gaussian distributions of u and ΔT) are given by,

$$u_m = 11.3 \left(\frac{Q}{z} \right)^{1/3} \quad \text{and} \quad (17)$$

$$\Delta T_m = 2500 \cdot \frac{1}{z} \left(\frac{Q}{z} \right)^{2/3}. \quad (18)$$

For two-dimensional plumes from line sources, they are given by,

$$u_m = 5.7Q^{1/3}z^{0.041} \quad \text{or} \quad (19)$$

$$u_m = 6.8Q^{1/3} \quad \text{and} \quad (20)$$

$$\Delta T_m = 710 \frac{Q^{2/3}}{z}, \quad (21)$$

where in both cases,

Q is the heat release into the plume in MW (that is, the fraction of the total heat of combustion, excluding radiation and other losses, that directly heats the plume gases) and

z is the height above the plume virtual origin in m.

The contribution of the height term in Equation (19) is so weak that it can usually be ignored. The value of $z^{0.041}$ is within 10% of 1.2 for heights between 5m and 500m, so substituting this factor into Equation (19) leads to Equation (20). The result is that the peak velocity in a line source fire plume is predicted to be independent of height.

The lateral spreads, σ_u , (the standard deviation of the Gaussian distribution), of vertical velocity, u , are given by,

$$\sigma_u = 0.132z, \quad (22)$$

for axi-symmetric plumes from circular sources and

$$\sigma_u = 0.192z \quad (23)$$

for plumes from line sources.

The lateral spread of temperature difference, σ_T , is slightly less than of vertical velocity, σ_u . Zukoski(1995) gives a ratio of σ_T/σ_u of 0.96, so that,

$$\sigma_T = 0.127z, \quad (24)$$

for axi-symmetric plumes from circular sources and

$$\sigma_T = 0.184z, \quad (25)$$

for plumes from line sources.

Equations (22) to (25) also give the spread half-angle of the plume, which (to a width of 2σ) is constant at about 15° for axi-symmetric plumes and about 21° for plumes from line sources.

There is more variation between different models and empirical formulae over the height of the virtual origin of the plume above the surface, z_0 . Its value depends on both the heat release and the fire source dimensions and is mostly estimated to be between the top of the flames and below the surface. Gupta quotes a variety of formulae for this, which with some manipulation mostly fall into similar formats. They are given in terms of either the heat release or the effective flame height, L_f , as the flame height seems to correspond closely to the position of the neck in the plume. Gupta also notes that there is some agreement that the flame height for circular sources is most closely given by some function of, $Q_T^{2/5}$, for which there is some theoretical justification. Of these, Heskestad(1983) gives,

$$\frac{L_f}{D} = 3.8Q_T^{*2/5} - 1.02. \quad (26)$$

Most of the other references offer a simpler function of the form,

$$\frac{L_f}{D} = 3.3Q_T^{2/5}. \quad (27)$$

Both the constant and the exponent vary somewhat between references, the value of the constant lies mostly between about 1.8 and 3.8 and the exponent mostly between $2/5$ and $2/3$.

Here, Q_T^* is a dimensionless heat input defined as,

$$Q_T^* = \frac{Q_T}{C_p \rho_a T_a \sqrt{(gD)} D^2}, \quad (28)$$

where C_p , ρ_a and T_a are respectively the specific heat, density and temperature of the ambient air. Q_T is the total heat release from the combustion, including the radiated fraction.

Q_T^* is a form of dimensionless heat release commonly used in fire research. Substituting typical values for ambient air and for Q_T in MW and D in m (as used generally here), Equation (28) gives,

$$Q_T^* = \frac{0.9Q_T}{D^{5/2}}, \quad (29)$$

using which Equation (26) becomes,

$$\frac{L_f}{D} = 3.6 \frac{Q_T^{2/5}}{D} - 1.02 \quad (30)$$

and Equation (27) becomes,

$$\frac{L_f}{D} = 3.2 \frac{Q_T^{2/5}}{D} . \quad (31)$$

Values of the flame height, L_f , from Equations (30) and (31) are shown in the upper plot of Figure 3. Heskestad's Equation (30) yields negative flame heights for large source diameters and small heat releases, effectively beyond the range of his experiments. For practical purposes flame heights can be taken as zero under these conditions, for which Equation (31) also predicts low flame heights.

Work on other source shapes is relatively limited. For line and rectangular sources with turbulent flames, Yuan and Cox(1996) (following Hasemi and Nishihata(1988)) give,

$$\frac{L_f}{w} = 3.64 Q_T^{*2/3} , \quad (32)$$

where w is the width of the fire. The value of the exponent, of $2/3$, is well known and predictable from theoretical considerations. Q_T^* in Equation (32), has the form for two dimensional and rectangular sources,

$$Q_T^* = \frac{Q_T}{C_p \rho_a T_a \sqrt{(g w) l w}} , \quad (33)$$

which reverts to Equation (28) for square or circular sources, when $w=l$, and to the solution for line sources as l becomes large. Substituting similarly for Q_T^* gives, for line and rectangular sources with Q_T in MW and dimensions in m,

$$Q_T^* = \frac{0.9 Q_T}{l w^{3/2}} , \quad (34)$$

so that, following Equation (31) for circular sources, for rectangular and line sources,

$$\frac{L_f}{w} = 3.23 \frac{Q_T^{2/3}}{l^{2/3} w} . \quad (35)$$

Of the virtual origin formulae given by Gupta, that of Heskestad(1983), represents a reasonable median and has the form,

$$z_0 = 3.7 \frac{Q_T^{*2/5}}{D} - 1.02 D . \quad (36)$$

Substituting for Q_T^* , using Equation (29) as previously, yields,

$$\frac{z_0}{D} = 0.41 \frac{L_f}{D} - 1.02 , \quad (37)$$

where z_0 is the height of the origin above the ground.

Most of the virtual origin formulae quoted by Gupta can be reduced to this form, the first constant (0.41) varying between 0.33 and 0.73, the second constant (1.02) varying between 2.4 and zero. Equation (37) indicates that the virtual origin reduces in height (to below ground level) with reducing heat release and increasing source diameter. In cases where the fire has reduced to a smouldering state and there is no longer a flame (a condition of significant interest in plume dispersion calculations as the contaminant emission rate can still be high) it seems rational to take L_f as zero. The lower plot in Figure 3 shows estimates of the virtual origin height for circular fires from Equation (37) for a range of values of heat release and source diameter, in the units used here, based on values of L_f obtained from Equations 30 and 31, as in the upper plot of Figure 3. It can be seen that the height of the virtual origin is dominated by the pool diameter, the effect of the heat release on the position of the virtual origin being relatively weak.

It would be better in many ways to base the estimate of the virtual origin on the position of, and conditions at, the neck of the plume. However, this appears to be a more complex condition to predict and has received less attention. Recent work by Fanelop and Webber(2003) has provided a better theoretical foundation for this, but following a discussion with the authors it appeared that useful empirical solutions could not be derived without significant further work.

Most papers on fire plumes deal mainly with temperature and velocity in the plume. Only Heskestad(1984) gives a relationship for contaminant concentration in a fire plume. This can be estimated from the direct analogy between the temperature in the fire plume from a heat source and the concentration from a source of contaminant. Both are scalars and disperse in nearly the same way. Thus the concentration in the plume can be derived from Equations (18) and (21) by substituting a mass release rate of a contaminant, q , for the rate of heat release, Q , and a contaminant concentration, c , for the local heat content in the plume since,

$$\frac{Q}{C_p \sigma_a \Delta T} = \frac{q}{c}, \quad (38)$$

as long as consistent units are used. In the far field, if the temperature difference is assumed to be relatively small, for typical ambient values of C_p and σ_a , Q in MW, ΔT in K, q in $g s^{-1}$ and c in $g m^{-3}$, we have,

$$\frac{q [g s^{-1}]}{c [g m^{-3}]} = \frac{825Q [MW]}{\Delta T [K]}. \quad (39)$$

The above formulae are sufficient to define the approximate character of a fire plume in still air. However, they are limited to the main source cases of research interest, circular, line and rectangular sources. Many surface fires are of different shape and this can significantly affect both the fire and the plume behaviour. It is known, for example, that fire behaviour is sensitive to the difference between even square and circular fire sources that are otherwise similar (see for example Gupta(1993) and Sinai and Owens(1994)).

Besides the instability of the fire itself, discussed earlier, there are a number of other forms of disturbance to which fire plumes in still air or low wind speeds are prone:

They can attach to nearby vertical surfaces due to the Coanda effect.

The convergence of residual angular momentum in the inflow at the base of the fire can show instabilities that lead to the fire plume developing an intermittent single or double vortex that may affect its dispersion. Secondary vortices associated with the plume can also develop in some circumstances. These are sometimes known as 'fire whorls' (see, for example, Emmons and Ying(1967), Dessens(1962), Carrier et al(1985), Murgai(1976)).

In stable atmospheres, where the temperature increases with height, there may be a limit to the plume rise if the plume temperature falls below ambient values. This behaviour is of interest in fires both in enclosed spaces and in the atmosphere, so has been a subject of some interest. This is not considered further here, details can be found (amongst other sources) in Heskestad(1989) and in Zukoski(1995).

3.2 Fire Plume Transition from 'Still Air' to Wind Driven Dispersion.

The concept of 'still air' is something of a misnomer as there is rarely no air movement at all in the atmosphere (Deaves and Lines(1998)). Quite light winds appear to be capable of destroying the essential structure of most 'still air' fires, except for the largest. Not only does the elevated plume pass rapidly to a 'conventional' (from a dispersion point of view) dispersing buoyant plume, but the combustion process itself is modified. Drysdale(1990) discusses this transition briefly and notes that the combustion flame is largely unaffected up to a limiting wind speed, but for higher wind speeds the flame is rapidly markedly deflected away from the vertical and the combustion zone starts to move partially downwind of the fuel supply. The entrainment rate of air into the combustion zone is then (perhaps not surprisingly) increased. Drysdale quotes the experiments of Raj(1979), which gave the angle of the rising plume from the vertical, θ , as being,

$$\sin(\theta) = 1 \quad \text{for } V' < 1 \quad \text{and} \quad (40)$$

$$\sin(\theta) = (V')^{-0.5} \quad \text{for } V' > 1, \quad \text{where} \quad (41)$$

$$V' = V \left(\frac{2C_p T_a \rho_a}{\pi \rho_c \Delta H_c} \right)^{-1/3}. \quad (42)$$

V is a velocity ratio, U_{ref} / u_m , of the reference wind speed to plume velocities and

ρ_c and ΔH_c are the density and heat of combustion of the fuel vapour.

Feeding typical values for ambient air and hydrocarbon fuels into Equation (42) and assuming ρ_c is of order unity, the value of the scaling factor becomes about 5, so that,

$$V = \frac{U_{\text{ref}}}{u_m} \approx 0.2 \quad \text{at the boundary condition of } V' = 1. \quad (43)$$

Figure 4 illustrates this behaviour. The critical value of V is given by the broken line at 0.2, as estimated above. Since the heat of combustion of common materials does not vary greatly and the $-1/3$ power gives a weak coupling in Equation (42), Equation (43) and Figure 4 are approximately generally applicable. It can be seen that, on this basis of prediction, the characteristic 'still air' behaviour degenerates very quickly beyond the critical wind speed and the plume reverts to conventional wind-driven dispersion behaviour. Figure 4 follows a similar plot by Quintiere(1981) (reproduced by Drysdale) who also obtained a critical value of V of 0.2 for methane. The axis of Drysdale's similar plot to Figure 4 should be V , not V/u^* .

The maximum velocity in the plume is at the neck, approximately at the top of the flames, and can be calculated from Equations (17) or (20), knowing the position of the flame height, L_f , from Equation (30) and the virtual origin from Equation (37). Approximate estimates for both line and circular sources with diameters between 0.1m and 100m and for heat releases between 0.1 and 100MW give plume maximum velocities mostly in the range 3 m s^{-1} (for large diameter sources or small heat release) to 25 m s^{-1} (for small diameter sources and/or large heat release). Thus the transition from the 'still air' condition usually occurs at quite low wind speeds, below $2\text{-}3 \text{ m s}^{-1}$, unless the fire has a large heat release from a small diameter source.

3.3 Wind-Driven Fire Plume Dispersion in Open Terrain.

Above the critical wind speed of Equation (43), the fire plume dispersion is largely controlled by the atmospheric wind and turbulence in the conventional manner. The aspects of fire plume dispersion that may affect the conventional assumptions of plume rise and dispersion were noted in the introduction. These are:

the fire source may cover a relatively large area;

the fire plume is initially at the ground, in a region of pronounced wind shear, which may affect both the plume rise and its dispersion;

where the plume is sufficiently buoyant to rise clear of the ground, the rise may be modified by the presence of the ground.

Experimental data on near-field plume rise and dispersion from area sources at the ground, especially field data, are quite limited (as Fisher et al(2001) note), so that it is difficult to parameterise this behaviour reliably. It is known that when the surface area of the fire source is large, the plume rise can be

significantly reduced; this is discussed further below. There is less evidence for the effects of the other two factors. An important effect of the high wind shear near the ground is the significantly varying local wind speed through which the plume rises. This is often ignored in plume rise calculations. It is likely that the pronounced longitudinal shear spreading at the surface will affect the behaviour of short term (or 'puff') releases, but it is less certain that it affects continuous plume dispersion. This is discussed later in Section 10 on short term releases. The presence of the ground must to some extent affect plume rise when the buoyancy is low or moderate. For a plume to largely clear the ground, there must be a transfer of clean air under the plume and the presence of the ground must inhibit this transfer process to some extent. This behaviour is discussed further in Section 6, on 'Lift-Off'.

The effect of source size and shape on plume rise from the ground is illustrated in Figure 5, taken from the small scale wind tunnel experiments of Hall and Walker(2000), carried out as part of the EC URAHFREP programme on hydrogen fluoride dispersion. These experiments measured the rise and dispersion of buoyant plumes from area sources at the ground with a range of sizes and shapes (square, wide across the wind and long in the wind direction). The upper part of Figure 5 shows the layout of the experiment. The lower part of Figure 5 shows the centreline height of plumes from different sources with three values of the dimensionless buoyancy flux, F/U_{ref}^3L , of 0.01, 0.1 and 1; the source heat release and wind speed to which these conditions correspond can be derived from Figure 1 and range from slight to quite pronounced plume buoyancy. The length scale, L , is here the reference height for the wind speed and all other dimensions are factored by this. The plume height measurements are those for the nearest vertical measurement station, at $x/L = 15$, in the near field and examples of vertical concentration profiles for four source shapes are shown in Figure 6. On investigation, it was found that the most important shape parameter controlling the plume rise was the width of the source across the wind. The lower part of Figure 5 therefore uses the width or length (in the case of sources elongated along the wind) as its axis rather than the source area. The plots show two separate types of behaviour. Square sources and wide sources across the wind (the red curve fits) with similar widths show similar behaviour for the same value of the dimensionless buoyancy flux, with the plume rise markedly reducing as the source width increased across the wind. Sources aligned along the wind in these experiments (the green curve fits) retained a constant width and there was as a result only limited change in the plume rise, which increased rather than decreased with increasing source length along the wind.

Further analysis of this data allowed the reduction of the plume rise data to a single form for all source types and buoyancies. The result of this analysis is shown in Figure 7, in which the plume rise, h , at the two downwind vertical traversing distances of the experiments is plotted against a dimensionless buoyancy flux per unit width, of the form,

$$\frac{F_w}{u^3L}, \text{ where,} \quad (44)$$

$$F_w = \frac{F}{\left(\frac{W}{L}\right)}. \quad (45)$$

'Source D', specifically noted in Figure 7, was the square source common to all the shape distributions. Considering the wide range of sources sizes, shapes and emission buoyancies covered, the data collapse was reasonably good. There is a lower limit of the dimensionless buoyancy flux below which there was little or no observable plume rise. The linear regression fits through the remainder of the data at the two measurement distances were,

$$\frac{h}{L} = 8.9 + 4.4 \log_{10} \left(\frac{F_w}{u^3 L} \right), \quad (46)$$

at the nearest vertical traversing station ($x/L=15$) and

$$\frac{h}{L} = 13.2 + 6.9 \log_{10} \left(\frac{F_w}{u^3 L} \right), \quad (47)$$

at the farthest vertical traversing station ($x/L=30$).

The limit values of F_w/u^3L below which plume rise was negligible (the intercepts of Equations (46) and (47) with $h/L = 0$) were 0.0095 and 0.012 respectively at the two measurement distances. Thus a nominal limit value of $F_w/u^3L = 0.01$ for no significant effect of heat release on the plume rise is acceptable in both cases.

The data furthest from this fit in Figure 7 were for the longer sources along the wind and are well above the correlation lines of Equations (46) and (47). This behaviour is partly due to the centre of the source effectively moving upwind from the plume measurement station, so that the plume rise apparently increased as the along-wind length of the source increased, despite the increased source area. However, there additionally seems to be an element of self-reinforcement of the plume rise with these along-wind sources.

Where the source area is small, Briggs' plume rise model seems reasonably applicable as long as the plume rise is corrected for the varying wind speed over the height range of the calculation. Figure 8 shows an example of a comparison with such a calculation, taken from Hall et al(1995), which was collected as open terrain base data for a series of experiments on warehouse fire dispersion (which are considered later in Section 5.3). The circular source was relatively small ($w/L=0.4$) and comparisons with Briggs plume rise formulae (see Jones(1983)) were made for both buoyant (with small momentum) and for momentum (neutrally buoyant) discharges at two downwind distances equivalent to 15L and 30L. The plume rise was calculated using in each case the wind speed at the measured height of the plume, except for very low plumes where the wind speed at a height equal to the usual vertical plume dispersion coefficient, σ_z was taken. It can be seen that on this basis, Briggs' estimates of plume rise were close to the experimental measurements at the higher plume buoyancy levels, but overestimated the physical model plume rise at the lowest buoyancies. The

difference was attributed in the original report to the uncertain choice of wind speed for these low buoyancy plumes in contact with the ground. Though this may be the case, it is also possible that the plume rise was inhibited by the proximity of the ground. In practice, the plume rise is so low in these low buoyancy cases that it has only a limited effect on calculated concentrations, including at the ground, a little way beyond the source.

The data in Figure 8 is generally consistent with the later work shown in Figures 5 and 7, in terms of both plume rise and limits to the effects of plume buoyancy.

There are only a few simple models dealing with plume rise and dispersion from area fires at the ground. Fisher et al(2001) reviewed three of these and compared them with field experimental plume rise data from pool fires collected by Yates(1996) and from a separate experiment using a larger, approximately 15m in diameter, aviation fuel pool fire, using visual analysis of the smoke plume. The three models are due to Mills(1987), Carter(1989) and Zonato et al(1993). The main feature of these models is in dealing with the effect of the finite source size in reducing the plume rise. They are described briefly below. All essentially deal with circular pool fires of diameter D.

Mills' model is a modified version of Briggs' plume rise model, for buoyancy only, in the form,

$$h_M = \left(h_B^3 + \left(\frac{D}{1.2} \right)^3 \right)^{1/3} - \frac{D}{1.2}, \text{ where,} \quad (48)$$

$$h_B = \frac{1.6F^{1/3}x^{2/3}}{U_{ref}}, \quad (49)$$

Equation (49) is the usual term for buoyant rise, h_B , in Briggs' plume rise formulae. h_M is the overall plume rise.

Since the summation term in the brackets in Equation (48) is also Briggs' form for summing the effects of plume rise for both buoyancy and momentum, it seems probable that the addition of the momentum rise term in the bracket would also account for the effects of source momentum where this was additionally present.

Carter's model, incorporated into his FIREFLY model, uses a modified form of Moore's plume rise model (see Jones(1983)) and has the form (for Q in MW and lengths in m),

$$h_B = \frac{2.25}{U_{ref}} (Qx_{eff}^2 (x_{eff} + 27D))^{1/4} \text{ and} \quad (50)$$

$$x_{eff} = x \cdot \frac{x_t}{\sqrt{x^2 + x_t^2}}, \text{ where,} \quad (51)$$

$$x_t = x_s \cdot \frac{x_n}{\sqrt{x_s^2 + x_n^2}}, \text{ for which,} \quad (52)$$

$$x_s = 120 \cdot \frac{U_{ref}}{\sqrt{\Gamma}}, \text{ where,} \quad (53)$$

Γ is the potential temperature gradient (approximately $0.98\text{K } 100\text{m}^{-1}$ in neutral stability; both Carter and Fisher et al give this incorrectly) and

$$x_n = 19.2(100 + L_f). \quad (54)$$

The origin of the plume rise calculation is taken from a virtual origin below and upwind of the actual pool. For the depth of the virtual origin, Carter gives,

$$z_0 = 1.5A^{0.5}, \quad (55)$$

where A is the area of the fire. For circular sources of diameter D , this is,

$$\frac{z_0}{D} = 1.33, \quad (56)$$

which can be compared with Equation (37) for still air fires.

The upwind distance of the virtual origin is not given explicitly, but determined by back iteration of the dispersion formula until the plume spread at the source matches the source area.

The object of Equations (51), (52) and (53) is to limit the plume rise as a function of distance and vertical temperature gradient. This is more appropriate for longer range plume calculations, whereas Mills' model uses the limited version of Briggs' model appropriate for short-range calculations in the surface layer. Equation (54) effectively lifts the source height to the flame height, L_f , for which estimates are given in Section 3.1.

Zonato et al's model was based on empirical curve fits to small scale wind tunnel fire plume measurements, which they also compared with Mills' and Carter's models. Their empirical equations for the plume rise have the form (as reduced by Fisher et al),

$$h_B = 2.3Q^{0.26} \frac{x^{0.63}}{U_{ref}^{0.5}}, \quad (57)$$

for which the limit to plume rise at distances beyond $x/D > 45$ is given by,

$$h_B = 25.3Q^{0.26} \frac{D^{0.63}}{U_{ref}^{0.5}}. \quad (58)$$

This is an empirical data fit rather than a model based on some physical principles. Note that the basic plume rise, Equation (57), has no dependence on the pool size, which only appears in the limit to plume rise, Equation (58). Their limit to plume rise seems to occur in a relatively short distance and may have been affected by constraints of the wind tunnel's size. Zonato et al's comparative plots of Mills' and Carter's models against the experimental data regression fit for presumed pool diameters of 2, 5, 10 and 20m, from Figure 5 of their paper, are shown in Figure 9. By the usual standards of accuracy to which

plume rise calculations are regarded, both Mills' and Carter's models could be regarded as reasonable fits to the data. The differences between them in Zonato et al's and in Fisher et al's comparisons are no greater than are known to exist between the two base models due to Briggs and to Moore.

Fisher et al also noted that, ignoring the niceties of the physical processes, all the models could be expressed mathematically in similar form, of,

$$\log_{10} h_p(x) = a \log_{10} x + b \log_{10} Q - c \log_{10} U_{ref} + d, \quad (59)$$

where a , b and c are effectively the exponents for x , Q and U_{ref} in the model formulations and d is the scaling factor. On this basis they compared the coefficients derived from a statistical data fit against their experimental data (derived from Yates(1996), who used 1m diameter pool fires and other measurements from a large, nominally 15m diameter, kerosene pool fire) with those of the models. A brief résumé of the results of this are shown in Table 1 (Taken from their Table 2, which excluded outliers from the comparison).

Most of the exponent and coefficient comparisons can be considered as similar, within the accuracy of this type of work, though there are some marked differences and none of the models proved inherently superior. Fisher et al's comparison of their field data (from Yate's approximately 15m diameter kerosene pool fire) with the models is shown in Figure 10. Overall, the differences in the calculated plume path from the three methods in this figure are within the variation that can be expected of a field experiment.

Table 1. Values of the Coefficients a, b, c and d for Equation (59) for the Three Plume Rise Models Investigated by Fisher et al(2001).

Model	Source	a	b	c	d	Correlation Coefficient
Zonato et al	Paper*	0.63	0.26	0.63	0.38	
	Data Fit**	0.58	0.29	0.71	0.54	0.88
Carter	Paper	0.25	0.25	1.0	0.40	
	Data Fit	0.25	0.17	0.67	0.49	0.87
Mills	Paper	0.67	0.33	1.0	1.6	
	Data Fit	0.80	0.25	0.80	1.22	0.87

* From the equation constants given in the original paper.

** From Fisher et al's revised curve fits.

Figure 11 shows a direct comparison of calculated plume rise at three distances from the source (10m, 100m and 1000m) from Mills, Carter and Zonato et al, together with a conventional plume rise calculation using Briggs' usual model for heat release only (see Jones(1983)), for a range of plume heat release and pool diameter at a fixed wind speed of 5m s⁻¹. Briggs' original model does not recognise effects of source size per se. The upwind distance of the virtual origin for Carter's model was taken from the lateral dispersion due to the R91 model (Clarke(1979)) assuming that $D = 4\sigma_y$. The three plots for different distances are deliberately identical, but this does lead to some apparent anomalies for the shorter distances and larger sources, where the plume rise is partly calculated

over the release area; all the models permit this. Overall, Carter's model shows the greatest effects of source size on plume rise, followed in order by Mills, Zonato and finally (since no account is taken of source size) Briggs. Mills and Carter both indicate a decreasing plume rise with increasing source diameter, which would be expected. Zonato et al predict the opposite behaviour, with plume height increasing as the source diameter increases. This is due to the limit to plume height applied by Zonato et al, which operates at the two smaller pool diameters at this distance. Both Mills' and Carter's models converge towards Briggs' model as distance from the source increases and pool size decreases; despite Carter's model being based on Moore's original plume rise model rather than Briggs.

Figure 12 shows calculated concentrations from area sources in open terrain for the ADMS model and Hanna et al's(1998) estimate of concentration at the ground due to large area buoyant plumes. The latter work is more related to prediction of lift-off in relation to plume building interactions (discussed in Section 6) from Equation (65), but is shown here as it is essentially a dispersion estimate for open terrain. The wind speed is fixed at 5 m s^{-1} , as in Figure 11. Though comparable with each other on a basis of concentration at the ground, neither calculation is directly comparable with the work above as Mills, Carter and Zonato predict plume height and do not include a dispersion model. Hanna et al predict concentration at the ground as a function of distance and source conditions, but the plume rise is embedded in the calculation. The ADMS model does not output a plume rise for area source calculations as it subdivides the source in some way using multiple plumes. As with the comparison in Figure 11, there are some apparent anomalies in the calculation where it is within the source area. There are quite substantial differences in predicted concentration at the ground between the two calculations, the ADMS model predicting maximum concentrations typically between one and two orders of magnitude lower than Hanna et al. The ADMS model shows a marked effect of the source size at all distances, the differences increasing with increasing heat release. Hanna et al show a more limited effect of source size, which is minimal at the calculation distance of 1000m. Both calculations show increasing concentrations at the ground with increasing source size, consistent with a reducing plume height with increasing source size. However, there are opposing effects on concentration at the ground due to the increase of source size. Increasing the width of the source increases the spread of the plume, so reducing concentrations, while at the same time the reduced plume height tends to increase concentrations.

4 SURFACE OBSTACLE INTERACTION AND FIRE PLUME DISPERSION FROM BUILDING SURFACES

Despite the interest in pool and other surface fires in open terrain, the majority of fires from hazardous accidents are associated with surface obstacles of some

sort, most commonly buildings (including warehouses), chemical or engineering plant, road and rail vehicles and aircraft. Unless the fire area is very large compared with any surface obstacles, these invariably interact with the fire plume, modifying the initial dispersion and plume rise. The fire source may be external to the obstacle (for example the spilled fuel from a damaged road vehicle, aircraft or storage tank), in which case it mainly interacts with the downwash field of the obstacle. Alternatively, the plume may arise from inside the obstacle; from a fire inside a building or warehouse for example. In the latter case both the fire itself and the dispersion of the fire products are additionally influenced by the building ventilation process which exchanges combustion air for the emitted fire products. This behaviour may be modified further during the course of a fire in which the structure of the building or other obstacle suffers progressive destruction, allowing steadily greater rates of ventilation, fire growth and the discharge of fire products.

It is difficult to treat this complex behaviour solely theoretically in the first instance, so the main recourse initially has been to experimental data. Most of the fire plume behaviour described here has used the small-scale experimental wind tunnel work of Hall et al(1980), Hall and Waters(1986) and of Hall et al(1995). However, there has been a previous review of buoyant plume rise associated with buildings for NRPB, by Robins(1997) as well as attempts at modelling this behaviour using the ADMS 2 model by Carruthers et al(1999). This and other work is also discussed here.

The behaviour of buoyant releases from building forms was first investigated by Hall et al(1980) and in further experiments by Hall and Waters(1986), using small scale wind tunnel models. The application was to hazard assessment of plumes from reactor accidents, leading to a range of possible heat releases from cold to around 1000MW. The building shape was fixed in the ratio 2:1:1 in width (initially across the wind), height and depth respectively, with an assumed nominal height of 50m, though the dimensionless scaling allows application of the data to any building height. The releases were over the whole area of the single faces. Figure 13 shows plume flow visualisation photographs from these experiments for three release conditions (down the page) and a range of releases buoyancies (across the page, approximate values of F/U_{ref}^3L are appended). The three release conditions were for a release from the upwind face of the building (the top row), a release from the downwind face of the building (the centre row), with the long building face set across the wind in both cases. In the bottom row, the release was from the long downwind face of the building, which is skewed with its faces at 45° across the wind. In this latter case, a principle feature of the flow is the strong trailing vortex shed from the long upper upwind edge of the building, which greatly affected the flow and dispersion patterns.

Related centreline ground level plume concentrations to the centre row of photographs, with the release from the downwind face, are shown in Figure 14. The concentration is given in the dimensionless form, K , where,

$$K = \frac{cU_{ref}L^2}{q}, \text{ for which,} \quad (60)$$

c is contaminant concentration and U_{ref} is the wind speed at the reference height, L , taken here as the building height.

The concentration can, of course, be converted to plume temperature above ambient using Equation (39).

In Figure 14, for values of F/U_{ref}^3L below about 0.002, the plumes were indistinguishable from neutrally buoyant releases, the plume was entrained into the building wake and the position of the release had little effect on the resultant dispersion pattern. For increases in F/U_{ref}^3L beyond this, an increased plume height and its effect on the resultant concentration pattern at the ground was apparent. For values of F/U_{ref}^3L around 0.02 and beyond, the plume buoyancy became sufficient to modify the building entrainment patterns. In the upper row of photographs in Figure 13 (with the building square across the flow and the emission from the upwind face), the horseshoe vortex around the upwind face of the building can be clearly observed in the left hand photograph, with a nearly neutrally buoyant release, but has disappeared from the right hand two photographs. With these latter levels of plume buoyancy the rising buoyant air motion up the front face of the building was sufficient to destroy the opposing motion due to the horseshoe vortex. In both the top two rows of photographs, the plume buoyancy altered the entrainment into the downwind building wake. As values of the dimensionless buoyancy flux exceeded about 0.02, unentrained air appeared under the plume immediately downwind of the building, showing that the vertical mixing in the immediate building wake had been modified by the plume buoyancy. At the highest buoyancy levels the plume had lifted entrained material well clear of the ground and thus modified the building wake entrainment process to reduce mixing to the ground. The lower row of photographs show the additional effect on this process of including a strong trailing vortex, shed from the long edge of the building skewed to the flow. When present, such vortices can be quite intense and may dominate the local flow patterns. In the present case, the trailing vortex has affected the plume dispersion at all buoyancy levels. The plume became entrained in the trailing vortex and its rotation was clearly apparent during direct observation. The plume's dispersion pattern was altered and, since the plume was entrained into the vortex, as the plume buoyancy increased the plume height increased, lifting the vortex from the ground.

Some plume cross section concentration patterns associated with this behaviour are shown in Figure 15. The measurements were made about six building heights downwind, close to the downwind edge of the separated wake behind the building. The upper plots are of the discharge from the downwind face of the building set square across the wind, as for the results of Figure 14, and the centre row of photographs of Figure 13, for no plume buoyancy and for a value of the dimensionless flux parameter, F/U_{ref}^3L , of 0.2. The lower plots are for the same plume buoyancy conditions, but with the building skewed 45° across the

wind, as in the lower row of photographs in Figure 13. In the upper plots the non-buoyant plumes are entrained into the building wake in conventional fashion (see, for example, Snyder(1994)). At the moderate plume buoyancies shown in Figure 15, the building entrainment pattern is altered, the plume from the building set square across the wind has largely lifted from the ground and shows the classical form of an entrained double vortex. The buoyant plume from the skewed building, having entrained into the trailing vortex, showed a different pattern consistent with only a single vortex. Interestingly, the measured concentrations within these two markedly different plume cross sections are approximately similar.

A summary of the effects of a building on local plume rise from these experiments is shown in Figure 16. This gives the dimensionless concentration, K , at the ground at three downwind distances from the building, for the whole range of the dimensionless buoyancy parameter and source arrangements used in the experiments for the building set square on to the flow. The upper plot shows the effect of the source position and two levels of surface roughness; values of z_0 of 0.2m, open country with some buildings and other surface disturbances, and 0.6m a suburban surface with relatively sparse building density. The lower plot shows the effect of building shape, the upper plot is for a single, 2x1x1, building shape. The '60m' spacing (for a full scale building height of 50m) was within the separated wake region behind the building. There was little effect due either to the surface roughness or the point of release on the building. Measurements at the three distances showed only limited variations in plume concentrations at the ground for values of the dimensionless buoyancy flux below about 0.01. For dimensionless buoyancy fluxes increasing beyond this, the plume rose rapidly and concentrations at the ground fell markedly, by some orders of magnitude within the range of the experiments. Higher values of the dimensionless buoyancy flux, $F/U_{ref}^3 L$, around 1 and above, resulted in plumes largely lifting clear of the ground. The lower plot shows concentrations at the ground reduced as the width of the building increased with low plume buoyancy, as might be expected due to the increased wake cross sectional area within which the plume was dispersed. However, with higher plume buoyancy, concentrations at the ground increased as the width of the building increased. It was presumed that this was due to the plume rise reducing in the wider building wakes as the buoyant force was distributed over a larger plume cross section.

This work also included experiments on sources in open terrain, but this has not been used here as the work on area sources from the URAHFREP programme (Hall and Walker(2000)) is a preferred data set. There was also one experiment using a source at the ground just behind the building, in the separation region. Dispersion patterns from this source position were not markedly different from those for the source on the downwind building face shown in Figure 14, except in the very near field within the separation region, where concentrations at the ground (just over the source) were higher.

Carter(1991), described a simple fire model, SMOKE, a modified version of his FIREFLY model discussed above, for modelling fire plumes from fires within

buildings. This used the same principle of a virtual origin which produced a plume at the downwind edge of the building matching its dimensions. He compared this with some data from Hall and Waters'(1986) experiments. A diagram of the principle of the model and two comparison results of ground level concentrations from his paper are shown in Figure 17, with a nearly neutrally buoyant release and with a low buoyancy (of $F/U_{ref}^3L = 0.01$). The neutrally buoyant plume calculation was quite close to the experimental data. That for the slightly buoyant plume within about a factor of two of the experimental concentrations up to a scaled distance of 2km from the building, though the experiment and prediction had dissimilar trends. A further comparison was described, for a plume with buoyancy close to the 'lift-off' condition (discussed in Section 6), with $F/U_{ref}^3L = 0.1$, where the model predicted a region behind the building with no significant concentration at the ground but higher concentrations further downwind. The experimental data for these conditions indicated a marked reduction in concentration at the ground, with a continuous decrease in concentration with increasing distance. The differences may simply be due to greater effects of building downwash than were assumed. Possibly also in a need to allow for partitioning of the plume to leave a low buoyancy component of the plume, which did not rise with the rest of the plume, entrained in the building wake.

5 VENTILATION OF FIRE PLUMES FROM INTERNAL FIRES

5.1 Ventilation Processes During the Course of a Fire.

The interactions between fire plumes and buildings described in Section 4 did not consider the manner in which discharges appeared on the building surfaces. In practice, many fires develop inside buildings and their discharge externally is via the building ventilation processes. For a fire plume to discharge, there must be a related ingress of make-up air into the building. This also supplies the combustion air for the fire, so that the fire's development, its external discharge plume and the building ventilation process are intimately related. The building ventilation processes are similar to those for conventional ventilation, except that the combustion air temperatures can be very high (ca 300°C or more) compared with those for conventional ventilation, so that the buoyancy forces in fire ventilation processes are relatively high.

Further, the development of a major fire in a building often follows a pattern, which results in the progressive destruction of the building. A typical major fire in a closed warehouse will proceed in a number of discrete stages:

Initially a small fire may start in a closed building; the fire will develop relatively slowly as it uses up combustion air in the building, which must be replaced via external ventilation. If the building is modern and well sealed, with doors and other vents closed, the ventilation can only be by

infiltration, which will be limited. The rate of combustion will then be ventilation limited and the fire plume will discharge over relatively large areas of the surface (driven either by wind or buoyancy forces) as it exfiltrates through small cracks and faults in the structure. The heat release in the fire plume will be controlled by this limited ventilation rate, as will the rate of contaminant discharge.

Over time, the temperature in the building rises and starts to damage the structure. Translucent daylighting panels of plastic or glass fibre are common in warehouses and other large storage facilities, especially in the roof. These will start to melt or burn through, making openings in the structure through which enhanced ventilation can occur. A door may be opened, further enhancing the ventilation rate. Alternatively, thermal stresses from the rising temperature in the building may cause distortion of the building surfaces, increasing the rate of infiltration. The net result is a rapid increase in the ventilation rate and the potential burning rate of the fire. Both the heat release in the plume and the rate of contaminant discharge will then increase.

Eventually, the rising rate of burning from the increased air supply will increase the internal temperatures to a level where the structure loses its strength and integrity; unprotected steelwork, common in warehouses, can easily reach red heat and lose all significant stiffness. There is then a more general structural collapse, usually associated with the roof falling in. From this point there is little constraint on the rate of burning due to ventilation limits and the fire plume is also largely free to disperse unconstrained by the building structure. Both the heat release in the plume and the rate of contaminant discharge can then be very large, the heat release reaching hundreds of MW.

Over time, possibly due to using the available fuel or to the efforts of the fire services, the fire dies away and the heat release in the plume reduces. This tends to result in plumes from large area sources with limited heat release and, from both causes, relatively low plume rise. The level of contaminant discharge can, however, remain high as the low temperature smouldering that accompanies this stage of a fire's development can be rich in partial products of combustion. In some of the more spectacular large fires this process has been known to continue for days or weeks. If the building roof has collapsed but the shell of the wall remains, a common occurrence, the fire plume will then disperse from inside a hollow shell.

5.2 Estimates of Ventilation Rates in a Building in Open Terrain During a Fire.

Because of the critical part played by the building ventilation in defining the plume heat release and the area of the building over which it is released, some methodology for predicting these is required. Hall et al(1995) made estimates of the plume ventilation rates from a typical warehouse building during the course

of a fire. This is described briefly here as an example of the methodology and to give an indication of the ventilation rates to be expected. Full details of the calculations are in the original report. The building form used for the ventilation and subsequent dispersion experiments is shown in Figure 18. Three building planforms were used; of 30mx30m (that shown), 30mx60m and 30mx100m.

The ventilation calculations followed conventional building ventilation practice (for which a good introduction can be found in the ASHRAE Handbook (ASHRAE(2001))), the main distinction of fire ventilation being the much higher buoyancy forces generated by the high temperatures of fire plumes.

In light winds or still air, the ventilation process is driven by buoyancy forces. In a closed building the heated fire products accumulate in the upper part and ventilate through the surfaces in this region, while replacement (and combustion) air is drawn in lower down the walls of the building. However, this ventilation pattern can be modified if there are openings in the structure. An opening in a building occupying only a few percent of the surface area can have a marked effect on the internal pressure pattern as it sets the building mean internal pressure at a level close to that at the opening. Figure 19 shows some examples of these ventilation patterns. The top diagram is the classic diagram for buoyancy-driven ventilation in a closed structure, with infiltration and exfiltration through the wall and roof of the building. The middle diagram shows the effect of a single roof opening. In this case most of the fire plume is diverted from exfiltration through the upper walls and roof to flow through the opening. The infiltration flow is through the building walls as before. The ventilation rate is only slightly increased as the pressure drop of the infiltration is relatively large and still controls the ventilation. An open door would allow greater infiltration rates and a higher ventilation rate. With additional roof openings, this pattern may remain unaltered, but the lower diagram shows a possible alternative with both in and outflow through separate roof openings. This latter flow pattern is a stable ventilation mode and can significantly increase the ventilation rate over a closed building.

