NRPB-R157

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

J A Jones
Secretary of the Working Group

National Radiological Protection Board

Chilton, Didcot, Oxon OX11 0RQ
December 1983

NRPB-R157

The National Radiological Protection Board was established by the Radiological Protection Act 1970 and is responsible for carrying out research and development and providing information, advice and services to those with responsibilities for radiological protection.

Any questions relating to this report should be addressed to the Publications Officer, National Radiological Protection Board, Chilton, Didcot, Oxfordshire, England.

Further copies of this report are available from Her Majesty's Stationery Office

---

UNITS

As from 1 April 1978 NRPB adopted the International System of Units (SI). The relationship between the new SI units which are used in this report and the previous units are shown in the table below.

Quantity	New named unit and symbol	In other SI units	Old special unit and symbol	Conversion factor
Exposure	–	$C\ kg^{-1}$	röntgen (R)	$1\ C\ kg^{-1} \sim 3876\ R$
Absorbed dose	gray (Gy)	$J\ kg^{-1}$	rad (rad)	1 Gy = 100 rad
Dose equivalent	sievert (Sv)	$J\ kg^{-1}$	rem (rem)	1 Sv = 100 rem
Activity	becquerel (Bq)	s^{-1}	curie (Ci)	$1\ Bq \sim 2.7 \times 10^{-11}\ Ci$

NRPB-R157

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

J A Jones
Secretary of the Working Group

ABSTRACT

This report is the fifth in a series giving practical guidance to estimate the dispersion of radionuclides released to the atmosphere. It represents the conclusions of a Working Group established to review recent developments in atmospheric dispersion modelling and to propose models for use within the UK. This report describes methods proposed by the Group to extend the models given in its earlier reports to cover dispersion at coastal sites, the effects of plume buoyancy and initial momentum, and the effects of buildings on dispersion. It also includes guidance on the values of deposition velocity and washout coefficient for use in the models recommended in the Group's second report.

National Radiological Protection Board
Chilton
Didcot
Oxon OX11 ORQ

December 1983

HMSO, £5.00 ISBN 0 85951 216 9

The following changes have been made to this report since its first publication (December 1983).

August 2003

Page vi	Definition of momentum flux F_m corrected
Page 18	Definition of momentum flux F_m corrected Units of effluent density ρ_o corrected Units of specific heat of air c_p corrected
Page 20	Definition of the heat emission rate Q_H corrected Definition of the momentum emission rate Q_M corrected
Page 31	Equation C12 corrected

CONTENTS

CONTENTS (contd)

FOREWORD

In December 1977 a meeting of representatives of UK 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 established in order to facilitate the review. In 1979 the Working Group published a first report giving practical guidance on estimating the dispersion of radioactive releases in the atmosphere within a few tens of kilometres of the release point, for both continuous and short duration releases. That report dealt specifically with nuclides which do not deposit on the ground and are not removed from the plume by interaction with rain. Subsequently, the Group published a second report describing methods for including dry and wet deposition in the models given in its first report, and a third report describing an extension of the models to long range dispersion from continuous releases. The Group's fourth report describes a model for long range dispersion from a short release.

This report, the fifth by the Group, describes ways in which the models given in the earlier reports can be extended to allow for the effects of buildings, plume rise, and dispersion at coastal sites. It also contains guidance on the values of deposition velocity and washout coefficient for use in the models given in the second report.

The membership of the Working Group while this report was being prepared was:

Dr R H Clarke (Chairman)	National Radiological Protection Board
Dr H M ApSimon	Nuclear Power Section, Imperial College of Science and Technology, London
Dr C D Barker	Central Electricity Generating Board, Research Department, Berkeley Nuclear Laboratories, Berkeley
Dr B E A Fisher	Central Electricity Generating Board, Research Department, Central Electricity Research Laboratory, Leatherhead
Dr S F Jagger	United Kingdom Atomic Energy Authority, Safety and Reliability Directorate, Culcheth
Dr D J Moore	Central Electricity Generating Board, Research Department, Central Electricity Research Laboratory, Leatherhead
Dr F B Smith	Meteorological Office, Bracknell

Dr M L Williams*	Department of Industry, Warren Spring Laboratory, Stevenage
Dr J A Jones (Secretary)	National Radiological Protection Board

Because of the specialised nature of the topics considered, the Working Group established sub-groups to advise it on each topic. The following people were members of sub-groups.

Mr P J Cooper	United Kingdom Atomic Energy Authority, Safety and Reliability Directorate, Culcheth
Dr J E Fackrell	Central Electricity Generating Board, Research Department, Marchwood Engineering Laboratory, Southampton
Mr J A Garland	United Kingdom Atomic Energy Authority, Atomic Energy Research Establishment, Harwell
Dr D J Hall	Department of Industry, Warren Spring Laboratory, Stevenage
Dr J C R Hunt	Department of Applied Mathematics and Theoretical Physics, Cambridge University
Dr G Jenkins	Meteorological Office, Bracknell
Dr W Nixon	United Kingdom Atomic Energy Authority, Safety and Reliability Directorate, Culcheth
Dr A G Robins**	Central Electricity Generating Board, Research Department, Marchwood Engineering Laboratory, Southampton
Ms J R Simmonds	National Radiological Protection Board
Dr J E Simpson	Department of Applied Mathematics and Theoretical Physics, Cambridge University
Dr B Y Underwood	United Kingdom Atomic Energy Authority, Safety and Reliability Directorate, Culcheth
*Current address:	Department of Industry, London
**Current address:	Central Electricity Generating Board, Research Department, Central Electricity Research Laboratory, Leatherhead

ACKNOWLEDGEMENTS

The Chairman and Secretary of the Working Group would like to thank all members of the Group and its sub-groups for their assistance in the work which led to the preparation of this report.

PREVIOUS REPORTS BY THE GROUP

1. Clarke, R H, The first report of a Working Group on Atmospheric Dispersion: A model for short and medium range dispersion of radionuclides released to the atmosphere. Harwell, NRPB-R91 (1979) (London, HMSO).

2. Jones, J A, The second report of a Working Group on Atmospheric Dispersion: A procedure to include deposition in the model for short and medium range atmospheric dispersion of radionuclides. Chilton, NRPB-R122 (1981) (London, HMSO).

3. Jones, J A, 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. Chilton, NRPB-R123 (1981) (London, HMSO).

3. Jones, J A, The fourth report of a Working Group on Atmospheric Dispersion: A model for long range atmospheric dispersion of radionuclides released over a short period. Chilton, NRPB-R124 (1981) (London, HMSO).

LIST OF SYMBOLS

A_c	A constant, typically about 2/3
A	Cross-sectional area of the building
A_i	Depth of the overland mixing layer
A_s	Area of the source
b_r	Width of the recirculating wake
B	Shape factor, typically about 0.5
C	Concentration in air
C_p	Specific heat of air at constant pressure (J kg^{-1} K^{-1})
d_o	Diameter of the stack (m)
F	Initial buoyancy flux (m^4 s^{-3}) = $\frac{g\ W}{\pi\ c_p\ \rho_a\ T_a}$ for a hot air plume
F'	A dimensionless buoyancy flux parameter = $\pi F/u_b^3 H_b$
F_m	Momentum flux of the source (m^4 s^{-2}) = $\frac{1}{\pi}\frac{\rho_o}{\rho_a} w_o\ V_o$
F'_m	A dimensionless momentum flux parameter = $F_m/\pi u_b^2 H_b^2$
g	Acceleration due to gravity (m s^{-2})
h	Release height (m)
h_e	Effective height of release
h_{sb}	Depth of the sea-breeze inversion (m)
H	Surface sensible heat flux (w m^{-2})
H_b	Height of the building (m)
H_L	Building length
L_p	Lift-off parameter
L_r	Wake length
p_i	Interception factor
P	Probability of a given wind direction occuring
Q	Release rate
r	Distance from a continuous source
r_p	Radius of the top-hat distribution of concentration in a rising plume (m)
R	Gas constant
s'	A stability parameter (s^{-2}) = $\frac{g}{s_2\theta}\gamma$
s_2	A dimensionless parameter
t	Travel time (s)
T	Release duration (hours)
T_a	Temperature of the atmosphere (K)
T_p	Vertical thickness of the plume (m)
T_r	Normalised residence time in the building wake = $u_b \tau/H_b$

u	Mean wind speed (m s^{-1})
u_{10}	Wind speed (at 10 m)
u_a	Wind speed averaged over the height through which the plume has risen (m s^{-1})
u_b	Wind speed at building height (m s^{-1})
u_f	Velocity of the sea-breeze front in still air
u_h	Velocity within the sea-breeze relative to that of the front
u_{sb}	Effective wind speed in the sea-breeze
u_g	Component of the gradient wind velocity along the direction of the sea-breeze
u_l	The greater of the average wind speed over the height of the plume or 0.2 (m s^{-1})
u_*	Friction velocity over the land (m s^{-1})
V_g	Deposition velocity
V_o	Volume release rate (m^3 s^{-1})
w	Herbage density, dry weight (kg m^{-2})
w_o	Efflux velocity of the effluent (m s^{-1})
W	Heat emission rate (W)
W_b	Width of the building
x_f	Distance travelled over the land (m)
x_L	Distance travelled within the internal boundary layer
x_s	Distance of the source from the down-wind building edge
x_{St}	Distance travelled in the stable layer
x_V	An effective distance such that $\sigma_L(x_V) = \sigma_S(x_{St})$ (subscripts L and S to σ denote values for travel entirely within land and sea stabilities, respectively)
x	Rectilinear co-ordinate along the wind direction
y	Across wind rectilinear co-ordinate
z	Vertical rectilinear co-ordinate
z_p	Rise of the plume centre-line above the release point (m)
z'_p	Rise of the plume centre-line above the position of the streamline passing through the source (m)
α	Width of the sector in which concentration is calculated (radians)
α_h	A constant, typically about 0.9 in UK conditions
α_2,	A constant, typically about 0.2 in UK conditions
β	An entrainment constant in Briggs' plume rise equation
γ	Vertical gradient of potential temperature in air (K m^{-1})
$\Delta\theta$	Land—sea temperature difference (K)
$\Delta\rho$	Density difference between the plume and the atmosphere (kg m^{-3})
$\Delta T/\Delta Z$	Lapse rate over the water (K m^{-1})
θ	Potential temperature of the atmosphere (K)

θ_s	Air temperature over the sea (K)
θ_1	Low-level potential temperature over the sea (K)
θ_2	Temperature of the land (K)
θ_c	Potential temperature of the atmosphere at the release height
θ_w	Wind direction
λ	A constant, typically about 4 in UK conditions
λ_r	Normalised wake length = L_r/H_b
μ	Uptake coefficient ($m^2\ kg^{-1}$)
ρ_a	Density of air ($kg\ m^{-3}$)
ρ_o	Density of the effluent ($g\ m^{-3}$)
σ	Value of plume spread appropriate to a point source
σ_{ysb}	Plume lateral spread in the sea-breeze
σ_{yt}	Standard deviation of the turbulent cross-wind spread of the plume for the appropriate overland category as defined in the Group's first report
σ_{yw}	Standard deviation of the cross-wind spread of the plume resulting from wind direction fluctuations as defined in the Group's first report
σ'_y, σ'_z	Standard deviation of the horizontal and vertical Gaussian distributions of activity, modified by the building
σ_{zD}	Standard deviation due to passive diffusion (m)
σ_θ	Standard deviation of wind direction distribution
τ	Residence time in the building wake
χ_w	Normalised concentration = Cu_bA/Q

A — DISPERSION AT COASTAL SITES

A1. INTRODUCTION

This part of the report deals with the prediction of atmospheric dispersion over land following a release from a site located close to a large body of water, such as a sea or a large lake. For simplicity such sites are referred to as coastal.

Patterns of dispersion at coastal sites differ from those at inland sites primarily because dispersion is affected by differences between temperatures and roughness of land and water surfaces. The temperature difference between land and water can affect dispersion through two mechanisms. First, it tends to cause a difference in the air pressure above land and water surfaces, leading to the existence of land–sea breezes; second, it tends to produce a different atmospheric stability in the air over water and land, with an interface between them. The Working Group considers that dispersion close to the coast will be dominated by the effects of layers of different stability even when a sea-breeze is blowing, and that the main effect of a sea-breeze is its ability to transport material well inland with relatively little dispersion. The Group considers that the effects caused by the change of roughness length are of secondary importance.