The wind imposes a pressure pattern on the building and with increasing wind speed it eventually generates larger pressure forces on the building surfaces than those due to the buoyancy forces. At this point the fire plume ventilation becomes controlled by the building surface wind pressure pattern and, for a given building and configuration of openings, the ventilation rate is then proportional to the wind speed. Pressure patterns and the resulting fire plume ventilation patterns depend considerably on the wind direction over the building and the relative positions of any openings. The most general pattern of the pressure distribution is for relatively high pressures on the upwind faces of the building and the downwind regions of the roof. The downwind facing wall tends to have pressure levels close to the mean (which is also that inside the building), so will usually play only a limited part in the ventilation process. Relatively low pressures occur on the walls parallel with the wind flow and the upwind regions of the roof. Thus, depending on the position of an opening on a wall or roof relative to the wind direction, it may act as an inlet or an outlet. Figures 20 and 21 show examples of the wide variety of wind-driven ventilation patterns that

can result from different distributions of openings on the walls or roof of a building.

Pressure patterns on simple building forms, such as those shown here, can be found from standard data on building ventilation. Hall et al(1995) used building pressure pattern data from the Building Research Establishment's data for assessing wind loads (BRE(1989)) to estimate the discharge rates of fire plumes from the building shape of Figure 18 during different stages of the degeneration of a building. For more complex building shapes it is more difficult to predict pressure patterns reliably and it is then usual to obtain these from small scale wind tunnel experiments. This procedure is very common in determining pressure patterns on complex building forms and layouts for wind loading estimates, but can be as readily applied to complex ventilation problems.

Figure 22 shows example calculations by Hall et al(1995) of variation in the heat release and discharge momentum with the fire plume temperature from a single 1.5m x 2m opening in the roof of a building. In the previous discussion of fire plumes in open terrain it was noted that any momentum in the plume is controlled solely by the plume buoyancy, which is thus the governing parameter of the plume behaviour. However, this is not necessarily so for fire plumes ventilated from buildings, where the manner of the discharge can also affect the discharge momentum. For example, a fire plume escaping from a building by infiltration has negligible discharge momentum, while a fire plume escaping through a roof opening has a significant vertical discharge momentum. Since the discharge momentum affects the initial plume rise, and particularly the probability of the fire plume's entrainment into the building wake, it has been subject to specific attention.

Both plots in Figure 22 show a characteristic form for the heat and momentum discharges. At low wind speeds the plume buoyancy and release momentum are constant, as the ventilation is buoyancy driven. Beyond a critical wind speed, wind-driven buoyancy becomes dominant and the ventilation rate then increases in proportion to the wind speed. Thus the line for the heat release in wind-driven ventilation has a 1:1 slope, as the heat release is proportional to the wind speed at a fixed plume temperature, but the line for wind driven discharge momentum has a 2:1 slope as the discharge momentum increases with the square of the wind speed. It can also be seen in Figure 22 that, due to the high fire plume temperatures, the critical wind speed separating buoyancy and wind driven ventilation is quite high, around 10-20m s⁻¹ depending on the gas temperature; this is around the 90-98%ile of UK wind speeds. This compares with typical critical wind speeds for conventional building ventilation, driven by much lower temperature differences, of around 3 m s⁻¹.

At the critical boundary between the buoyancy and wind driven ventilation process, there is most commonly a progression between the two processes, usually defined by the quadrature average of the two ventilation rates, as shown in the upper plot of Figure 22. However, there are circumstances where the ventilation rate can pass through a minimum in this region, as is also shown (hypothetically) in the upper plot of Figure 22. This occurs when there is a

marked change between the buoyancy-driven and wind-driven ventilation patterns. Here, the wind pressures around the critical velocity may be sufficient to overcome the buoyancy-driven ventilation process, but not to fully establish the wind driven ventilation pattern; the ventilation process then becomes inefficient and a minimum in the ventilation rate results.

Figures 23 and 24 show similar plots to those of Figure 22, but for a fixed fire plume temperature of 300K above ambient and a progressively increasing number of openings in the structure. The building form is that of Figure 18, 60m wide with a total of 18 roof lights, which were presumed to burn through successively during a fire. Also overlaid on the Figures are plots, respectively, of the values of the dimensionless buoyancy flux, F/U_{ref}^3L , Equation (7), and the dimensionless momentum flux, $M/U_{ref}^2L^2$, Equation (15). The Figures show a number of important features of fire plume ventilation from buildings:

The plume heat release and total discharge momentum increase with the number of openings in the building, as the consequent ventilation rate increases.

The critical wind speed, the boundary between buoyancy-driven and wind-driven ventilation, reduces as the number of openings increases; in the case in Figure 23 from a sealed building to one ventilated by a door and eighteen roof openings, the critical wind speed reduced from about 22m s^{-1} to 6m s^{-1} .

Until there are a relatively large number of openings in the structure, the critical wind speed is so high (above about 10m s^{-1}) that wind driven ventilation occurs only for conditions when the plume rise is small or negligible.

Similarly, unless there are a relatively large number of openings in the structure, the discharge momentum in wind driven ventilation is too low to have any significant effect on plume rise.

When there is ventilation only by infiltration or through a limited number of openings, the plume heat release is quite limited (typically a few MW or less) unless the wind speed is high.

In the most frequently occurring meteorological conditions, fire ventilation in largely intact buildings can be assumed to be buoyancy-driven. This assumption fails only in high wind speeds or when serious degeneration of the building structure has occurred.

For the usual range of wind speeds, fire development in buildings which are closed or have only a few openings is probably ventilation limited.

Similar results and conclusions on warehouse fire ventilation were obtained by Miles and Cox(1996) using the JASMIN CFD model.

5.3 Fire Plume Dispersion from Warehouse Structures.

As well as estimating plume buoyancy and momentum discharge rates from warehouse buildings, described above, Hall et al(1995) also carried out a large number of small scale wind tunnel dispersion experiments on the fire plume dispersion patterns resulting from this range of discharge conditions. Some of the basic characteristics of fire plume/building interactions have already been described in the earlier work in Section 4. However, this later work contained some specific additional matters of interest in predicting fire plume discharges from buildings. These are described briefly here, the full data set can be found in the original work. The experiments included dispersion from warehouse building surfaces, from diffusion over half the roof area (as usually occurs in exfiltration), over a range of single and multiple roof openings and of plumes from building shells, the latter replicating the conditions of a building with a collapsed roof.

An example of the effect of the warehouse building and its different discharge conditions on ground level concentrations from the plume centreline is shown in Figure 25. The left hand plot is of ground level concentration from fire plumes discharging from relatively small and large (3m and 10m diameter) area surface sources in open terrain. Though for non-buoyant releases increasing the source size had little effect, with buoyant releases increasing the source size significantly increased the plume concentration at the ground in the near field.

The right hand plot of Figure 25 shows the effects of different plume discharge arrangements from the building on ground level plume concentrations downwind of a 100m wide (across the wind) building. The discharge was either from the centre of the building shell or through an increasing number of roof openings spread laterally across the wind; the fifteen roof openings were across almost the whole width of the building. Though concentrations at the ground reduced with increasing plume buoyancy, ground level concentrations of buoyant plumes increased as the discharge was spread across the building through a greater number of roof openings, due to the resultant reduced plume rise. If there was no plume buoyancy, ground level concentrations decreased as the plume was distributed across the building, due to the increased lateral dispersion. The effect on the plume rise of distributing the source across the roof openings on the plume rise is shown in the photographs in Figure 26. These show, in descending order, the effect of increasing the number of discharge openings across the building on a plume with a value of the dimensionless buoyancy flux, F/U_{ref}^3L , of 0.3. The plume through a single opening appeared to rise clear of the building, though the related concentration measurements in Figure 25 show that it did not entirely do so. By the time the plume was distributed across all fifteen openings across the building, the plume rise appeared to have been largely lost. However, plume concentrations at the ground were lower than for a neutrally buoyant release. This was partly due to the distributed plume buoyancy still influencing the plume dispersion and partly due to the increased initial width of the source. Discharges from the building shell produced the lowest concentrations at the ground for a given release buoyancy. This was

partly because the discharge was from a small area source in the relatively sheltered region inside the building shell. The experiments showed that the entrainment of buoyant plumes by the building wake was not so severe as from similar discharges through roof openings.

A broad summary of these experiments is given in Figures 27 and 28, which show, respectively, the plume height and concentration at the ground 300m (30 building heights) downwind of the building. Four plots are given in each Figure, respectively for the plume in open terrain, a plume discharged from a building shell, a plume discharged through a variable number of roof openings and a plume discharged from an open door. The common line through each plot in Figure 27 is of the plume height for the open terrain discharge, in order to show the different trends in the data. That in Figure 28 is of the ground level concentrations for the plume in open terrain: there is, similarly, a common line through all four plots, derived from the open terrain measurements.

In open terrain, at this distance there were only relatively small differences in plume height and ground level concentration between the two source diameters (about 3m and 10m at the scales of the experiment). However, Figure 25 shows greater differences at shorter distances.

Discharges from a building shell square on to the wind produced similar plume heights and ground level concentrations to those in open terrain. Varying wind direction introduced about a factor of two additional variation in these parameters. By far the greatest variation in plume height and ground level concentration resulted from distributing the discharge across the roofed building, either through openings or diffused through the roof surface. The resulting reduction in plume height appeared to be permanent and ground level concentrations at this distance varied by up to two orders of magnitude depending on the discharge conditions.

The bottom left plots in Figures 27 and 28 are for diffusion through door openings set in the side (along the wind) of a 100m long building with its long side either along (90°) or across (0°) the wind. For low plume buoyancies, concentrations at the ground were similar (within a factor of two), despite the 3:1 difference in the building widths across the wind. For high plume buoyancies, the plume heights were markedly lower with the long side of the building along the wind, but concentrations at the ground were also lower.

Most of the features of fire plume interactions with buildings described here are not accounted for by any of the current simple models. There has been one attempt at reproducing some of this behaviour using a proprietary dispersion model, by Carruthers et al(1999), using the ADMS 2 model. In these comparisons, multiple plumes were used to simulate discharges through several openings and area sources flush with the building for the discharges from the building roof. Examples of this data comparison are shown in Figures 29 and 30. Figure 29 shows a comparison of ground level concentrations for fire plume discharges from different numbers of roof openings for neutrally buoyant releases (the upper plots) and buoyant releases for a dimensionless buoyancy

flux, F/U_{ref}^3L , of 0.1 (the lower plots). Beyond the immediate building wake (up to about 50m distance from the building) the comparison is quite close for the neutrally buoyant discharges. However, there were greater differences, typically around a factor of two, in the near field and with the buoyant releases; in the latter case the ADMS model predicted lower concentrations for discharges through a single opening and higher concentrations with the discharge distributed through four openings. Figure 30 shows a direct data scatter plot of the experimental and modelled concentrations for two warehouse building shapes, of 30m (the upper plot) and 100m (the lower plot) widths across the wind, for neutrally buoyant and for two plume discharge buoyancies with values of F/U_{ref}^3L of 0.1 and 0.3, and for discharges through one, four and fifteen openings. About two thirds of the compared model and experimental values fell within a scatter band of a factor of two. The only directly observable differences outside the scatter band were due to the discharges through a large number of openings across the wind, where the experiments indicated the presence of a significant residue of the plume at the ground which the numerical model did not predict. Considering the complex nature of the buoyant plume (including multiple plume) and building interactions involved in the experiments, the comparison is as good as may be expected. ADMS, like other models of this type, uses relatively simple building entrainment models, which cannot readily deal in detail with these complex interactions.

6 LIFT-OFF

A particular feature of ground-based fire and other plumes which has been of continued interest, is the occurrence of 'Lift-Off', which defines the conditions for which the body of the plume lifts clear of the ground. Its significance is in the greatly reduced exposure to the fire plume that results in the near field at the ground, so that it represents an important break point in short range exposure calculations. This concept originated in some unpublished dimensional analysis by Briggs(1973) and has been the subject of further analysis and some experimental validation since. There is only a brief discussion of this here, together with the most important results. There is a longer review of lift-off by Ramsdale and Tickle(1998).

Briggs originally proposed defining the lift-off condition as,

$$L_p = g \frac{\Delta\rho}{\rho_a} \frac{H}{u_*^2}, \text{ where,} \quad (61)$$

L_p is the 'Lift-Off' criterion,

$\Delta\rho/\rho_a$ is the plume density difference against ambient,

u_* is the friction velocity and

H is a height related to the depth of the plume.

This is a form of Richardson's number, as in Equation (5), which applies to the local state of the plume. Briggs tentatively proposed a lower limit of $L_p=2.5$ for

lift-off, which he later (in another unpublished note) revised to 29, partly as a result of Meroney's (1979) experiments. Meroney investigated lift-off with small scale wind tunnel experiments on buoyant sources at the ground, both two-dimensional and three-dimensional, and suggested a value of L_p between 9 and 27 for three-dimensional (that is, from point and small area sources) plume lift-off, and between 4.5 and 1600 for two-dimensional sources (that is, line sources across the wind). There is a fundamental difference between lift-off of buoyant plumes from two- and three-dimensional sources, in that clean air must pass under the plume in order for it to clear the ground. This is not possible for two dimensional sources without either a separated flow behind the plume or its degeneration into separate three-dimensional elements. The latter process is the more likely, but this has not been subject to discussion in the usual buoyant plume literature. Meroney also noted that buoyant plumes exhibited a behaviour where lift-off was delayed for some distance from the source and he provided criteria for this distance. In his experiments, lift-off appeared to occur for all levels of source buoyancy, its occurrence being delayed for increasing distances as the plume buoyancy reduced. In their initial investigation of interaction between buildings and buoyant plumes, Hall et al (1980) argued that this delay of plume lift-off was a surprising occurrence as the buoyant force in the plume was at its greatest nearest the source, so that if lift-off did not occur initially it would not occur later. Briggs thought the finite distance to lift-off was related to the need for the plume to develop some vertical growth and for clean air to circulate underneath it, which required some time to occur in a ground-based plume. In none of their own experiments did Hall et al (1980, 1986, 1995) clearly identify a finite distance to lift off, though most of their work was concerned with buoyant plume/building interactions at short ranges. However, other workers have also described the phenomenon of delayed lift-off (via personal communication) to the first author.

Hall et al (1980) also noted that it should be possible to express the lift-off criterion in terms of a dimensionless buoyancy flux, as a source parameter rather than a local plume parameter, given a few simple assumptions. For their experiments with a building, this led to Briggs' estimate of L_p of 29 yielding a critical value of the dimensionless buoyancy flux, F/U_{ref}^3L , of about 0.11 if L was taken as the building height. This value is marked on the plot of Hall et al's (1980, 1986) data in Figure 16. It did indicate reasonably well the value of F/U_{ref}^3L around which there was a marked reduction in plume concentrations at the ground.

A band of similar values of F/U_{ref}^3L is marked on the plot of warehouse ventilation conditions from Hall et al (1995). Observation of the plume height and concentrations from this work, as in the examples of Figures 27 and 28 showed that the same lift-off criterion was valid for relatively compact discharges, from one or a few roof openings, for example. However, it failed when the source material was distributed over a larger area of the building surface, due to the collapse in the plume rise in these cases. There seemed, therefore, to be a need for accounting for the source size in a lift-off criterion for other than relatively small sources.

Hall and Walker(2000) also examined their plume rise data for area sources in open terrain for a lift-off criterion. On the basis of the reduced plume rise data in Figure 7 and the measured plume vertical spread rates, they estimated the value of their dimensionless buoyancy flux per unit width, F_w , for which the concentration at the ground had fallen to about 15-20% of the plume maximum concentration. This corresponded approximately to a plume height, $h = 2\sigma_z$, which occurred for an approximate value of $F_w / U_{ref}^3 L = 0.035$.

Poreh and Cermak(1988a) investigated lift-off for plumes with both buoyancy and horizontal momentum, partly to see if Meroney's work was affected by this parameter as he used discharges of this sort. It appeared that this was probably not the case, but the work also provided a data correlation for this type of discharge, which is shown in Figure 31, for a distance about twenty plume heights downwind of the source. Their data of their ratio, P , of concentrations to the ground for a non-buoyant to a buoyant plume, $c[0]/c_{max}$ in their terminology, collapsed when scaled using the ratio of the plume source buoyancy to forward momentum, $F^*/M^{*1/2}$. F^* and M^* are similar to the dimensionless buoyancy and momentum fluxes used here (Equations (7) and (15)), but used reference wind speeds and length scales from the depth and upper wind speed for their experimental boundary layer rather than at heights related to the plume and its source within the boundary layer. An approximate relationship with the present terminology and for length scales and wind speeds closer to plume scales and wind speeds is,

$$\frac{F^*}{M^{*0.5}} \approx 1.5 \frac{(F/U_{ref}^3 L)_{Plume}}{(M/U_{ref}^2 L^2)_{Plume}} \quad (62)$$

Poreh and Cermak also gave a data correlation for their concentration ratio, P , at this distance for conditions where the plume buoyancy significantly reduced the plume concentration at the ground. Converted to local wind speeds and plume scales using the corrections, as in Equation (62), this becomes approximately,

$$P = \frac{c(\text{neutrally bouyant})}{c(\text{buoyant})} \approx 0.3 \frac{(M/U_{ref}^2 L^2)}{(F/U_{ref}^3 L)^2} \quad (63)$$

Hanna et al(1998) attempted to quantify a more general criterion for lift-off and derived an expression which fitted Hall and Waters'(1986) data of Figure 16 and the warehouse fire data of Hall et al(1995) described previously. This has the form (in the terminology used here),

$$\frac{cU_{ref}R^2}{q} = \frac{\exp\left(-6\left(\frac{F}{U_{ref}^3 W}\right)^{0.4}\right)}{\left(0.037 + 0.03\left(\frac{X}{H}\right)^2 + \left(\frac{F}{U_{ref}^3 W}\right)^2\left(\frac{X}{H}\right)^4 + \left(\pi\frac{\sigma_y\sigma_z}{R^2}\right)\right)^{1/3}} \quad (64)$$

W is here the building width and H the building height,
 R is a length scale, taken for buildings as $H^{2/3}W^{1/3}$.

The wind speed reference height is at a nominal value associated with the plume or building. It is assumed that $U_{ref}/u_* = 10$.

The fit of this Equation by Hanna et al to the data of Hall and Waters(1986), is shown in Figure 32. The fit to the data is reasonably good for the two longer distances, of 600m and 2km, though slightly high for the near field distance of 60m, which was within the building wake.

For sources in open terrain or where the building is small relative to the initial source or plume size, Hanna et al reduced Equation (64) to,

$$\frac{cU_{ref}}{q} = \frac{\exp\left(-6\left(\frac{F}{U_{ref}^3 W}\right)^{0.4}\right)}{\left(\left(\frac{F^{1/3} X^{2/3}}{U_{ref}}\right)^6 + (\pi\sigma_y\sigma_z)^3\right)^{1/3}} \quad (65)$$

Hanna et al also noted that the methodology of this model derivation led to a simple correction for plume concentration at the ground based on ground level concentrations for an equivalent plume with no buoyancy, in the form,

$$\frac{c(\text{with buoyancy})}{c(\text{without buoyancy})} = \exp\left(-6\left(\frac{F}{U_{ref}^3 W}\right)^{0.4}\right) \quad (66)$$

No validation of Equations (65) or (66) was offered in the paper, but the need to do so against further data as it became available was recognised. Equation (66) is not equivalent to Poreh and Cermak’s Equation (63), so that the two formulae cannot be directly compared. The latter seems only to be valid in conditions with some horizontal momentum in the discharge, while Hanna et al’s Equation (66) has no momentum component at all.

Robins(1997) discussed some experiments on plume rise from the ground, due to Macdonald et al(1988), in his more general review of plume rise associated with buildings. These examined the relationship between discharge buoyancy and momentum on plume lift-off from circular sources at the ground in open terrain using flow visualisation. The main result of this work, taken from Robins(1997), is shown in Figure 33. The plume behaviour is divided into categories of:

- passive (showing no significant plume rise due to buoyancy or momentum),
- active (showing some effects due to buoyancy and momentum),
- intermittent (occasionally rising clear of the ground) and
- lifted (rising clear of the ground).

The ‘lifted’ category may arise from high buoyancy or high momentum. An interesting feature of Figure 33 is that for moderate levels of discharge momentum there appears to be a requirement for increased buoyancy before

lift-off occurs, so that the combined effects of buoyancy and momentum in the discharge are not necessarily complementary to the plume rise. At the lowest levels of buoyancy, the minimum value of Macdonald's buoyancy flux parameter for lift-off is around 0.01-0.02. It is not perfectly clear, but Macdonald's buoyancy flux parameter (F_B in Figure 33) is probably related to that used here by,

$$\frac{F}{U_{\text{ref}}^3 D} \approx \frac{F_B}{4}. \quad (67)$$

Macdonald's lift-off parameter for sources with low momentum then appears to be around 0.01 - 0.1. Comparison with the data of Hall and Walker (2000) in Figure 7 (for which, in this case, $F_w = F$) leads to a lift-off criterion with an equivalent value of $F/U_{\text{ref}}^3 D$ of about 0.0025 - 0.025. The upper bound of this range is comparable to, but lower than, the equivalent value quoted by Hall and Walker for their experiments, of about 0.035.

7 THE GROUND-BASED COMPONENT OF OPEN TERRAIN FIRE PLUMES AND PLUME PARTITIONING

There is a case for considering the existence of a residual, detrained ground-based component of fire plumes which otherwise have risen clear of the ground in the near field. This behaviour is recognised as a common feature of plume interaction with surface obstacles, but is not usually considered in fire dispersion in open terrain. In open terrain, if it occurred, this detrained component would have relatively little buoyancy of its own and act as a partitioned fraction which remained on the ground, separated from the main body of the rising plume. If this process were of any magnitude, it would clearly represent a significant factor in estimating fire plume contaminant concentrations at the ground. There are a number of possible mechanisms by which this might occur and some limited evidence of its existence. These are:

The shedding of material from the outer edges of rising plumes, where the vertical velocity component may be small and boundary layer turbulence may be sufficient to remove material from the plume.

The separation from the main plume of combusting material at the outer edges of surface based fires, where the inflow velocity that carries material into the main plume can be very low, allowing the entrainment of material out of this region by boundary layer turbulence. Experimental measurements by Poreh(1985) noted the low inlet velocities at the edges of fires and gave (in the units in use here),

$$U_r(\text{m s}^{-1}) = 0.5 \left(\frac{Q(\text{MW})}{D(\text{m})} \right)^{1/3}, \quad (68)$$

where D is the pool diameter (R , in Poreh and Cermak's notation in Figure 34) and U_r is the inflow velocity at this radius. Poreh et al's original experimental data are shown in Figure 34, together with a plot of inlet velocity based on Equation (68). It can be seen that, except in extreme cases, the radial inlet velocities are generally very low, below 1 m s^{-1} , and could easily be overcome by atmospheric turbulence even in light winds. Fannelop and Webber(2003) also note, in their theoretical calculations, the very low values of inlet velocities in fire plumes rising from the ground.

Visual observation in wind tunnels of buoyant smoke plumes, rising well clear of the ground, have shown intermittent fine striations of smoke extending to the ground. The cause of this process is uncertain, but the striations may be the cores of vortices reaching from the plume to the ground, generated by the modified wind pattern around the rising plume. Extreme examples of this type of behaviour have been observed in the atmosphere behind strongly rising fire plumes, where an intense (often intermittent) vortex extends from the plume to the ground, carrying plume material to the ground. Figure 35 shows photographs by Dessens(1962), of an intense vortex of about 10m diameter and 200m depth behind a fire source about 125m by 125m releasing around 500MW heat into the plume over a light wind (of perhaps 1.5 m s^{-1} near the ground). This was not Dessens' sole observation of this behaviour and it may be a common, though often unobserved, feature of fire plumes. The subject has been of occasional interest and Murgai(1976) discusses various aspects of vortex generation associated with fires. There are similar observations by Church and Snow(1980). The mechanism may be similar to that associated with dust devils in strongly convective atmospheric boundary layers.

8 PARTICLE DISPERSION FROM FIRE PLUMES

There are, broadly, two types and size ranges of particles discharged in fire plumes. The first are the direct products of combustion or partial combustion, for example smoke, fume (condensed particles from vaporised solid materials) and their agglomerated products. These are generally of quite small size, with aerodynamic diameters from sub-micron up to perhaps 10-20 μm .

The second are particles generated by mechanical processes occurring during fires, the collapse of structures or small explosions which eject particles and small items of debris into the fire plume; these particles may be of the raw materials of the fire, from the building's structure or partially combusted materials. The smaller end of the size range of these mechanically produced particles can be of μm size, similar to those of the fire combustion products, from fine powders stored in the fire area or dust from collapsing masonry for example, up to quite large particles. The core velocity of a large fire plume can be relatively high due to the high buoyancy forces usually involved; for example the plume gas velocities through the warehouse building roof openings discussed in Section 5.2 were estimated to be around 10 m s^{-1} for a fire plume temperature

of 300K above ambient. Thus any particle with a falling speed below this can be carried out of a building in the fire plume. This can include quite large pieces of material and practical examples of large particulate materials from major fires which have deposited on to the local populace include pieces of charred wood (some still alight), pieces of asbestos construction materials and pieces of charred plastic (from storage bags) up to a centimetre across, contaminated with toxic agrochemicals.

The treatment of these particles in dispersion calculations depends on the particle size range of interest, as this governs both the falling speed and the inertial behaviour of the dispersing particles.

The inertia of the particles is conveniently described by the 'stop distance', D_s , which for small particles in the Stokes flow regime is defined by,

$$D_s = \frac{v_f U}{g}, \text{ where} \quad (69)$$

v_f is the particle falling speed under gravity and
 U is the wind speed.

The significance of the stop distance is normally in relation to the physical scale of the flow. In the present case this is related to discharges from and dispersion around buildings, which are largely defined by their height, H , so the particle inertial scaling parameter is of the form of D/H or similar, which can be defined from Equation (69) as,

$$\frac{D_s}{H} = \frac{U^2 \alpha}{gH}, \quad (70)$$

where α is the slope of the particle falling trajectory in uniform flow.

D_s/H is effectively a Stokes number for the flow and it can be seen from Equation (70) that in this representation D_s/H increases both with the particle falling angle in the flow and with the wind speed.

Broadly, dispersing particle behaviour can be divided into three classes, depending on the value of D_s/H . These are,

- | | |
|--|---|
| D_s / H Large ($D_s / H > 10$) | 'Ballistic Particles' driven by inertia. Wind effects are of minimal significance. |
| D_s / H Moderate ($0.01 < D_s / H < 10$) | Both particle inertia and wind effects can be important. |
| D_s / H Small ($D_s / H < 0.01$) | Inertia unimportant. Particle motion is controlled by wind effects, with dispersion patterns similar to those of gases. |

Some sense of these differences can be gained from the example of Figure 36, taken from Hall et al(1998), which shows the aerodynamic characteristics of particles in the size ranges discussed above in relation to a building with a characteristic length scale of 10m. The example is directly related to the warehouse fire dispersion measurements of Hall et al(1995). The plot is of the ratio of particle falling speed, v_f , to wind speed, v_f/U (the slope of the falling angle, α , in a uniform flow) against the wind speed, U . The conditions of the calculation are essentially those of a fire plume discharging through an opening, as shown in Figures 22 and 23. Formally, Equations (69) and (70) apply only in the Stokes flow regime, for low falling speeds and low values of D_s/H . However, in the interests of a simple analysis, they have been applied to the whole particle size range of interest here, which extends well beyond the Stokes flow regime.

Figure 36 shows lines of both constant falling speed (broken) and of constant D_s/H (solid). In practice, the non-linearities associated with particle behaviour beyond the Stokes flow regime should result in the lines curving upwards at their right hand extremities. There are also a number of shaded areas on the plot, noting various bounds to the flow and particle behaviour.

The shaded right hand side of the plot is beyond the upper wind speeds likely to occur in practice, taken here as 20m s^{-1} , approximately the 98%ile UK wind speed. The upper right shaded area represents the limit of particle falling speed, which is assumed to be controlled by the highest velocities in the fire plume, above which particles cannot be carried away by the fire plume. This is taken in the example here as 10m s^{-1} , the nominal fire plume velocity calculated previously for a roof opening. Thus particles in a fire plume are limited to those occurring in the lower left region of the plot, outside these two boundaries. The shaded area over the lower left region represents particles for which $D_s / H < 0.02$, which is taken (a little arbitrarily) to denote the region within which there are no significant particle inertial effects within the scales of the building and its associated dispersing plume. This is the third class of particle dispersion behaviour listed above. The remaining clear trapezoid of the plot is the region within which particle inertia affects the plume dispersion. The region of truly 'ballistic' particle behaviour, for approximately $D_s / H > 10$, is outside the limits of fluid dynamically discharged particles on this plot and the upper bound value of D_s / H for discharged fire particles is about unity. At this upper bound, particle paths are still dominated by inertia and the falling angle, ca 45° , is so steep that most particles will be deposited very close to the source.

A brief indication of the aerodynamic particle diameters, d_a , associated with values of v_f/U and D_s / H (for $H=10\text{m}$ as in Figure 36) is given in Table 2 for particle sizes up to $10,000\mu\text{m}$.

The values of v_f are given to within about 10% up to particle aerodynamic diameters of $10,000\mu\text{m}$ by,

$$\log_e (v_f) = -10.2403 + 1.888 \log_e (d_a) + 0.06 (\log_e (d_a))^2 - 0.0128 (\log_e (d_a))^3 . \quad (71)$$

Modelling particle dispersion in this region of significant inertia is difficult for particles in rising buoyant plumes, as the particle paths divert from the buoyant gas plume, passing out below it, thereby losing their own buoyant rise.

Table 2. Particle Aerodynamic Diameters, d_a , for Some Values of v_f/U and D_s .

Wind Speed ($m s^{-1}$)	Particle Parameters	Particle Trajectory Slope (v_f/U)		
		0.01	0.1	1
1	v_f ($m s^{-1}$)	0.01	0.1	1
	D_s (m)	0.001	0.01	0.1
	d_a (μm)	18	58	280
2	v_f ($m s^{-1}$)	0.02	0.2	2
	D_s (m)	0.004	0.05	0.4
	d_a (μm)	25	88	500
5	v_f ($m s^{-1}$)	0.05	0.5	5
	D_s (m)	0.025	0.25	2.5
	d_a (μm)	40	160	1250
10	v_f ($m s^{-1}$)	0.1	1	10
	D_s (m)	0.1	1	10
	d_a (μm)	58	277	4000
20	v_f ($m s^{-1}$)	0.2	2	20
	D_s (m)	0.4	4	-
	d_a (μm)	88	500	-

Since there seemed to be no experimental data on this subject, a few wind tunnel experiments were carried out by Hall et al(1998) using suitably scaled particles. The results of these experiments are shown as ground level concentrations in Figure 37 for a neutrally buoyant plume, on the left, and a buoyant plume, with a value of $F/U_{ref}^3 L$ of 0.1 and a dimensionless discharge momentum of 0.1, on the right. The particle properties for the experiments are noted as the large diamonds plotted on Figure 36. Two of the test conditions had similar values of v_f/U and different values of D_s/H , 0.6 and 0.1, and two had broadly similar values of D_s/H (0.04 and 0.1) and significantly different values of v_f/U (0.1 and 1.0). One test condition had very low values of D_s/H and v_f/U , in the range of largely gaseous dispersion characteristics; this concentration data proved unreliable due to small particle agglomeration problems, but the visualised dispersion seemed identical to that of a gas. Concentration

measurements were made for a plume in open terrain and a plume discharged from a 30mx30m building shell. The solid data points are for ground level concentrations of the gas plume, the open data points for concentrations of the particles in the plume. The measurements were not perfectly self consistent, concentrations for $v_f/U=1$ and $D_s/H=0.1$ appeared to be too low, but all showed a far more rapid fall in particle concentration at the ground with increasing distance than for the gas plume, due to the high deposition rates.

The presence of the building shell mostly had a relatively limited effect on particle concentrations, as with the gaseous plumes. Particles discharged with the buoyant plume showed higher concentrations than the gas plume close to the source, but particle concentrations at the ground fell rapidly with increasing distance to levels well below those of the gas plume. It appeared that the separation of buoyant plume and particles occurred quite rapidly and affected concentrations at the ground very quickly.

In terms of modelling and deriving empirical rules for fire plume particle behaviour, the following are suggested, on the basis of the previous division of particle characteristics.

D_s/H Large ($D_s/H > 10$) 'Ballistic Particles' driven by inertia:

It seems that this behaviour is unlikely to occur in a fire plume unless the plume discharge velocity is very high (in excess of 20m s^{-1}), or unless there has been a relatively violent explosion or mechanical collapse in the fire. 'Ballistic' particle deposition calculations are then required, based on simple particle dynamics.

D_s/H Moderate ($0.01 < D_s/H < 10$) Both particle inertia and wind effects can be important:

The particle deposition velocities and resultant plume depletion are probably too high for a conventional dispersion calculation, especially as there may be rapid separation of the buoyant and particle plumes. However, at the lower end of this range, approximately for values of $D_s/H < 0.1$ and $v_f/U < 0.1$, a conventional 'tilted plume' model provides a plausible representation of the particle behaviour. This effectively accounts for the value of v_f/U , but not for D_s/H . If this is done the plume depletion must be accounted for in the calculation as this is relatively rapid even over short ranges. The 'tilted plume' model could be extended to the upper end of this calculation range without numerical difficulty, but it would have to be accepted that the accuracy of the calculation degenerates as the values of v_f/U and D_s/H increase.

D_s/H Small ($D_s/H < 0.01$) Inertia unimportant. Particle motion is controlled by wind effects, with dispersion patterns similar to those of gases:

The distinction between particle and gaseous behaviour is small and a conventional gaseous dispersion calculation is adequate for this regime. Further, since the plume depletion rate is relatively small, this can probably be ignored in short range calculations. Small particle deposition, as of fire combustion products up to about 20 μ m, is relatively complex and deposition velocities depend on a number of variables; this has been recently reviewed by Underwood(2001), who provides nominal values of the deposition velocity. Deposition of larger particles is by gravitational settling and the deposition velocity is thus the same as the particle falling speed v_f , given in Equation 71.

The behaviour of fire plume particles with high falling speeds and inertia has many parallels with the behaviour of snow and of wind raised dust and soil. Though no attempt has been made here to use data from these research fields, they may well merit further investigation.

9 FIRE PLUMES IN URBAN AREAS WITH HIGH SURFACE ROUGHNESS

The literature on fire plumes and fire plume dispersion generally takes little or no notice of the effects of surface roughness, except in the usual effects of roughness on rates of dispersion. None of the simple fire plume rise models discussed here account for varying surface roughness at all and the common presumption is of a fire occurring in low roughness (rural) environments. Hall et al's various wind tunnel experiments, described here, all used relatively high values of aerodynamic surface roughness, which at the typical scales of the experiments produced full scale equivalent values of z_0 in the range 20-50cms, the upper levels being consistent with relatively low density urban areas with small buildings. Known experiments involving buildings are concerned with single structures that dominate the local dispersion. There are no known experiments involving buoyant fire plume dispersion from urban building arrays, though there is a growing database of experiments from neutrally buoyant plume dispersion within urban arrays.

Most fires in urban areas of practical interest are likely to involve only one or a few buildings directly. The properties of large area urban fires have been of some previous interest, relating to fire storms following urban bombing in the Second World War. These are not discussed further here but there is some work in the Appendix of references accompanying this review, by (amongst others) Nielsen(1965), Ebert(1963), Carrier et al(1984, 1985), Faure(1959), Long(1967) and by Small and Brode(1980).

Lacking any positive direction on the behaviour of smaller fires in urban areas, only speculation is possible, but some probable properties of small urban fires may be predictable, based on what is known of the main characteristics of urban flow and dispersion. These depend on the urban array area density (the plan

area occupational density). For low urban area densities (below about 15-20%), the individual building wakes can still be identified, so that the plume entrainment is probably similar to that for individual buildings, but within a modified wind field. The main effects are firstly, reduced wind speeds and increased sheltering within the urban building array and, secondly, high levels of vertical mixing and enhanced turbulence up to about twice the mean urban array height. At higher area densities, above about 20%, the individual building wakes start to merge, wind speeds near the ground reduce considerably and there is a more ready transfer of material laterally from one building wake to another. There has been a recent review of urban dispersion and wind fields by Robins and Macdonald(2001), and earlier by Hall et al(1996).

The combination of wind sheltering and rapid vertical mixing in urban areas provide opposing forces respectively encouraging and inhibiting buoyant plume rise from the ground or from building surfaces. Wind sheltering reduces local wind speeds and encourages plume rise, while the rapid vertical mixing within the urban canopy (up to 2-3 building heights) encourages their rapid dispersion back down to the ground. The same dichotomy was discussed by Hall et al(1980) and by Hall and Waters(1986) in relation to plume rise associated with isolated building wakes.

Overall, with plumes interacting with single building wakes, the effect of the building in the available experiments has been to reduce plume rise and increase concentrations at the ground compared with a ground-based source of the same size in open terrain. This implies that the rapid lateral and vertical mixing in the building wake reduced the relative buoyant force in the enlarged plume in excess of any enhancement in plume rise due to the reduced local wind speed. Further, the region of the building from which the plume was discharged (as distinct from its width across the wind) had little effect on concentrations at the ground.

There seems no particular reason why this behaviour of buoyant plume interaction with single buildings should be different in principle within an urban array, though the typical wind flow patterns within the array suggests that some of these characteristics will be enhanced. Firstly, the array will probably encourage initial lateral spreading of the plume beyond any associated single building, thus tending to reduce the plume rise. Secondly, the higher levels of turbulence within the building canopy, compared with those due to a single building, will enhance the initial plume dispersion, further inhibiting plume rise and encouraging generation of a low buoyancy partitioned fraction of the plume that remains at the surface. It also seems probable that lift-off would be delayed by this behaviour.

An important effect of urban building density on internal fire ventilation is the reduction in wind-driven ventilation rates with increasing building occupational density. The phenomenon is well-known in building ventilation practice and ventilation calculations account for 'shielding' effects on the wind-driven component. This is usually done by scaling the wind pressure coefficients on the structure by a 'shielding' or 'sheltering' coefficient. For example ASHRAE(2001,

Volume 1, 'Fundamentals', Chapter 25) quotes a factor of ten reduction in the wind pressure coefficients on a building passing from open terrain to an urban area with a building plan area occupational density of about 20%. This is equivalent to a reduction in wind driven ventilation rates of about a factor of three and a similar proportionate increase in the critical dividing wind speed between buoyancy-driven and wind-driven ventilation. Considering the already high critical wind speeds for fire plume ventilation shown in Figures 22 and 23, it is clear that internal fire plume ventilation from buildings in urban areas is only likely to be buoyancy-driven.

10 FIRE PLUMES FROM SHORT TERM RELEASES

Many fires are of relatively short duration and their discharges should not necessarily be treated as continuous (or semi-continuous) plumes. A very rapid release of flammable vapour well mixed with air may burn within a few seconds without an explosion. The distinction between a near instantaneous or a short term release (commonly described as a 'puff') and a plume, in terms of its dispersion behaviour, depends on the dimensionless release time, t_D defined as,

$$t_D = \frac{U_{ref} t}{L}, \quad (72)$$

where t is the time of the release. U_{ref} and L are, as before, respectively a reference wind speed and dimensional scale, for example of a building height or source dimension. A release for which $t_D < 1$ constitutes a near-instantaneous 'puff' release, as the released material travels less than its own length during the time of the heat release. A release for which $t_D > 100$ can be treated as a segment of continuous plume over a short distance, but beyond this, for times $>> t_D$, the release approaches the properties of a puff. Releases for which $1 < t_D < 100$ constitute an awkward group which are neither puffs nor plumes in the first instance, but develop puff properties relatively rapidly as they travel downwind. The discussion here will largely refer to 'puffs', with inclusion of the intermediate group as relevant.

Though the characteristics of neutrally buoyant puff releases at the ground have been subject to a moderate amount of investigation and there is enough theoretical and experimental work to define their averaged properties reasonably well, there is very little data on buoyant puffs discharged from the ground. Only two directly applicable papers were found, by Snyder et al(2002) and by Hall et al(2001), the latter as an extension of their work on buoyant plumes from the ground, described here previously, from the EC URAHFREP programme. Both papers have only a limited data content, so that, as with dispersion of plumes in urban areas, any comments must be to some extent speculative.

Since puffs disperse in three dimensions, rather than the two dimensions of a plume, the buoyant forces are applied to a more rapidly growing mass of material, so that in principle the buoyant rise of a puff is less than of a plume.