This part of the report gives guidance on calculating dispersion when a sea-breeze is blowing, and on the conditions in which sea-breezes are likely to occur. It also gives guidance on models which take account of the effect of the roughness and stability changes occurring at the coast. The model described in Section A2 should be used at all times when calculating concentrations within a few kilometres of the coast. Coastal effects at larger distances should be assessed using the models given in Section A3 if a sea-breeze is blowing and those given in Section A2 if other conditions prevail.

There are a large number of reports covering aspects of dispersion at coastal sites, but few comprehensive reviews of the topic. Mention should be made, however, of the review by Lyons[1], and of the work of Raynor et al[2], who have considered in detail the applicability at a coastal site of methods for calculating dispersion recommended by USNRC and intended primarily for inland sites. Ludwig[3] has recently described in detail the atmospheric phenomena occurring at the coast which are important to dispersion modelling. Pechinger[4] has reviewed models for predicting the properties of the land–sea breeze on a specified occasion.

A2. DISPERSION CLOSE TO THE COAST

A2.1 Wind directions towards the water

The Group considers that the models given in its first report[5] and elsewhere in the present report can be used to calculate air concentrations at points between the discharge location and the coast, provided the stability of

the atmosphere has been correctly specified. The deposition rate can be calculated using the methods given in the Group's second report[6].

A2.2 Wind directions towards the land

The effects on a dispersing plume of the presence of a large body of water upwind of a source depend on whether the water is colder or warmer than the land. This section describes models for application when calculating dispersion near a body of water in these two temperature-difference situations. The problem of dispersion from a source near a building is considered in Section A2.2.4.

A2.2.1 Dispersion when the water is colder than the land

When the temperature of the water is lower than that of the land, the air over the water may be more stably stratified than the air over the land. As air passes from over the water to over the land it is heated from the ground so that a growing unstable layer exists over the land. The unstable layer above the land is termed the internal boundary layer. Dispersion in this case is illustrated in Figure A1(a,b) for sources outside and inside the internal boundary layer.

A number of models have been proposed for calculating the concentration at ground level following fumigation (ie, Figure A1(a)). In this situation, material disperses at different rates above and inside the internal boundary layer (because stability in the two layers is different), and the greater turbulence within the internal boundary layer carries the plume fairly rapidly to ground level. Some models[1,7] are based on the assumption of an instantaneous vertical mixing of all material which has crossed the interface between the layers. A more complex model[8] has been developed in which dispersion within the interface is calculated from the Gaussian plume model, while the interface itself forms an area source whose strength is given by the concentration distribution in the stable layers. Numerical methods using second-order turbulence modelling have been used to simulate the effects of changes in surface conditions on the flow, the development of turbulence and heat transfer, and the dispersion of pollutants[9]. In view of the uncertainties in modelling dispersion at a coastal site, the Group suggests that a relatively simple model should be adequate. The Group notes that, in certain conditions, the model prediction could be extremely sensitive to small changes in the assumed parameter values. It is likely to be especially sensitive if the predicted rate of deepening with distance of the internal boundary layer is very small at the point where the plume impinges on the boundary. Plumes with substantial rise and those from tall stacks are most likely to impinge at relatively large distances inland, where such small rates of deepening apply. Thus the modelling of plumes from high-level coastal sources will be particularly sensitive to small changes in the parameter values. In these cases the model given below should be used with caution and sensitivity analyses should be considered.

The concentration from a release near the coast can be calculated using the method given for an inland site in the Group's first report[5], provided that the

parameter values are evaluated allowing for the effects of the coast. The air concentration for a short release is therefore given by

$$C(x,y,z) = \frac{Q}{2\pi u_{10}\,\sigma_y \sigma_z}\ \exp[-y^2/(2\sigma_y^2)]\ F(h,z,A_i), \quad \text{if } \sigma_z < A_i \qquad \ldots\ldots (A1)$$

with $$F(h,z,A) = \exp[-\frac{(z-h)^2}{2\sigma_z^2}] + \exp[-\frac{(z+h)^2}{2\sigma_z^2}] + \exp[-\frac{(2A_i-z-h)^2}{2\sigma_z^2}]$$

$$+ \exp[-\frac{(2A_i-z+h)^2}{2\sigma_z^2}] + \exp[-\frac{(2A_i+z-h)^2}{2\sigma_z^2}] + \exp[-\frac{(2A_i+z+h)^2}{2\sigma_z^2}];$$

and by

$$C(x,y,z) = \frac{Q}{2\pi u_{10}\,\sigma_y A_i}, \text{ if } \sigma_z > A_i \qquad \ldots\ldots (A2)$$

In this case the depth of the mixing layer, A_i, must be replaced by the depth of the internal boundary layer, and the plume standard deviations, σ_y and σ_z, for a source in the stable layers must be evaluated allowing for the effects on plume growth of the different stability in the two layers as described in Section A2.2.1.2.

It should be noted that the use of equations (A1) and (A2) involves a number of approximations when calculating concentrations for sources in the stable layer or the internal boundary layer. First, dispersion in a region in which the diffusion coefficient is varying rapidly cannot strictly be described by the Gaussian model. Second, the way in which plumes reflect from the top of a growing boundary layer is not correctly described by equation (A1). Near the coast the internal boundary layer grows rapidly, with the growth generated, to some extent, by the same mechanisms that cause plumes to grow. This implies that the plume may never 'catch up' with the growing boundary layer and therefore may never be reflected from the top of the layer. This is partially accommodated by using the value of boundary layer depth at the point at which concentration is to be calculated, rather than the lower value at the point at which reflections, if any, occur. Third, the model given in equation (A1) is also somewhat simplistic in its assumption that a plume released in the stable layers crosses the internal boundary layer at a single point. However, the Group believes that the simple model will be adequate in practice.

A2.2.1.1 The depth of the internal boundary layer

Several formulae are available for determining the depth of the internal boundary layer; to some extent the choice is left to the user of the Group's report and will depend on the available data.

Raynor et al[10] have suggested that the depth of the internal boundary layer, A_i, is given by

$$A_i = \frac{u_*}{u}\left(\frac{x_f|\theta_1 - \theta_2|}{|\Delta T/\Delta Z|}\right)^{\frac{1}{2}} \quad \ldots\ldots \text{(A3)}$$

where u_* is the friction velocity over the land (m s^{-1})

u the mean wind speed (m s^{-1})

x_f the distance travelled over the land (m)

θ_1 the low-level potential temperature* over the sea (K)

θ_2 the temperature of the land (K)

and $\Delta T/\Delta Z$ the lapse rate over the water (K m^{-1}).

Venkatram[11] has developed a similar formula from theoretical ideas, but with the temperature T replaced by the potential temperature. Raynor et al[10] do not state at what height the wind speed, u, is to be measured. The Group suggests that it should be the mean value over the internal boundary layer, as in Venkatram's formula.

Carson[12] has developed a model which predicts the rate at which the boundary layer depth grows with time as a result of heating. This could be used to give the rate of growth of the internal boundary layer depth with distance from the shore, the formula then becoming

$$A_i^2 = \frac{2H(1+2A_c)}{\rho_a C_p \gamma}\,\frac{x_f}{u} \quad \ldots\ldots \text{(A4)}$$

where H is the surface sensible heat flux (W m^{-2})

A_c a constant defined by Carson for which the value of 2/3 may be used in this context

ρ_a the density of air (kg m^{-3})

C_p the specific heat of air at constant pressure (J kg^{-1} K^{-1})

and γ the vertical gradient of potential temperature in air over water (K m^{-1}).

Parameters ρ_a and C_p are functions of the air temperature, though their product is close to 1250 J m^{-3} K^{-1}. A limited verification study[13] has shown good agreement between this formula and measured values of internal boundary layer depth.

---

* The potential temperature, θ, of a parcel of air, at temperature T_g and pressure p is the temperature that would result if the parcel were brought adiabatically to a pressure of 10^5 Pascal (1 standard atmosphere), ie,

$$\theta = T_g\left(\frac{10^5}{p}\right)^{R/C_p}$$

where R is the gas constant

and C_p the specific heat at constant pressure (for air $R/C_p = 0.286$).

The formulae given above are recommended for use if the values of their parameters are known. However, the formulae are fairly sensitive to the values chosen for some of the parameters. Therefore, the Group suggests that they should not be used for a specific short release unless the appropriate parameter values have been determined. They would, however, be appropriate for use in calculation of long-term average concentration if joint frequency distributions of the parameter values are available.

The formulae are unlikely to give acceptable results in near neutral conditions when the lapse rate or the potential temperature gradient tend towards zero.

Pasquill has suggested that the depth of the internal boundary layer produced by a change of surface roughness is approximately equal to σ_z for a source situated at the interface[14]. A limited study[13] suggests that σ_z appropriate to the down-wind conditions of stability and ground roughness also gives a reasonable estimate for the depth of the internal boundary layer down-wind from the coast. This method effectively takes into account the transcoastal change in surface roughness and heat flux.

The Group suggests that the Raynor et al[10] or Carson[12] formulae be used if the required data are available but notes the sensitivity of these formulae to the vertical temperature gradient, which may not be well known. If the data required for these formulae are not available the Group suggests that the depth of the internal boundary layer be taken to equal σ_z.

A2.2.1.2 The value of the dispersion coefficients, σ_y and σ_z

(a) Source in the stable layers

The Group suggests that the dispersion coefficients should be evaluated using a modification of the virtual-source model so that

$$\sigma(x) = \sigma_L(x_L + x_V) \qquad \ldots\ldots \text{(A5)}$$

where σ is the value of plume spread appropriate to a point source

x the distance from the source

x_L the distance travelled within the internal boundary layer

x_V an effective distance such that $\sigma_L(x_V) = \sigma_S(x_{St})$

x_{St} the distance travelled in the stable layer (see Figure A1)

and the subscripts L and S to σ denote values for travel entirely within land and sea stabilities, respectively.

Comments on the use of this formula are given below.

There have been a number of studies of dispersion over water (eg, Raynor et al[10] and Van der Hoven[15]. These suggest that concentrations observed in a plume passing over water are greater than those for overland plumes, implying that either or both σ_y and σ_z are less over water than over land. This may merely reflect the different stability and roughness length for the two surfaces. The

model described in this report was derived primarily for application to releases on land from a stack which is sufficiently tall that the effluent is released into the stable air flowing from the water. In this case most of the plume growth occurs in the unstable air over the land and the use of values for plume growth over land is probably adequate.

Hosker[16] has compared model predictions of σ_z with plume dimensions measured after travelling over water. He showed that the Smith formulation, recommended in the Group's first report[5], gave good agreement if a value of roughness length appropriate to water surfaces was used. The Group suggest that σ_z for over-water dispersion be calculated using that model.

Horizontal dispersion is the result of both atmospheric turbulence and fluctuations in the wind direction. The contributions to the standard deviation of plume width, σ_y, due to these two components were designated σ_{yt} and σ_{yw}, respectively, in the Group's first report[5]. The turbulence term, σ_{yt}, is the dominant contributor to total plume width for sampling periods of a few minutes duration, while for releases of a few hours duration the dominant contribution comes from wind direction fluctuations (ie, the term σ_{yw}). Hosker[16] compared predicted and observed values of σ_y for sampling times of a few minutes and found that the Pasquill–Gifford curves, used in the Group's first report, gave a reasonable prediction. There are very few data available from which a reliable model for wind direction fluctuations, and hence the σ_{yw} term, over large areas of water can be derived. Wind direction fluctuations over land reflect the effects of surface obstacles and non-uniform terrain and also of large-scale eddies in the mixing layer. These two components are likely to be less and greater, respectively, for over-water travel compared to overland travel. Zanetti et al[17] reported on a determination of σ_y for over-water travel for sampling periods of 1 hour. They found that the observed σ_y was roughly equal to the Pasquill–Gifford σ_y for a stability category which is one or two categories less stable than the actual category. This implies that there is a contribution to plume growth from wind direction fluctuations for a 1 hour sampling time comparable with that from atmospheric turbulence. This finding is consistent with the relative magnitude of the σ_{yt} and σ_{yw} terms given in the Group's first report[5]. Therefore, in the absence of any better data, the Group suggests that both σ_{yt} and σ_{yw} for overland conditions should be used for dispersion over water.