Moore(1966, 1974) argued that two dimensional buoyant plume behaviour is in fact that of a series of discrete puffs rather than of the continuous two-dimensional form usually assumed. This gives rise to a plume/puff rise that varies with $F^{1/4}$, rather than with $F^{1/3}$ as used in Briggs plume rise model (see Jones (1983)). This matter was never entirely resolved (see Briggs(1975)), but suggests that Moore's model, or a variant of it, may be more suitable for calculating puff rise above the ground. As with the application of plume rise models near the ground, it is also desirable to account for the rapid variation of the local wind speed with height.

The rise of puffs close to the ground is further complicated by the high level of longitudinal shear dispersion at the ground, which is typically around three times that due to the longitudinal turbulence and thus dominates the overall longitudinal dispersion ((Chatwin(1968), Wilson(1981), Hanna and Francese(2000)). Above the ground, the longitudinal shear spreading component reduces rapidly, so that it then has relatively little effect on longitudinal dispersion. A result of this is that puffs close to the ground should lose their overall buoyancy more rapidly due to enhanced longitudinal dispersion compared with a dispersing continuous plume. This may also affect the lift-off condition. It seems most probable that the lift-off condition will be more sharply defined, as puffs with relatively low buoyancy are more likely to remain close to the ground, while those with high buoyancy and a rapid initial rise will be less affected by the longitudinal shear spreading at the ground.

Buoyant puffs discharged in the vicinity of buildings and entrained or discharged into their recirculating wakes will be subject to the relatively low air exchange rate across the wake boundaries. This will effectively result in a delayed release of the puff material over time, an extension of its release time and an overall reduction in its buoyancy. Wake residence times for single buildings have been subject to some investigation (for example by Fackrell(1984) and by Mavroidis et al(1999)) and can be estimated approximately.

An important characteristic of buoyant puff releases is their irregular form and high repeat variability, so that prediction of puff behaviour is inevitably associated with a high degree of statistical uncertainty. The two papers containing measurements of buoyant puffs rising from the ground show this very clearly. Snyder et al(2002), investigated convective cells in the unstable boundary layer using a small scale water channel experiment, visualising the buoyant puffs with a laser light sheet and obtaining concentration profiles from the visualised images. Figure 38, from this work, shows four individual realisations of moderately buoyant puffs rising in a small-scale rough wall boundary layer, together with an ensemble average of thirty-three puffs. The ragged and highly variable nature of the individual realisations is very clear and even the ensemble average of thirty-three realisations is quite irregular. Figure 39 shows single point concentration/time traces of the passage of highly buoyant puffs (strictly, short term releases, but with values of U_t/L between 1 and 4) from Hall et al(2001). These are similarly variable between realisations and the figure is typical of the measurements. Flow visualisation of a high buoyancy short term release showed it to be in the classical form of a rising ring

vortex (see, for example, Scorer(1978, p.290)) leaving a tail of residual material as it rose; lower buoyancy releases did not show this behaviour. A main concern of Hall et al(2001) was to determine the differences in the rise of plumes and equivalent short-term releases. Their data was too limited and variable to provide a definitive conclusion, but it showed no clear differences between the rise of equivalent plume and short-term releases.

Of the generally accessible models, only the most recent version of the ADMS model calculates puff rise and dispersion. Puffs are treated as plume segments with a finite release time and include an element of longitudinal shear spreading in the dispersion calculation. The rise of the buoyant puff and any loss of material by deposition area estimated from the rise and deposition of the equivalent plume from an equivalent plume pre-calculation. Thus the puff rise is the same as that of the equivalent plume and there is no effect of longitudinal dispersion on the puff rise included in the calculation.

11 DISCUSSION AND CONCLUSIONS

The present review has aimed at providing practical guidance on the behaviour, at short ranges, of fire plumes rising from the ground or discharged from buildings, including releases from still air and conventional dispersing plumes from the ground or building surfaces. It has largely restricted itself to publicly available guidance that can be used directly or modelled at about spreadsheet level or using existing conventional models. To this end it has also tried to use consistent units and converted various formulae and dimensionless forms to these units where practicable. Most of the more complex models are either not readily accessible to the general user or require the preparation of specific software. However, the NIST ALOFT long range model and FDS CFD model are available as free downloads. CFD modelling has been dealt with only marginally for several reasons. Its more general use has already been discussed previously in NRPB reports by Hall(1997) and by Robins(1997). Its application is also a specialised matter in its own right. Finally, though generally common in fire research, its application to external fire plumes seems to have been quite limited: few papers were found using CFD models to contribute to the understanding of fire plume behaviour, or to validating this aspect of CFD modelling (see, for example Venetsanos et al(2003)).

The application of the present main regulatory models, ADMS and AERMOD, to fire plume dispersion has also been considered as these are generally available and have a high level of validation for other applications. Neither is specifically aimed at fire plumes, but the ADMS model has a recursive plume rise model which may deal more satisfactorily with buoyant area sources. Its comparison with Hall et al's(1995) warehouse fire data by Carruthers et al(1999) showed a plausible prediction of the dispersion of warehouse fire, though there were some deficiencies with discharges spread widely across the building. It was not possible to compare the ADMS model plume rise for area sources in open terrain

against the other plume rise models of Mills and Carter or against Briggs, as the ADMS model does not output plume heights for area sources. The AERMOD model is not easily usable for calculations with a single meteorological condition as it is intended mainly for annual hourly regulatory calculations. In any case the AERMOD model does not recognise a calculation which includes both area sources and buoyancy. Its plume rise model is based on Briggs' model, which in its basic form is suitable for point sources only. The meteorological input to the ADMS model can, however, be modified to model single meteorological conditions.

An important feature of fire plume behaviour is the effect of the source shape on plume rise from the ground and it has been generally recognised that increasing source size appears to reduce plume rise. However the source shape, in relation to the wind direction also appears to be important. There is a substantial reduction in plume rise from the ground or building surfaces as fire sources are spread across the wind. There is a less clearly apparent effect also of the length of plume sources along the wind, which appears from the experiments of Hall et al(1995) and Hall and Walker(2000) to encourage plume rise. Mills' and Carter's plume rise models and the ADMS model all account for source size (as a pool diameter) rather than width, but do effectively reduce the plume rise with increasing source width. Hall et al's(1995) experiments recognised the effects of source shape on plume rise from buildings but did not offer a direct criterion for its effects. Hanna et al's(1998) lift-off analysis and Hall and Walker's(2000) wind tunnel experiments both offered direct criteria for the effects of source width on lift-off. There is presently no criterion for the effects of distributing sources along the wind.

This review has noted a number of deficiencies in both the available simple models and limitations in the experimental database against which they can be either designed or verified. Overall, there is a substantial database on fire plumes in still air, especially of the classic cases of circular pool and line fires, and the 'far-field' plume characteristics are well quantified both experimentally and theoretically. There is less data on fire sources of other shape, on the inflow characteristics at the base of the fire (though there is recent work by Fanelop and Webber(2003)) and on the transition from the still air to wind driven plume behaviour. Though not perfect, this database is sufficient to define the properties of fires in still air reasonably well.

The situation with regard to wind-driven fire plumes is less satisfactory. There are only a few sets of published data suitable for developing wind driven fire plume dispersion models, as Fisher et al(2001) have noted. The largest data sets appear to be the field data of Yates (1996), the building entrainment data of Hall and Waters(1986), the warehouse fire data of Hall et al(1995) and the area source data of Hall and Walker(2000). For effective use in model development and validation, such data should preferably be formally archived for ready access by other parties from a suitable source; as, for example, has been done with point source dispersion data for conventional dispersion models by Olesen(1997, 1998) and others. At present only the area source data of Hall and Walker(2000) is so treated and is directly accessible via the Danish RISO

Laboratory's REDIPHEM web site or from the authors. Yates(1996) field data is detailed in an Appendix to his PhD Thesis, though it would be better formally archived. Hall and Waters(1986) and Hall et al's(1995) data is only accessible in plotted form in their reports; since these are no longer readily available, they are presently being converted to PDF format to allow wider access. The original data files still exist, but require conversion to current file formats and archiving to allow ready access.

It would be worth revisiting the simple models discussed here with a view to revising them to validate against this existing database, which post dates most of them. For fires in open terrain the principle difficulty is in predicting the plume rise. Models like those of Mills and of Carter, suitably modified to account for wide and long sources, ought to be adequate for this purpose. Plume rise involving building entrainment is more complex, but Hanna et al's(1995) plume lift-off formula could be usefully compared with Hall et al's(1995) more recent data and their open terrain lift-off formula with Yates(1996) field data and Hall and Walkers(2001) wind tunnel data.

There is a clear need for a more formal intercomparison of fire models, using both the limited available data sets and some standard test cases. This has been attempted here only within limits, but has been partly hampered by the varying nature of the model outputs. Some provide plume rise and some ground level concentration, few provide both.

There are other models which deal with plume rise from the ground, but have not been considered in any detail here as either they are not readily useable without some software development or they are not generally accessible. Tickle(2000) developed an integral model of plume lift-off and dispersion for area sources, based on a methodology devised by Slawson et al(1990). This achieved some success in fitting the small scale experimental data of Poreh and Cermak(1986) and of Hall and Walker(2000), though in the latter case it underestimated the effects of source width on plume rise. There is also an empirical model, 'FIREPEST', by Maddison et al(1996), which deals with a number of aspects of fire development and fire plume dispersion, including building interactions. The dispersion component of the model is mainly based on the small scale wind tunnel experiments of Hall et al(1995). This model is only used internally within the HSE.

There seems to be no experimental data on fire plumes in urban arrays, in keeping with a more general lack of information on the effects of surface roughness on ground-based buoyant plume behaviour. Nor are there any simple models for this application, which, due to the lack of data for validation, would in any case be speculative. It seems most likely that lift-off would be delayed and a residual element of the plume would remain at the surface as surface roughness increased. There is also a more general case for considering buoyant plume partitioning for plume interactions with single buildings and in open terrain, leaving a surface residue with little or no buoyancy.

It has been possible to define the characteristics of particle dispersion in fire plumes and especially of the conditions of different types of particle behaviour. Smaller particle dispersion can be dealt with using conventional dispersion modelling or tilted plume models. Larger particles having high inertia and falling speeds, which may be ejected from fires, are more difficult to deal with as the particle and buoyant plume trajectories may separate. A (heavily) tilted plume model may provide a first order approximation to this condition. There is little experimental data on this large particle behaviour; the only saving is that this type of deposition is mostly in the very near field of the source, where it is perhaps of less concern than at greater distances.

The behaviour of short term releases is difficult to quantify in view of the limited experimental data available. The two papers known, by Snyder et al(2002) and Hall et al(2001) both show puffs above the ground with ragged contours and high levels of variability in internal concentrations and repeat releases. In principle, the rise of a puff ought to be less than of its equivalent plume, due to enhanced puff dispersion from the additional longitudinal dispersion, especially at the ground. However, the limited data of Hall et al(2001), though uncertain due to the limited measurements, did not find a clear difference between the rise of buoyant puffs and their equivalent plumes. Lacking better evidence it is suggested that puff rise be calculated presently using Moore's plume rise model, which presumes that a plume is, in any case, a series of puffs. The ADMS model will also model buoyant puffs, though the puff rise is the same as that of the equivalent plume.

There is a case for arguing that there is little justification in developing complex numerical models for fire plumes and that relatively simple models should be acceptable. The source terms for fires, both for the emitted pollutants and the physical properties of the plume such as the heat release (or, for that matter, often the wind speed), are normally quite uncertain so that great accuracy or reliability in fire plume calculations is not achievable. Rates of dispersion are similarly uncertain. One of the features of practical fire plumes is their frequent failure to behave in the relatively simplified ways described in the models used here. Examples of this are; the development of axial vorticity in fire plumes (due either to shed trailing vorticity from building wakes or the concentration of atmospheric shear vorticity entrained in the plume to produce 'fire whorls'); the unsteady nature of many combustion processes (including regular pulsations in the combustion); the probable tendency of rising fire plumes (especially those associated with buildings) to leave a ground based residue of low buoyancy.

The references in this review have been limited to those with some direct relevance to its immediate needs, providing advice on fire plume behaviour and suitable simple models for their prediction. However, there is a substantial related literature on fires, fire plume behaviour and buoyant rise in the atmosphere (from thermals for example) which can provide useful background information on fire plume behaviour. The Appendix to this review contains a bibliography of many related additional papers and reports found during the course of the work.

12 ACKNOWLEDGMENTS

This review was funded by the Atmospheric Dispersion Liaison Committee (ADMLC)). Thanks are due to David Webber of Integral Science and Software Ltd and to Geoff Cox (Ex Fire Research, BRE) for help and advice on several aspects of fire plume behaviour. Also to Bill Snyder for providing the original images for Figure 38 and to Dr Arthur Jones of NRPB for his great patience and forbearance during the execution of this work.

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14 FIGURES

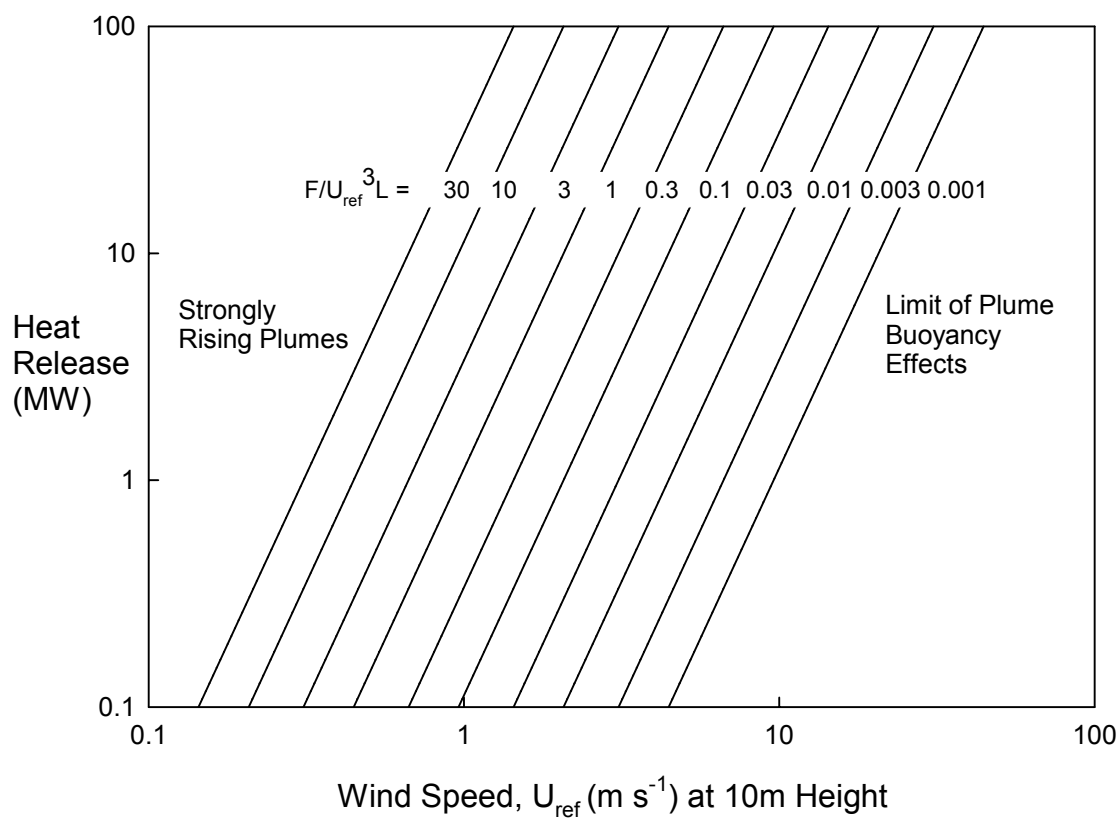


Figure 1. Relationship Between Scale, Heat Release and Wind Speed for Buoyant Plume Scaling, from Equation (7). For a Reference Plume Length Scale and Wind Speed Reference Height Both of 10m.

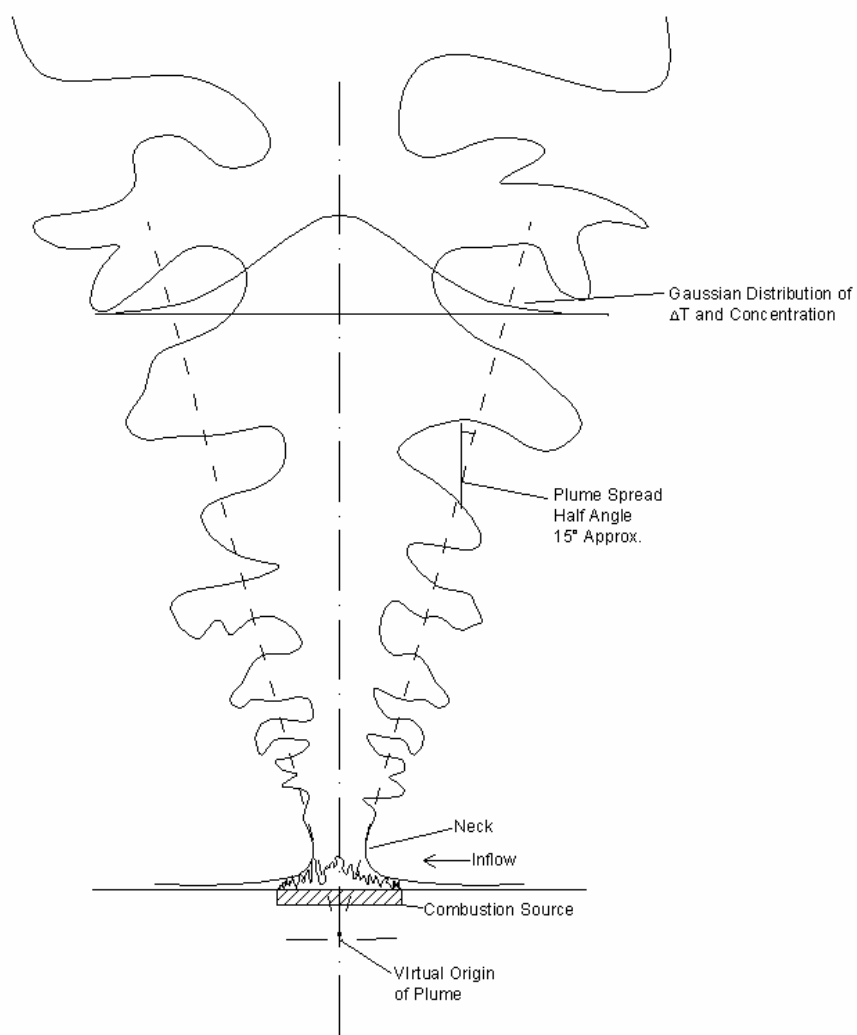


Figure 2. Diagram of Essential Features of a Ground-Based Fire in Still Air.

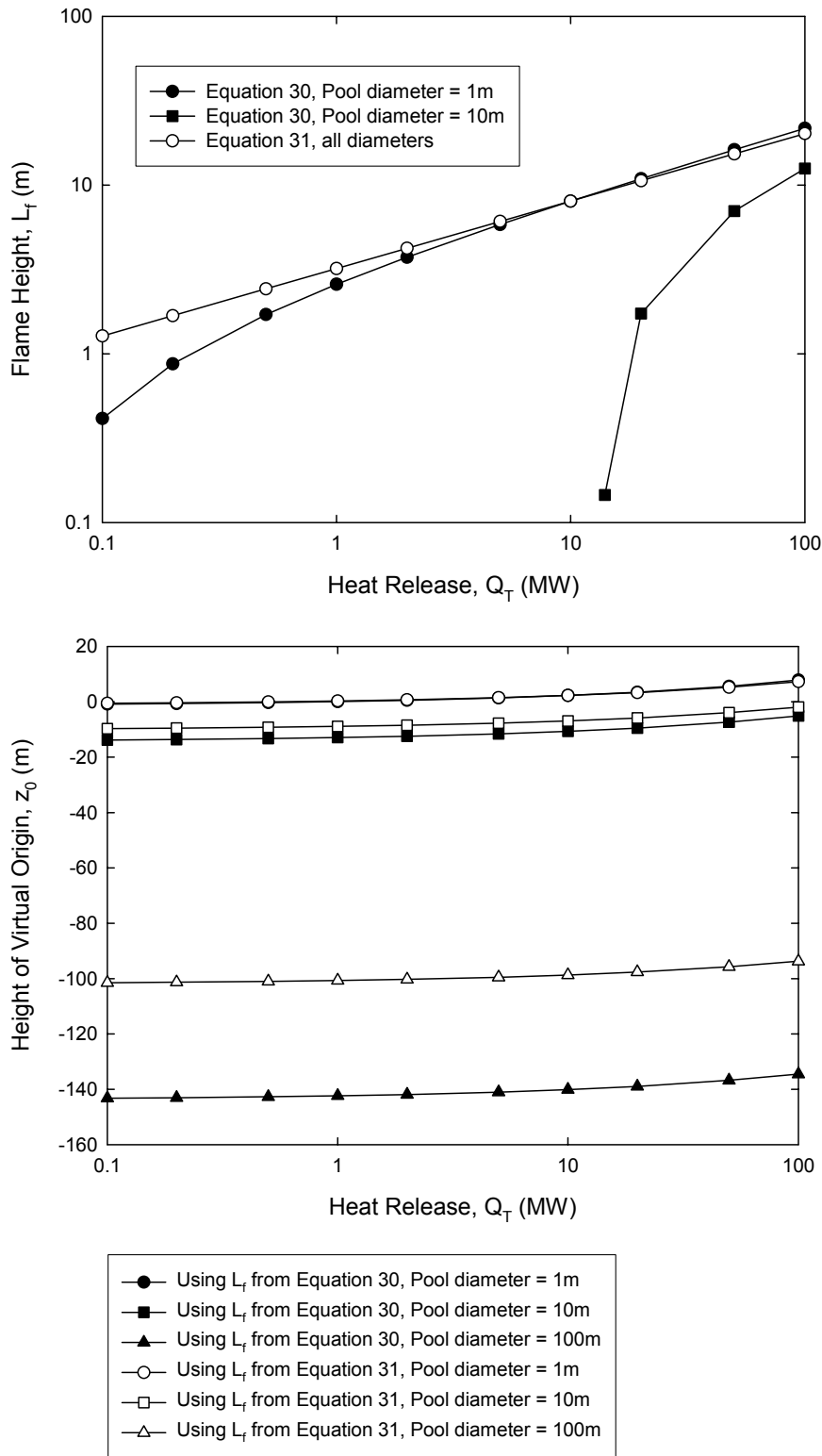


Figure 3. Upper:
Values of Flame Height, L_f , for Fires in Still Air from Equations (30) (Due to Heskestad(1983)) and (31) for Circular Pool Fires.
Lower:
Heights of Plume Virtual Origin from Equation (37), Using Values of L_f Derived from Equations (30) and (31), as in the Upper Plot.

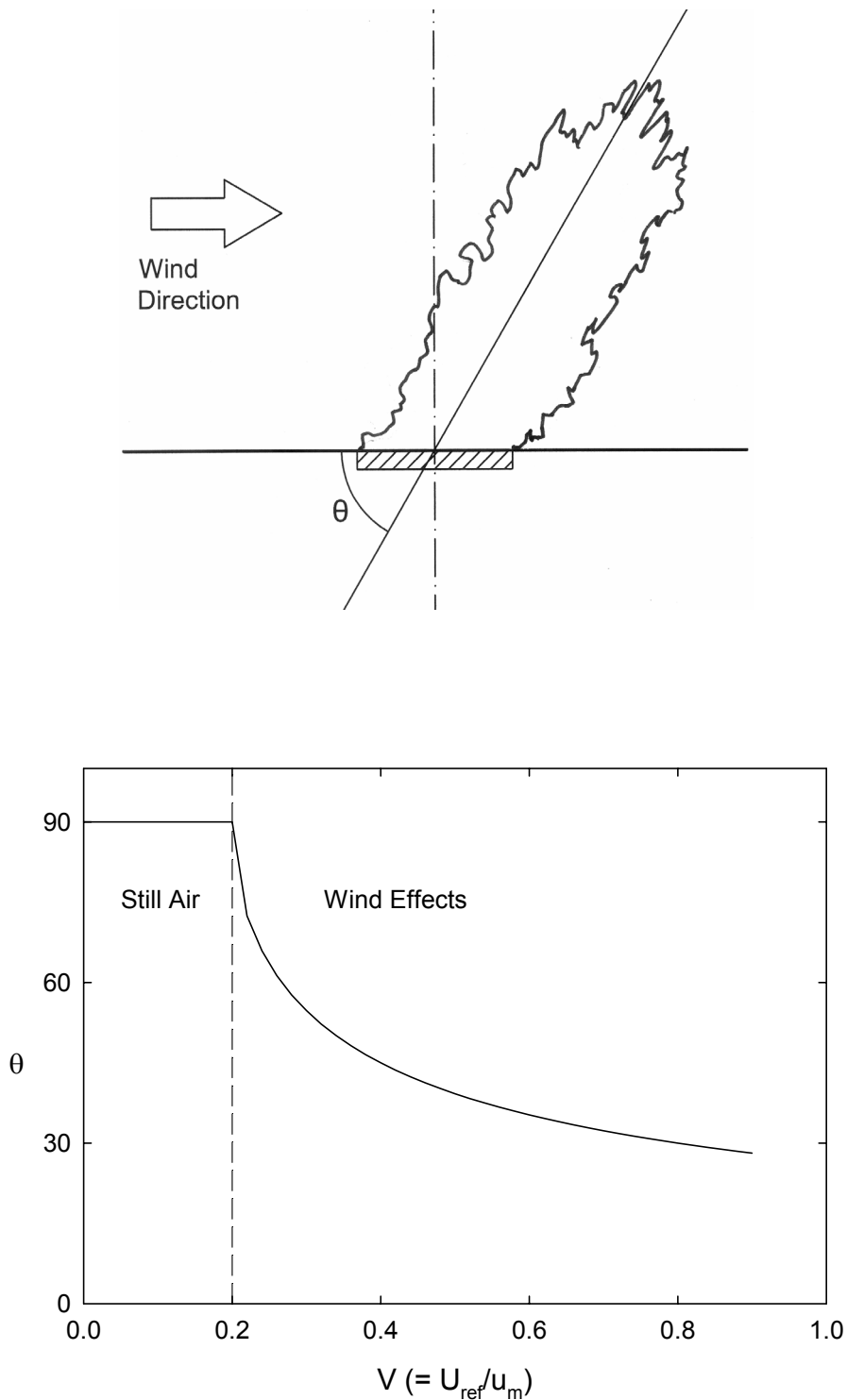


Figure 4. Effect of Wind on Fire Plume Flame Behaviour.
From Raj(1979), following Quintiere(1981) and Drysdale(1990).

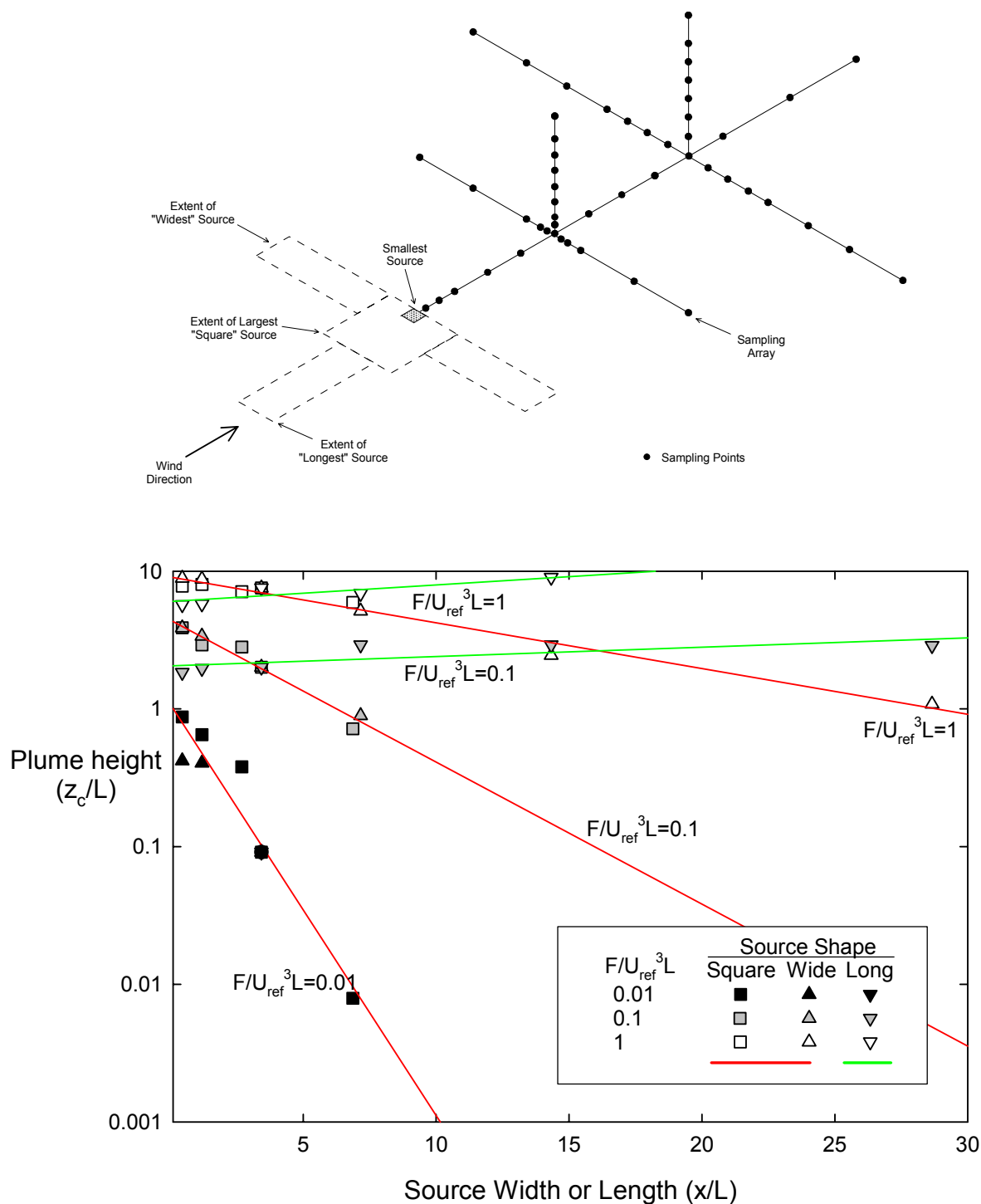
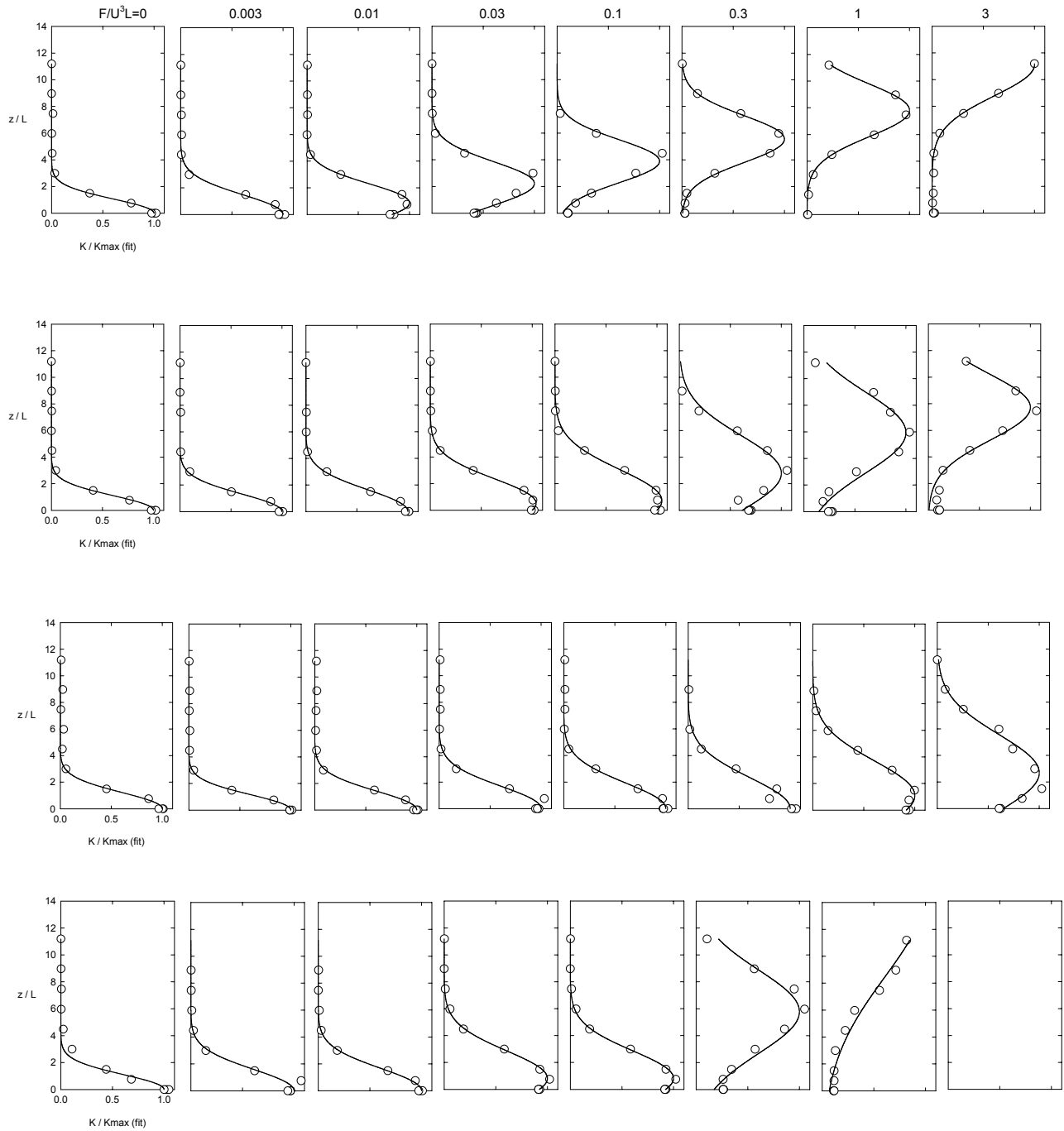


Figure 5. Effect of Source Size and Shape on Short Range Plume Rise of Buoyant Sources at the Ground.
Upper Figure: Layout of Sources and Concentration Sampling Stations.
Lower Figure: Plume Centre Height (z_c/L) Measured at the Nearest Vertical Sampling Station ($15L$ Downwind of Sources) as a Function of Plume Buoyancy ($F/U_{ref}^3 L$).
 L here is the Reference Height for the Wind Speed.
From Hall and Walker(2000).



**Figure 6. Variation of Plume Height with Source Buoyancy (Across) and Source Size and Shape (Downwards).
 For the Measurements of Figure 5 at a Distance 15L Downwind of the Source.
 In Descending Order for:
 Smallest Square Source
 Largest Square Source
 Widest Source.
 Longest Source.
 From Hall and Walker(2000).**

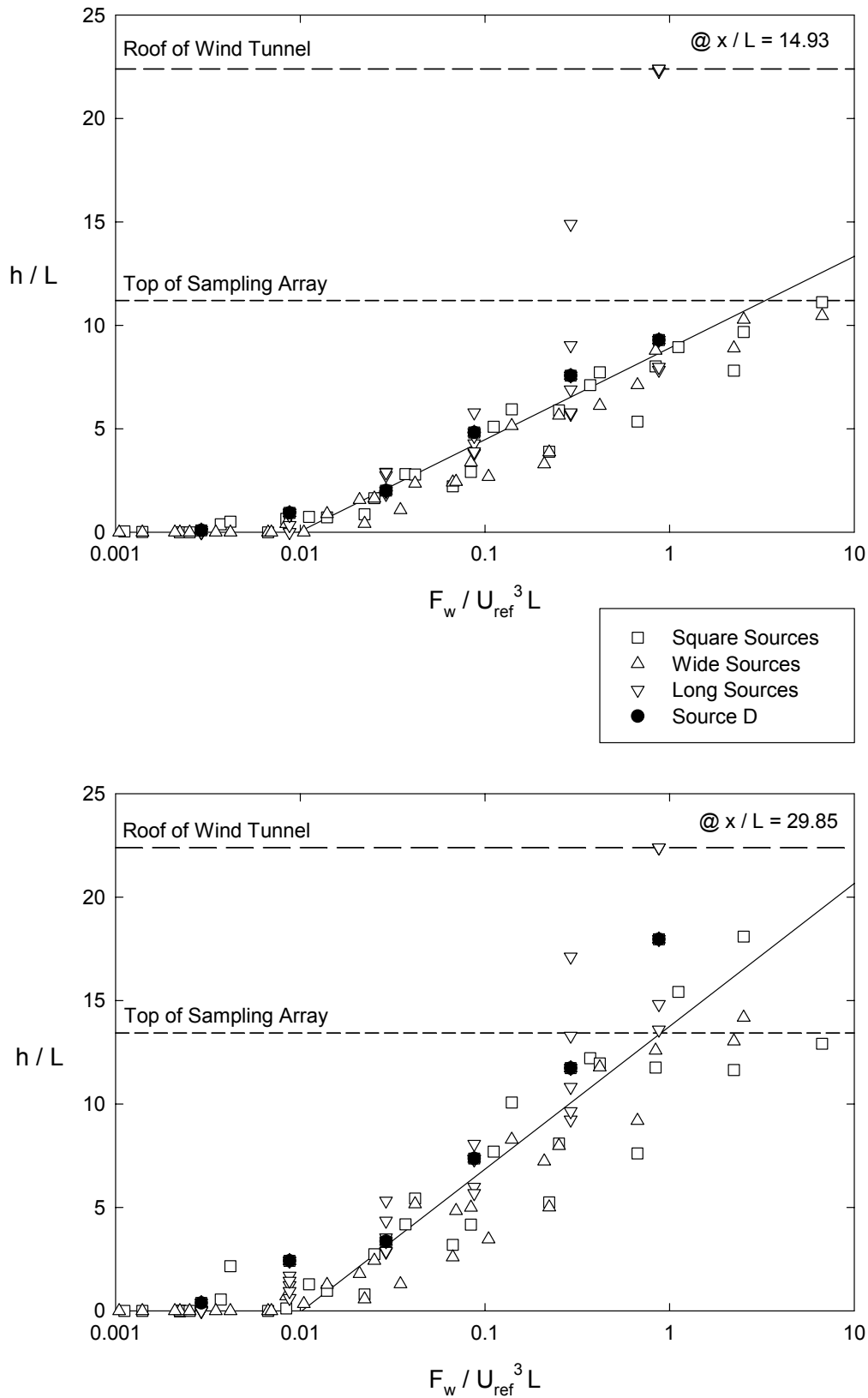


Figure 7. Plume Height at Two Downwind Distances from the Experiments of Hall and Walker(2000) (Figure 5), Reduced Using F_w , the Dimensionless Buoyancy Flux per Unit Width.