(b) Source within the internal boundary layer

The Group suggests that the models given in its first report[5] should be used in this case. The depth of the mixing layer should be taken as the depth of the internal boundary layer as given above.

A2.2.1.3 Illustrative examples of the effect of coastal sites on dispersion

An example of the concentrations predicted by the model suggested here is given in Figure A2(a). This example is for a source in the stable air above the

internal boundary layer, as shown in Figure A1(a). The conditions assumed were stability categories over water and land of F and C, respectively, with a wind speed of 2 m s^{-1} and a 30 minute release. The release point was taken to be at a height of 100 m at the land–water interface. Also shown in Figure A2(a) is the concentration predicted for the same release conditions but at an inland site. The comparison shows that the peak concentration at the coastal site is less and that the distance to the maximum concentration is greater than for the inland site. At larger distances than that of the peak concentration, the model predicts greater concentrations at the coastal site than at the inland site. This stems from the assumption that the plume is trapped within the internal boundary layer so that vertical dispersion is less than at an inland site.

The differences between coastal and inland sites are somewhat less for sources within the internal boundary layer (see Figure A2(b)). In this case there is very little difference between the predicted peak concentrations at the two types of site. The concentration at larger distances is predicted to be greater at coastal than at inland sites because of the more limited vertical dispersion at coastal sites.

A2.2.2 Dispersion when the water is warmer than the land

The Group suggests that the models given in its earlier reports are appropriate for this case, which is likely to coincide with stable conditions over the land.

A2.2.3 Calculation of long-term average concentrations

The calculation of average concentrations over long periods can be carried out using the method given in the Group's first report. This is based on a modification of equation (A1) to give sector averaged concentrations in each stability category which are summed to give the long-term average concentration. The same procedure is recommended here. When calculating concentrations for different wind directions allowance should be made for the different distances air must travel over land before reaching the source.

A2.2.4 The effects of buildings

The formulae given in Section A2.2.1 for the depth of the internal boundary layer suggest that the top of the internal boundary layer could either pass through, or be very close to the top of, the main buildings at many coastal installations. If this is the case then the disturbance of the air flow caused by the buildings could invalidate the formulae for depth of the internal boundary layer. In view of the difficulties and uncertainties of modelling both dispersion at coastal sites and the effects of buildings, the Group suggests that the models given in Section C of this report be used with no correction for the coastal effects.

A2.2.5 The case with more than one land–sea interface

Dispersion calculations are sometimes required for a site with more than one interface between land and water, eg, for a site near a lake or estuary when

calculations are required after the plume has travelled across land, water and a further section of land. There is almost no guidance in the literature for this situation. Raynor et al[2] consider a series of internal boundary layers growing from each change of surface. The models described in this section could be generalised to the case of more than one discontinuity, but it is impossible to estimate the accuracy of the predicted concentrations.

A3. DISPERSION DURING A SEA-BREEZE

This section gives only a very brief description of the conditions in which a sea-breeze is likely to occur and its effect on dispersion. The models are mainly based on the findings about the structure of sea-breezes and gravity currents by Simpson et al[18] and Simpson and Britter[19], and on work on the behaviour of pollutants and balloons by Cole and Lyons[20].

Sea-breezes typically occur on days when quite strong thermal convection occurs and the wind is light, ie, they occur on days when the atmospheric stability would fall into the Pasquill categories A or B, (or the Smith stability index less than 2)[5]. If the sea-breeze is to penetrate more than a few kilometres inland from the coast, the land and sea temperature difference must typically be greater than 3°C. A number of ways have been derived for predicting whether or not a sea-breeze will blow on a particular day, and for predicting how far inland the sea-breeze has penetrated on a specific occasion (these are reviewed in the Handbook of Weather Forecasting[21]). More complex models for this have been reviewed by Pechinger[4].

Wickham[22] has produced a map (see Figure A3) showing the prevailing direction of the sea-breeze at a number of locations, and the mean position of the sea-breeze front in various parts of the UK in the afternoon. The results presented do not imply that sea-breezes do not exist elsewhere, but only that they are less well documented or less consistent in their behaviour. Information on inland penetration is given in Figure A4, which shows the frequency with which sea-breezes have been detected at four sites up to 100 km from the coast.

The velocity of the sea-breeze front in still air, u_f, is given by

$$u_f = \alpha_h \left(g \frac{\Delta\theta}{\theta_s} h_{sb} \right)^{\frac{1}{2}} \qquad \ldots\ldots \text{(A6)}$$

where α_h is a constant, typically about 0.9 in UK conditions

g the acceleration due to gravity (m s^{-2})

$\Delta\theta$ the land–sea temperature difference (K)

θ_s the air temperature over the sea (K)

and h_{sb} the depth of the sea-breeze inversion (m).

Within the sea-breeze there is a wind travelling in the same direction as the front, with a velocity, u_h, relative to the front of

$$u_h = \alpha_2 \left(g \frac{\Delta\theta}{\theta_s} h_{sb} \right)^{\frac{1}{2}} \quad \ldots\ldots (A7)$$

where α_2 is a constant, typically about 0.2 in UK conditions based on laboratory and field measurements.

Therefore, in the absence of other winds, the velocity within the sea-breeze upwind of the head is $u_f + u_h$. In general, however, other wind fields are present. Assuming that there is a gradient wind produced by the general atmospheric motions in the absence of a sea-breeze, the effective wind speed in the sea-breeze, u_{sb}, is given by

$$u_{sb} = 0.6\, u_g + (\alpha_h + \alpha_2) \left(g \frac{\Delta\theta}{\theta_s} h_{sb} \right)^{\frac{1}{2}} \quad \ldots\ldots (A8)$$

where u_g is the component of the gradient wind velocity along the direction of the sea-breeze

and 0.6 is a numerical factor derived from laboratory experiments[19].

There cannot be a sea-breeze if there is a large head wind (ie, offshore wind), $0.6\, u_g < -u_f$. If there is a large onshore or following wind the sea-breeze only forms about 10 km inland, and the front only forms in the afternoon about 40 km inland. If the wind is strong enough ($|u_g| > 2\, u_f$) the sea breeze is hardly detectable.

The effects of a sea-breeze on a plume dispersing in the atmosphere are illustrated in Figure A5, which shows the position before and after a source is engulfed in the sea-breeze for gradient wind directions that are following and opposing the sea-breeze direction. The concentration, C, in this final stage, when the plume is restricted to the region between the source and the sea-breeze front, is given approximately by

$$C = \frac{Q}{(2\pi)^{\frac{1}{2}}\, u_{sb} h_{sb} \sigma_{ysb}} \quad \ldots\ldots (A9)$$

where Q is the release rate

and σ_{ysb} the plume lateral spread in the sea-breeze.

The depth of the sea-breeze inversion is given by

$$h_{sb} = A_i / \lambda \quad \ldots\ldots (A10)$$

where A_i is the depth of the overland mixing layer

and λ is a constant, typically about 4 in UK conditions.

The plume lateral spread due to atmospheric turbulence in the sea-breeze is given by

$$\sigma_{ysb}^2 = \left(\frac{1}{\lambda}\right)^{4/3} \sigma_{yt}^2 \qquad \ldots\ldots (A11)$$

where σ_{yt} is the standard deviation of the turbulent cross-wind spread of the plume for the appropriate overland category, as defined in the Group's first report[5].

The direction of the sea-breeze changes systematically during the day because of effects of the Coriolis force or coastline irregularities, but direction changes at a particular site are regular[21]. The value of σ_{ysb} used in assessing concentration should allow for this change of wind direction, ie, an appropriate addition to the value derived from equation (11) must be made. This correction can be derived for some sites from the Handbook of Weather Forecasting[19], which contains graphs showing the direction of the sea-breeze at different times of day. If a calculation is to be made for a site for which no information is available the Group suggests that the method given in its first report[5] (ie, introduction of a σ_{yw} term as defined in the Group's first report) be used to modify σ_{ysb} for the effects of release duration.

The regular change in the direction of the sea-breeze prevents released material being carried backwards and forwards over the site on more than one occasion, unless extreme orographic features restrict the flow.

As sea-breezes tend to be confined to stability categories A and B they are unlikely to affect annual average concentrations and need only be considered for short duration releases. They may be important as they can transport material for considerable distances inland.

The land-breeze in the UK is rarely well developed. The Group suggests, therefore, that it is not considered when calculating concentrations at points between the release point and the coast.

A4. REFERENCES

1. Lyons, W A, Turbulent diffusion and pollutant transport in shoreline environments. IN Lectures on Air Pollution and Environmental Impact Analaysis. Boston, MA, Am. Meteorol. Soc. (1978).

2. Raynor, G S, Michael, P and SethuRaman, S, Meteorological measurement methods and diffusion models for use at coastal nuclear reactor sites. Nucl. Saf., 21, 749 (1980).

3. Ludwig, F L, A review of coastal zone meteorological processes important to the modelling of air pollution. To be published in the proceedings of the 14 NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application, Copenhagen, September 1983.

4. Pechinger, U, Review of selected three-dimensional numerical sea-breeze models. To be published in the proceedings of the 14 NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application, Copenhagen, September 1983.

5. Clarke, R H, The first report of a Working Group on Atmospheric Dispersion: A model for short and medium range dispersion of radionuclides released into the atmosphere. Harwell, NRPB-R91 (1979) (London, HMSO).

6. Jones, J A, The second report of a Working Group on Atmospheric Dispersion: A procedure to include deposition in the model for short and medium range atmospheric dispersion of radionuclides. Chilton, NRPB-R122 (1981) (London, HMSO).

7. Van Dop, H, Steenkist, R and Nieuwstadt, F T M, Revised estimates for continuous shoreline fumigation. J. Appl. Meteorol., 18, 133 (1979).

8. Misra, P K, Dispersion from tall stacks into a shoreline environment. Atmos. Environ., 14, 393 (1980).

9. Ghobadian, A, Goddard, A J H and Gossman, A D, The APT computer program for the numerical solution of problems in atmospheric dispersion. Presented at the NATO/CCMS Air Pollution Meeting, Menlo Park, California (August 1981).

10. Raynor, G S, Michael, P, Brown, R M and SethuRaman, S, Studies of atmospheric diffusion from a nearshore oceanic site. J. Appl. Meteorol., 14, 1080 (1975).

11 Venkatram, A, Internal boundary layer development and fumigation. Atmos. Environ., 11, 479 (1977).

12. Carson, D J, The development of a dry inversion-capped convectively unstable boundary layer. Q.J.R. Meteorol. Soc., 99, 450 (1973).

13. Smith, F B, Private communication.

14. Pasquill, F, Some aspects of boundary layer description. Q.J.R. Meteorol. Soc., 98 (417), 469 (1972).

15. Van der Hoven, I, Atmospheric transport and diffusion at a coastal site. Nucl. Saf., 8 (5), 490 (1967).

16. Hosker, R P, A comparison of estimation procedures for over-water plume dispersion. ATDL Contribution File 99 (1974). Presented at a Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, California (1974).

17. Zanetti, P, Wilbur, D M and Schacker, G E, Characterising coastal atmospheric diffusion from three-dimensional monitoring of SF6 releases. IN Proceedings First International Conference on Meteorology and Air/Sea Interaction of the Coastal Zone, The Hague (1982). AMS/Royal Netherlands Meteorological Institute.