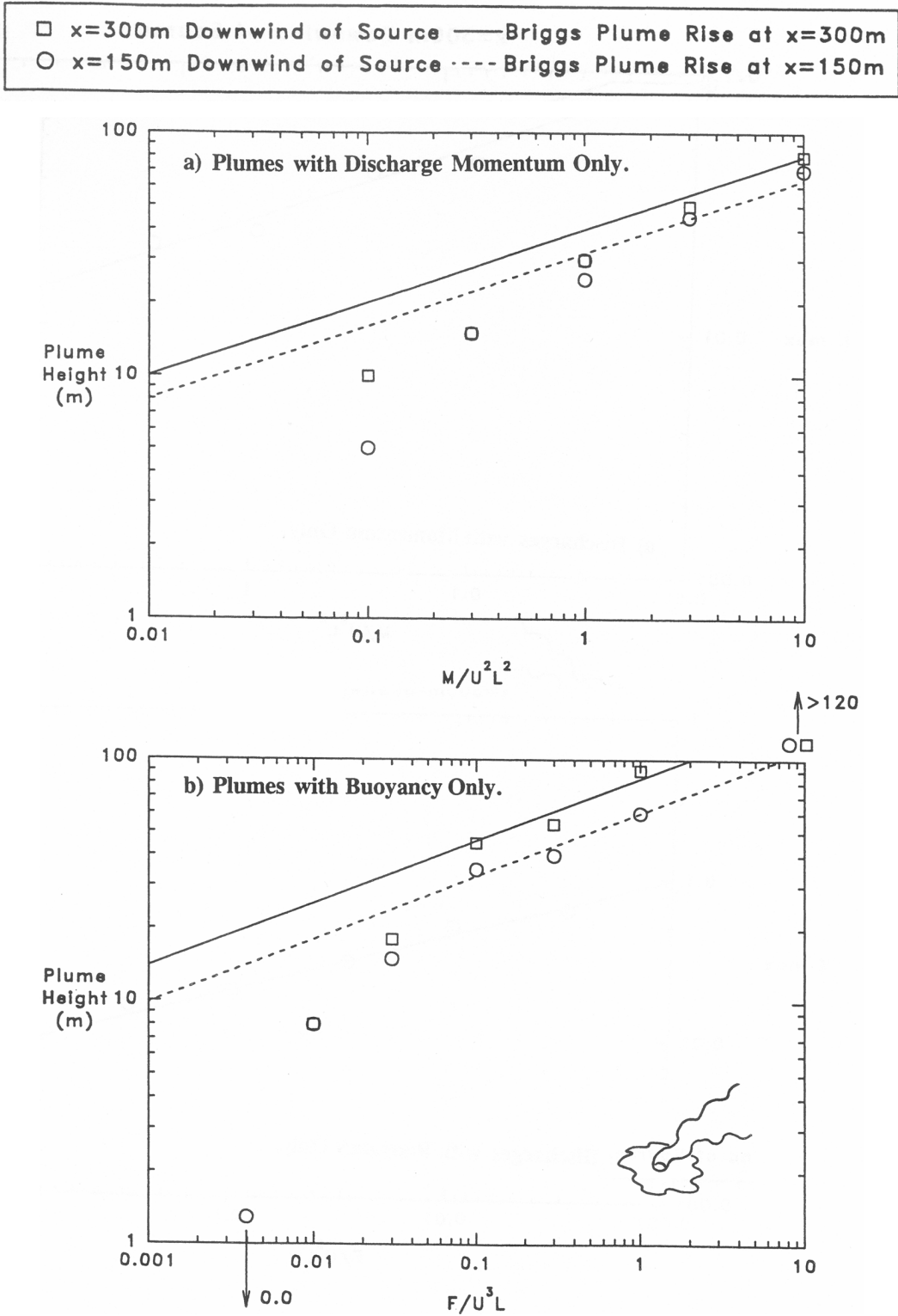


Figure 8. Plume Rise from Small Area Source at the Ground from Small Scale Experiments of Hall et al(1995) Compared with Briggs(1969) Plume Rise Equations.

Model Scale 1/150, L= 10m, Source Width (=Diameter) w/L=0.4.

Plume Rise Calculation at Distances x/L= 15 and 30.

$F_w/U_{ref}^3 L = F/U_{ref}^3 L \times 2.5.$

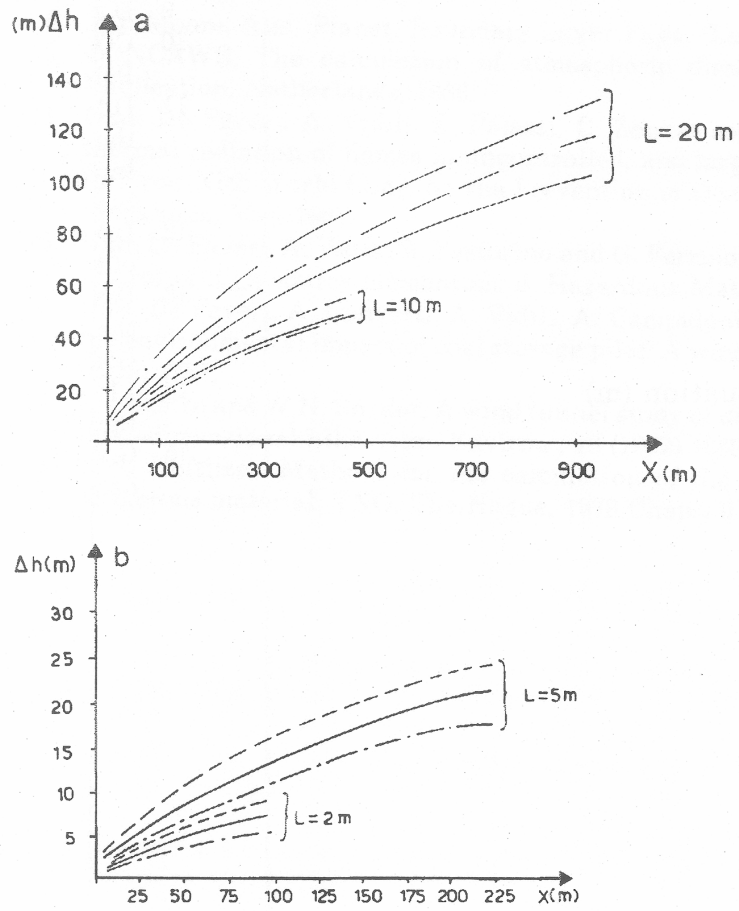
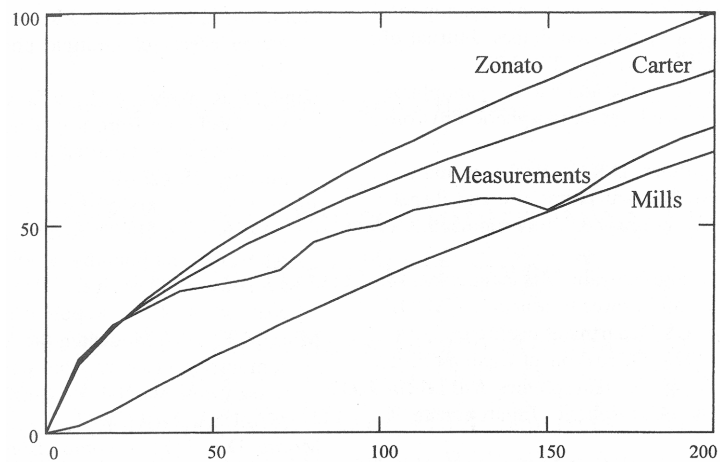
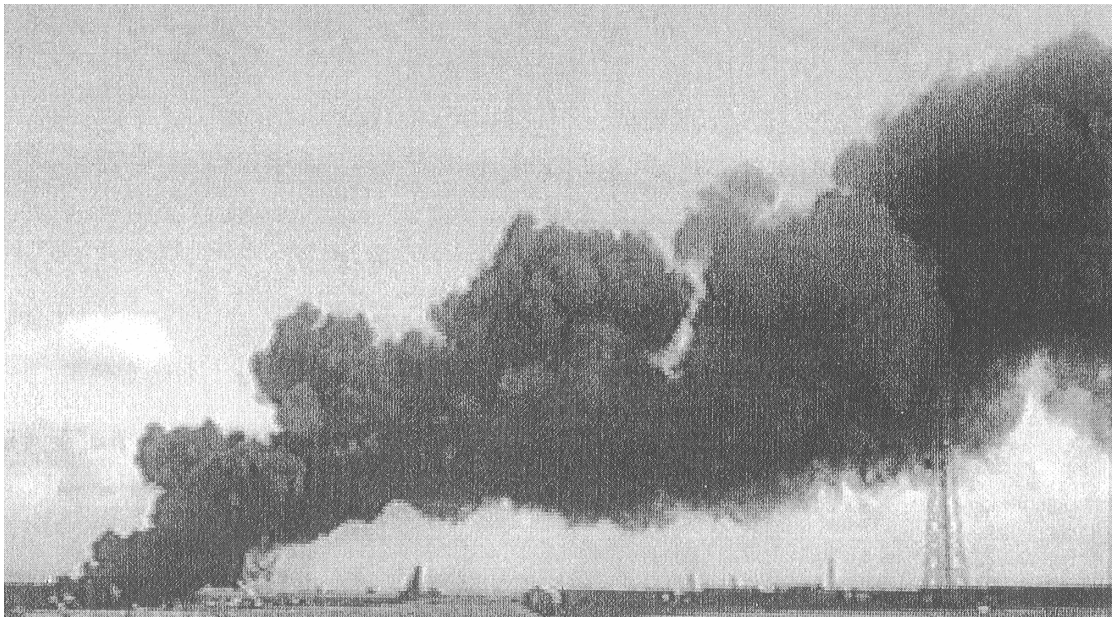


Figure 9. Estimates of Plume Rise from Pool Fires, from Zonato et al(1993). For Hypothetical Pool Fires of 2, 5, 10 and 20m Diameter and 10 m s^{-1} Wind Speed.

- Carter(1989)
- - - - Mills(1987)
- _____ Zonato et al(1993), from Experimental Data.



**Figure 10. Upper: Kerosene Pool Fire. From Yates(1996).
Lower: Calculated Plume Rise from the Same Pool Fire Using Various Models. From Fisher et al(2001), Derived from Yates(1996).
Pool About 18m x 12m, Heat Release About 72MW.
Wind Speed 5m s⁻¹ @ 10m Height.**

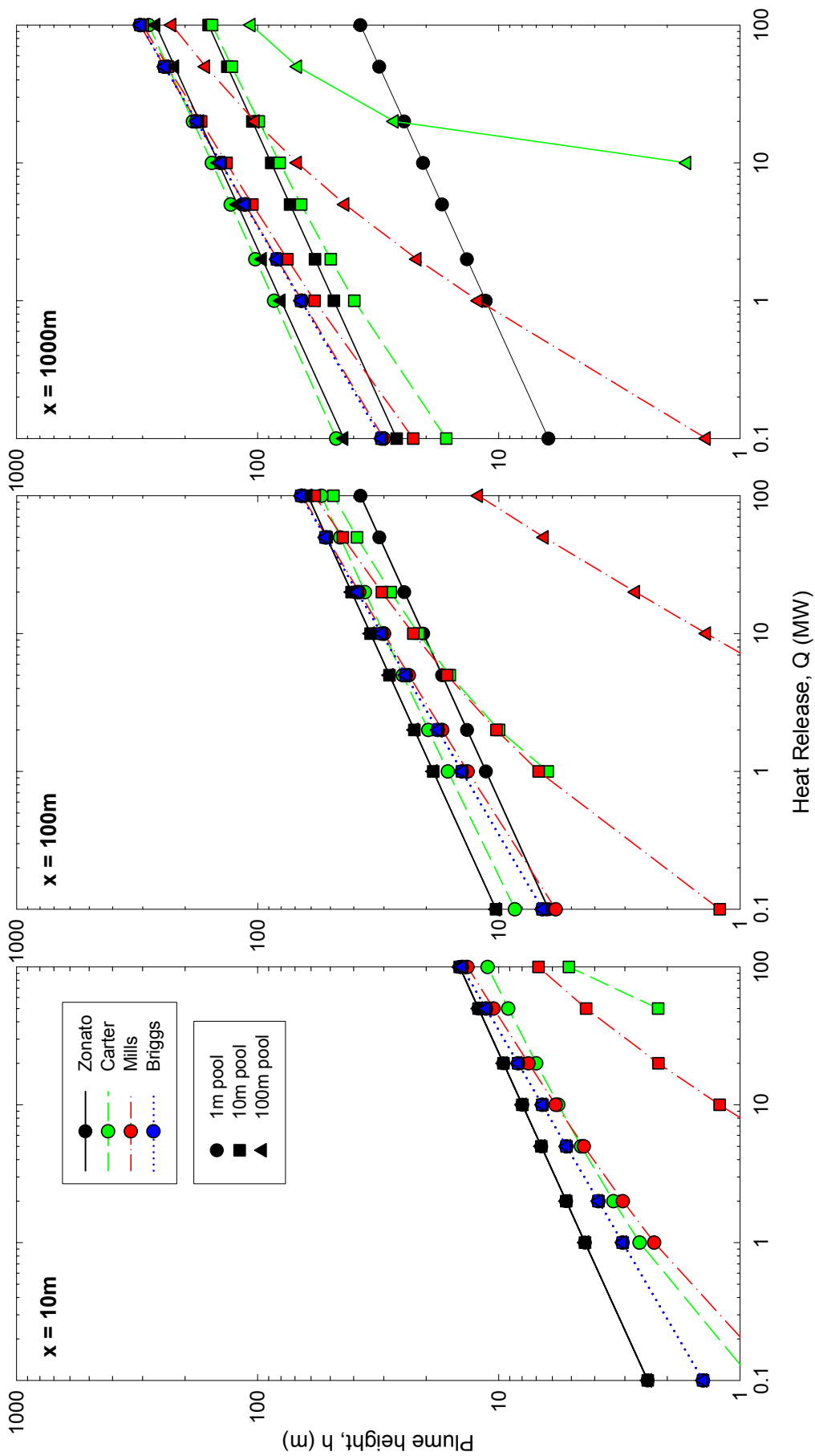


Figure 11. Values of Plume Height from Zonato(1993), Mills(1987), Carter(1989) and Briggs (see Jones(1983)).

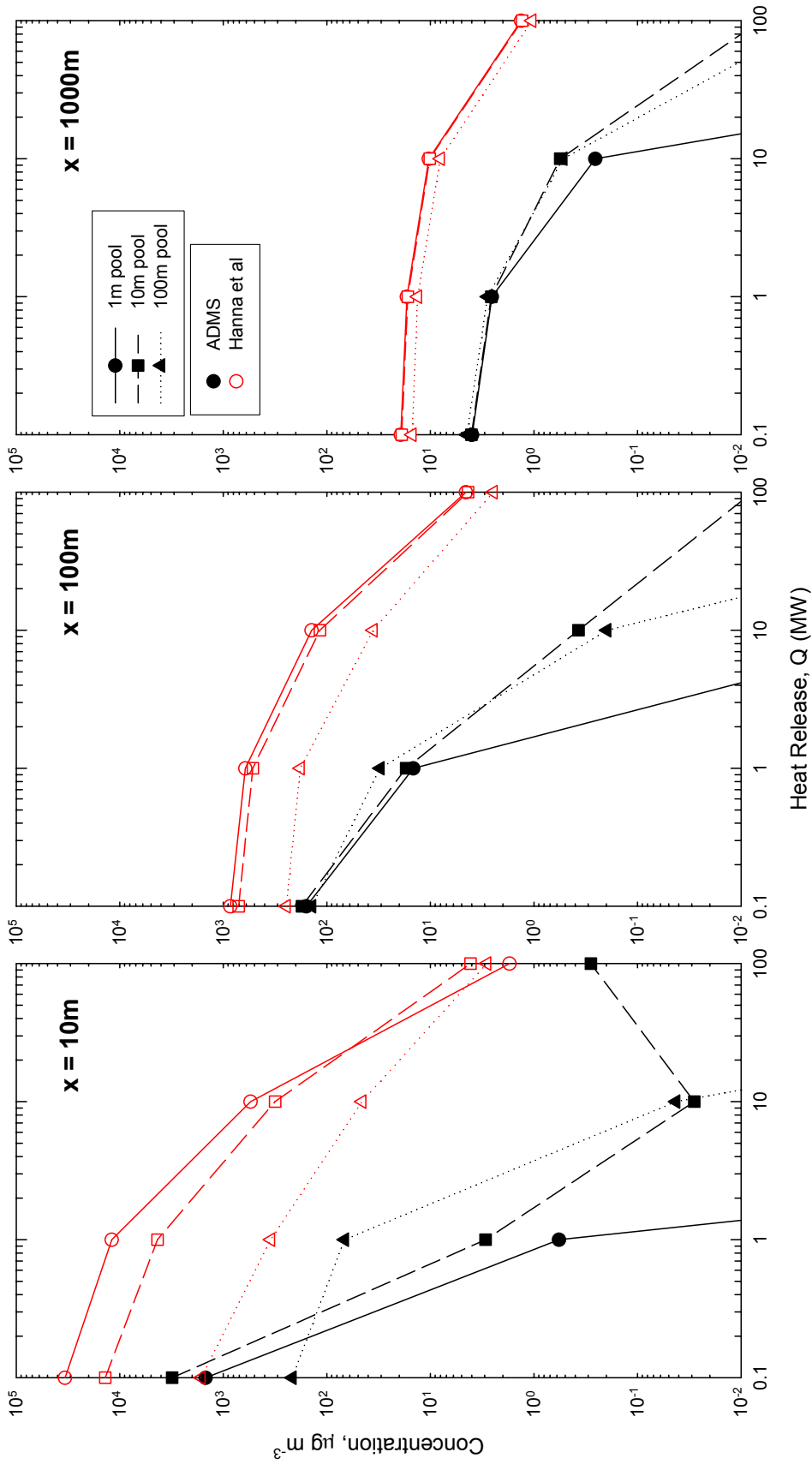
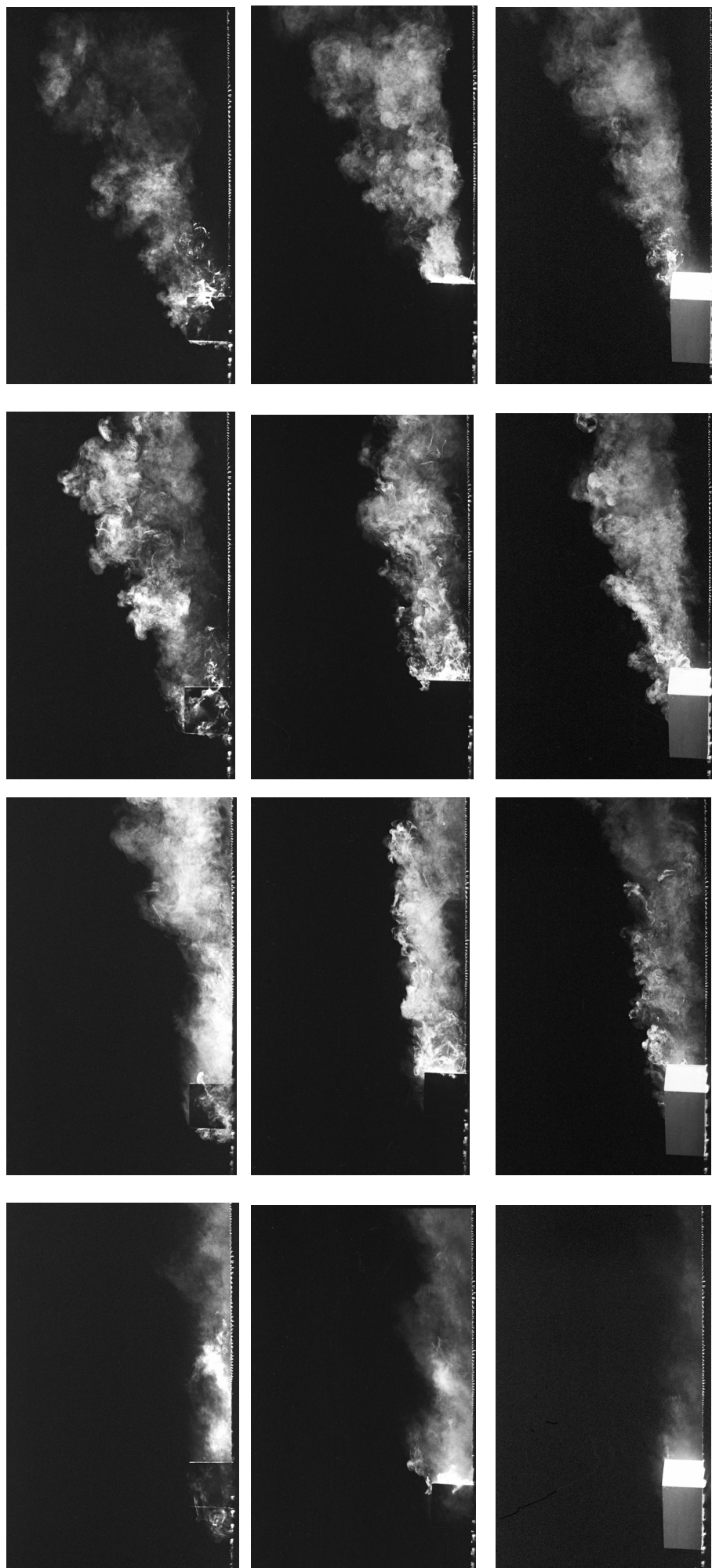


Figure 12. Estimates of Ground Level Concentration from Buoyant Area Sources in Open Terrain.
 - - - - - Calculated Using ADMS 3 model.
 - - - - - Calculated Using Prediction from Hanna et al(1998).



$F/U_{ref}^3 L = <0.002$

[O] 0.01-0.02

[O] 0.1

[O] 1

Figure 13. Flow Visualisation of Buoyant Plumes Discharged from a Building Surface. From Hall and Waters(1986).

Upper Row: Discharge from Upwind Face of Building.

Centre Row: Discharge from Downwind face of Building.

Bottom Row: Discharge from Downwind face of Building Skewed at 45° to the Flow Direction.

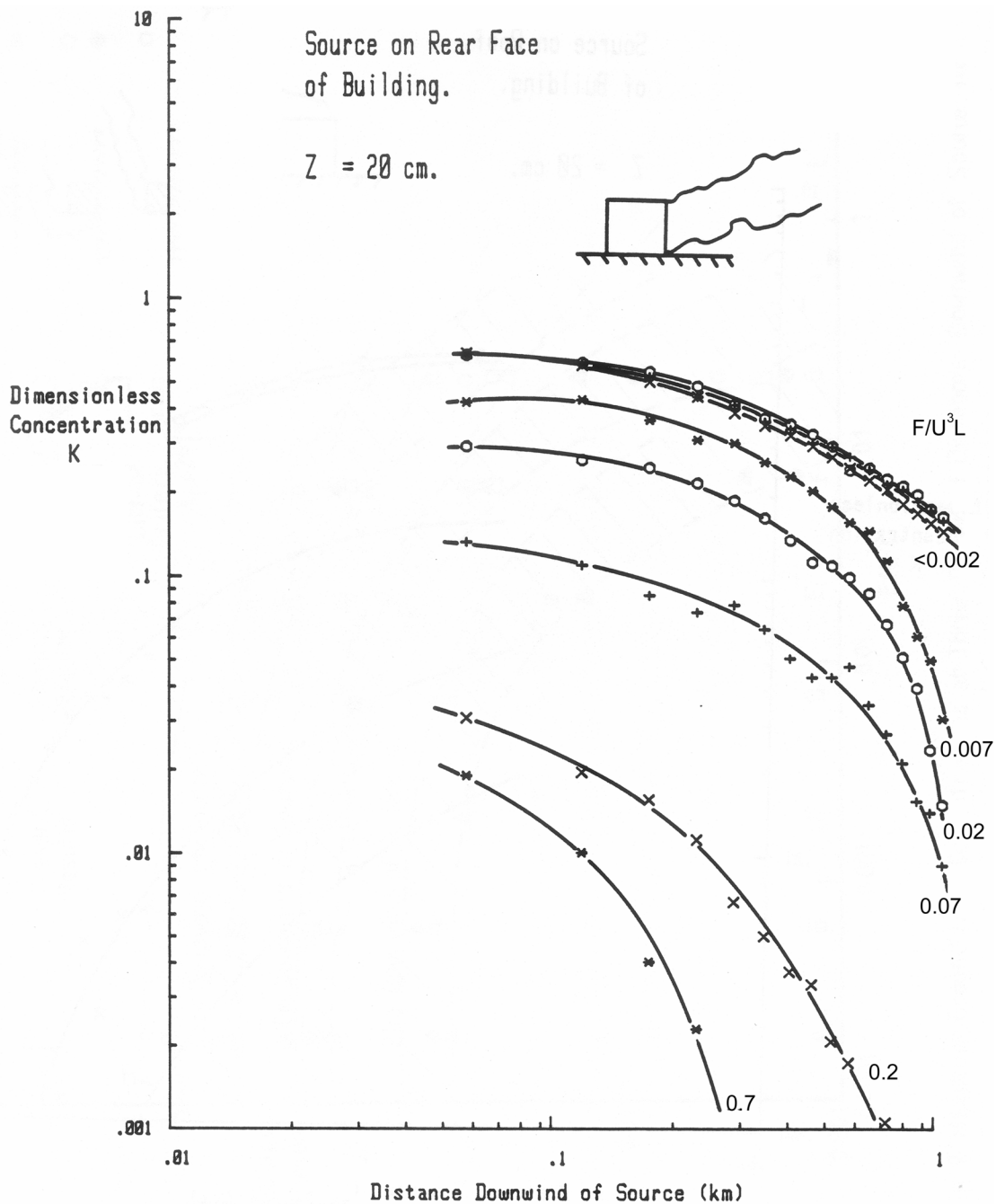


Figure 14. Ground level Centreline Concentrations Downwind of a Buoyant Release from the Downwind Face of a 2x1x1 Building Shape. From Hall and Waters(1986).

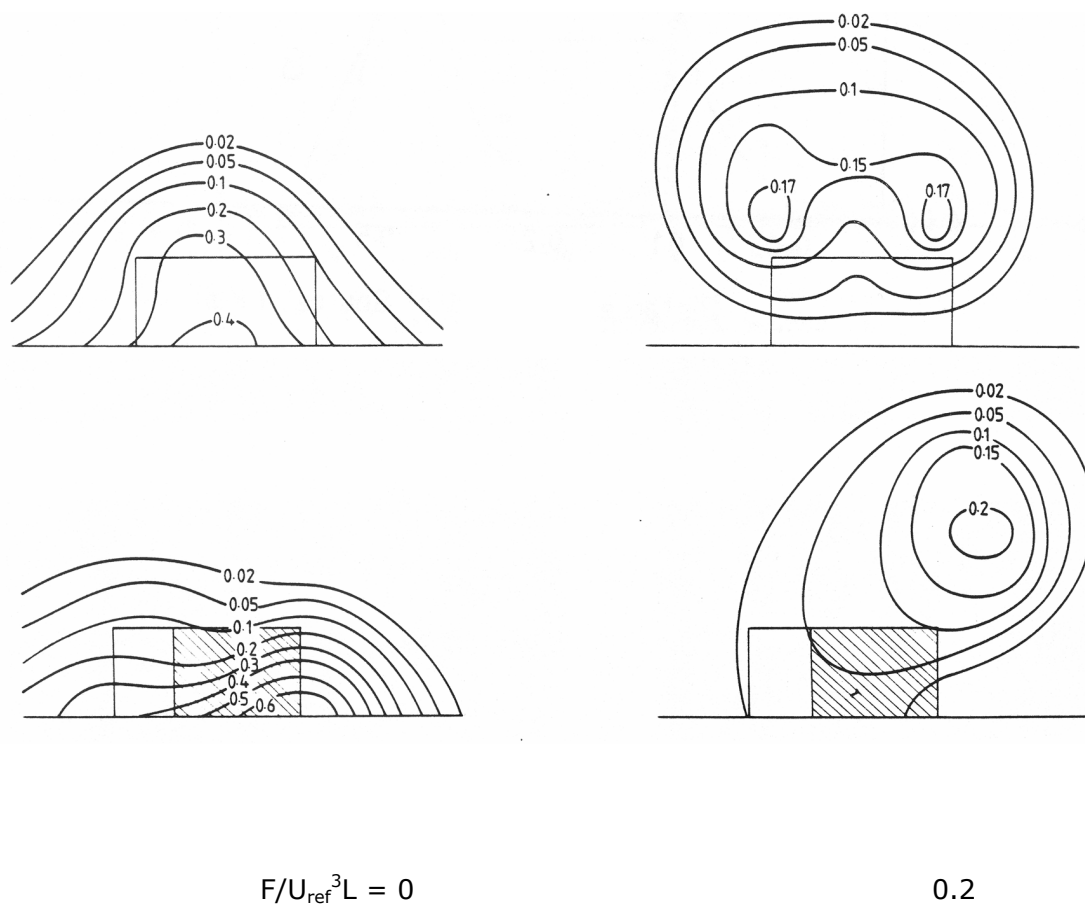


Figure 15. Plume Cross Section Concentration Contours for the Buoyant Plume/Building Interactions Shown in Figures 13 and 14. Measurements at Six Building Heights Distance Downwind of Rear Building Face for an Emission From Downwind Building Face. Upper Row: Building Square Across the Wind (Middle Row of Photographs in Figure 13). Lower Row: Building Skewed at 45° Across the Wind (Lower Row of Photographs in Figure 13). From Hall and Waters(1986).

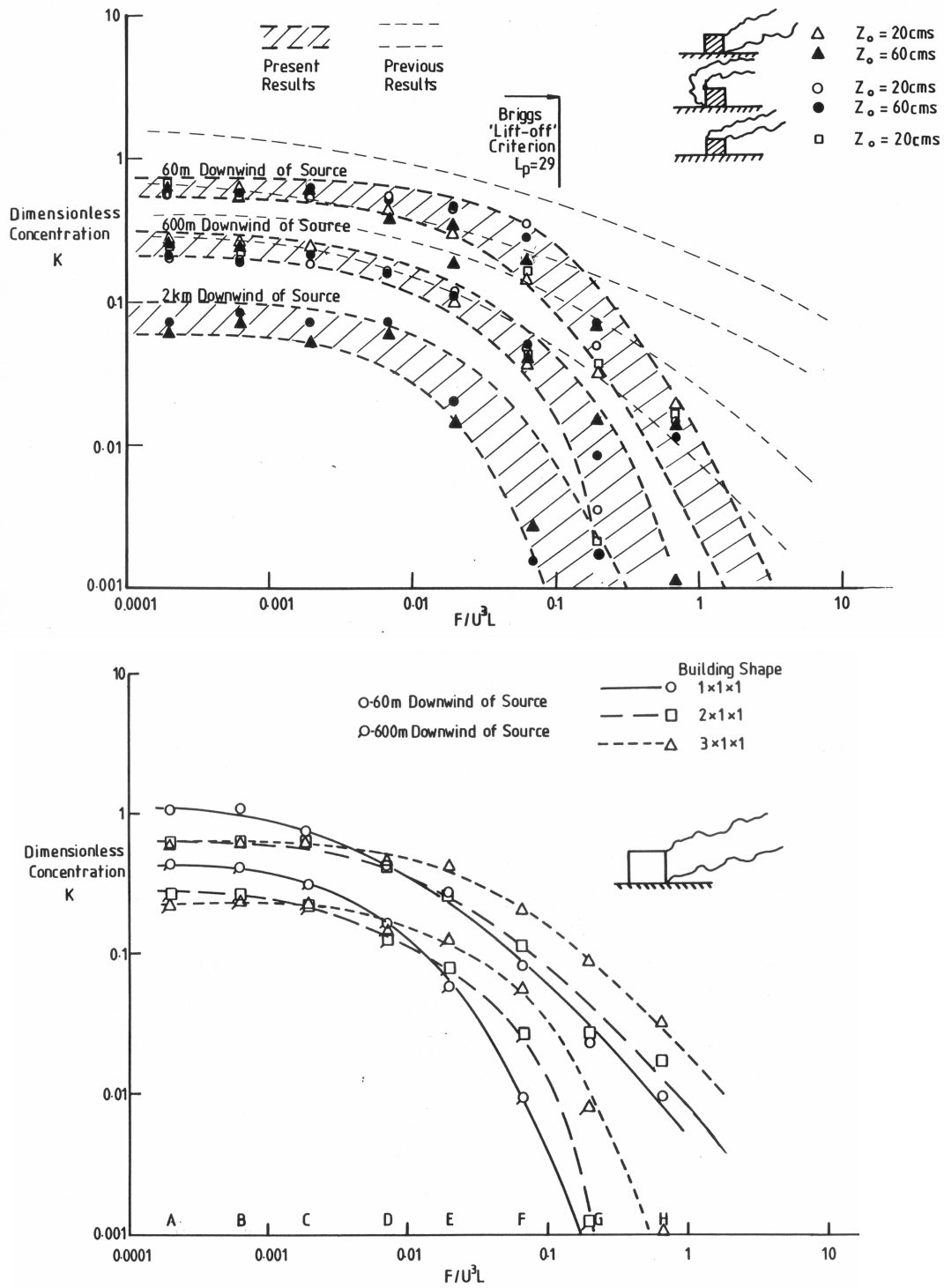


Figure 16. Dimensionless Concentration at the Ground from Plumes Arising from Building Surfaces at Three Downwind Distances. From the Experiments in Figures 13, 14 and 15. Upper Plot: Effects of Source Position and Surface Roughness. Lower Plot: Effect of Building Shape. From Hall and Waters(1986).

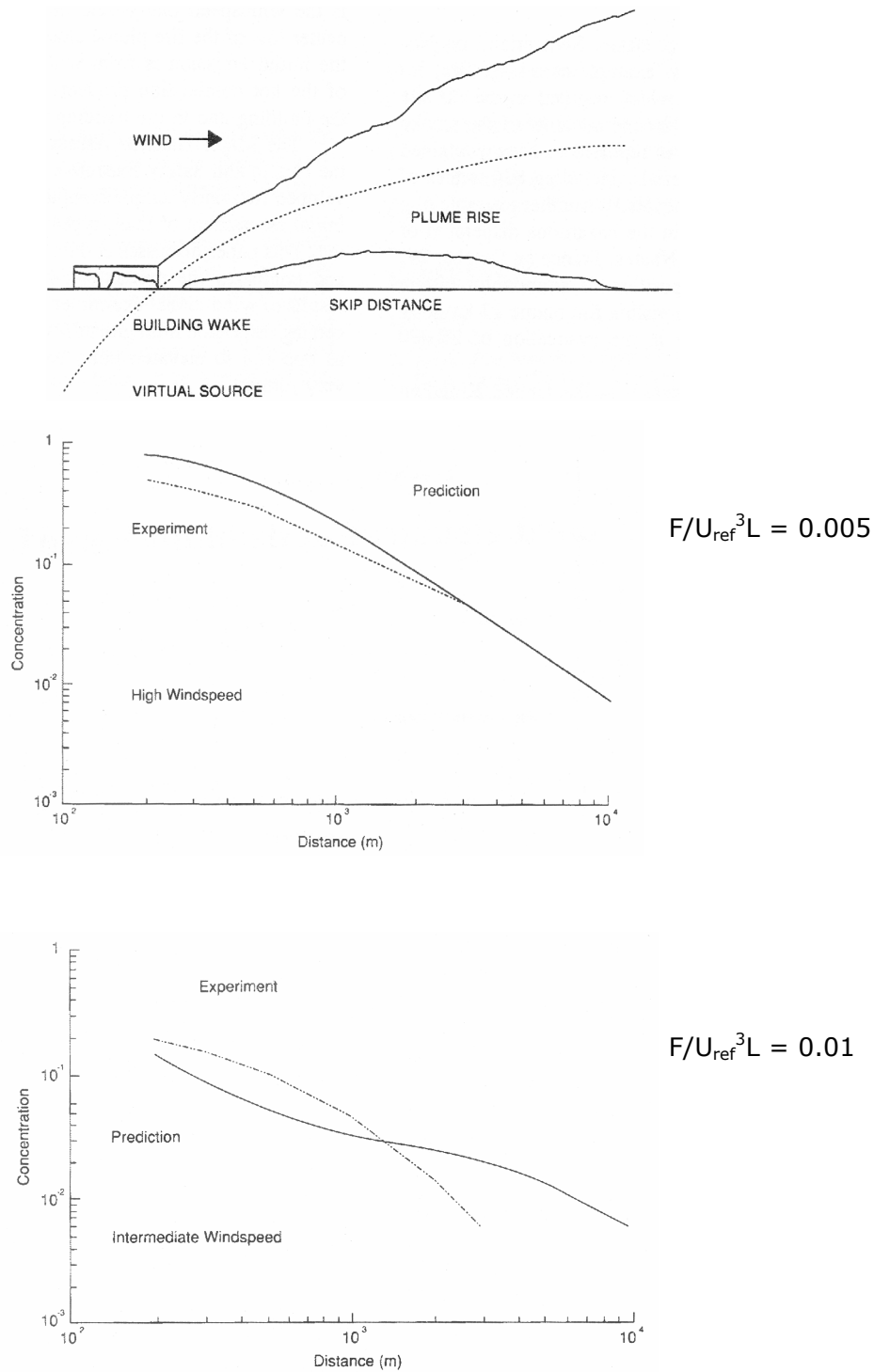


Figure 17. Comparison of Carter’s ‘SMOKE’ Fire Plume Dispersion Model with Experimental Data of Hall and Waters(1986). From Carter(1991).

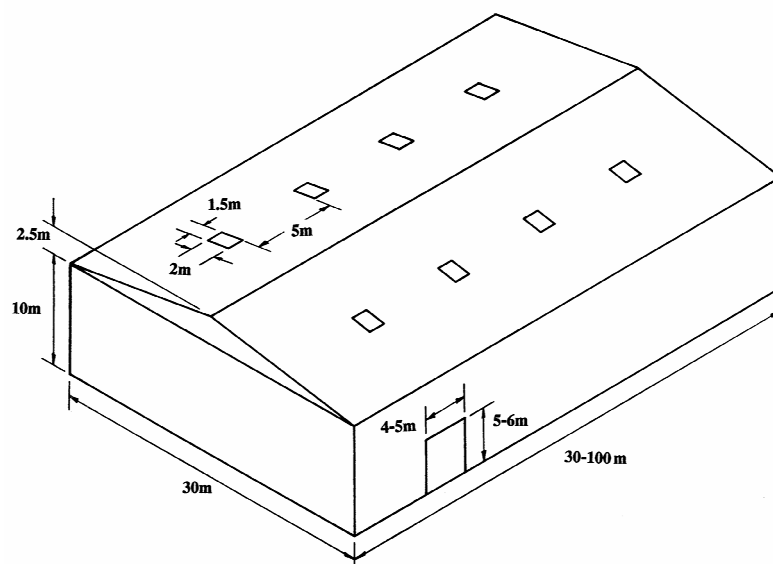


Figure 18. Typical Warehouse Building Used for Fire Plume Ventilation and Modelling Studies.
From Hall et al(1995).

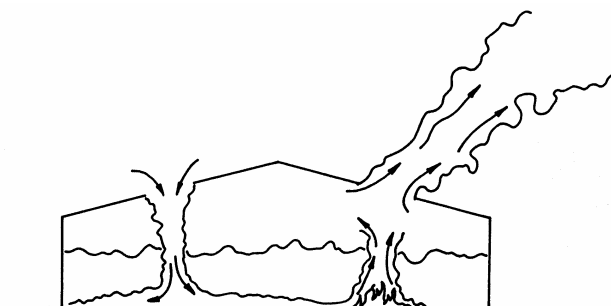
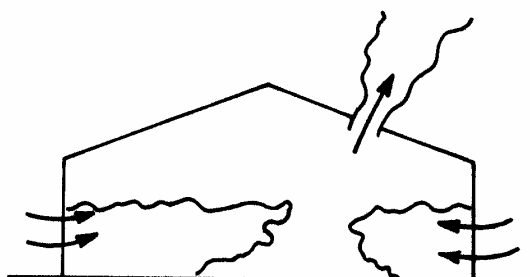
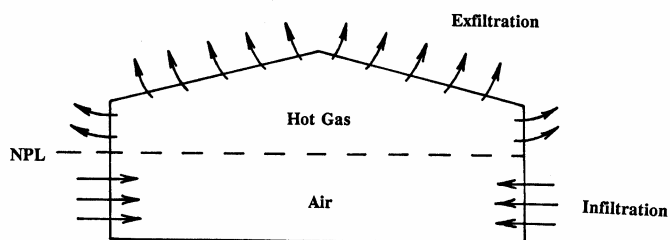


Figure 19. Examples of Still Air Fire Plume Ventilation Patterns
Upper: Closed Building Infiltration/Exfiltration Ventilation Pattern around 'Neutral Pressure Line' (NPL)
Middle: With Single Roof Opening – Infiltration Plus Vented Discharge.
Lower: One Possible Ventilation Pattern Through Two or More Roof Vents.
From Hall et al(1995).