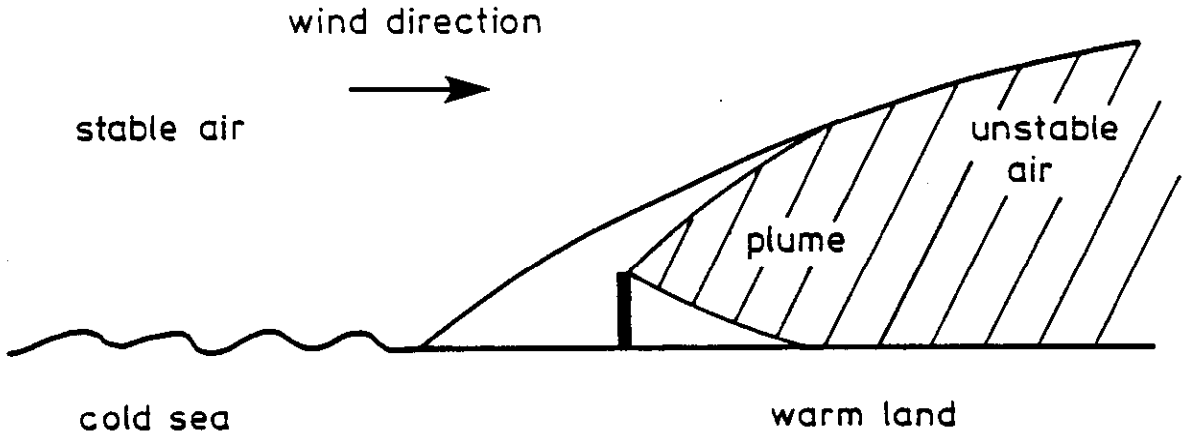
18. Simpson, J E, Mansfield, D A and Milford, J R, Inland penetration of sea-breeze fronts. Q.J.R. Meteorol. Soc., 103, 47 (1977).

19. Simpson, J E and Britter, R E, A laboratory model of an atmospheric meso-front. Q.J.R. Meteorol. Soc., 106, 485 (1980).

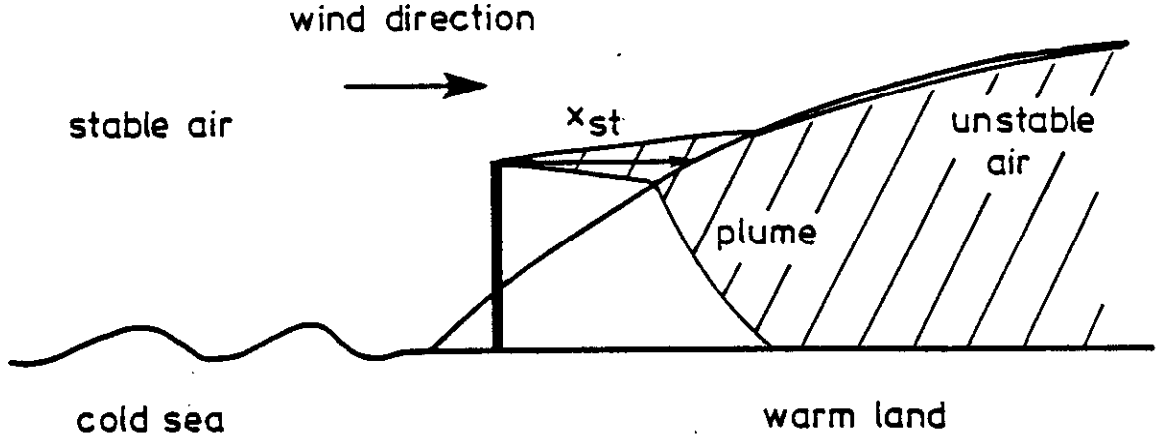
20. Cole, H S and Lyons, W A, Impact of the great lakes on the air quality of urban shore-line areas. IN Proceedings 15th Conference on Great Lakes Research (1972).