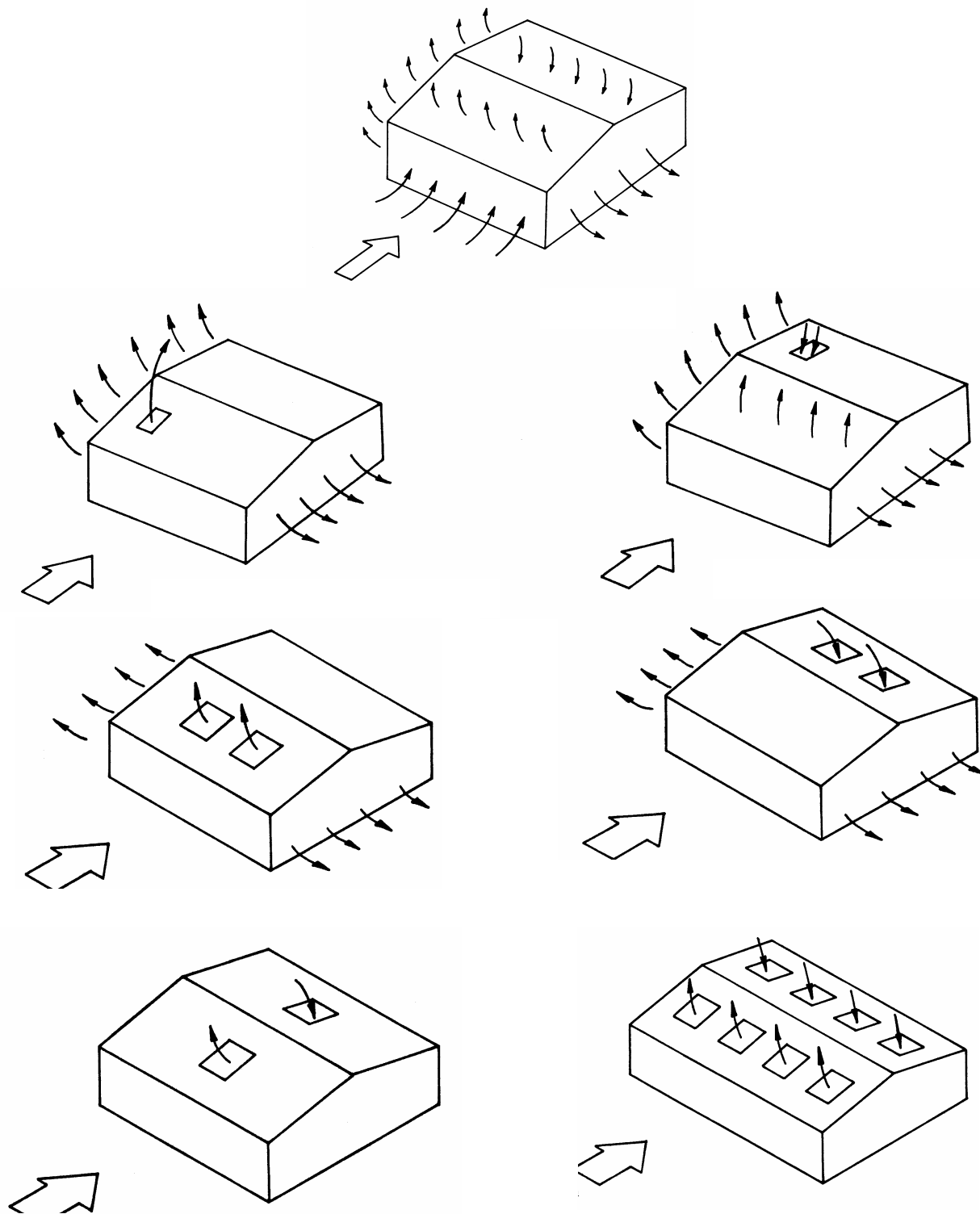


Figure 20. Examples of Wind-Driven Ventilation From a Warehouse Building with the Form of Figure 18. For a Closed Building and with Various Arrangements of Roof Openings. From Hall et al(1995).

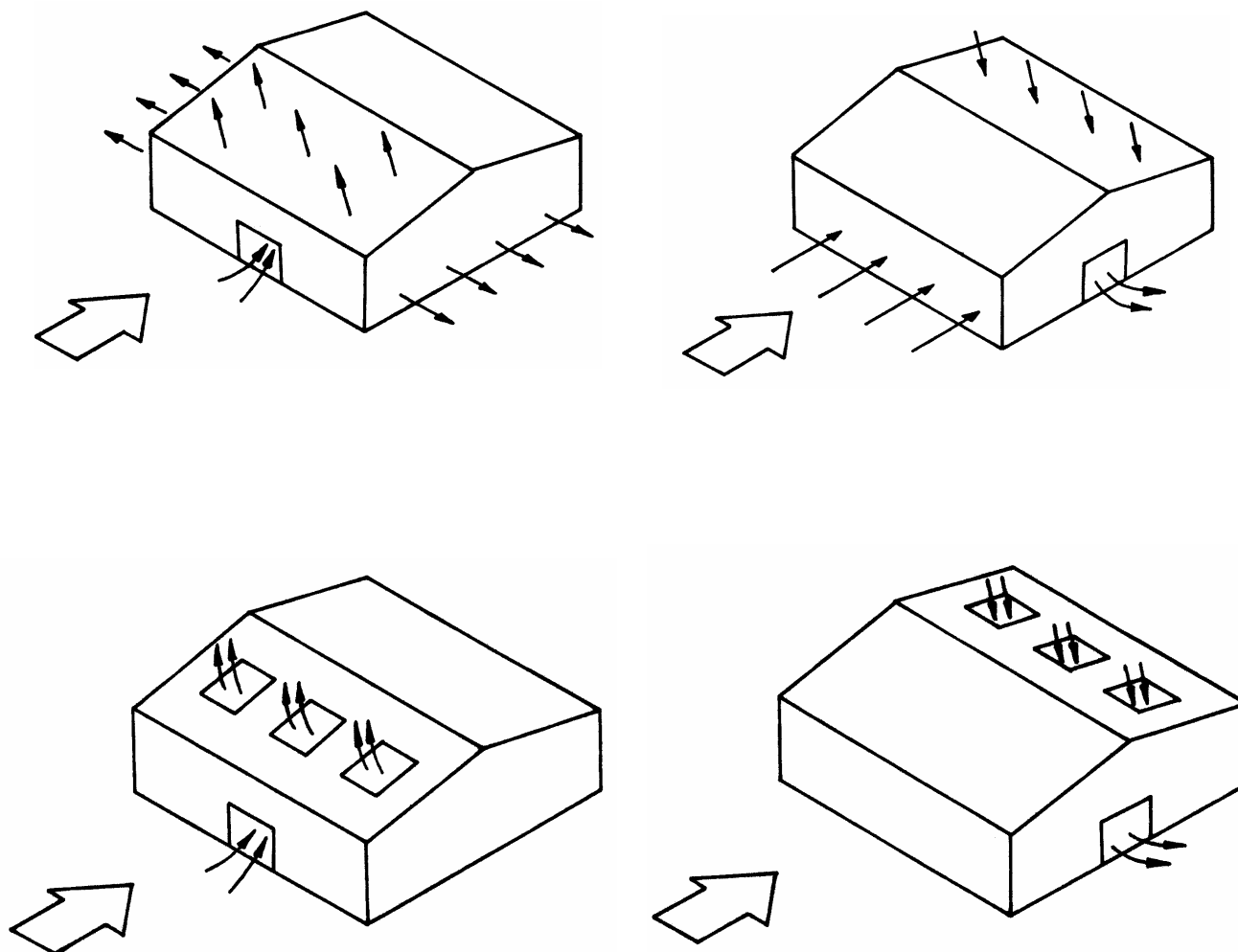


Figure 21. Examples of Wind-Driven Ventilation From a Warehouse Building with the Form of Figure 18. For a Building with an Open Door, with and without Roof Openings. From Hall et al(1995).

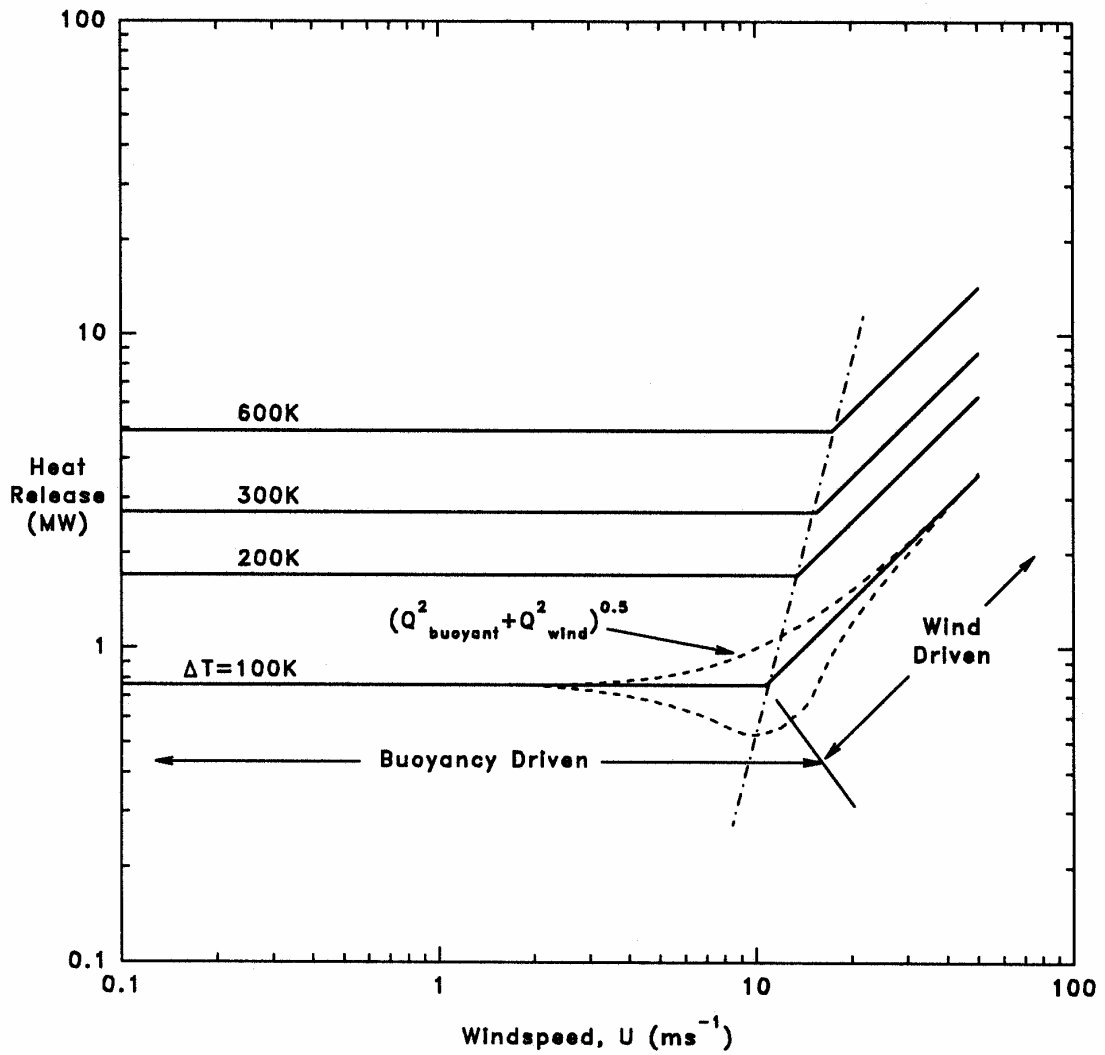


Figure 22. Estimates of the Effects of Fire Gas Temperature on the Heat Release and Discharge Momentum from a Single Roof Opening 1.5m x 2m. From Hall et al(1995).

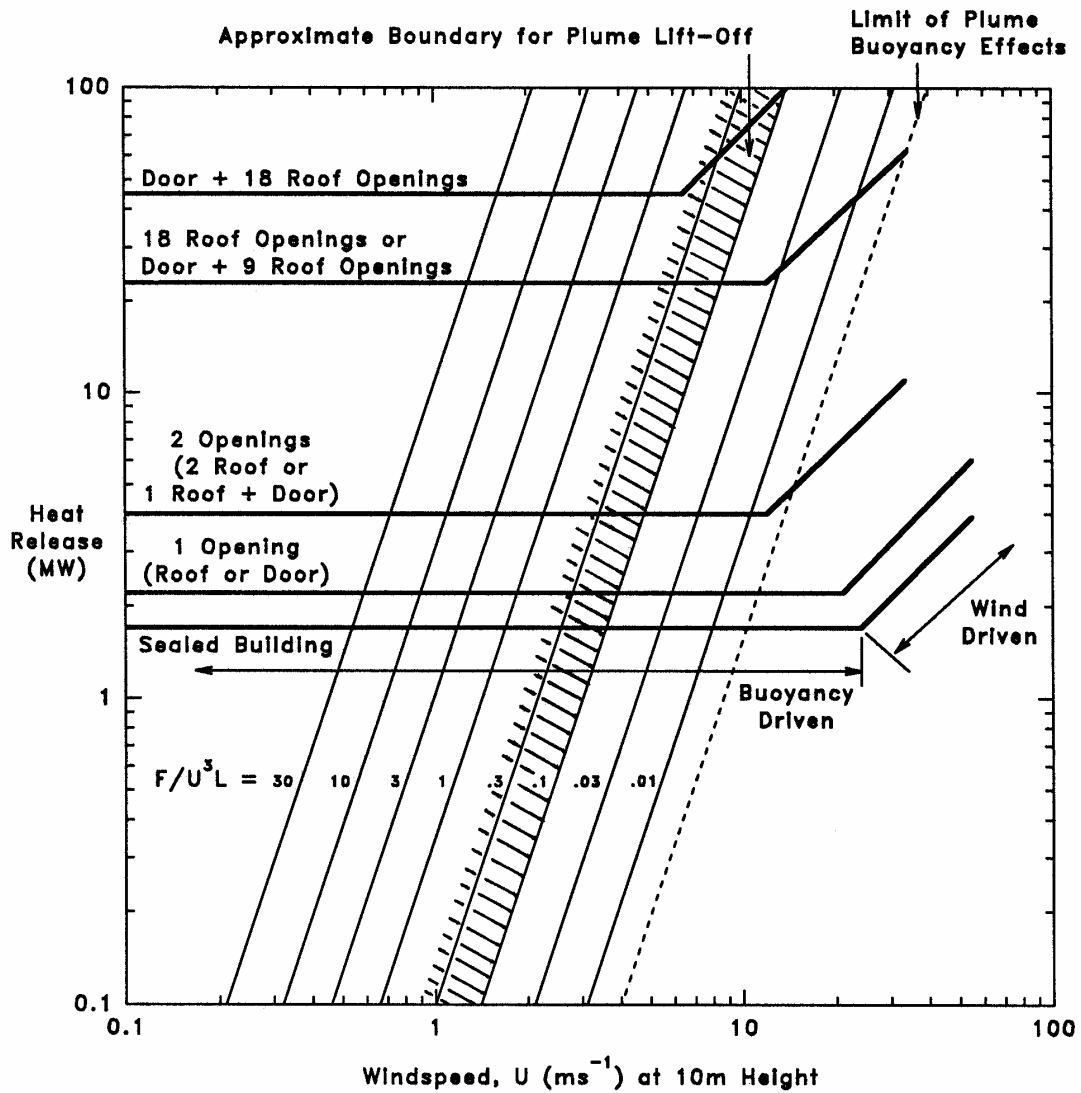


Figure 23. Estimates of Heat Release from a Fire in a Warehouse Building of 30mx60m Plan (as in Figure 18) Through an Increasing Number of Surface Openings. For a Fire Plume Temperature of 300K Above Ambient. From Hall et al(1995).

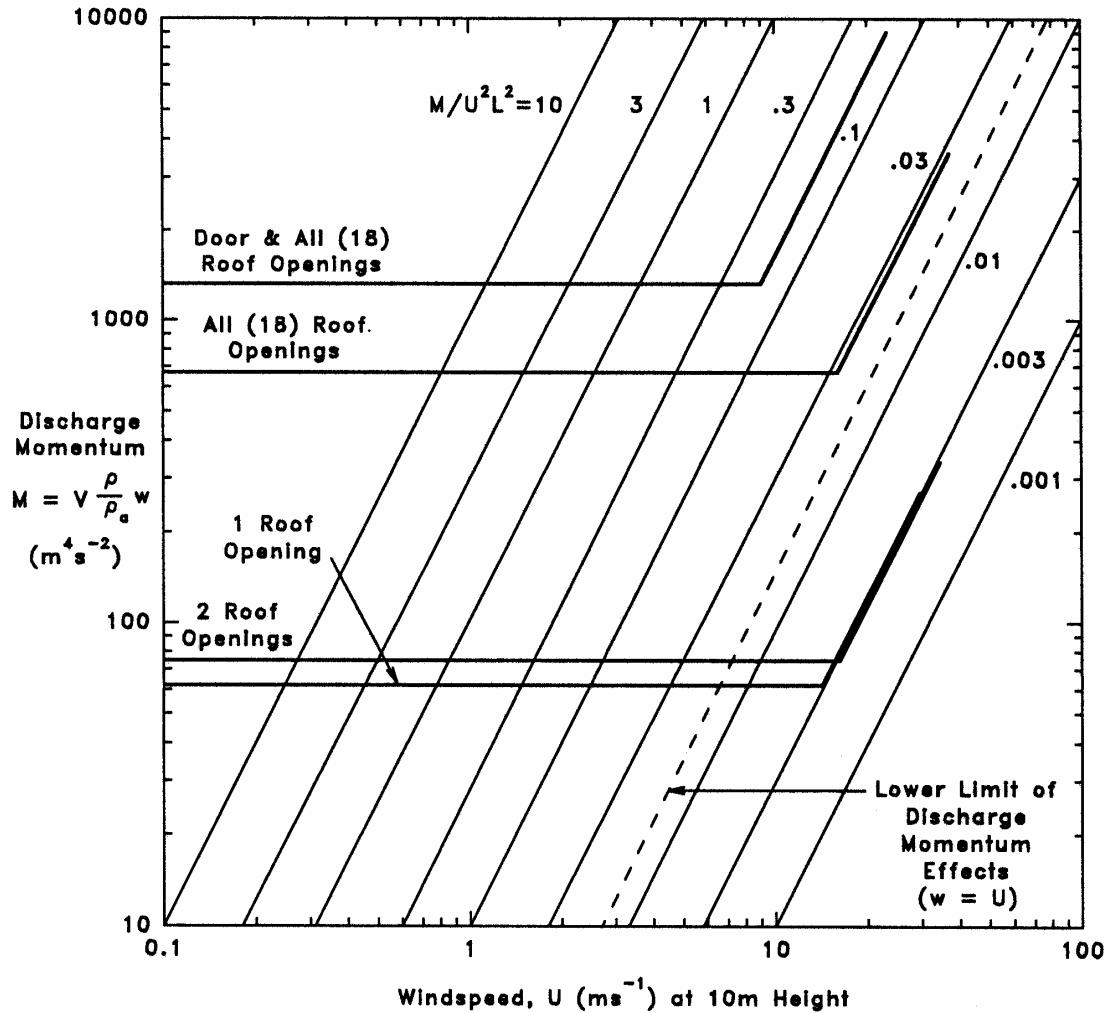


Figure 24. Estimates of Total Roof Exit Discharge Momentum from a Fire in a Warehouse Building of 30mx60m Plan (as in Figure 18) Through an Increasing Number of Surface Openings.

The Data Match the Heat Release Estimates in Figure 23.

From Hall et al(1995).

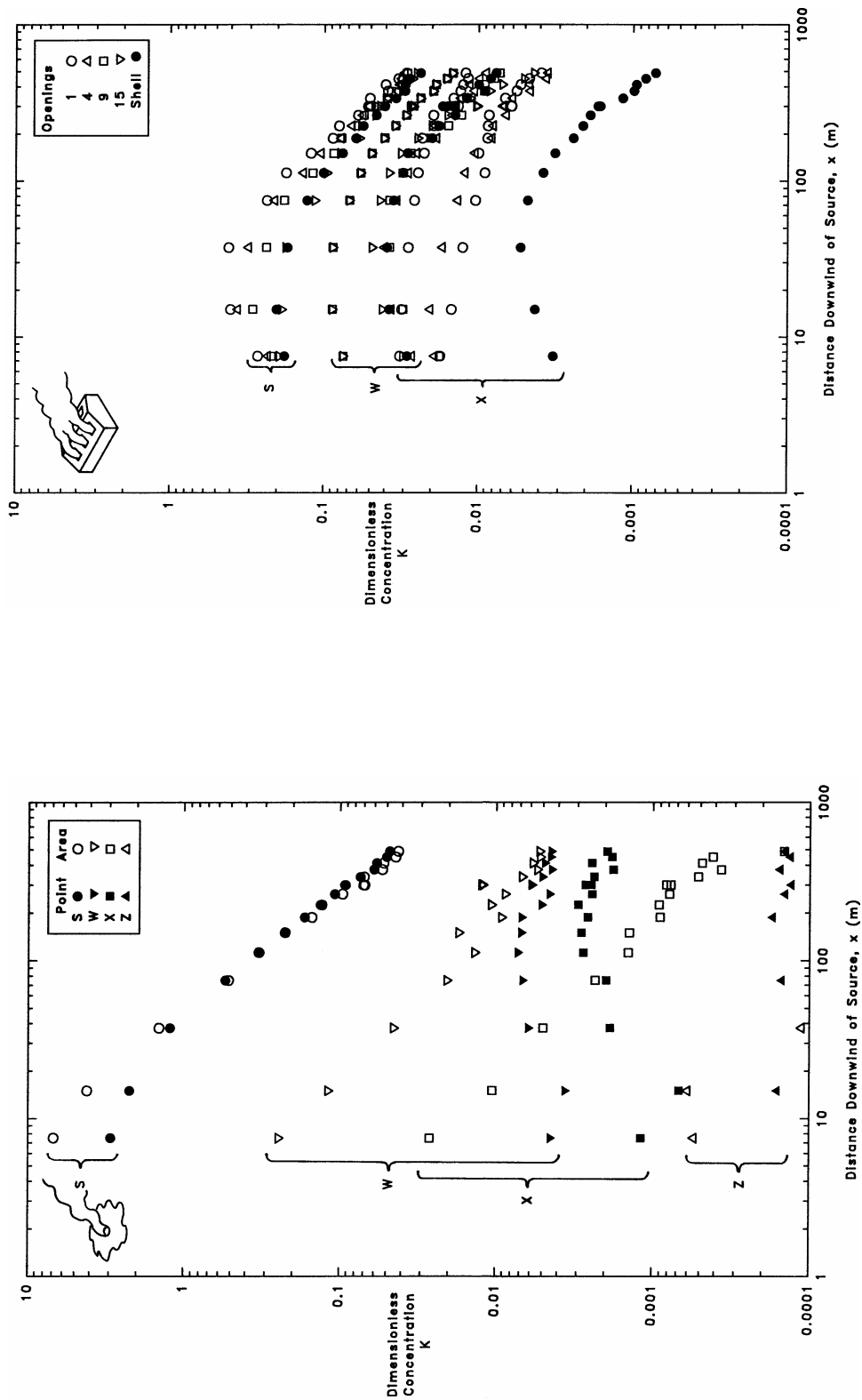


Figure 25. Ground level Concentrations Downwind of a Fire Plume with Varying buoyancy and Discharge Conditions. Left: Fire Plume from Surface in Open Terrain. Source Diameters Approximately 3m (Point) and 10m (Area). Right: Discharges Through 10m High Warehouse Building Shell and 1-15 Roof Openings. Dimensionless Buoyancy Flux, $F/U_{ref}^3 L$: S = 0; W = 0.1; X = 0.3; Z = 3. From Hall et al(1995).

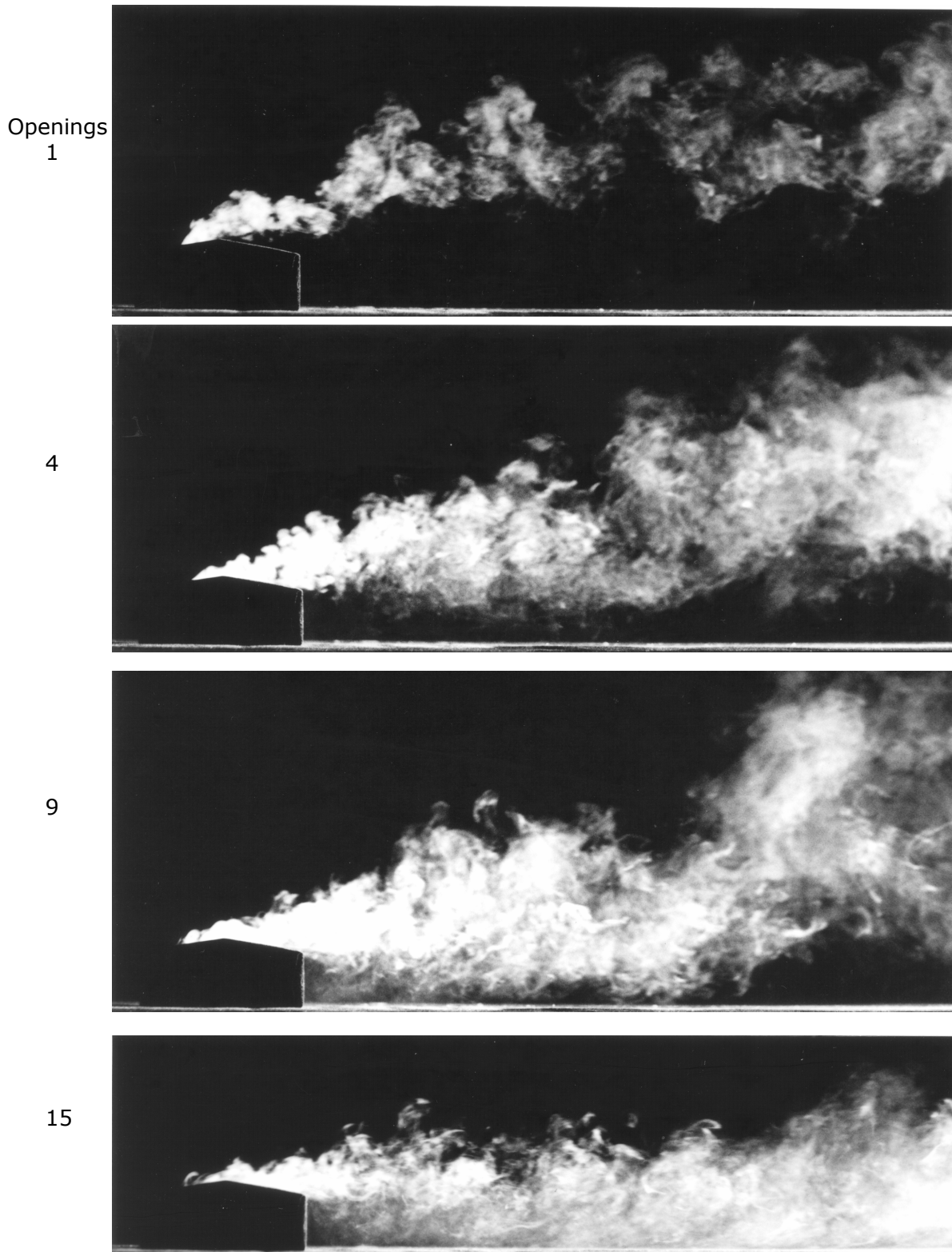


Figure 26. Flow Visualisation Photographs of a Warehouse Fire Plume Distributed Across Varying Numbers of Roof Openings. 100m Wide Building with up to 15 Roof Openings, Set Normally Across the Flow. Dimensionless Buoyancy Flux, $F/U_{ref}^3L = 0.3$. From Hall et al(1995).

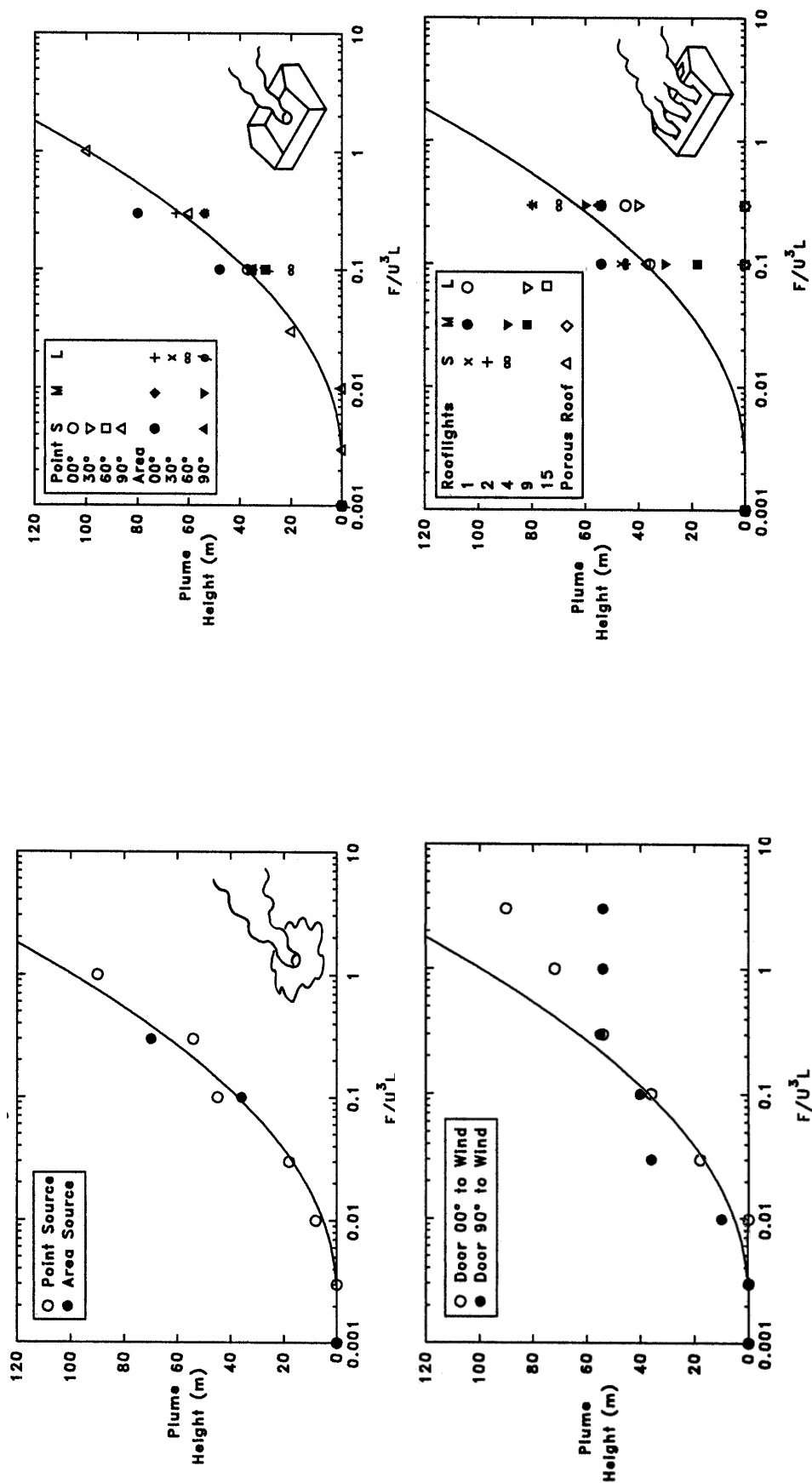


Figure 27. Variation in Fire Plume Centreline Height at 300m Distance for Different Discharge Conditions.

Top Left: Point Source **Plume in Open Terrain.**

Top Right : Discharge from Building Shell
Bottom Left: Plume Discharge through Door. **Bottom Right:** Plume Discharge through Roof Openings.

S, M, L Refer to Building Widths of 30m(4 Pairs of Roof Openings), 60m(8 Pairs of Roof Openings) and 100m(15 Pairs of Roof Openings) respectively.

From Hall et al(1995).

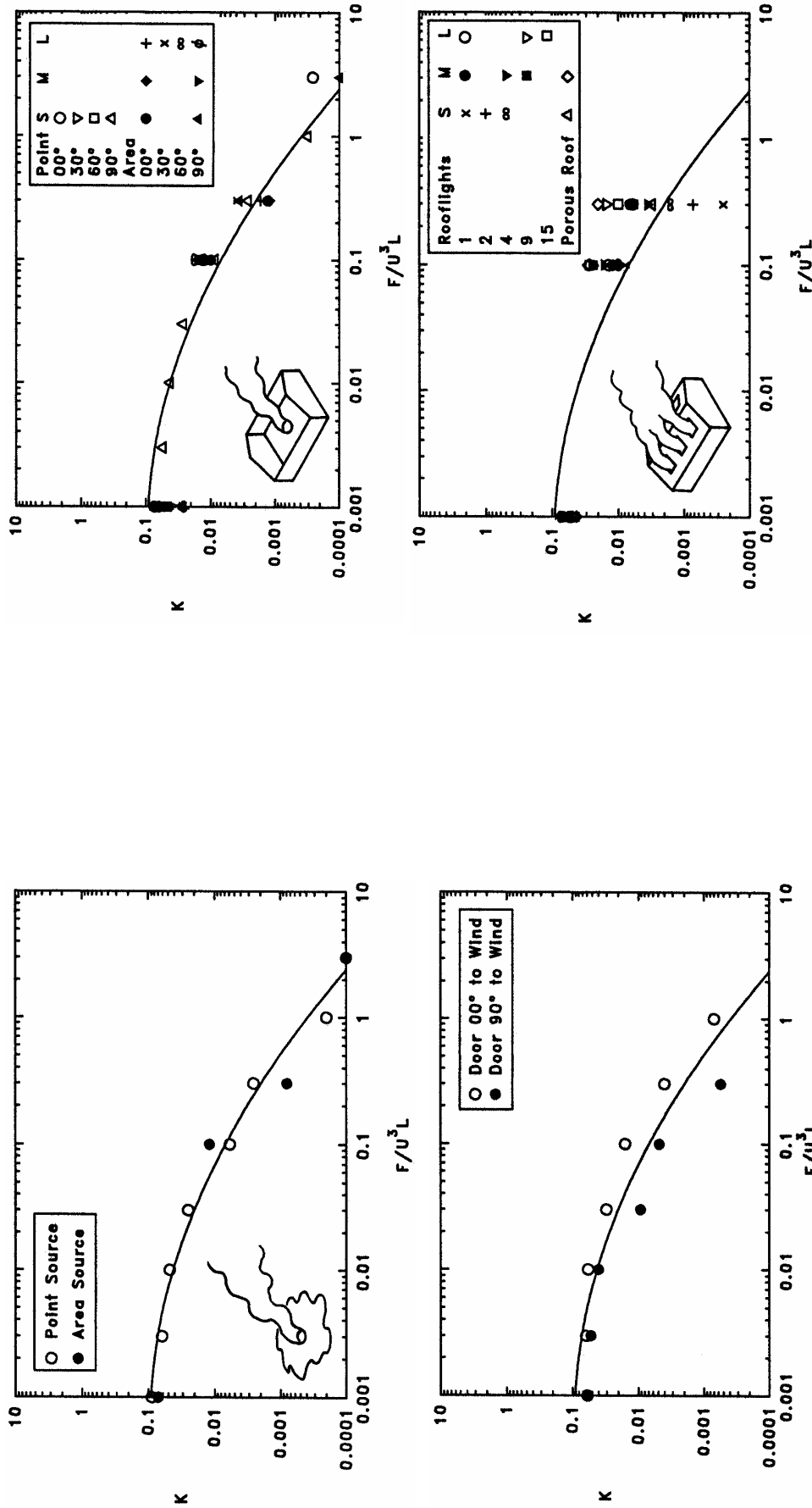
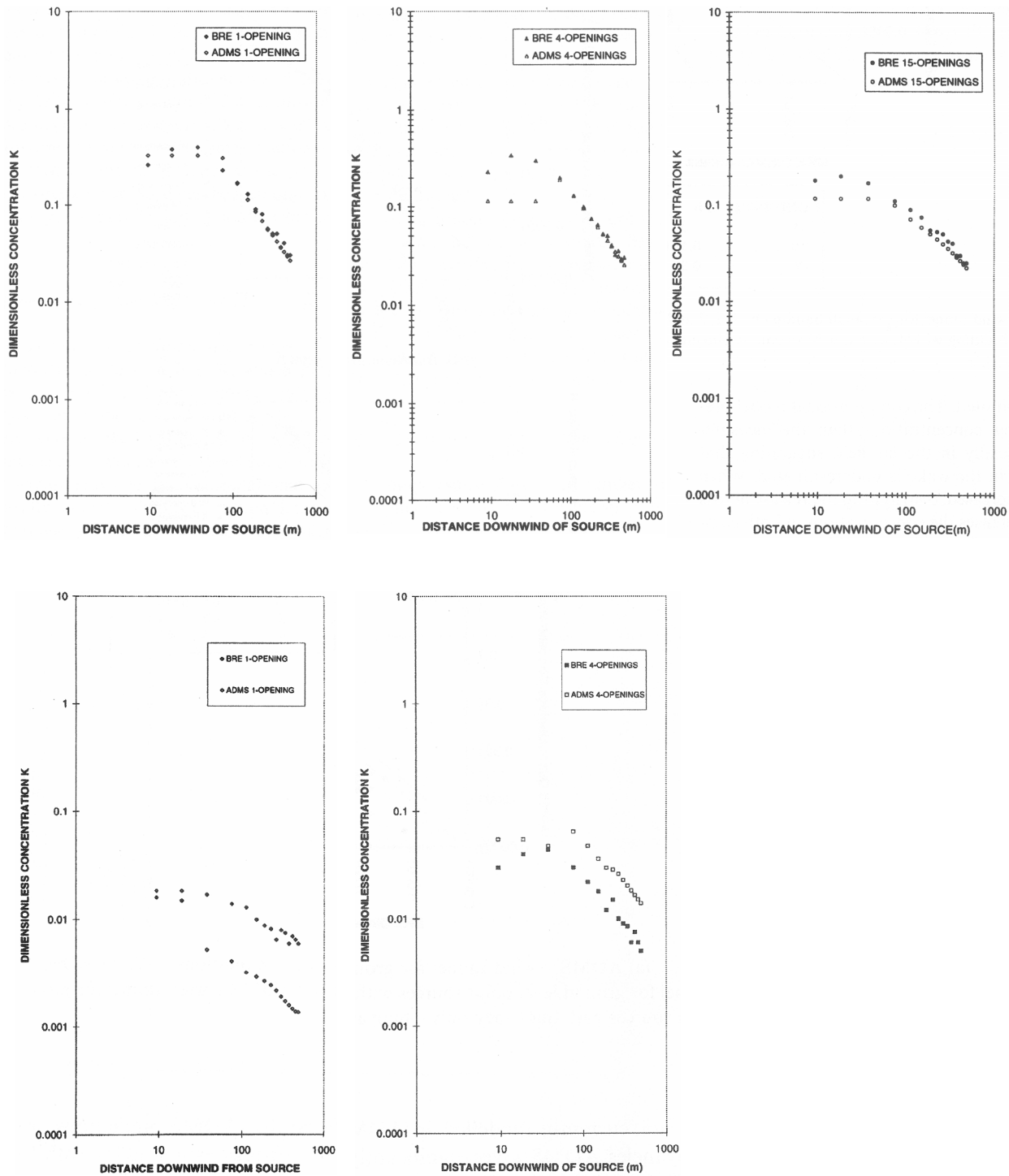


Figure 28. Variation in Fire Plume Ground Level Concentrations at 300m Distance for Different Discharge Conditions. Top Left: Plume in Open Terrain. Top Right : Discharge from Building Shell Bottom Left: Plume Discharge through Door. Bottom Right: Plume Discharge through Roof Openings. S, M, L Refer to Building Widths of 30m(4 Pairs of Roof Openings), 60m(8 Pairs of Roof Openings) and 100m(15 Pairs of Roof Openings) respectively. From Hall et al(1995).



**Figure 29. Comparison of Ground Level Concentrations Between ADMS 2 Model and BRE Warehouse Fire Plume Experiments of Hall et al(1995).
 Upper: Neutral Plume Buoyancy – Discharges Through 1, 4 and 15 Roof Openings. 100m Wide Building.
 Lower: Buoyant Plume, $F/U_{ref}^3 L = 0.1$ - Discharges Through 1 and 4 Roof Openings. 30m Wide Building.
 From Carruthers et al(1999).**

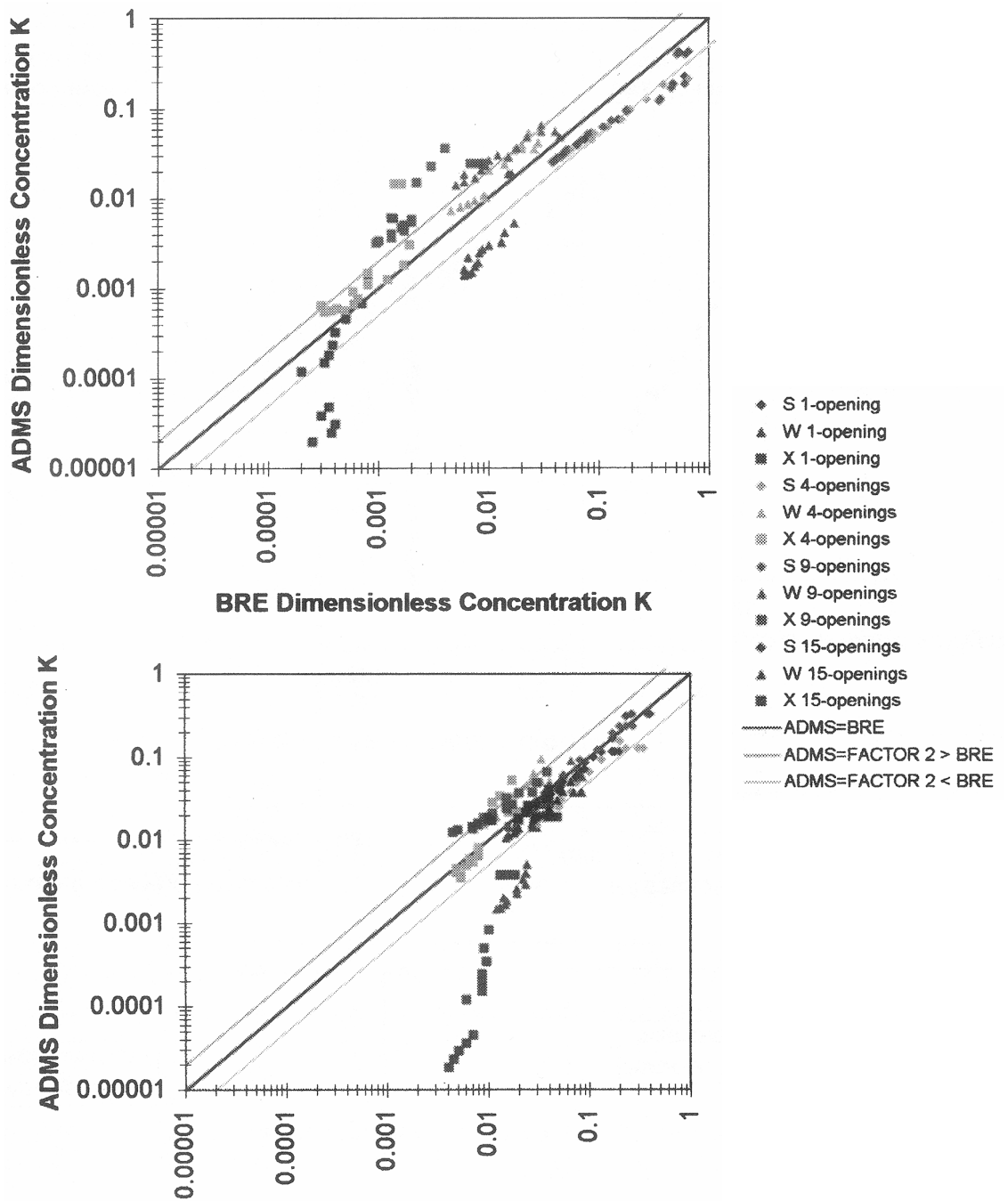


Figure 30. Comparison of Ground Level Concentrations Between ADMS 2 Model and BRE Warehouse Fire Plume Experiments of Hall et al(1995). Ground Level Concentrations for Plume Buoyancy, $F/U_{ref}^3 L = 0, 0.1$ and 0.3 (S, W and X Respectively in Figure Notation). Upper: Comparison with 30m Wide Building. Lower: Comparison with 100m Wide Building. From Carruthers et al(1999).

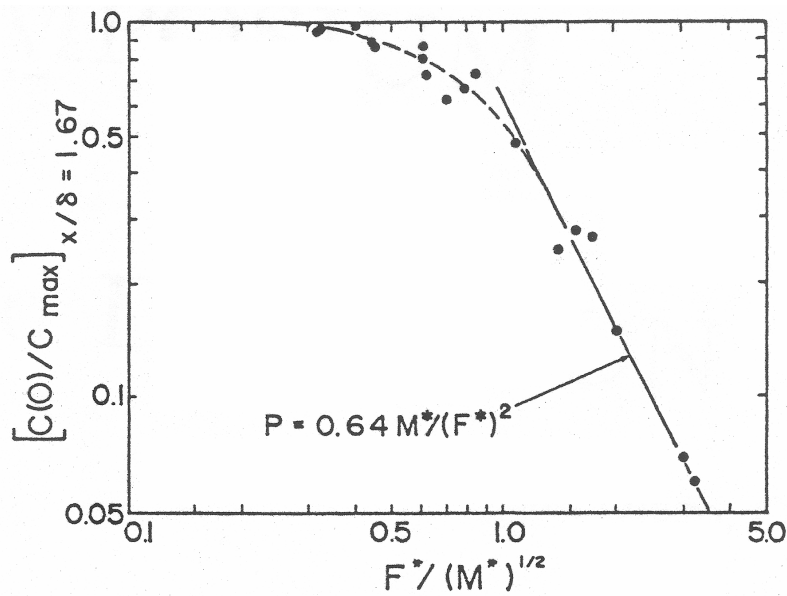


Figure 31. Correlation of Reduction in Plume Concentration at the Ground for Discharges with Both Buoyancy and Horizontal Momentum. From Poreh and Cermak(1988a), Derived from Poreh and Cermak(1986).

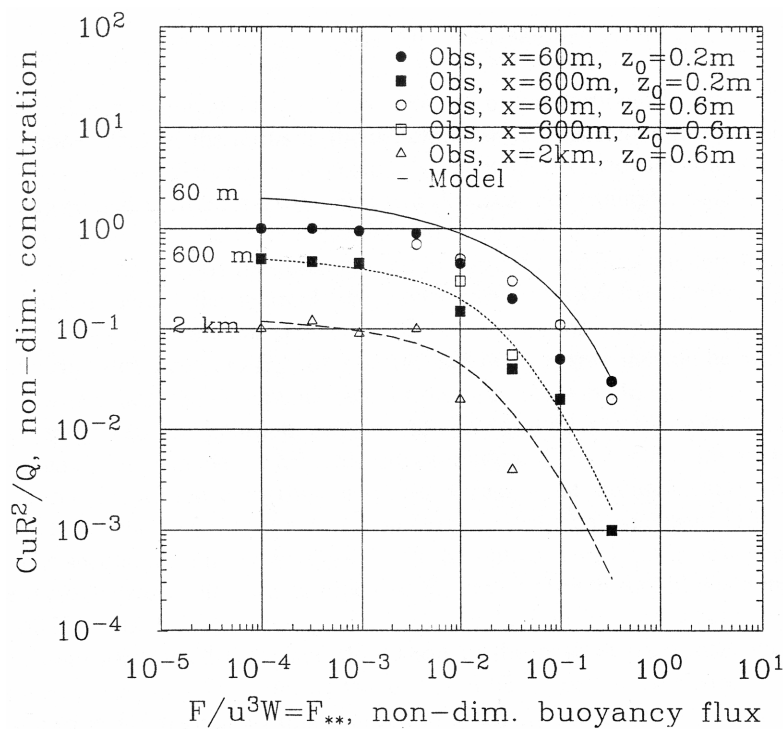
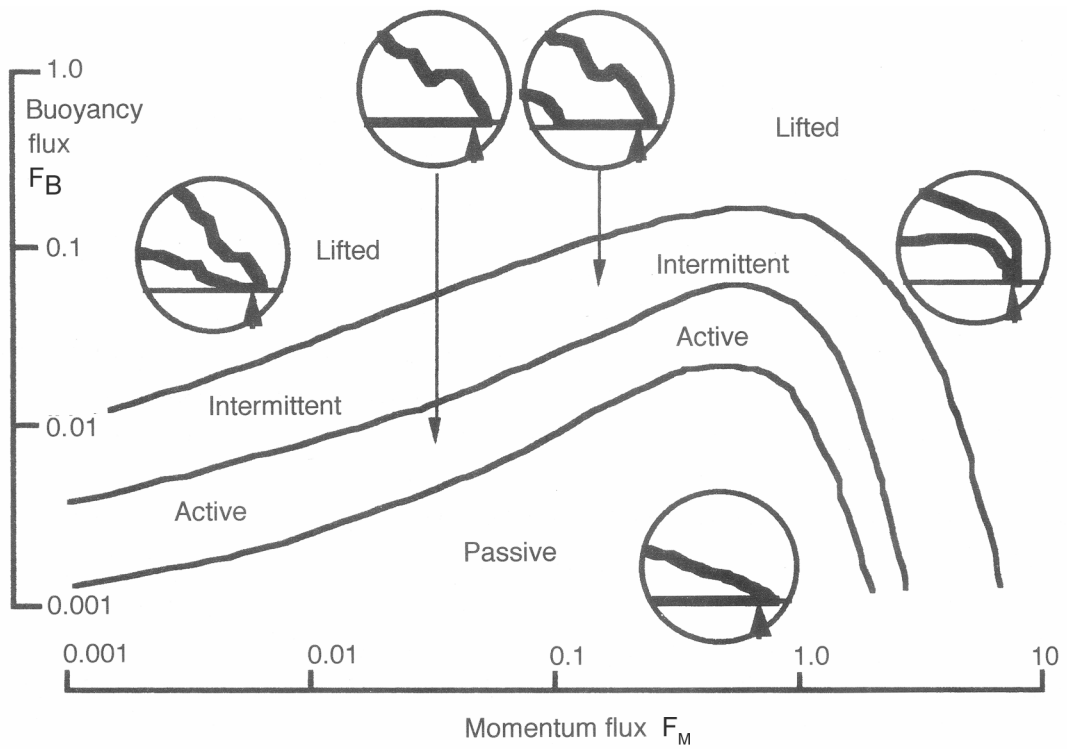


Figure 32. Hanna et al's(1998) Comparison of Their Lift-Off Criterion, Equation (64), with Hall and Waters(1986) Data on Buoyant Plume Rise from a Building, as Shown in Figure 18.



The source diameter, d , is used as the characteristic length scale

$$F_M = \rho_s W^2 / \rho_a U_{ref}^2 \quad F_B = g'dW / U_{ref}^3$$

Figure 33. Relationship Between Discharge Buoyancy and Momentum for Plume Lift-Off from the Ground. From Robins(1997), Due to Macdonald et al(1988).

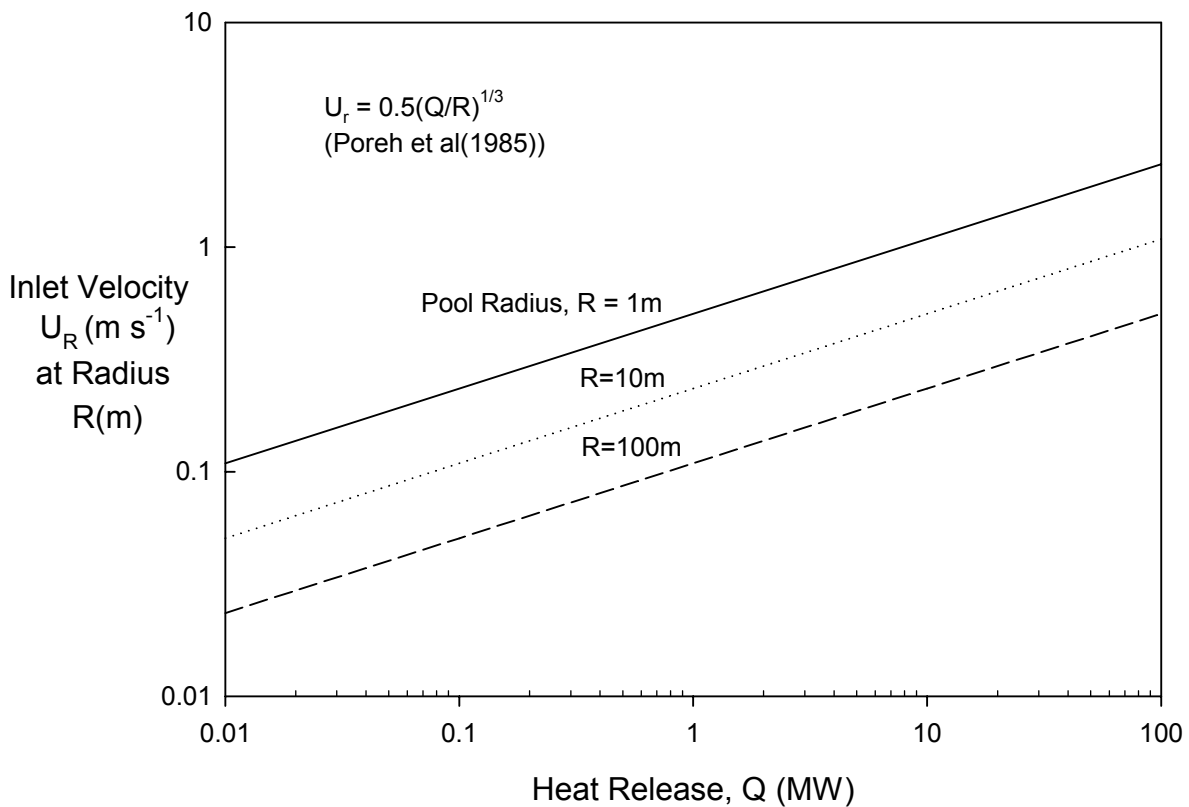
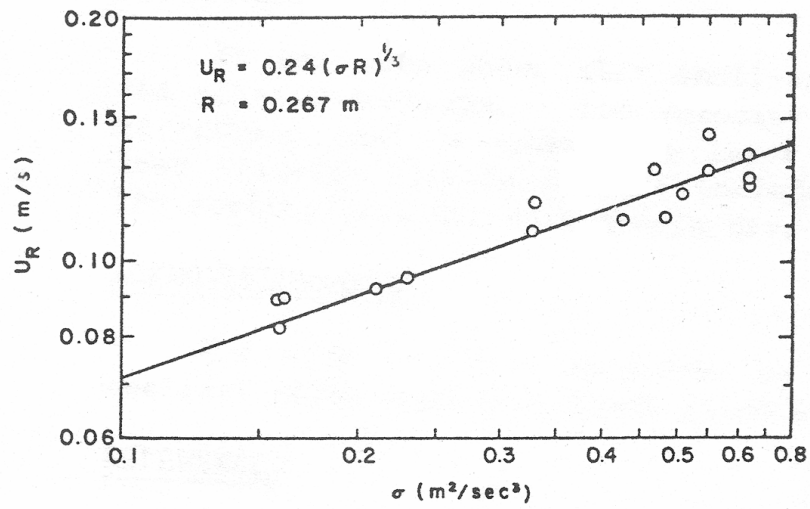
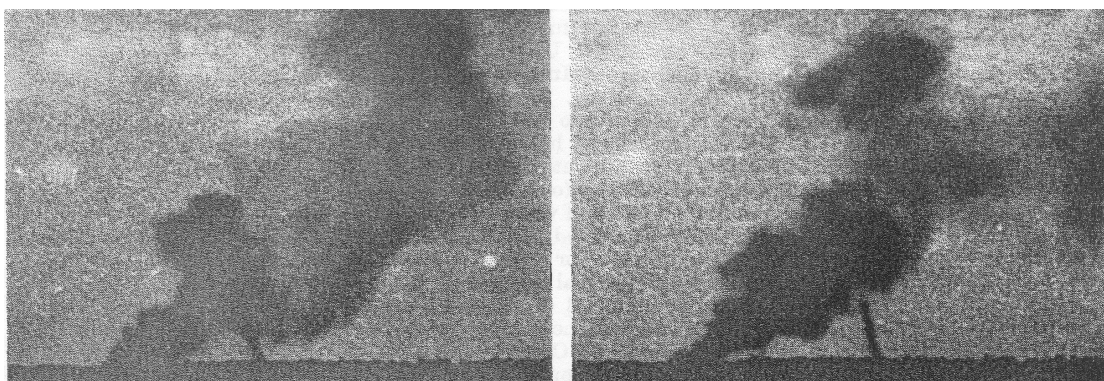


Figure 34. Air Inlet Velocity at the Edge of a Pool Fire of Radius, R (m), in Still Air. Upper: From Small Scale Measurements by Poreh et al(1985). (σ is buoyancy flux/unit area, R is pool diameter). Lower: Upper Data Fit in Present Units for a Range of Source Conditions.



**Figure 35. Vertical Vortices Extending to the Ground Behind a Rising Plume.
From Dessens(1962).**

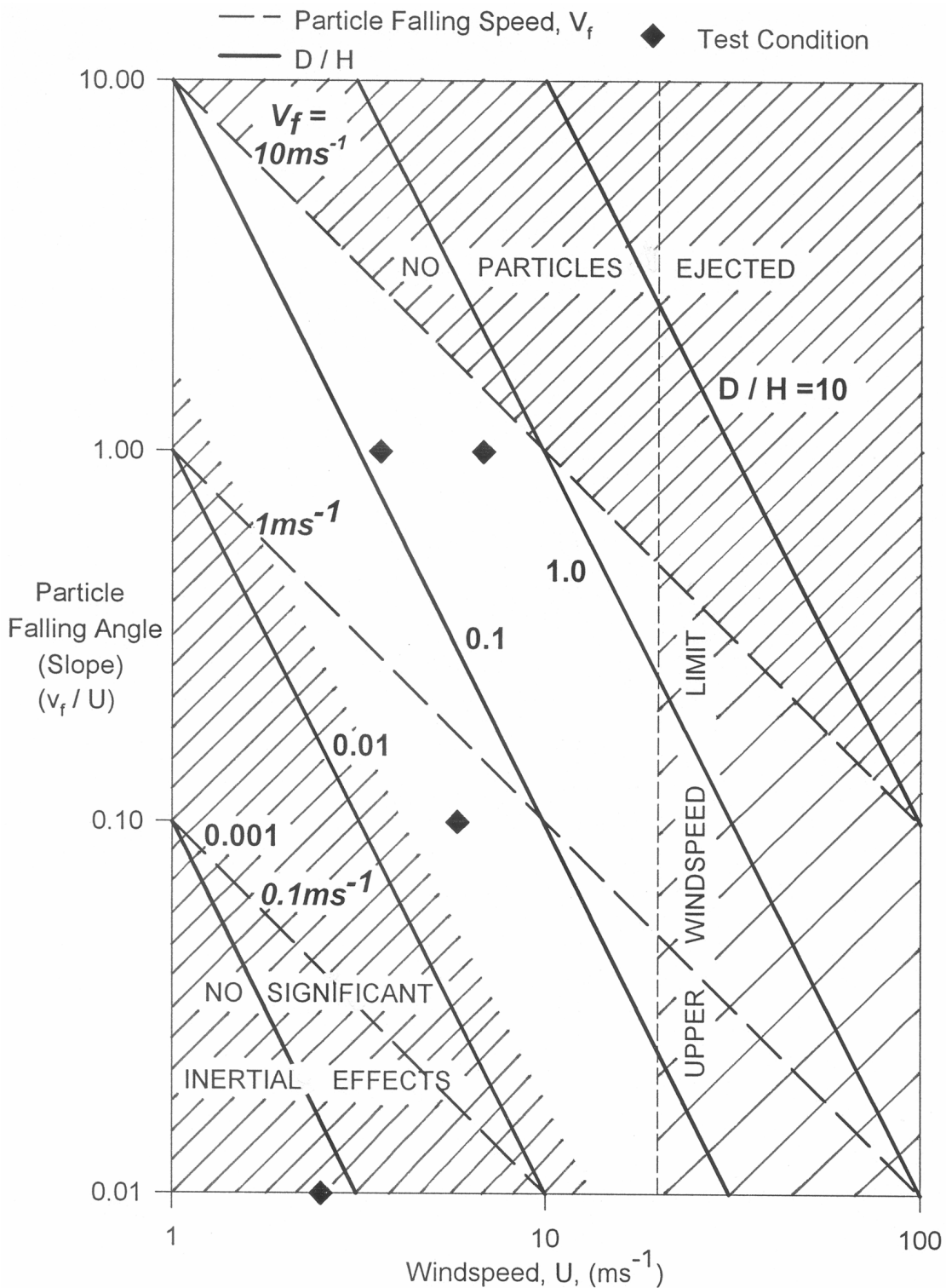


Figure 36. Aerodynamic Characteristics of Discharged Particles in Fire Plumes, for the Plume Conditions of Figures 23 and 24.
D in this Plot is the Particle Stop Distance, D_s .
From Hall et al(1998).

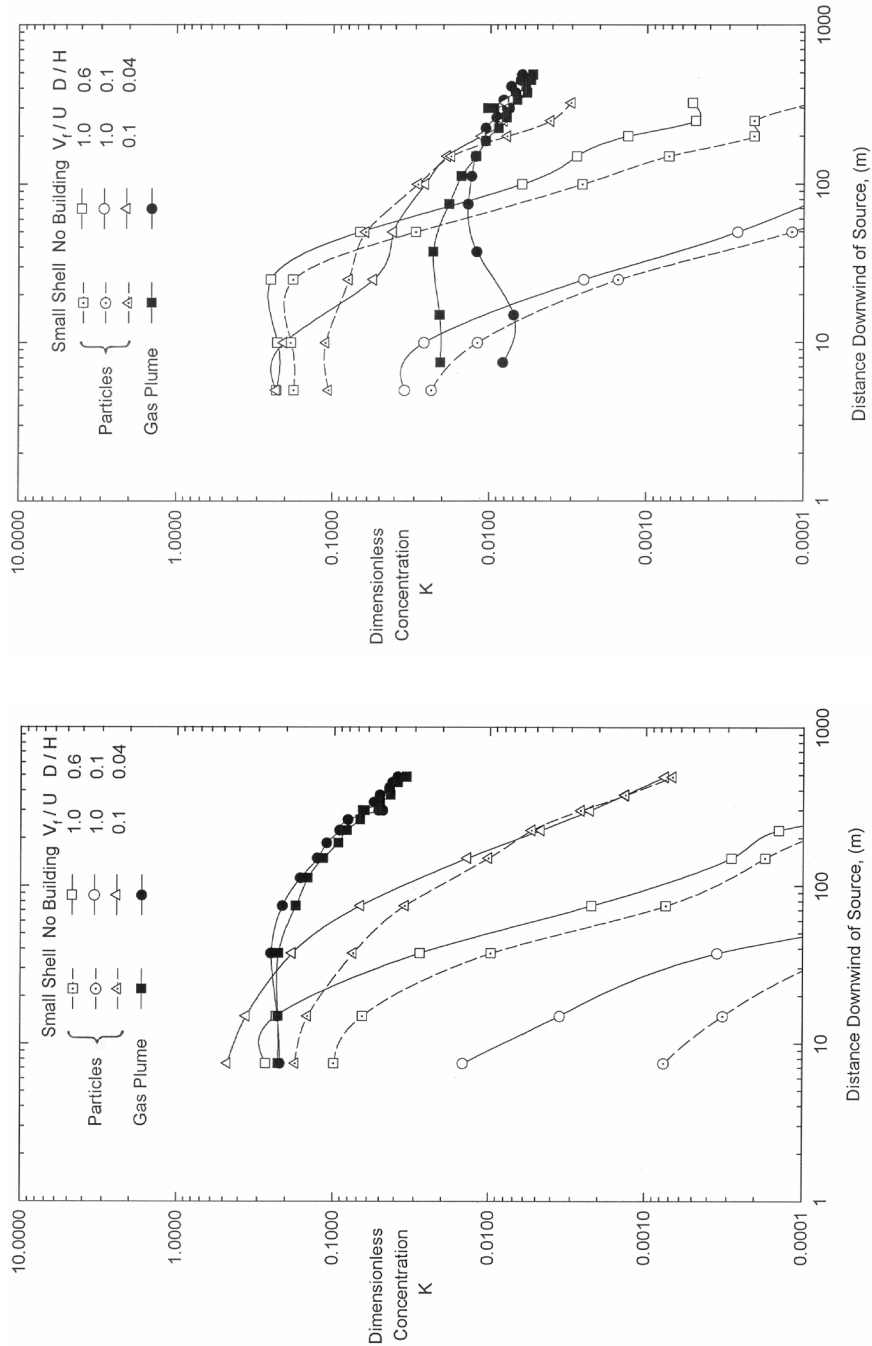


Figure 37. Small Scale Wind Tunnel Measurements of Large Particle Concentrations at the ground from a Warehouse Fire Plume. The Particle Properties for the Test Cases are Plotted on Figure 36. D in this Plot is the Particle Stop Distance, D_s . From Hall et al(1998).

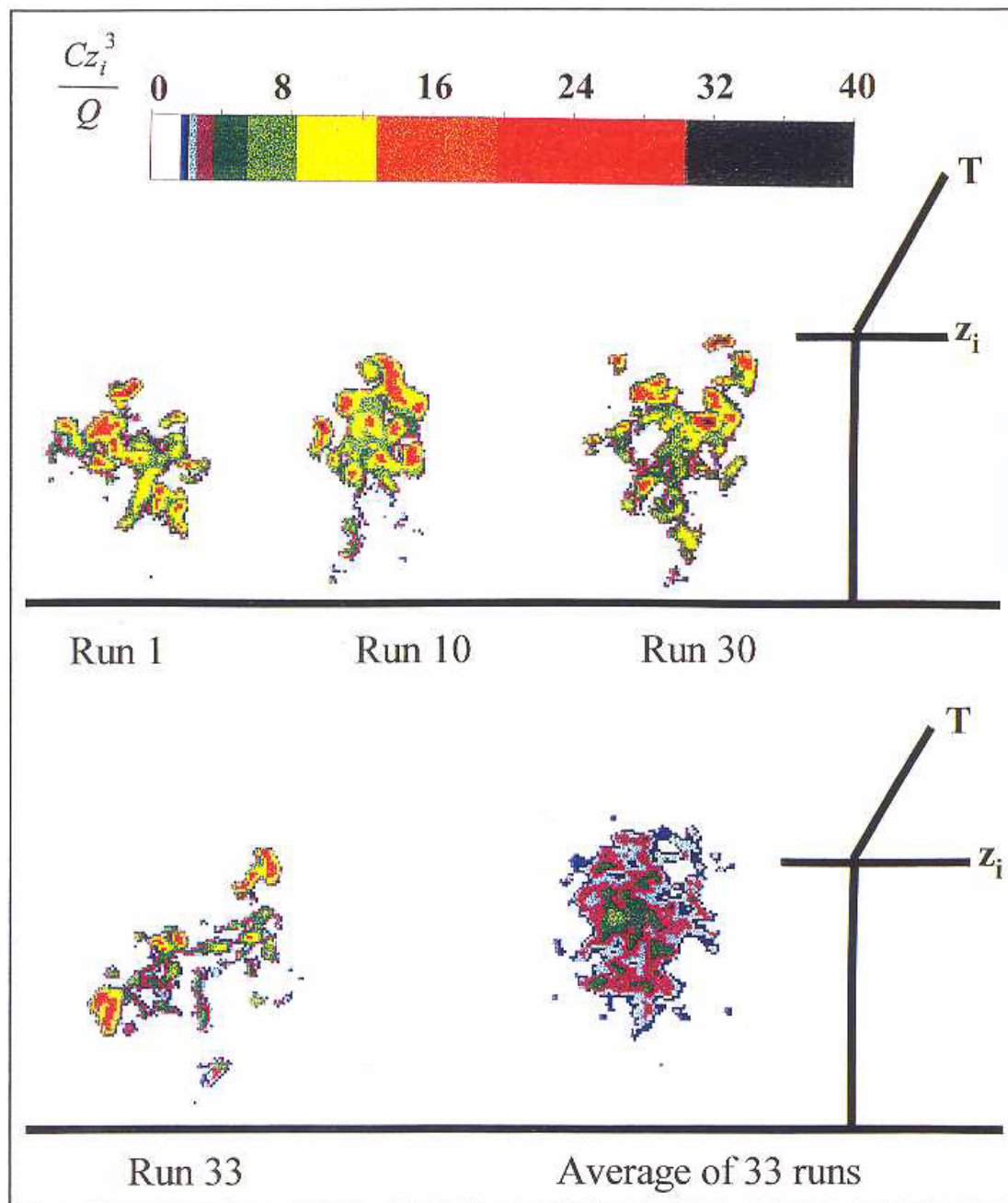


Figure 38. Instantaneous Concentration Cross Sections of Four Realisations of Moderately Buoyant Puff Releases and the Ensemble Average of 33 Such Releases Under Near-Identical Conditions. From Small-Scale Water Tunnel Measurements of Snyder et al(2002).

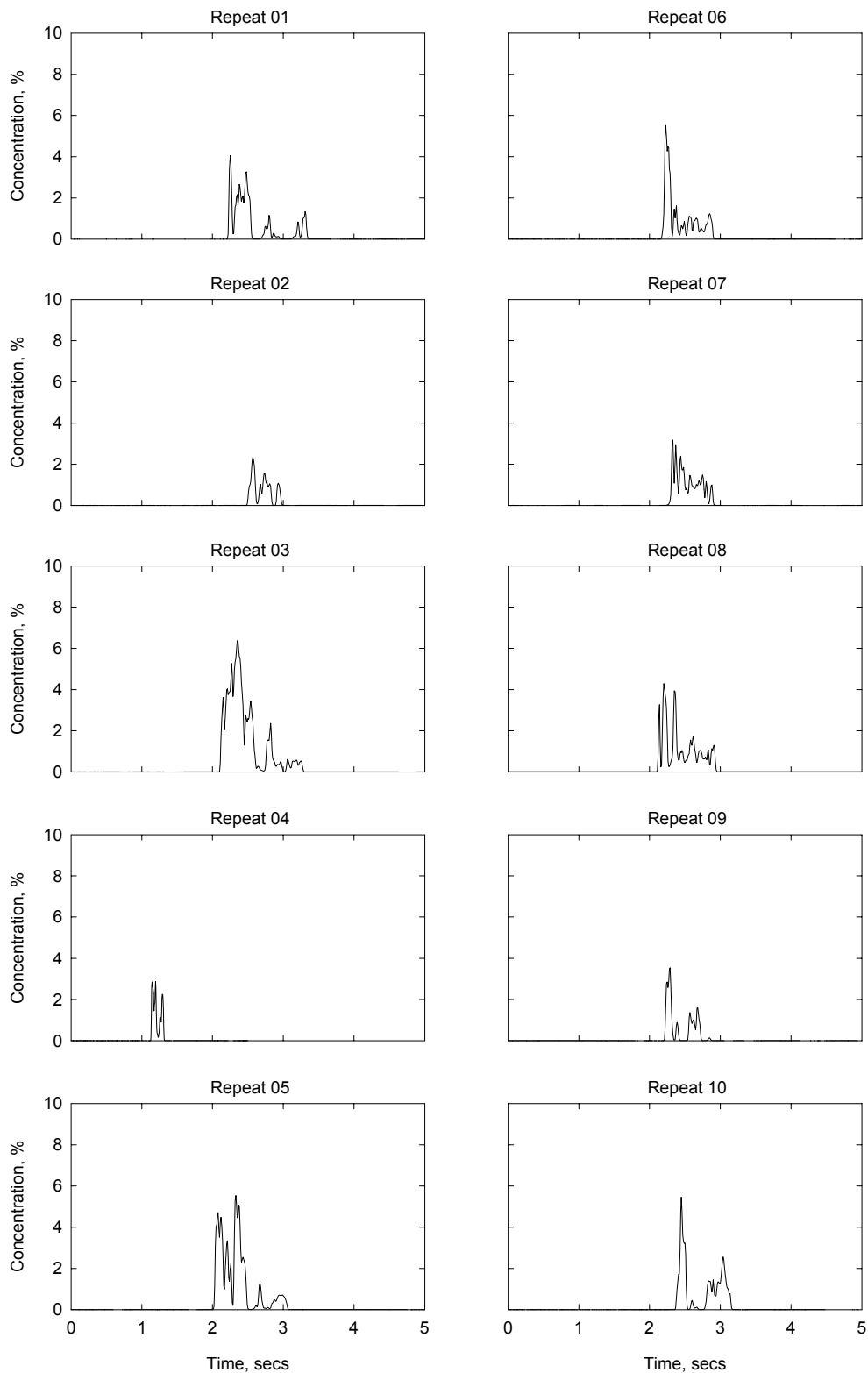


Figure 39. Concentration/Time Traces from Ten Realisations of a Highly Buoyant Short-Term Release.
Release $F/U_{ref}^3 L = 3$, $U_{ref}/L = 4$. Sampling Point at $x/L=15$, $z/L = 9$.
From Small Scale Wind Tunnel Measurements of Hall et al(2001).

APPENDIX A

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Summary of Work Funded by ADMLC

A report prepared for ADMLC by

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ABSTRACT

ADMLC and the earlier ADMWG have undertaken reviews of a large number of topics in atmospheric dispersion and deposition modelling. This document presents a review of the topics that have been covered by ADMLC and ADMWG. In some cases, different reviews have covered similar areas. The aim of this work was to identify whether there are any overlaps or gaps in those cases where similar topics have been tackled on different occasions.

This review concluded that there are no instances where reports contradict, rather than update, earlier reports. Gaps in the areas covered by the earlier studies were identified, and suggested topics for future work by ADMLC were proposed.

This study was funded by the UK Atmospheric Dispersion Modelling Liaison Committee.

The views expressed in this report are those of the authors, and do not necessarily represent the views of ADMLC or of any of the organisations represented on it

EXECUTIVE SUMMARY

ADMLC and the Steering Committee which preceded it have produced a total of 30 reports. In some cases different reports relate to similar topics. ADMLC wanted a review of the work which has been carried out, intended to identify any contradictions between different reports and any gaps in the areas covered. The aim was not to provide a scientific critique of each report, nor to consider whether subsequent work elsewhere would support a possible review or revision of any of the earlier reports.

The 30 reports were divided into 12 groups where the reports referred to topics that were related; for example four reports related to aspects of dispersion from releases near buildings, and five reports related to aspects of the use of meteorological data. The main topics covered by each of the reports have been summarised, and the areas of overlap between reports or gaps in the areas covered have been identified. Many of the reports included recommendations for future work; these recommendations have also been summarised in this report.

There are several instances where different reports describe models for the same or very similar applications. In almost all such cases, the later report references the earlier one. In this case, the later report can be regarded as updating, rather than contradicting, the earlier report. In the few cases where the later report does not reference the earlier one, there are no instances of contradictions between the two reports. In all cases, the reports can be regarded as updating earlier documents or providing additional, complementary, information.

There are two instances where the authors of this report have reservations about the conclusions reached in ADMLC reports; these relate to the portability of met data and the use of "old" met data, i.e. whether concentrations predicted using data from a site over a period of years show a trend with time.

This review also identified a number of gaps, either in the coverage of a single report or between the coverage of different reports on related topics. This will provide a useful input into discussions within ADMLC on future work programmes. The main gaps are:

- a Models for dispersion of dense gases.
- b Modelling of chemical reactions in the atmosphere, either between different materials within a single plume or between material in a plume and the general background levels of other chemicals.
- c Modelling the dispersion and deposition of particles which are large enough that their settling under gravity should be considered.
- d Models for dispersion and plume growth over bodies of water.
- e Models for concentration indoors resulting from a plume outdoors or from a release within the building.
- f Dispersion of material released at high speed, or in directions other than vertically upwards.
- g Dispersion of material released in an explosion.

This list was derived simply from the comments on the coverage of the previous reports for ADMLC, and so reflects gaps in the areas which are similar to those considered in previous work. It does not include possible topics which are completely outside the range of previous work undertaken for ADMLC.

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1 INTRODUCTION

The Atmospheric Dispersion Modelling Liaison Committee (ADMLC) was established in 1995, replacing an earlier (less formal) Steering Committee and its Working Group (ADMWG) which was established in December 1977.

This document presents a review of the work undertaken by ADMWG and ADMLC. It is intended to assist ADMLC in choosing topics to fund in future years, by identifying the topics that have been covered so far. The aim of this work is to identify the topics that have been covered in earlier work, and whether there are any overlaps or gaps in those cases where similar topics have been tackled on different occasions. Therefore this document does not present a summary of the scientific content of the various reports, nor does it attempt to identify whether reports should be updated because relevant work has been undertaken since they were originally published.

ADMWG published seven reports with one report including sections on four different topics. Four organisations on the Steering Committee funded a review on the preparation for a complex dispersion model to replace R91. This report was not published at the time, but has now been included on the ADMLC web site, and is included in this review of previous work. ADMLC has published seven annual reports, from the 1995/96 to 2002/03 financial years (at the moment two of these are not published) with annexes covering a variety of different topics. ADMLC and ADMWG have together published reports on a total of 30 topics. The list of reports is presented in Table 1. In the remainder of this report, it is necessary to refer to the reports on these 30 topics separately. For convenience each "topic report" was given a code-name, and this report refers to the code-names rather than the full report title. The list of code-names is also given in Table 1. So, for example, Annex A of NRPB-R292 "Atmospheric dispersion at low wind speed", is referred to as "R292a" in this report.

TABLE 1 List of ADMWG and ADMLC reports, and the code-names used in this report

Code-name	Full title
R91	The first report of a Working Group on Atmospheric Dispersion: a model for short and medium range dispersion of radionuclides released to the atmosphere. NRPB-R91 (1979)
R122	The second report of a Working Group on Atmospheric Dispersion: a procedure to include deposition in the model for short and medium range dispersion of radionuclides. NRPB-R122 (1981)
R123	The third report of a Working Group on Atmospheric Dispersion: the estimation of long range dispersion and deposition of continuous releases of radionuclides to atmosphere. NRPB-R123 (1981)
R124	The fourth report of a Working Group on Atmospheric Dispersion: a model for long range atmospheric dispersion of radionuclides released over a short period. NRPB-R124 (1981)

TABLE 1 List of ADMWG and ADMLC reports, and the code-names used in this report

Code-name	Full title
	The fifth report of a Working Group on Atmospheric Dispersion: models to allow for the effects of coastal sites, plume rise and buildings on dispersion of radionuclides and guidance on the value of deposition velocity and washout coefficients. NRPB-R157 (1983)
R157a	Effects of coastal sites
R157b	Models for plume rise
R157c	Effects of buildings
R157d	Guidance on the value of deposition velocity and washout coefficient
R198	The sixth report of a Working Group on Atmospheric Dispersion: modelling wet deposition from a short release. NRPB-R198 (1986)
R199	The seventh report of a Working Group on Atmospheric Dispersion: the uncertainty in dispersion estimates obtained from the Working Group models. NRPB-R199 (1986)
HB9	Preparatory studies for a complex dispersion model. CERC Report HB 9/88 (1988)
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 1995/96. NRPB-R292 (1997)
R292a	Atmospheric Dispersion at Low Wind Speed
R292b	Application of Computational Fluid Dynamics Codes to Near-field Atmospheric Dispersion
R292c	Rise of a Buoyant Plume from a Building Wake
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 1996/97. NRPB-R302 (1999)
R302a	Atmospheric Dispersion at Low Wind Speed
R302b	Review of Models for Calculating Air Concentrations when Plumes Impinge on Buildings or the Ground
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 1997/98. NRPB-R316 (1999)
R316a	Portability of Weather Data for Dispersion Calculations
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 1998/99. NRPB-R322 (2001)
R322a	Review of Deposition Velocity and Washout Coefficient
R322b	Review of Flow and Dispersion in the Vicinity of Groups of Buildings
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 1999/2000. NRPB-W2 (2002)
W2a	Review of dispersion over bodies of water
W2b	Best practice for binning meteorological data
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 2000/01. NRPB-W3 (2002)
W3a	Options for the most appropriate meteorological data for use in short range dispersion modelling
W3b	Methods for undertaking uncertainty analyses
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 2001/02. ADMLC-R1 (To be published in 2004)
R1a	Data assimilation following accidental releases in rain
R1b	Dispersion in complex terrain
R1c	Workshop on reliability of atmospheric dispersion models

TABLE 1 List of ADMWG and ADMLC reports, and the code-names used in this report

Code-name	Full title
	Atmospheric Dispersion Modelling Liaison Committee. Annual Report 2002/03. ADMLC-R2 (To be published in 2004)
R2a	Sources of meteorological data for use in dispersion modelling
R2b	Uncertainty in deriving dispersion parameters from meteorological data
R2c	Dispersion from accidental releases in urban areas
R2d	Effect on atmospheric dispersion of changing land use around Heathrow

The report R1b has been delayed, and was not available at the time of writing this report. It is not considered further in this review.

One of the aims of the work was to identify gaps or overlaps where different reports relate to similar topics. The reports were divided into a set of groups relating to similar topics. The groups and reports in each are listed in Table 2. One report (R302b) deals with concentrations when plumes impinge on buildings or on terrain features, and was included in both the buildings and the complex terrain group. One report (HB9) describes the prospects for updating the dispersion model; this report includes extensive sections for flat and for complex terrain, and is considered in both the "basic Gaussian model" and the "complex terrain" groups. One "report" (W3b) deals only with methods of undertaking uncertainty analyses, and is not considered further in this review. The remaining sections of this report discuss the different groups identified here, with a section describing each of the groups. The sections summarise the contents of the different reports and comment on the overlap and gaps between the coverage in the different reports in a section. The sections also include recommendations for future work; this is a summary of the recommendations given in the original reports rather than an outcome of this review.

A check was also made that there are no overlaps between reports in different groups. This was achieved by identifying any aspects of a report that might relate to a different group while undertaking the original review of the report.

TABLE 2 Groups of topics

Topic	Reports in group
Basic Gaussian model	R91, R122, R123, HB9
Plume rise	R157b, R292c
Values for deposition parameters	R157d, R322a
Dispersion at low wind speeds	R292a, R302a
Effects of buildings	R157c, R302b, R322b, R2c
Complex terrain	HB9, R302b
Coastal effects	R157a, W2a
Use of meteorological data	R316a, W2b, W3a, R2a, R2d
Rain and data assimilation	R198, R1a
Model uncertainty	R199, R1c, R2b
Capabilities of CFD modelling	R292b
Long range dispersion from a short release	R124

Some of the ADMLC reports which were published by NRPB appear on the NRPB web site. A further part of this work was to put copies of all other reports onto the ADMLC web site, and to include a set of keywords with each report that would enable them to be found by other people undertaking web searches. The reports held on the ADMLC website are in pdf format but the report text is also included in a hidden, searchable bitmap that accompanies each pdf. Some search engines on the Web are capable of searching these bit map files and will pick up the associated pdf if a match is found. In this case the user would access the pdf directly from the search engine which could present problems if the pdf is very large. It would be better if the search engine first picked up the HTML page that gives a summary of the report. This can be achieved using keywords and the hierarchical structure of the HTML Web page. The chosen keywords are entered into the title section of the HTML page which is the first part of the page to be searched by the search engine. This increases the likelihood that the HTML page is picked up first and the user can then access the pdf through the link provided.

Inevitably some keywords could be used for more than one of the ADMLC documents, and so a consistent set of keywords was devised and keywords for each of the reports were then chosen from that list. The complete list of keywords used is presented in Table 3, which also shows which report each keyword is used in. The information on keywords is also summarised in Table 4, which shows the complete set of keywords for each of the reports. This table gives keywords for parts of reports, such as R157a. However, the web site will not be able to distinguish the different parts of a report in this way, and the keywords will apply to the report as a whole.

TABLE 3 Keywords used for the reports, and included in the web site

Keyword	Used for
Accidental release	R1a
Atmospheric dispersion	All reports
Atmospheric stability category	R91, R123, HB9

TABLE 3 Keywords used for the reports, and included in the web site

Keyword	Used for
ADMS	HB9, R1c, R2b, R157b, R292c, R322b, W2a
AERMOD	R1c, R2b
Binning	W3a
Boundary layer	R91, HB9
Boundary layer parameters	R1c, R2b, HB9
Buildings	R157b, R199, R292c, R302b, R322c, R1c, R2c
Calm conditions	R292a, R302a, R2b
CFD	R292b, R292c, R302b
Coastal effects	R157a, R199, W2a
Complex terrain	R302b, HB9
Continuous release	R123, W2b
Data assimilation	R1a
Deposition	R122, R123, R124, R157d, R199, R322a, R1a
Deposition velocity	R122, R123, R157d, R322a
Evaluation	R1c, R2b
Friction velocity	R322a
Fumigation	R157a
Gaussian plume model	R91, R122, R123, R157a, R157b, R157d, R198, R199, HB9, R292a, R292c, R302a, R302b, W2a, R1a, R1c, R2b
Groups of buildings	R322c, R2c
Impinging plumes	HB9, R302b
Interception	R157d
Internal boundary layer	R157a, R199
Interpolation	R1a
Kriging	R1a
Long range dispersion	R123, R124, R199
Low wind speed	R199, R292a, R302a, R2b
Met data	R199, R292a, R302a, R316a, W2b, W3a, R1c, R2b, R2d
Meteorological data	R199, R292a, R302a, R316a, W2b, W3a, R1c, R2b, R2d
Met pre-processor	R1c, R2b
Mixing layer	R91, R123, HB9
Monitoring	R1a
NWP data	W3a, R2a, R2d
Occult wet deposition	R322a
Plume rise	R157b, R199, R292c
Puff model	R198
Rain	R122, R322a, R1a
Rainfall rate	R157d, R198
Rainout	R122, R157d, R198
Roughness length	R91, R322a
R91	R91, R122, R123, R157(all parts), R198, R199, HB9, R322c

TABLE 3 Keywords used for the reports, and included in the web site

Keyword	Used for
Scavenging coefficient	R322a
Sea-breeze	R157a, R199, W2a
Short release	R124, R198, R199
Single building	R157c, R322c
Uncertainty	R199, HB9, R292b, W3b, R1c, R2b
Urban dispersion	R322c, R2c
Validation	R199, R1c
Washout	R122, R157d
Washout coefficient	R122, R123, R157d, R198, R322a, R1a
Wet deposition	R198
Wet removal coefficient	R157d
Wind-tunnel	R292c, R302b, R3232c, R2c

TABLE 4 Keywords used for each of the reports

Report code-name	Keywords
R91	Atmospheric dispersion, atmospheric stability category, boundary layer, Gaussian plume model, mixing layer, roughness length, R91
R122	Atmospheric dispersion, deposition, deposition velocity, Gaussian plume model, rain, rainout, R91, washout, washout coefficient
R123	Atmospheric dispersion, atmospheric stability category, continuous release, deposition, deposition velocity, Gaussian plume model, long range dispersion, mixing layer, R91, washout coefficient
R124	Atmospheric dispersion, deposition, long range dispersion, short release
R157a	Atmospheric dispersion, coastal effects, fumigation, Gaussian plume model, internal boundary layer, R91, sea-breeze
R157b	Atmospheric dispersion, ADMS, Briggs, buildings, CFD, Gaussian plume model, plume rise, R91
R157c	Atmospheric dispersion, buildings, R91, single buildings, wind tunnels
R157d	Atmospheric dispersion, deposition, deposition velocity, Gaussian plume model, interception, rainfall rate, rainout, R91, washout, washout coefficient, wet removal coefficient
R198	Atmospheric dispersion, Gaussian plume model, puff model, rainfall rate, rainout, R91, short release, wet deposition, washout coefficient
R199	Atmospheric dispersion, buildings, coastal effects, deposition, Gaussian plume model, internal boundary layer, long range dispersion, low wind speed, met data, meteorological data, plume rise, R91, sea-breeze, short release, uncertainty, validation
HB9	Atmospheric dispersion, atmospheric stability category, boundary layer, boundary layer parameters, complex terrain, Gaussian plume model, impinging plumes, mixing layer, R91, uncertainty
R292a	Atmospheric dispersion, calm conditions, Gaussian plume model, low wind speed, met data, meteorological data
R292b	Atmospheric dispersion, CFD, uncertainty
R292c	Atmospheric dispersion, ADMS, Briggs, buildings, CFD, Gaussian plume model, plume rise, wind-tunnel
R302a	Atmospheric dispersion, calm conditions, Gaussian plume model, low wind speed, met data, meteorological data

TABLE 4 Keywords used for each of the reports

Report code-name	Keywords
R302b	Atmospheric dispersion, buildings, CFD, complex terrain, Gaussian plume model, impinging plumes, wind tunnels
R316a	Atmospheric dispersion, met data, meteorological data
R322a	Atmospheric dispersion, deposition, deposition velocity, friction velocity, occult wet deposition, rain, roughness length, scavenging coefficient, washout coefficient
R322b	ADMS, atmospheric dispersion, buildings, groups of buildings, R91, single buildings, urban dispersion, wind tunnels
W2a	ADMS, atmospheric dispersion, coastal effects, Gaussian plume model, sea-breeze
W2b	Atmospheric dispersion, met data, meteorological data, NWP
W3a	Atmospheric dispersion, met data, meteorological data, NWP
W3b	Atmospheric dispersion, uncertainty
R1a	Accidental release, atmospheric dispersion, deposition, data assimilation, Gaussian plume model, interpolation, kriging, monitoring, rain, washout coefficient
R1c	Atmospheric dispersion, ADMS, AERMOD, boundary layer parameters, buildings, evaluation, Gaussian plume model, met data, meteorological data, met pre-processor, uncertainty, validation
R2a	Atmospheric dispersion, met data, meteorological data, NWP
R2b	Atmospheric dispersion, ADMS, AERMOD, boundary layer parameters, calm conditions, evaluation, Gaussian plume model, low wind speed, met data, meteorological data, met pre-processor, uncertainty
R2c	Atmospheric dispersion, buildings, groups of buildings, urban dispersion, wind tunnels
R2d	Atmospheric dispersion, met data, meteorological data, NWP

2 REVIEW OF REPORTS RELATING TO THE BASIC GAUSSIAN MODEL

The basic model is considered in three reports, all from ADMWG (R91, R122 and R123). Options for updating this model are considered in HB9.

2.1 Scope of R91

R91 describes the basic formulation of the Gaussian plume dispersion model. This model enables calculations to be performed for a range of atmospheric stability, with allowance for the influence of duration of release. The original model was developed for application to the dispersion of radioactive material, but it found equal relevance to the dispersion of chemical species.

The report notes that the Gaussian plume model was chosen ahead of other models, considered to represent better the physical processes of turbulent diffusion in the atmosphere, for example closure models of which eddy-diffusivity models are the simplest. However these intricate models, according to

results obtained in previous studies, did not warrant the additional complexity and cost to users. In selecting the Gaussian plume model consideration was given not only to the developments in calculations of atmospheric dispersion, but also to the availability of a scheme to classify any given set of meteorological conditions into parameters for use in the various models available. On the basis of these considerations a Gaussian plume model was used.

The models included in the report apply to the atmospheric diffusion of a neutrally buoyant plume over land from an isolated stack for short and medium range dispersion i.e. less than a few tens of kilometres from the source, while the meteorological and topographical conditions remain steady. It is assumed that the released material undergoes no chemical or radioactive transformations. The procedure proposed in the report for estimating dispersion is only applicable when the release point is sufficiently distant from surrounding buildings for the air flow at the release height to be relatively undisturbed.

The report suggests that when modelling continuous releases the horizontal dispersion of the plume is no longer satisfactorily described by the Gaussian plume model. Instead the horizontal dispersion of activity is assumed to be constant over each individual sector.

R91 advises typical values of wind speed, boundary layer depth and stability category distribution. Furthermore, methods for calculating the vertical and horizontal plume standard deviations and the sector angle for meteorological data in continuous releases are provided.

The report considers atmospheric stability categories and recommends Smith's diffusion typing scheme. The scheme proposed is quantitative and attempts to account for sensible heat flux in the lower layers of the atmosphere, wind speed, the effect of ground roughness and also clearly distinguishes night-time conditions.

The models were chosen so that they could be extended to deal with dry and wet deposition, plume rise and entrainment of the effluents into the wake behind buildings.

2.2 Scope of R122

R122 describes methods for extending the original Gaussian dispersion model to include dry and wet deposition. This report contains a brief outline of the dispersion model followed by sections describing methods for the inclusion of dry and wet deposition.

The report highlights that the models for wet and dry deposition can be applied for any release duration although there are limitations on the use of the wet deposition model for short releases.

The report recommends that the dry deposition rate should be calculated using the concept of a deposition velocity. The report suggests the use of the source

depletion model for including dry deposition (as opposed to the alternative approach, surface depletion models). The source depletion model does not necessarily represent the physical distribution of activity in the atmosphere but it is simple to use and gives results which are considered sufficiently reliable for use in assessing the dosimetric consequences of radioactive discharges. The principal area in which the model breaks down is for dispersion from a low stack in stable conditions (especially categories F and G). A further restriction is that the model makes no allowance for gravitational settling and should not be applied to particles with a settling velocity greater than a few centimetres per second, corresponding to particles of diameter greater than around 10 μm .

The report suggests that the wet deposition rate during rainfall be calculated using a washout coefficient. This approach includes both of the main removal processes, washout and rainout.

The report considered three models which describe the intermittent nature of rainfall and lead to the calculation of the fraction of the time that a dispersing plume from a continuous release is subject to rainfall. The model describing the explicit passage of activity between periods of wet and dry conditions was selected, as it is physically more realistic and not much more complicated to apply.

The model was selected primarily for application to a continuous release and is only appropriate for application to short releases when a large number of short releases in category D are considered or when averages are being calculated. It predicts the amount of material left in the plume using a statistical treatment of the sequence of wet and dry conditions affecting a dispersing plume. For wet deposition the report recommends values of P_D and P_W (the probability of dry weather stopping in unit time and the probability of wet weather stopping in unit time respectively).

The report assumes that rainfall only occurs in category D conditions.

The report does not include consideration of values of washout coefficient for use in the model. Furthermore, the report suggests that when using the recommended model, the solution given will over estimate wet deposition due to rainout at short distances, where the plume has not spread fully through the mixing layer.

2.3 Scope of R123

R123 describes a method for extending atmospheric dispersion calculations to long ranges for continuous releases. In reaching its conclusions on a model for long-range dispersion from a continuous release, the report considered the results of two studies comparing concentrations and deposition rates predicted by a range of models. The model chosen represents a compromise between those giving a good description of the physical processes involved and those which are simple to use.

The report recommends that long-range dispersion should be evaluated assuming that all releases occur in neutral stability but allowing for a range of wind speeds, and using a mixing layer depth of 800m for all conditions. This was considered to reflect the average effect of changing conditions during plume travel.

The report suggests that, when calculating concentrations, the original model (R91) should be used at distances less than 50km and the model described in this report at greater distances.

Further recommendations are made for the values of numerous dispersion parameters including wind speed and frequency distribution in different directions and vertical standard deviation of the plume.

2.4 Scope of HB9

This report was written in response to concerns that the model in R91 was becoming dated, and that research since it was written might enable a relatively simple, but improved, model to be developed. It is restricted to considering dispersion within about 30 km of the source, and does not consider deposition. The report proposes the use of indicators of the stability of the atmosphere (and the corresponding turbulence and dispersion coefficients) which vary continuously in place of the discrete stability categories of earlier Gaussian models.

The report describes stable, neutral and convective boundary layers. It includes sections relating to the structure of the boundary layer and dispersion within the boundary layer. Much of the report relates to situations where the boundary layer is in equilibrium but there is a short discussion of problems when the boundary layer structure is changing with time, and does not fit into any of the idealised categories. There is also a discussion of the effects of spatial changes in the boundary layer structure, though this concludes that the boundary layer is likely to be able to accommodate such changes, retaining one of the idealised structures.

Other work (not through ADMLC) has shown that different methods of estimating atmospheric stability may give very different results. The report HB9 suggests that this reflects the general weakness of schemes (such as that in R91) which derive the boundary layer structure using only information on conditions at the ground, and that an improved model could remove much of this variation.

The report describes the motion of discharged particles and gases, leading to descriptions of the concentration distribution at different distances and for the different boundary layer structures considered. It identifies a number of aspects of dispersion which are not well described by Gaussian models generally. This leads to a more general description of where relatively simple changes could be made to improve simple Gaussian models, proposing formulae for an improved

model. Some predictions of the suggested model are compared to results from R91, and areas where the models might give different predictions are identified. The report notes that a limitation of the Gaussian plume model is that atmospheric conditions must remain constant over the period of interest, and discusses puff models as a means of avoiding some of the limitations. The report also gives a brief review of some research grade models, considering whether they might be useful in specific situations. It also comments on validation of models by comparing their predictions with those of numerical simulation techniques.

2.5 Areas of overlap between the reports

R91 describes a simple model which does not allow for deposition and is only appropriate within a few tens of kilometres of the release point. R122 extends this model to include dry deposition for both short and continuous releases. It also extends the model to include wet deposition primarily for continuous releases. R123 extends R91 by giving a method of applying the model at larger distances. There are no contradictions between these reports.

HB9 overlaps considerably with R91. It proposes ways of improving the original model and therefore is an update to the earlier report. It identifies a number of weaknesses in simple Gaussian plume models.

2.6 Gaps in the areas covered by the models

HB9 and R91 cover the same general areas, and therefore references in the following to R91 should be interpreted as meaning the scope of both R91 and HB9.

The reports only consider the dispersion of neutrally buoyant material. ADMLC and ADMWG have extended the models to consider plume rise from buoyant material (see Section 3) but have not considered dispersion of dense gases.

The reports neglect the consideration of large particles and the impact they have on atmospheric dispersion, notably in R122.

The models in the reports are incapable of dealing with variable atmospheric conditions. For example a condition of the model in R123 is neutral stability (representing changes of stability during travel) and the model in R91 is only applicable while the initial stability conditions persist.

R91 assumes no chemical and radioactive transformations occur, therefore the model does not account for radioactive decay.

R122 does not give any guidance on the values of the parameters for use in the models suggested. This is given in other reports, as discussed in Section 4 of this report.

The reports do not recommend models suitable for use when calculating wet deposition from a specific short release. ADMWG considered this in R198, as discussed in Section 10 of this report.

Finally the model from these reports does not consider plume rise or wake effects, however the model can be extended to account for these effects, which were considered in subsequent reports (See Sections 3 and 7 of this report).

2.7 Recommendations for future work

R91, R122 and R123 do not give explicit recommendations for future work. HB9 notes that it is possible to develop a more advanced airflow and dispersion model than that of R91, capable of running on a PC, and that such a model should be developed. This recommendation has been implemented; the resulting model is the commercial software package known as ADMS.

3 REVIEW OF REPORTS RELATING TO PLUME RISE

Plume rise is considered in two reports, one from ADMWG (R157b) and one from ADMLC (R292c).

3.1 Scope of R157b

R157b describes methods of modelling plume rise from isolated sources and discusses plume rise from sources discharging into a building wake.

For plume rise from an isolated source the report recommends two plume rise models, those suggested by Briggs or Moore. It suggests that the Moore model gives a marginally more accurate prediction of plume rise than the Briggs model. Termination of plume rise is discussed and the calculation of ground level concentrations under a rising plume is discussed. The problems associated with lift-off of buoyant plumes from sources at ground level are discussed.

For releases from a building wake, threshold values are defined for the source momentum and buoyancy fluxes such that if neither is exceeded then the emission can be assumed to be passive. The report does not give a model for plume rise from a building wake, for use if the threshold values are exceeded. However, a formula is given for the final height of a plume emitted with vertical momentum from a source on or above the building roof.

3.2 Scope of R292c

R292c is a review of the (then) current practical modelling options for the rise of buoyant plumes from building wakes and a review of the likely future developments. Models to calculate the ground level concentration under a rising plume are recommended. The physical processes within a buoyant plume are discussed as well as the experimental and theoretical aspects which need to be considered. The report deals with source heights ranging from ground level to a little above roof level.

The report lists cases where it is reasonable (or at least conservative) to treat emissions as passive and other cases where this approach should not be adopted. The report then considers different modelling approaches and recommends situations where specific models may be appropriate.

The report suggests the ADMS model is potentially suitable for modelling plume rise as it contains a reasonably detailed representation of the modifications to flow and dispersion brought about by large buildings together with an integral model for plume rise. The report notes that small scale building or site details near to the source may introduce dispersion features at a scale well below that which the ADMS model can be expected to handle.

The use of computational fluid dynamics (CFD) calculations is discussed and results from a number of studies which use the $k-\epsilon$ model are presented. The report notes that the accuracy of the calculations, where comparisons with data are possible, is best for passive emissions and tends to degrade with increasing plume buoyancy. The deficiencies in $k-\epsilon$ modelling are also noted.

Wind-tunnel modelling is only mentioned briefly as it was outside the scope of the review. Situations where wind-tunnel modelling can be considered are listed and the report notes that results from wind-tunnel studies can be used in conjunction with computer modelling to complete an assessment procedure.

The report finishes by discussing areas where future development might proceed with reasonable expectation of success.

3.3 Areas of overlap between R157b and R292c

The methods discussed in R157b should be considered as screening approaches and R292c notes that the threshold approach suggested in R157b is a very crude approximation. R292c considers more complex modelling techniques and uses experimental data to draw conclusions. There is little overlap but if there are any areas of disagreement, R292c should be considered as updating R157a.

3.4 Gaps in the areas covered by the models

Plume rise from area and volume sources, directional releases, jets and heavier than air releases dominated by buoyancy have not been considered by ADMLC/ADWMG.

3.5 Recommendations for future work

R157b does not give any specific recommendations for future work.

R292b notes possible extensions to simple Gaussian models, and suggests that these should be explored further. It also suggests that the capabilities of CFD modelling in this area should be assessed. It notes that a comprehensive set of test cases should be defined for which adequate data are available, so enabling future developments to be evaluated.

4 REVIEW OF REPORTS RELATING TO VALUES OF DEPOSITION PARAMETERS

Values for the deposition parameters are considered in two reports, one from ADMWG (R157d) and one from ADMLC (R322a).

4.1 Scope of R157d

R157d includes guidance on the values of deposition velocity and washout coefficient for use in the models recommended in R122.

The report advises that deposition velocity, integral in determining dry deposition, be expressed in terms of the resistance to transfer through the turbulent boundary layer, the viscous boundary layer and the surface.

R157d considers the processes affecting dry deposition. The report summarises the impact of surface roughness and atmospheric stability, notably grass in neutral conditions, on the deposition velocity. The report also pays particular attention to the effect that material type (particles or gases) and the size of particular material have on deposition velocity. The report emphasises that the recommended values of deposition velocity are described by a range, as opposed to individual values.

R157d considers the processes affecting wet deposition. The report examines the variation of the washout coefficient with rainfall rate and particle size. Guidance is given on a range of values for the wet removal coefficient incorporating the effects of both rainout (removal within rain clouds by incorporation in rain drops as they form) and washout (removal by rain falling through the dispersing

plume) as it is very difficult to separate their individual contributions. The report suggests that use of the wet removal coefficient at short distances will tend to overestimate the deposition rate.

The report considers it adequate to ignore the variation of washout coefficient with rainfall rate, when calculating long-term average deposition rates, and to assume that rain falls at a rate of 1 mm per hour. The report considers type and intensity, and spatial and temporal extent of precipitation for a short release. This includes comparisons of frontal rainfall and showers. However the range of wet removal coefficient values given in the report does not consider these processes but assumes average conditions for a continuous release. The report also comments on the use of a washout coefficient when considering reactive gases.

Finally R157d considers the interception of deposits from the atmosphere by plants. The report considers an additional factor to determine the amount of material deposited on the edible parts of plants. The report recommends an approach using an interception factor and a retention half-life, and includes formulae for calculating the interception factor. Furthermore, the report recommends generic values for calculating the interception factor on pasture grass, however it notes that this recommendation does not extend to crops due to a lack of experimental data available.

4.2 Scope of R322a

R322a seeks to expand upon and update the advice given in R157d, taking account of new information that has become available since its publication.

The report makes recommendations which are robust in terms of their dependence on meteorological conditions, on physico-chemical form of the pollutant, and in representing the trends in variation amongst a number of key surface types, whilst at the same time reflecting current uncertainties. Where recommendations are made, two types of value are given in the report, a "best judgement" value and a "conservative" value.

A review of values of deposition velocity for particulate material and for those gases of interest to the nuclear industry was undertaken. The report considers particles in the (aerodynamic) diameter range 0.1 micron to 10 microns, paying particular attention to those particles in the range 0.1 micron to 1 micron since many of the pollutant particles surviving well beyond the immediate vicinity of primary sources lie in this size range. The report also considers iodine in elemental and organic forms.

For dry deposition, the dependence on surface type and weather conditions is considered. The primary surface type of interest is taken to be grass and crop canopies, but separate consideration is given to forest canopies and water bodies. In addition, the particular features of the urban environment are discussed and recommendations of deposition velocity for all mentioned surface

types are made. The dependence on weather conditions is discussed in terms of windspeed and atmospheric stability.

For wet deposition, both washout and rainout are discussed. Separate consideration is also given to deposition in fog or in hill cloud.

A review of values of washout coefficient for particulate material (as for deposition velocity) concentrates on particles in the size range from about 0.1 to a few microns AMAD and iodine in elemental and organic forms. The report gives little guidance on the variation of washout coefficient with rainfall rate and with the type of rain (e.g. rain from frontal systems or thunder storms) but does consider the enhancement of deposition under conditions of orographic rainfall, described by the seeder-feeder mechanism.

Furthermore the report compares its own approach to modelling wet and more notably dry deposition with other approaches. The comparison of deposition velocities comprises of data compilations, empirical relationships, semi-empirical approaches and theoretical models.

4.3 Areas of overlap between R157d and R322a

R157d and R322a both review deposition velocity and washout coefficient and therefore there exists a significant amount of overlap. Both reports consider values for reactive gases intended primarily for elemental iodine. Particle sizes of 0.1 to 10 microns are considered in both reports, as is a generic rainfall rate of 1 mm per hour.

R322a describes the deposition velocity in an analogous manner to R157d. That is in terms of a transfer resistance, which can be broken down into the components: aerodynamic resistance, sub-layer resistance and surface resistance.

R322a expands and updates the recommendations in R157d. Therefore, if there exist any areas of disagreement, R322a should be considered as updating R157d.

4.4 Gaps in the areas covered by the models

The reports give little guidance on the variation of washout coefficient with rainfall rate and with the type of rain. It is out of the scope of R322a (and R157d) to consider the impact of the large-scale motions associated with thunderstorms, which can lead to pollutants being deposited at locations far removed from those implied by the boundary-layer wind field.

There exists relatively little guidance regarding the deposition of methyl iodide (organic iodine), particularly for its deposition velocity in urban areas and its washout coefficient.

4.5 Recommendations for future work

Neither of these reports makes explicit recommendations for future work.

5 REVIEW OF REPORTS RELATING TO DISPERSION AT LOW WIND SPEEDS

Atmospheric dispersion in conditions with low wind speeds is considered in two reports, R292a and R302a.

5.1 Scope of R292a

This report reviewed dispersion models for two sets of situations (i) where there is very small wind speed over the period of interest and (ii) where the vector average of the wind velocity over the period of interest is zero. It also looked at the frequency of calm conditions and anemometer response at low wind speeds.

The report reviews several models for conditions with a very low wind speed, including ways of adapting the simple Gaussian plume model, approaches based on modelling puffs and solutions of the diffusion equation. While there is no clear recommendation on choice of model, the emphasis is on simple modifications to the R91 model.

The report also describes a model for concentration in unstable conditions in periods when the vector average of wind velocity is zero, but where there are shorter periods with non-zero wind speed. This model leads to predictions for the probability distribution of concentration for different averaging times and distances from the release; some results of the model are presented graphically.

The report also briefly considers plume rise, the effects of buildings and terrain on dispersion, and the calculation of annual average concentration including that during "calm" conditions. The review for plume rise notes that Briggs discussed how elevated inversions would terminate rise. The report points out that modern integral plume rise models automatically include rise at low wind speed if the atmospheric conditions are adequately described.

5.2 Scope of R302a

This report was written by W S Atkins. At the time of this report, they were working for HSE on the importance of modelling dispersion at low wind speed when undertaking quantified risk analyses; this work was extended for ADMLC to include methods for allowing for low wind speed conditions when calculating annual average concentrations. This report therefore concentrates on the cross-wind integrated air concentration, rather than the centre-line concentration.

The report reviews appropriate models, referencing R292a. It points out that the travel distance is limited by the wind speed and the typical duration of low wind speed conditions, and therefore that the models should only be used close to the site. It suggests that the simple Gaussian plume model, as in R91, with a minimum wind speed and an allowance for the possible travel distance in low wind speeds is a reasonable approach. The report advises that the best approach is to consider the application and to use an appropriate methodology with suitable assumptions.

The report discusses the availability of data on the frequency distribution of wind speed, and suggests that using a single representative wind speed for each stability category is not adequate, but that the frequency of different wind speeds should be considered.

This report presents a number of comparisons of the variation of concentration with distance predicted using different dispersion models or different amounts of detail on the distribution of wind speed, for annual average concentrations and for concentrations in specific conditions.

5.3 Areas of overlap

During the period when these reports were being prepared, W S Atkins were undertaking work on low wind speed dispersion for HSE, with a report on the first part of their study published in 1996, and referenced in R292a. The work for ADMLC was added on to the second part of the study by slightly extending its objectives. Although R302a references R292a there is some overlap between the two reports.

Both reports review dispersion models for low wind speeds, and make comments on the assumptions involved in such models. However, neither report comes to clear conclusions on the most appropriate model for particular applications and so the reports do not contradict each other.

5.4 Gaps in the areas covered by the models

The two reports provide a reasonable review of models for dispersion of non-buoyant material from point sources. There are probably no gaps here. The reports make some comments on the effects of buildings, complex terrain and plume rise on dispersion, and the variation of deposition velocity with wind speed or stability. Some of this seems to be little more than speculation, and there may be some benefit in a more detailed examination of these topics.

R302a includes numerical comparisons of different models or assumptions. Many of these are limited to annual average concentrations or the cross-wind integrated concentration in specific conditions. The report says that specific modelling is less important in the nuclear industry than in the chemical industry, because of the linear dose response relationship used in studies for releases of

radioactive material. There may be benefit in doing similar calculations for peak concentration for short releases.

5.5 Recommendations for future work

R292a notes that there are no simple models for calculating concentration in stable conditions at very low wind speeds, and suggests that the likely importance of such conditions should be assessed. R302a does not make any specific recommendations for further work.

6 REVIEW OF REPORTS RELATED TO DISPERSION FROM SOURCES CLOSE TO BUILDINGS

Dispersion from sources close to buildings is considered in 4 reports; R157c mainly relates to sources near single buildings, R302b relates to concentrations when plumes impinge on buildings, R322b relates to dispersion from sites with several buildings while R2c relates to dispersion from short duration releases within urban areas.

6.1 Scope of R157c

R157c gives advice on dispersion for five positions of the source relative to the building.

It gives a detailed description of models for concentration in the near and main wake for use when all emitted material is entrained (i.e. for a source on or just above the roof, or within the re-circulating wake region). The model for the near wake is appropriate for an averaging time of a few tens of minutes and the report gives a method of extending this to longer duration releases, including continuous releases. For sources well above the roof, R157c recommends the use of a model by Hunt and Robins, which is said to be too complex for the equations to be included in the report. Concentrations at distances beyond the wake for a source well above the building roof should be calculated using an effective stack height.

For a source upwind of the building where the plume can impinge on the building face, the report suggests that the concentration on the building face should be taken as the maximum concentration at that distance from the source in the absence of the building. The report also suggests when plumes should be considered as impinging on the building face. The report notes that material may travel upwind for some source positions, but gives no information on the concentration or extent of upwind travel; it also gives no recommendations for calculating the concentration downwind of the building for sources upwind.

The report discusses the problems of modelling sources within the main wake, on the upwind face of the building or on or near a side face of the building, but does not recommend a model for these cases. It identifies a method giving a conservative prediction of the concentration at locations on a building surface from a source at another point on the surface of the building.

The report suggests that physical modelling (i.e. the use of wind or water tunnels) could be appropriate for many situations for which there is no suitable analytical model.

R157c relates only to the dispersion of neutrally buoyant material released without vertical momentum. The plume rise section, R157b, gives criteria for which it is reasonable to ignore plume rise for releases near a building. It suggests that wind tunnel studies should be considered if the conditions are such that the criteria are not met.

6.2 Scope of R302b

The main aim of this project was to review concentrations on building surfaces when plumes impinge on the building. However, it addressed a number of other aspects of modelling dispersion near buildings.

The report sets out the interactions between plumes and buildings for different sizes of the plume compared to the building, and concentrates on the situations where the plume width is less than or comparable to the building size. This implies that the source is relatively close to the building, and so the report considers dispersion from sources which are close to buildings. The report describes the airflow around a single building, and briefly considers the influence of nearby buildings. The report considers methods for calculating the concentration on a building face for sources which are upwind of the building, on the building, above the building roof or within the re-circulating wake. The discussion for the re-circulating wake covers the concentration close to the source before it diffuses through the wake as well as the average concentration in the wake. The report also examines the amount of material that becomes entrained into the wake for sources in various locations near the building. The report states that it is nearly impossible to formulate an accurate empirical model for complex sites, but gives some pointers to work on this topic.

The report includes a simple model for calculating the concentration indoors from plumes outdoors, in terms of air exchange rates. It also considers the applicability of CFD modelling to dispersion around buildings.

6.3 Scope of R322b

R322b is entitled "review of flow and dispersion in the vicinity of groups of buildings". It primarily encompasses modelling for nuclear/industrial sites and

urban areas but also covers some aspects of dispersion from a single building as this is required in understanding the effects of groups of buildings.

The report gives a description of the physical processes involved in flow and dispersion, including single buildings, groups of buildings, porous obstacles and the development of plumes over arrays of obstacles. The discussion on dispersion over arrays of obstacles is divided into three regimes - close to the discharge, the intermediate region and the region far from the source. The discussion on dispersion close to the source relates mainly to dispersion from a single building, but extends the discussion of R157c by giving more information for source positions other than in the main wake. The report states that "the precise prediction of concentrations resulting from specific arrangements of source and obstacles generally requires wind tunnel or field experiments, as observed distributions of concentration are usually quite different from those found for obstacles in isolation".

The report then describes current practical approaches to dispersion modelling for single buildings, groups of buildings and urban areas. The review for single buildings covers R157c, ISC and PRIME but concentrates on the ADMS model which covers all aspects of dispersion near a single building. The discussion for groups of buildings is short, covering effective building sizes as used in ISC and ADMS. The discussion for urban areas covers the role of Gaussian models, street canyon models and methods linking detailed numerical modelling close to the source with Gaussian modelling at longer distances.

The report covers the role of what it terms "more complex approaches", namely physical modelling and computational modelling. The section on physical modelling includes wind tunnels, scale models in the field and full scale urban dispersion experiments. The section on computational modelling covers solutions of the diffusion equation and flow field modelling such as $k-\epsilon$ or CFD modelling.

The report includes a review of recent experimental work on dispersion following emissions above building arrays, through porous obstacles and within groups of buildings. It then discusses the implications of recent work for modelling, with the emphasis on plumes where σ_z is greater than the general building height. This identifies problems with enhanced spread along the wind direction as a result of material "held up" in the wakes of buildings.

Finally the report reviews the limitations of current understanding and the prospects and limitations of future modelling work.

6.4 Scope of R2c

The report distinguishes three aspects of the problem, namely dispersion at the building/street scale, the neighbourhood scale and the meso-scale; these regions correspond to the three regimes considered in R322b. It discusses models for the airflow and dispersion for each of these scales. There is also a

brief section on dispersion in enclosed spaces, such as a courtyard surrounded by tall buildings.

The report distinguishes between fully computational models (FCM) and fast approximate models (FAM) for both the air flow and the dispersion. FCM require substantial amounts of computer time, and are essentially research models. FAM are based on simplifications of the appropriate equations or other parameterisations of the dispersion process.

The section on airflow at the building/street scale distinguishes several regions depending on the typical sizes and spacings of the buildings, and gives criteria for identifying the different regions.

The section on dispersion concentrates on FAMs. It gives detailed equations for dispersion very near the source and for the building/street scale. Dispersion on the larger scales is described mainly by references to appropriate published papers and a small number of equations. The emphasis, particularly for the shorter scales, is on releases from sources below the height of the buildings, though models for the dispersion of material which has spread above the height of the buildings are described.

The report gives a review of field experiments on dispersion in real cities and artificial structures and on laboratory experiments in modelled realistic cities or artificial structures.

The report notes that the meteorological data currently available are not sufficient to support the use of urban models for assessments of dispersion from an actual release. It suggests that information on wind direction could perhaps be obtained by examining CCTV pictures.

6.5 Areas of overlap

R157c, R302b and R322b all review aspects of dispersion near a single building. R302b and R322b both reference R157c, but R322b does not reference R302b.

R157c considers five positions of the source relative to the building, but does not recommend models for all situations. There are no recommended models for sources in the main wake, or for most aspects of sources upwind or to the side of the building. R322b reviews dispersion modelling for a single building, giving models for more situations than R157c. In this respect R322b should be regarded as updating R157c, rather than contradicting it. R302b gives further information, particularly for the concentration close to a source in the re-circulating wake. R322b concentrates on when plumes impinge on buildings, rather than the concentrations further downwind.

R322c and R2c both cover dispersion in urban areas, though the emphasis is rather different. R322c tends towards dispersion from sources above the building height while R2c concentrates on sources below roof level. Both include discussions and descriptions of air flow and dispersion in urban areas; these can

be considered as complementing each other. R322c gives more detailed equations than R2c for dispersion from a single building, while R2c gives a more detailed treatment of dispersion from a point source for different building sizes and spaces.

The reports complement, rather than contradict, each other.

6.6 Gaps in the areas covered by the models

None of the reports include detailed guidance on dispersion from explosions. R2c presents information on the initial plume size but does not relate this to the force of the explosion. The section in R2c on dispersion in courtyards mentions partially covered areas such as railway stations, but does not give much information on this; it could not be considered as a report on dispersion within buildings.

6.7 Recommendations for future work

The recommendations given in the reports can be summarised as follows.

R157c did not give recommendations for further work.

R302b points out that there is a large amount of published information on wind tunnel studies, but that they tend to concentrate on simple rectangular objects. It suggests that further studies for buildings which are wide and squat or tall and slender, or for groups of buildings, walls, lattice structures would be useful. It also points out that the simple extensions to the Gaussian plume model identified in the report could be incorporated into computer programs for modelling dispersion.

R322b concludes with an extensive discussion of the limitations of current understanding and the prospects and limitations of modelling. This lists research topics for 12 general modelling areas. Unfortunately, this section is too long to be easily summarised here.

There are a number of statements throughout R2c pointing to areas where models might be improved, including extending current street canyon or traffic models to consider the effects of short releases, or where comparisons would be beneficial. The conclusions and recommendations section ends by suggesting that more data on wind direction in urban locations are needed, methods for using measured concentrations in urban areas to locate a source should be developed and that further work is needed to validate FAMs against predictions of FCMs.

7 REVIEW OF REPORTS RELATING TO EFFECTS OF COMPLEX TERRAIN

Aspects of dispersion in complex terrain are considered in three reports. HB9 discusses ways of updating the simple Gaussian dispersion model, with extensive discussions on dispersion in complex terrain. R302b discusses models for calculating concentration when plumes impinge on the ground. Complex terrain will also be considered in R1b, which is not included here as it is not currently available.

7.1 Scope of HB9

This report gives separate discussions on airflow and dispersion in complex terrain. It relates to changes in elevation and to changes in surface roughness.

The report gives a description of why terrain affects dispersion, concentrating on the effects on the maximum concentration at ground level and on the distance from the source to the maximum concentration at ground level. It identifies the features of air flow which can affect dispersion, namely the change in the height of the streamlines, streamline convergence and divergence, changes in wind speed and changes in the turbulence levels along the streamlines. It describes a range of models for calculating the wind field in complex terrain, including deflection/impingement models, interpolation models and predictive models (i.e. ones based on differential equations including perturbation methods for their solution) and discusses the strengths and weaknesses of the various models.

The report describes a range of possible dispersion models for complex terrain, covering simple Gaussian plume models which allow only for the deflection and/or impingement of the plume, Gaussian plume models which include specific consideration of the effects of complex terrain, and research grade models. The report comments on the validity of the different types of models in terms of the assumptions that they make.

7.2 Scope of R302b

The aim of this study was to examine models for the concentration when plumes impinge on higher ground in complex terrain. In order to do this, it examined a number of features of flow and dispersion in complex terrain. The report describes flow around hills, discussing the deflection of streamlines and the concept of a dividing streamline height, and identifies mechanisms that can bring plumes to ground level. It considers the conditions for hills to behave like two or three dimensional obstacles.

The report describes the derivation of the diffusion equation, and how its assumptions relate to flow over hills. It considers several corrections, of different

degrees of complexity, to extend simple models for application to flow over hills and discusses where the extensions are applicable. It then describes models specifically designed for dispersion over hills. The report includes comments on the likely accuracy of some models for calculating dispersion over hills, and restrictions on their applicability. The report indicates situations where model predictions might be particularly sensitive to atmospheric conditions.

There are several areas where the report considers the use of CFD models, identifying some problems in the models and possible pitfalls in their use.

7.3 Areas of overlap

There is considerable overlap between HB9 and R302b, as both discuss modelling of airflow and dispersion in complex terrain. Both describe models for particular applications with equations for some idealised situations, and make comments on the applicability of different techniques. The description in HB9 gives more detail than that in R302a. The reports complement, rather than contradict, each other. There are differences in emphasis, with HB9 giving more attention to analytical methods while R302b tends towards the benefits of CFD methods, although it points out that there are problems with them. This could reflect the change in computer power over the period between the reports.

7.4 Gaps in the areas covered by the models

The reports HB9 and R302b provide an extensive discussion of the general features of airflow and dispersion in complex terrain, and the strengths and weaknesses of various modelling approaches or specific models. There are no obvious gaps in such a general discussion. However, they do not give guidance on how to apply models in a specific situation (e.g. the choice of model for a specific situation, the balance between grid size and the area around the site which can be considered, the need to consider upwind flow in a particular calculation).

7.5 Recommendations for future work

The main recommendation of HB9 is that models based on the improvements to the simple assumptions used in R91 could be developed, suggesting that simple Gaussian modelling for dispersion would be improved by using better models for the airflow and turbulence levels in the boundary layer. It specifically recommends the perturbation approach (adopted in FLOWSTAR) for modelling airflow and dispersion on modest computer systems, but points out that there will need to be further testing and developments of existing codes before they can be relied on to cover most situations of importance.

R302b suggests that further experiments for idealised symmetrical hills are of limited value because of the problems in applying the results to more general situations. It suggests that studies in specific sites for which releases might occur would be valuable, particularly as the number of nuclear sites is limited. The report suggests that a scientific assessment of the assumptions made in a model is vital. It notes that the EPA model CTDMPLUS is a modified Gaussian model for application when plumes impinge on elevated terrain, and suggests that the assumptions behind this model should be examined carefully before it is used in the UK, pointing out that there are some situations, for example in reverse flows downwind of a hill, where this model would be completely invalid.

8 REVIEW OF REPORTS RELATING TO COASTAL EFFECTS

Coastal effects are considered in two reports, one from ADMWG (R157a) and one from ADMLC (W2a).

8.1 Scope of R157a

R157a describes models for dispersion during a sea-breeze, conditions when a sea-breeze is likely to occur and the effects of the changes in roughness length and stability at the coast.

The report gives little guidance on dispersion when the wind is towards the water. It recommends using the normal Gaussian model for dispersion between the source and the coast, but gives no information on the calculation of concentration while the plume is flowing over water.

The report concentrates on conditions where the wind is blowing towards the land. If the water is warmer than the land, the report suggests that coastal effects will be very small and that the normal model should be used. If the land is warmer than the water, then coastal effects are important. The report recommends a model for use close to the coast, whether or not a sea-breeze is blowing. This is essentially the normal Gaussian model but uses the depth of the thermal internal boundary layer (TIBL) in place of the depth of the mixing layer. The report gives three alternative formulae for the depth of the TIBL. It also gives methods of calculating the values of σ_y and σ_z for sources in either the stable air originating over the water, or the more unstable air over the land.

The report suggests that, for a site with large buildings near the coast, it would be better to ignore the coastal effects and simply use the buildings model.

The report also considers the calculation of long term average concentrations.

The report also gives a model for concentration when a sea-breeze is blowing; this covers the velocity of the sea-breeze front, the depth of the sea-breeze and the concentration in the region affected by the sea-breeze.

8.2 Scope of W2a

W2a concentrates on sea-breeze models. It includes a literature review covering the structure and general effects of a sea-breeze, fumigation effects and circulation/recycling, and recent advances in understanding sea-breezes. It describes dispersion in a sea-breeze, when sea-breezes might occur and their general prevalence, and their penetration inland. It includes sample calculations using different models and an assessment of the strengths of current modelling approaches, concentrating on simple models and CFD techniques. It includes a review of previous work on sea breezes, noting that a large number of studies have used CFD models. It points out that CFD is able to model all of the effects of sea breezes identified in the report, and suggests that results from simple models developed in this area should be compared with either field studies or results of CFD calculations. R157a is considered throughout the review. The ADMS model is also considered.

8.3 Areas of overlap between R157a and W2a

W2a extensively references R157a. Therefore, if there are any areas of disagreement, W2a should be considered as updating R157a.

8.4 Gaps in the areas covered by the models

W2a relates only to sea-breezes and so dispersion when the wind is blowing towards the land; R157a gives only limited information on dispersion when the wind is blowing towards the coast. Neither report considers plume growth over water, or concentrations over land after a plume has passed over water. The reports therefore do not consider dispersion over small bodies of water such as lakes or estuaries.

8.5 Recommendations for future work

R157a does not make any specific recommendations for future work.

W2a notes that, because of the complexity of the situations being modelled, it is unlikely that simple Gaussian models could be modified to take account of all relevant effects. It notes that CFD is much more suited to the problem, but suggests that its applications are likely to be site specific. It identifies a number of possible improvements to simple modelling as having potential for investigation.

9 REVIEW OF REPORTS RELATING TO THE USE OF METEOROLOGICAL DATA

Items relating to the use of meteorological data are covered in five reports from ADMLC. R316a considered the extent to which data from one site could be used for other sites. W2b considered the calculation of long term averages and whether this is best done using hourly sequential data or statistical data. Three reports (W3a, R2a and R2d) looked at the most appropriate source of data and some aspects of the use of data from numerical weather prediction (NWP) models.

9.1 Scope of R316a

This report describes two studies to compare concentrations calculated using meteorological data from different sites, for two releases (a buoyant release from a tall stack, representing a power station plume, and a weakly buoyant release from a short stack, representing a factory release).

The first study compared predicted concentrations using meteorological data for 17 sites in southern England; the sites were between 40 and 310 km apart. It compared the mean and the 99th percentile of the hourly concentration distribution for five cases (all conditions over a five year period together with day and night in both summer and winter). The concentrations were calculated on a grid around the site; the maximum values for each site were then compared.

Results are presented relative to the predicted concentration at one of the sites. The annual average concentrations range from 0.82 to 1.27 for the tall stack and 0.94 to 1.13 for the short stack. The ranges for the 99th percentile are smaller than this. There is no indication of a trend in concentration ratios with distance between the sites; however there are correlations between the mean concentration and the mean wind speed for the sites. The report suggests that meteorological data from other sites can be used for dispersion studies, and that the main requirement is that the annual mean wind speeds at the two sites should be similar. The report notes that other studies do not support this view, in particular a Met Office study by Davies and Thomson suggested that weather data should be taken from within 70 km for a typical factory source and within 20 km for a typical power station source.

The second study considered whether information on wind speed and direction from one site could be combined with other data from a neighbouring site. It calculated concentrations for a three month period in summer for three sets of meteorological data:

- a all data taken from Heathrow,
- b wind data from Gatwick with other data from Heathrow

c wind data from Stansted with other data from Heathrow. This showed that the combined data sets gave concentration predictions that did not compare well with those obtained using only the Heathrow data – the average concentrations predicted using combined data were between 0.76 and 0.95 of those predicted using data from only one site.

9.2 Scope of W2b

This report considers the differences between using statistical or sequential meteorological data when calculating long term average concentrations, or percentiles of the hourly concentration distribution. The calculations were undertaken using ADMS version 3, and some of the conclusions may reflect specific features of ADMS. Concentrations were calculated using data for three separate years.

The first part of the study considered concentrations from three sources, namely those used in R316a and a buoyant source from a short stack. This showed good agreement between the values calculated using statistical or sequential data; the results mostly differed by less than 20% with the worst discrepancy being almost 50% for one percentile and one year. Some of the comparisons were repeated using ADMS version 2.2; this showed larger differences, in one case with almost a factor of 2 between the predicted concentrations.

The study was extended to consider a range of release heights from 10 to 100 m for two release temperatures, 15° C and 40° C. The concentrations predicted using sequential or statistical data for the 40° C release differed by less than about 20%. The two predictions for the 15° C release however differed by up to about 70%.

Further studies were undertaken to identify the cause of this difference. These showed that changes to the binning scheme used in preparing the statistical data set had little effect on the results of the comparison. The differences are caused by a specific feature of ADMS version 3. If using sequential data, the code considers both the effluent and the ambient temperature for each hour – the effluent temperature of 15° C means that in some cases the plume is slightly buoyant and in others it is below ambient temperature. If using statistical data, the code assumes that the ambient temperature is 15° C, and therefore that the released plume is always at ambient temperature.

This study concluded that the use of statistical data is adequate, and that there is no evidence that the current binning scheme is inadequate, other than for one situation. The comments about modelling the release at 15° C may be specific to ADMS rather than to other dispersion programs.

9.3 Scope of W3a

W3a presents three studies, aimed to investigate whether meteorological data sets have a "shelf life", whether NWP data can be used in place of observational data and the capabilities of the Site Specific Model (a version of the NWP model used for detailed predictions at a specific location) in providing data in particular regions of the UK.

In the first part of the study, the "shelf life" of data sets was investigated by calculating maximum values of long term averages and 99.9th percentiles of the hourly concentration distribution for a buoyant release from a short stack for 12 years between 1950 and 1999, using meteorological data for Heathrow and for Waddington in Lincolnshire. The Heathrow results showed that the predicted peak annual average concentration generally decreased over time, with concentrations in the 1990's being around half the values from the 1950's. There is little variation in the predicted 99.9th percentile over the same period. However, for Waddington, the predicted annual average concentration increased slightly over time, again with little variation in the 99.9th percentile. The change in concentration predicted using the Heathrow data was considered to be an effect of the change in urbanisation around Heathrow over the period considered. The study concluded that some data sets do have a "shelf life", which may reflect changes in urbanisation rather than other changes in climatology.

The second part of the study considered the use of data from NWP output. This was used to calculate ADMS input data for one year, for two sites. Predicted concentrations (mean, 99th and 99.9th percentiles) were calculated for three sources at each site using the "NWP" data and observed data. This comparison used the minimum amount of data with which ADMS can be run. Mean values of various meteorological quantities (such as wind speed and cloud cover) were compared, showing reasonable agreement between values from the two types of data. The dispersion patterns predicted for the two types of data were found to be generally similar; the peak values for each of the quantities considered differed by between -28 and +31% for Ringway and between -31 and +6% for Waddington (a negative value means that the concentration predicted using NWP data is less than that predicted using observed data). On this basis, it was concluded that NWP data provide a reasonable alternative to observed data and would be appropriate for a site where there are no suitable observations. A further comparison was undertaken in which additional quantities, such as the depth of the mixing layer, were extracted from the NWP results, rather than allowing ADMS to calculate them. This data set gave a poorer representation of the results using observed data than was obtained from the comparison with the original ADMS data set using fewer input parameters. The report on this section ends with the somewhat ambiguous conclusion "... the results here show that while NWP data is a good viable alternative, including secondary variables should be seriously considered".

There is a section in R2b which discusses the use of NWP data to generate input data for dispersion models. This shows that data on the wind field derived from NWP compared well with measurements made at a site that was not used in the NWP process. Frequency distributions of heat flux, derived from NWP and the ADMS pre-processor, also showed good agreement.

The final part of the study considered the use of data from the Site Specific Model (SSM), for the Ringway site. Data were only available for a two month period. The average values of quantities such as wind speed, obtained from observations, the NWP and SSM models were compared. The SSM results were closer to the observed values than were those from the NWP model. However, both models "showed noticeable differences from the observations" for wind direction. Concentrations for the three sources predicted using observed, NWP or SSM data were compared. The differences between predictions using SSM and observed data were greater than those between predictions using NWP and observed data.

9.4 Scope of R2a

This report describes the ways in which observations of meteorological parameters are made and processed, and outlines the NWP and SSM process. It describes how data for dispersion models can be extracted from the results of the NWP or SSM, and the processing involved in deriving statistical data sets. It describes the data archives that are available, both for observed values and for values obtained from the various forecasting processes. It also describes the information that can be obtained for use in real time dispersion calculations.

The report also considers the representativity of meteorological data, discussing the spacing between observing stations that is required (mainly from the stand-point of weather forecasting). This discusses the conditions under which data from one site may be used at other sites, but does not compare concentrations calculated using data from different stations. It references R316a, W3a and R2d, together with other reports which have addressed similar questions.

9.5 Scope of R2d

This study was undertaken because of possible weaknesses in W3a, which used a grid spacing which may be too large to capture full details of the maximum concentrations.

W3a concluded that the change in urbanisation around Heathrow over the years may have explained some of the changes in predicted concentration. Changes in urbanisation are likely to affect mainly the roughness length, and so R2d includes a discussion on how roughness length changes might affect dispersion, and the most appropriate roughness length to adopt for calculations using Heathrow data.

Calculations of the annual average and high percentiles of the hourly concentration distribution were made for the same 12 years considered in W3a, for three releases (the buoyant release from a 10 m stack considered in W3a, a non-buoyant release from a 40 m stack and a buoyant release from a 150 m stack). These calculations assumed a roughness length for all years of 0.2 m. The predicted mean concentration for the buoyant releases decreases by about 50% over the period considered, with the changes showing a trend with time. The predicted mean concentration for the non-buoyant release tends to increase with time. The predicted percentiles of the distribution increase, but by different amounts for the three releases considered, with the values for the release from the 10 m stack changing by less than 10%. There is some evidence for a trend with time for the other releases.

Further calculations were carried out for the three releases, using the 1999 meteorological data but with a range of roughness lengths. The predicted percentiles for the buoyant releases increased with increasing roughness length; however, for the non-buoyant release the predicted percentiles decreased with increasing roughness length. The predicted annual average concentration also increased by factors of 1.9, 3.7 and 5.3 for the three releases as roughness length increased from 0.01 to 1 m. The earlier part of the study considered that the decrease in mean concentration with time might reflect the increase in roughness length over time, in disagreement with the finding here which shows that increasing roughness length increases the mean concentration. The study considered what the most appropriate roughness length might be for some years at Heathrow, and repeated some of the original calculations using the selected roughness length. This showed that the predicted mean concentrations decreased with time, but the decrease was smaller than that obtained in the first set of calculations. The report concludes that there is still evidence that the predicted concentrations vary systematically with time, and therefore supports the conclusion of W3a that meteorological data has a "shelf life".

Finally, the study compared predictions made using "spot data" (values measured over a period of a few minutes each hour) or hourly average data. This showed that the predicted higher percentiles of the distribution are generally greater for spot data than for average data, with the largest difference being an increase of 77%. The annual averages predicted using spot data are up to about 20% greater than those obtained using hourly average data.

9.6 Areas of overlap

These reports are for closely related topics, with similar areas covered in two or more of the reports. However, the reports generally refer to each other, and there do not seem to be any instances where one report contradicts something said in a different report. The reports make comments on the adequacy of particular things, such as the use of old meteorological data or data from other sites. There are no "official" numerical criteria which can form the basis of judgements on the adequacy of data sets in these situations and therefore the

choice of criterion for adequacy must depend on the feelings of the particular author. There is some inconsistency in what is deemed adequate in the different reports.

9.7 Gaps in the areas covered by the studies

There are no obvious gaps in the areas covered by the reports. However, they draw conclusions which are based on analyses of only a few, or even on only one, situation. There may be some benefit in repeating the studies for other situations to investigate whether the general conclusions drawn are robust. Some examples of this are given below.

R316a suggests that the most important point when using data from a "distant" met station is to find locations with similar mean wind speeds. This contradicts other Met Office work (Davies and Thomson (1996) not carried out for ADMLC) which suggests that data should be taken from a station within a few tens of kms of the point for which dispersion calculations are required. Reasons for this difference could be investigated further.

W3a concludes that met data has a "shelf life" as predicted concentrations differ over a period of years. This is supported by R2d. W3a shows that the predicted long term concentration decreases over time at Heathrow, but increases slightly at Waddington. W3a shows that the change in the predicted high percentiles of the hourly concentration distribution is much less than the change in the predicted long term average concentration. R2d supports these general findings for Heathrow. In all cases, there are large variations around the general increase. It is not clear if this represents an actual trend for concentrations to change systematically with time (with a large variation between years on top of this change) or to what extent the change is dominated by the effects of one or two particular years. For example, the following figure (taken from W3a) shows the predicted long term average concentration at Heathrow.

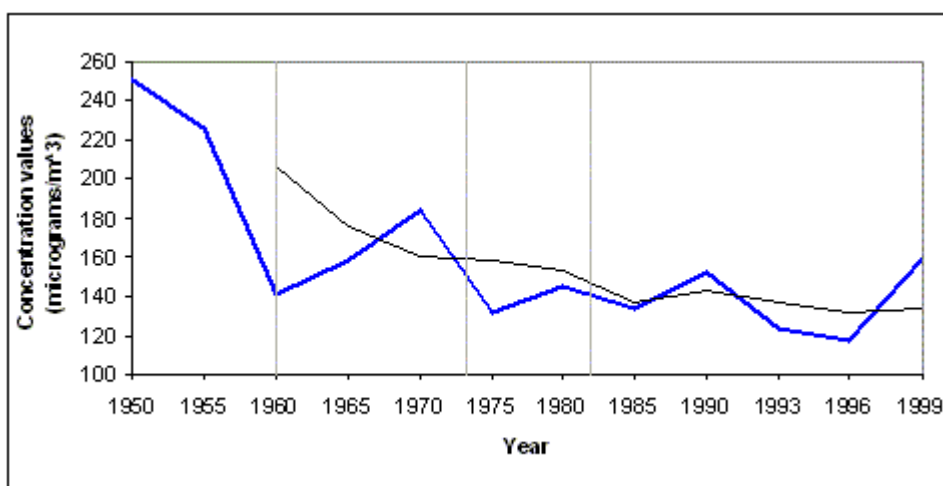


Figure 1 Graph to show how the spatial maximum of the long term concentration value has changed from 1950 (blue line) to 1999, and the 10 year rolling average (black line). The grey lines indicate the years when the position of the anemometer was changed

Examination of this graph by eye suggests that the systematic variation with time would be much less convincing if the results for 1950 and 1955 were omitted. Both W3a and R2d show other graphs where similar comments could be made.

R2d and, to a lesser extent, W3a demonstrate that some quantities vary systematically with time, while others do not. Therefore, whether met data has a "shelf life" would seem to depend on the quantities to be calculated. It is also noted that the differences quoted are in general less than a factor of 2, and so are likely to be smaller than the general uncertainty in dispersion modelling.

R2d considers the effects on predicted concentrations of changes in roughness length; this can have a large impact on the predicted concentrations, with mean concentrations for some release conditions changing by a factor of 5 as the roughness length is altered from 0.01 to 1 m. W3a suggests that part of the difference between concentrations predicted using observed data or NWP data for Ringway may be an effect of roughness length changes within the area covered by a single grid square in the NWP process. These points suggest that there may be a need to look more carefully at the choice of roughness length, as this may differ between the release point and the met station.

9.8 Recommendations for further work

R316a suggests further work on possible ways of improving the estimates of wind speed at locations away from a measuring station, and that physical models might be used for this. It also recommends a comparison of dispersion estimates using met data from different periods, which was undertaken in W2b and R2d.

W2b notes the problems in using statistical and sequential data in modelling plume rise, particularly in ADMS. It suggests that this could be investigated further, noting that it might be a study of specific features of ADMS rather than of met data. It also notes that the highest concentrations are associated with wind speeds in the range from 1 to 2 m s⁻¹, and suggests an investigation of how predictions could change for different methods of treating dispersion in calm conditions.

W3a includes a number of comments on things that should be considered in selecting the most appropriate data to use in a particular application; it identifies the use of SSM data as an area for further study.

R2a suggests that it would be useful to investigate whether alternative sources of met data are as good as, or better than, those currently available. It specifically suggests that it would be useful to investigate how sensitive dispersion calculations are to the use of cloud amounts from manual observations or derived from measurements using laser cloud base recorders (LCBR). Developing a better understanding of the NWP data products obtained from the model would also be very useful. A comparison of appropriate met parameters obtained from NWP model output with those recorded at a site (particularly if measurements from that site are not normally input to the model) could help understand how big the discrepancies are, and whether they are significant in dispersion modelling terms.

9.8.1 Comment from the authors of this review

Some of the discussion on the use of old met data is not convincing as the trend over time is not much larger than variations between concentrations calculated for different years or for different assumptions that might be made. This suggests that a more detailed review of this work, including investigations for other sites, would be justified.

10 REVIEW OF REPORTS RELATING TO RAIN AND DATA ASSIMILATION

Rain and assimilation are considered in two reports, one from ADMWG (R198) and one from ADMLC (R1a).

10.1 Scope of R198

R198 extends the scope of the second ADMWG report, to consider the problems involved in calculating wet deposition from a short release. It defines the situations for which the Gaussian plume model (used in R122) is appropriate, and illustrates other simple models applicable to short releases in idealised or more realistic conditions.

R198 considers the deposition of material travelling entirely in rain and the deposition of material first encountering rain at some distance from the source, and gives guidance on suitable methods for modelling deposition under these conditions. The simple Gaussian model can be extended to calculate deposition when the dispersing material first encounters rain. The report considers the implications of two simple, and possibly extreme, descriptions of the effects of material encountering rain for the first time some distance from the source. The first uses a plume model and assumes that all material encounters a change in conditions at the same point. The second uses a puff model and assumes that all material encounters a change in conditions at the same time.

The report summarises the difficulties of modelling the variability of rainfall, and airflow within storms. Reversibility of the washout of gases is considered (i.e. rain becomes contaminated as it falls through the plume but the dissolved material desorbs as the rain falls through a region of low concentration below the plume).

R198 gives guidance on the variation of washout coefficient with rainfall rate. The report is unable to recommend a value for the washout coefficient for particulates, however, it does indicate a range of likely values.

The report considers values for washout coefficients of gases. It suggests that wet deposition be calculated using a washout coefficient derived from the small amount of experimental information available or from washout ratios. However, the report recommends that in view of the considerable uncertainty in the value of the washout coefficient for gases, a value suggested for particulate material should be used for inorganic iodine.

R198 highlights the lack of information concerning the washout of organic iodine. Indeed the data available on gases other than inorganic iodine discharged by the nuclear industry is very sparse. Therefore, the report suggests that the value of washout coefficient given for particulate material be used for other gases.

Much of the report assumes a washout coefficient appropriate to rain falling at a specified constant rate. However the report considers the variability of the rainfall rate within the UK. Furthermore the report considers modelling rainout separately to washout as a single step process.

Finally the report considers the accuracy of the wet deposition models and attempts to put the uncertainties highlighted within the report into context. The report suggests methods for defining when, where and how much it rains in the vicinity of the release (assuming that reliable and accurate information on the rainfall distribution during and after the release is unavailable).

10.2 Scope of R1a

R1a considers the problems associated with assessing the consequences of an accidental release of radioactivity to the environment, concerning the interaction of the dispersing material with precipitation.

The report investigates the availability of rainfall data, and the likely spatial and temporal variation in rainfall in different conditions (frontal, showers, etc). The report considers ways of obtaining estimates of deposition in the period immediately after an accidental release, and in particular estimating deposition at places where it has not yet been measured. The report advocates supplementing the use of the measurements of radioactive contaminants in environmental samples with information on other quantities that are related to where the enhanced deposition is likely to occur and for which data are readily available (data assimilation). Procedures for interpreting monitoring data after an accidental release have been developed by considering the circumstances arising under wet conditions.

The effect of rain on dispersing plumes, considering the relative depositions in wet and dry conditions is discussed. The report considers the differences in interception, and in particular the short-term effects on plant surface contamination, in dry and wet conditions. The report also considers rainfall patterns typical of the UK and the way in which rainfall rates vary in time and space. The report identifies radar as a vital information source for determining rainfall rate at points away from meteorological measuring stations.

R1a considers the assimilation of rainfall information as an aid in making improved assessments of the amount of deposited radioactive material. The report considers both simple and advanced methods for estimating the rainfall rate at points where it cannot be measured directly. The simpler methods include Thiessen polygons and inverse distance weighted interpolation. The more complex methods generally use one of a number of geostatistical techniques, for example the Bayesian method. However other approaches such as basis function expansions and neural networks are also used. The report includes consideration of those processes deemed important in modifying a monitoring programme developed primarily for dry conditions, for use when rainfall has occurred after an accident. Within the comparison of methods for estimating rainfall, the procedure of weighting a model with the aid of linear estimation, known as kriging, is extensively used throughout the report. Subsequently a number of approaches are recommended for calculating the depletion of the plume due to rainfall. The report also considers the temporal effects of rainfall i.e. the importance of knowing when rain starts and ends in a particular area and when the dispersing plume passes over the area.

The report discusses the locations from which environmental samples are taken, and how these might be applied in an accident situation, notably preferential and optimal sampling. The report considers the modes of variation in monitoring programmes for accidents in wet and dry conditions, including the consideration of uniform and non-uniform rainfall. The method of obtaining suitable information for use in data assimilation procedures is also considered.

10.3 Areas of overlap between R198 and R1a

Both R198 and R1a base their recommendations on the same simple model for calculating the fraction of material remaining in the plume as a function of time. Furthermore both reports relax the assumption that rain falls at a constant rate. Both reports consider the variability of the rainfall rate within the UK.

R1a extensively references R198. Therefore, if there are any areas of disagreement, R1a should be considered as updating R198.

10.4 Gaps in the areas covered by the models

Neither report appears to consider the possibility of enhanced deposition during mist or fog, or in low-lying cloud on hills, frequently termed 'occult wet deposition'.

R1a recognises a number of areas where further investigations into the assimilation of rainfall data would be of use. Notably the suggested processes for assimilating the effect of enhanced radioactive deposition due to rainfall are not demonstrated due to a lack of data. There also exist some discontinuities between the boundary areas of rain and no rain.

10.5 Recommendations for future work

R198 does not make specific recommendations for future work. R1a suggests that work to compare results of data assimilation techniques against deposition measurements following a short release in wet conditions would be useful. It suggests that the data obtained in the UK after the Chernobyl accident together with radar data for the appropriate period might be used for this.

11 REVIEW OF UNCERTAINTY IN DISPERSION MODEL ESTIMATES

The uncertainties in dispersion estimates obtained from models recommended by ADMWG are considered in R199. Some of the papers in R1c also consider the uncertainty of dispersion modelling. Report R302b considers the performance of models used to calculate air concentrations when plumes impinge on buildings or the ground. R322b includes a discussion of model evaluation and uncertainty in models that predict dispersion in the vicinity of buildings. The uncertainty arising from the measurements of meteorological data and the derivation of the value for parameters representing atmospheric stability is discussed in R2b.

11.1 Scope of R199

The report identifies a number of sources of uncertainty, such as the random nature of atmospheric dispersion, the idealisations inherent in modelling and the choice of values for the many parameters involved. The report puts these uncertainties into context and comments on the reliability of models for use in practical situations in the UK.

To assess uncertainties associated with the idealisation inherent in modelling, the conditions where the Gaussian plume model (R91) and the deposition model (R122) can be applied are discussed. The uncertainty in parameter values depends on the type of application. The report concentrates on the range of values for parameters where realistic estimates of the mean concentration from a number of short releases or the average concentration from a continuous release are sought. The uncertainties associated with models for plume rise (R157b), building effects (R157c) and coastal effects (R157a) are also considered.

The report also summarises a number of experimental studies that have been carried out to validate dispersion models similar to those recommended by ADMWG. The level of agreement between predicted and observed values depends on the conditions and the type of application. For example, a ratio of between 0.5 and 2 is expected for long-term average concentrations at a specific point, over flat terrain and within 10 km of the release point. Experimental studies dealing with plume rise and the virtual source model for building effects are also included.

11.2 Scope of R302b

This report reviews models suitable for predicting the dispersion of plumes that impinge on buildings or the ground. A range of models is considered which includes the Gaussian plume model and k - ϵ turbulence model. Model uncertainty is not discussed in detail but the performance of the models under various conditions is considered and in many cases the magnitude and sign of any inherent errors are identified.

11.3 Scope of R322b

This report reviews flow and dispersion in the vicinity of groups of buildings with Section 4.4 addressing the issues of model evaluation and uncertainty. The requirements for successful model evaluation are identified and an example is given of typical uncertainties associated with computational modelling of a dense gas discharged from an L shaped building. Overall, solutions were found to be very sensitive to the modelling decisions employed by the modellers and consequently a need for 'codes of best practice' was identified. The report also includes tables that summarise the uncertainty, in qualitative terms, associated

with the application of various modelling techniques to different dispersion problems.

11.4 Scope of R1c

ADMLC held a workshop in 2000 to discuss the needs of atmospheric dispersion models used in a regulatory context and the reliability of existing models for those purposes. The presentations are published in R1c. Regulatory requirements include the need for input to nuclear site safety case assessments, estimates of the impact of radioactivity on food and COMAH safety reports. The reliability of dispersion models is addressed in several presentations that cover uncertainty, variability, validation and evaluation. In addition recent developments in research are discussed.

11.5 Scope of R2b

This report considers the uncertainty in deriving dispersion parameters from meteorological data. Measurement techniques and instrument accuracies associated with meteorological data are reviewed. The treatment of meteorological data in ADMS and AERMOD is considered and alternative meteorological data sources are discussed. A probabilistic assessment of uncertainty associated with meteorological inputs to ADMS is carried out. The conditions and parameters that contribute most to uncertainty in model predictions are identified.

11.6 Areas of overlap

The report R2b overlaps considerably with the issues discussed in the workshop presentation 'Uncertainties in meteorological pre-processing for dispersion models' published in R1c. However, in R2b these uncertainties are propagated through the 'new generation' atmospheric dispersion model ADMS to determine their impact on model predictions.

Two presentations given during the ADMLC workshop (R1c) expand on topics considered in R199. The performance of models for predicting dispersion affected by buildings and a study of concentration fluctuations arising from the inherent variability in the field of turbulence were discussed.

In general the different reports complement, rather than contradict, each other.

ADMLC has funded work in related areas. In 2000-2001 speakers were invited to give presentations on methods for undertaking uncertainty analyses. The overheads from these presentations are published in NRPB-W3. These relate to the techniques for undertaking uncertainty analyses, rather than the uncertainty on predictions of atmospheric dispersion models.

11.7 Gaps in the areas covered by uncertainty studies

At the time of publication of R199 there was insufficient information available to quantify the uncertainty associated with plume rise. However, this subject is likely to be addressed by ADMLC in the near future. More generally, the data available for validating the overall performance of dispersion models are limited and those experiments that have been carried out have often been used in the model development.

11.8 Recommendations for future work

R199, R302b and R3222b do not make specific recommendations for future work relating to uncertainty issues.

Two specific recommendations for future work are made in the presentations included in R1c. The first highlights the sensitivity of model predictions to the methods used to process meteorological data to provide estimates of boundary layer parameters and suggests that further development is required. The second suggests that it would be useful to establish a collection of data sets for dispersion in the vicinity of buildings that are judged to be of good quality and against which models such as ADMS-BUILD and AERMOD-PRIME could be assessed.

R2b included an uncertainty analysis for a particular source type, and suggests that further studies for a range of source types would be useful. It also suggests a more detailed consideration of the uncertainty in roughness length, including an intercomparison of methods for allowing for spatial variation in that quantity. It also suggests that further investigations into the use of data from NWP models, particularly including other than the minimum quantities required by the dispersion model, would be useful. It suggests that a comparison of the output of meteorological pre-processors with measured vertical gradients of wind speed, wind direction and temperature, and with turbulence measurements, would help address the uncertainty found between modelling systems.

12 REVIEW OF REPORTS RELATING TO THE CAPABILITIES OF CFD MODELS

ADMLC funded one project, reported in R292b, to review the capabilities of computational fluid dynamics (CFD) modelling in general. However, other reports consider the use of CFD modelling in particular applications, and are also considered here.

12.1 Scope of R292b

This report discusses the use of CFD for modelling dispersion in the near field. It discusses some problems with CFD, pointing out that, to obtain reliable results, users must be familiar with CFD (and the specific CFD program used) and with atmospheric dispersion modelling. The report identifies a number of studies where predictions of CFD models have been compared with results obtained in wind tunnel studies; it is not possible to draw general conclusions on the accuracy of CFD modelling from these studies.

The report describes a study where different organisations carried out calculations for the same situation, and points out that different users (or different CFD codes) generally produce different results for the same problem. Changes in the predicted values when users tried to improve their modelling tend to be smaller than the differences between predictions obtained by different users.

The report identifies a number of problems with the $k - \epsilon$ turbulence model, suggesting that Large Eddy Simulation (LES) may be a better approach in some situations but that it requires considerably more computer time. The report also points out that there are no very good methods of including wet and dry deposition in CFD models.

The report identifies the design and resolution of the grid as an area leading to uncertainty in results or differences between modellers, pointing out that results generally depend on the grid resolution used. There are several comments referring to the number of grid points considered and the computing power required. Increases in computer power since the report was written in 1996 may mean that some of these comments are no longer appropriate.

The report includes a section discussing the situations for which analytical models, CFD applications or wind tunnel modelling are more appropriate. This considers the capability of the techniques to represent real cases (including representing realistic geometry for buildings and complex terrain, plume buoyancy and momentum effects and stable atmospheres), the effort involved in undertaking the work, the likely accuracy and uncertainty arising from the way in which the technique is used.

12.2 Comments on CFD in other reports

R292c presents a review of models for the rise of a buoyant plume from a building wake, and considers the applicability of CFD for this application. It refers to a comparison of CFD and wind tunnel models, also considered in R292b, and notes that the accuracy of CFD calculations is best for passive emissions and tend to degrade with increasing plume buoyancy. This report also lists deficiencies in the $k - \epsilon$ turbulence model. It suggests that CFD methods did not then provide practical models (the report was written in 1996), but that they will be increasingly used and that their capabilities should be assessed.

R302b considers the application of CFD models to dispersion in complex terrain, identifying some problems and possible pitfalls for their use.

R322b presents a review of modelling for sites with many buildings. It makes a number of comments on when CFD is appropriate, but does not include any discussion on the strengths and weaknesses of CFD modelling. This report includes a lengthy discussion of possible approaches to modelling different aspects of dispersion from groups of buildings, including CFD techniques.

W2a describes models for dispersion in a sea breeze. It points out that CFD models are an appropriate tool for this application, as they can describe all features of sea breezes. W2a states that studies using CFD models have led to a greater understanding of dispersion in sea breezes, and that CFD can represent all aspects of this topic. It does not otherwise consider the merits of the technique.

R2c points out that CFD techniques are appropriate for some studies of airflow in urban areas.

12.3 Areas of overlap

R292b and R292c both make comments on the merits of CFD, giving the same general impressions of the capabilities of this technique.

12.4 Gaps in the areas covered by the reports

The authors of this review have no expertise in CFD modelling. As far as we can tell, there are no gaps from the discussions in R292b, supported by comments in R292c, of the advantages and disadvantages of CFD modelling.

12.5 Recommendations for future work

R292b points out the need to reduce the variability of results, and suggests that strict guidelines covering all aspects of applying CFD to a real site should be developed. It points out that good experimental data sets, which could be used as the basis of comparisons between results of CFD and other calculations, should be identified. It suggests that work is needed to improve the turbulence modelling for applications to atmospheric dispersion and to develop and validate appropriate techniques to enable CFD models to describe deposition.

R292c suggests that work should be done to assess the capabilities of CFD modelling.

13 MODEL FOR CONCENTRATION AT LONG RANGE FROM A SHORT RELEASE

The ADMWG only produced one report (R124) explicitly looking at the calculation of air concentration at long range from a short release. However, related problems are considered in other reports.

13.1 Scope of R124

The model was intended primarily for use in submissions prepared under Article 37 of the Euratom Treaty. This requires operators to make calculations of the radiation doses that might be received by inhabitants of the nearest Member State of the European Union from an accidental release from the site of interest; for UK sites this means that the calculation must consider travel distances of a few hundred kilometres. The model is intended to provide a reasonably pessimistic estimate of the concentration that might occur for a release at some stage during the operation of the site, and therefore the atmospheric conditions at the time of the release cannot be known. The model includes the effects of the changes of atmospheric conditions along the trajectory of the plume in calculating the vertical spread. The report also considers the calculation of dry and wet deposition at the point of interest.

13.2 Areas of overlap with other reports

R123 (see Section 2) and R124 model the likely concentration at a distance, allowing for the cumulative effects of changes of stability category during the travel time, but do not consider how to calculate concentration allowing for a known sequence of changes of atmospheric stability. R198 and, to a lesser extent, R1a (see Section 10) consider the problems caused by changes of rainfall rate.

The different reports relate to different applications, and there are no contradictions between the recommendations.

13.3 Gaps in the areas covered by the model

ADMLC/ADMWG has not specifically considered a way of describing dispersion in changing atmospheric conditions.

13.4 Recommendations for future work

Neither R123 nor R124 gave any specific recommendations for future work.

14 SUMMARY AND CONCLUSIONS

ADMLC and the Steering Committee which preceded it have produced a total of 30 reports. In some cases different reports relate to similar topics. ADMLC wanted a review of the work which has been carried out, intended to identify any contradictions between different reports and any gaps in the areas covered. The aim was not to summarise the work which has been carried out, nor to consider whether subsequent work elsewhere would support a possible review or revision of any of the earlier reports.

The 30 reports were divided into 12 groups where the reports referred to topics that were related; for example four reports related to aspects of dispersion from releases near buildings, and five reports related to aspects of the use of meteorological data. The main topics covered by each of the reports have been summarised, and the areas of overlap between reports or gaps in the areas covered have been identified. Many of the reports included recommendations for future work; these recommendations have also been summarised in this report.

There are several instances where different reports describe models for the same or very similar applications. In almost all such cases, the later report references the earlier one. In this case, the later report can be regarded as updating, rather than contradicting, the earlier report. In the few cases where the later report does not reference the earlier one, there are no instances of contradictions between the two reports. In all cases, the reports can be regarded as updating earlier documents or providing additional, complementary, information.

There are two instances where the authors of this report have reservations about the conclusions reached in ADMLC reports; these are identified below.

The first of reservation about the findings relates to the portability of met data, considered in R316a. R316a suggested that met data from a site at any distance from the source could be used provided that the mean wind speeds were similar in the two data sets. It also suggested that there is no correlation between predicted concentrations and the distance between sites from which met data are taken. This finding contradicts an earlier study by the Met Office (not undertaken for ADMLC) which suggested that met data should only be used for sites within a few tens of kilometres of the met station. Although R316a references the other Met Office study, it gives no discussion on the reason for the differences.

The second reservation relates to the "shelf life" of met data. Two reports considered the use of "old" met data and whether concentrations predicted using data from a site over a period of years show a trend with time. The reports identified a trend, which is not consistent between sites and differs depending on whether mean values or percentiles are being considered. There are large variations between years superimposed on a possible trend. The variation over time, particularly if using met data from Heathrow, may reflect changes in the urbanisation of the surrounding area, and so a change in the roughness length.

R2d compares the variation in predicted concentration over time with the variation in predicted concentration for different assumed roughness lengths; the variation with roughness length is greater than that with time. R2d also examines the difference between concentrations predicted using hourly average and "spot" winds, again identifying a difference comparable to that over time. The authors of this report feel that further work is justified to understand these topics. Commenting on the difference in the concentration predicted using different data sets is complicated by the lack of any general agreement on the accuracy required in regulatory applications.

This review also identified a number of gaps, either in the coverage of a single report or between the coverage of different reports on related topics. This will provide a useful input into discussions within ADMLC on future work programmes. The main gaps are summarised below.

There is no discussion in any of the reports of models for dispersion of dense gases. This may reflect a general assumption, particularly at the time that R91 was written, that there are no dense gases of importance in the nuclear industry.

There is no discussion of the modelling of chemical reactions in the atmosphere, either between different materials within a single plume or between material in a plume and the general background levels of other chemicals. Chemical reactions in the plume can affect both the predicted concentration and deposition rates of some materials. This omission reflects the restriction, until recently, of ADMLC interests to topics primarily of interest to the nuclear industry.

R122 described a model for calculating plume depletion due to dry deposition, and two subsequent reports recommended values for the deposition velocity. None of these reports have examined dispersion and deposition of particles which are large enough that their settling under gravity should be considered.

Two reports have looked at features of dispersion at coastal sites. Both concentrated on situations when the wind is blowing from the sea to the land, and did not consider dispersion over bodies of water. Although R124 considered the calculation of concentrations in other Member States of the European Union it did not explicitly examine dispersion over water. This means that ADMLC has not looked at situations where plumes travel over water bodies such as lakes or estuaries, or explicitly at the rate of plume growth over the sea.

There is only very limited coverage of the concentration indoors resulting from a plume outdoors. None of the reports have considered the question of concentration indoors from a release within the building.

Several reports relate to plume rise, from either a stack where airflow is not affected by buildings or a release into a building wake. These consider the contribution of plume vertical momentum and buoyancy to the rise; the models recommended are based on studies of typical plumes from power stations where the vertical velocity of the effluent is unlikely to be more than a few tens of metres per second. There may be accident situations, such as damage to a valve

on a container where a gas is under considerable pressure, in which material could be released at much higher speeds, or in directions other than vertically upwards. The authors of this report do not know whether the models given in ADMLC reports would be appropriate for such releases.

One report briefly mentions the size of an initial plume following an explosive release, although it does not relate this to the quantity of explosive (as in perhaps a terrorist act). A more detailed study of the likely size of a plume from an explosion, and its subsequent dispersion, would be of interest.

The authors note that these topics are identified as those needed to fill gaps in the general areas covered by previous ADMWG/ADMLC reports. Needs for future work outside these areas have not been considered.

15 REFERENCE

Davies B M and Thomson D J (1996) Investigating the importance of pre-processing in estimating dispersion climatology IN Proceedings of the Ostend Workshop on Harmonisation of Dispersion Models.