21. Handbook of Weather Forecasting. Met. Office Note, Met. O 875 (1975).

22. Wickham, P G, Weather for gliding over Britain. Weather, 21, 154 (1966).

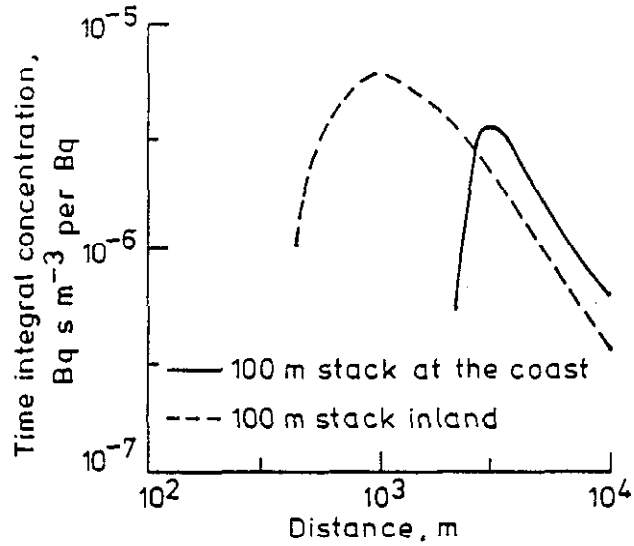


a) A source within the internal boundary layer

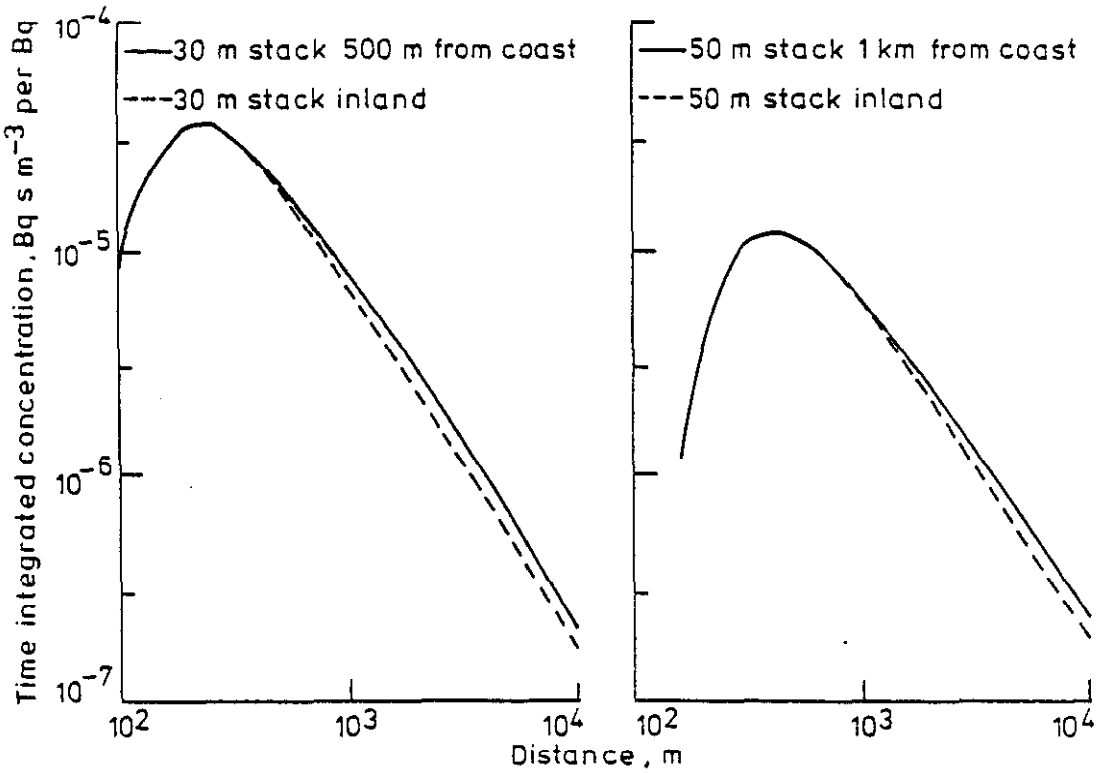


b) A source above the internal boundary layer

Figure A1 Dispersion at a coastal site (onshore wind, sea colder than land)



a) Source above the internal boundary layer (overwater stability F, overland stability C, wind speed 2 m s^{-1})



b) Sources within internal boundary layer (overland stability C, wind speed 5 m s^{-1})

Figure A2 Comparison between concentrations for coastal and inland sources

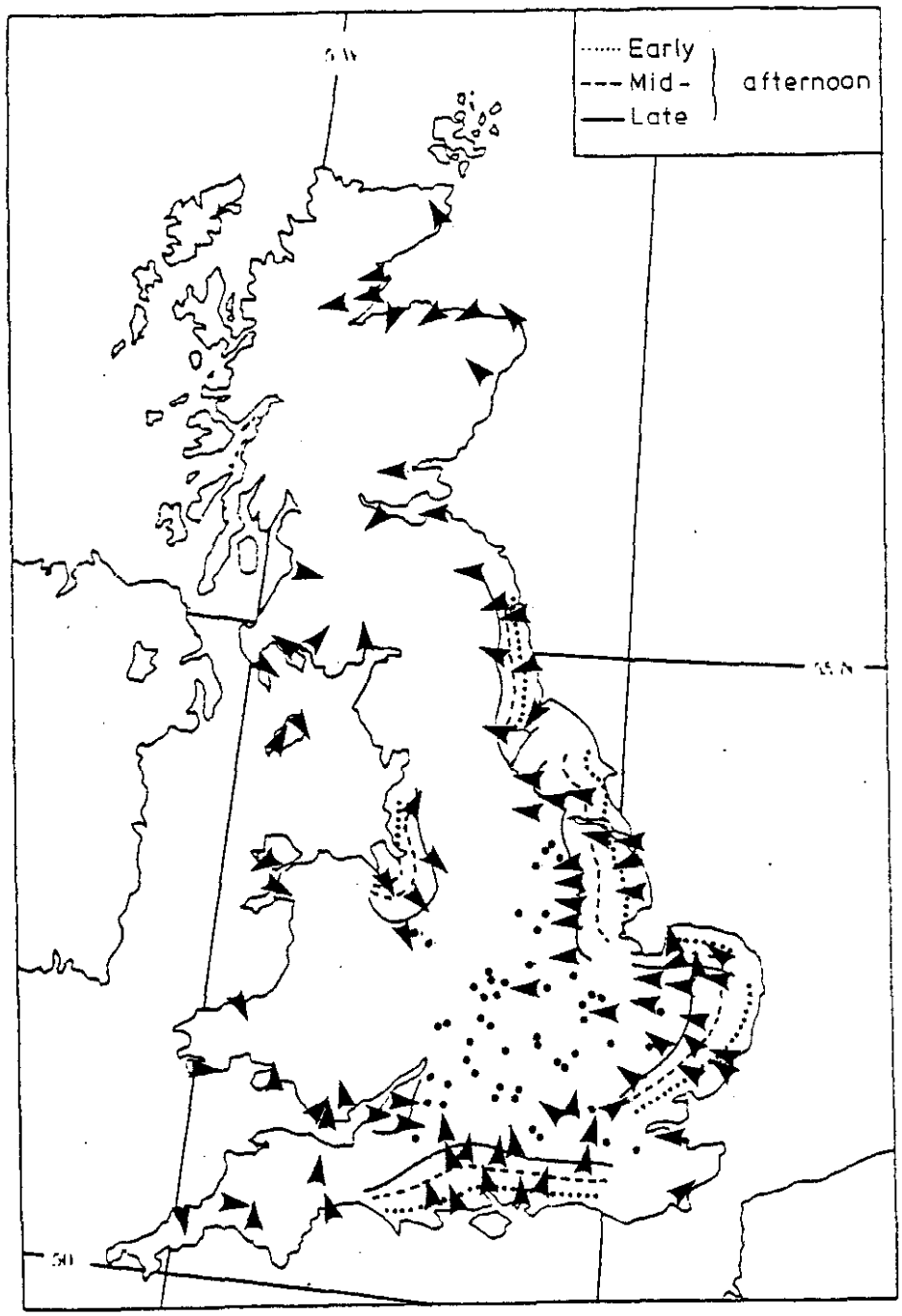


Figure A3 The normal direction and penetration of sea breezes during summer months

(Note: Each arrow or dot represents an individual airfield. Arrows show the late afternoon direction of the sea breeze (a few places having two preferred directions). Dots show airfields where sea breezes have not been specially recorded in the local weather notes. The isochrones show the normal rate of progress inland of the sea breeze on a summer afternoon. Taken from Reference 22)

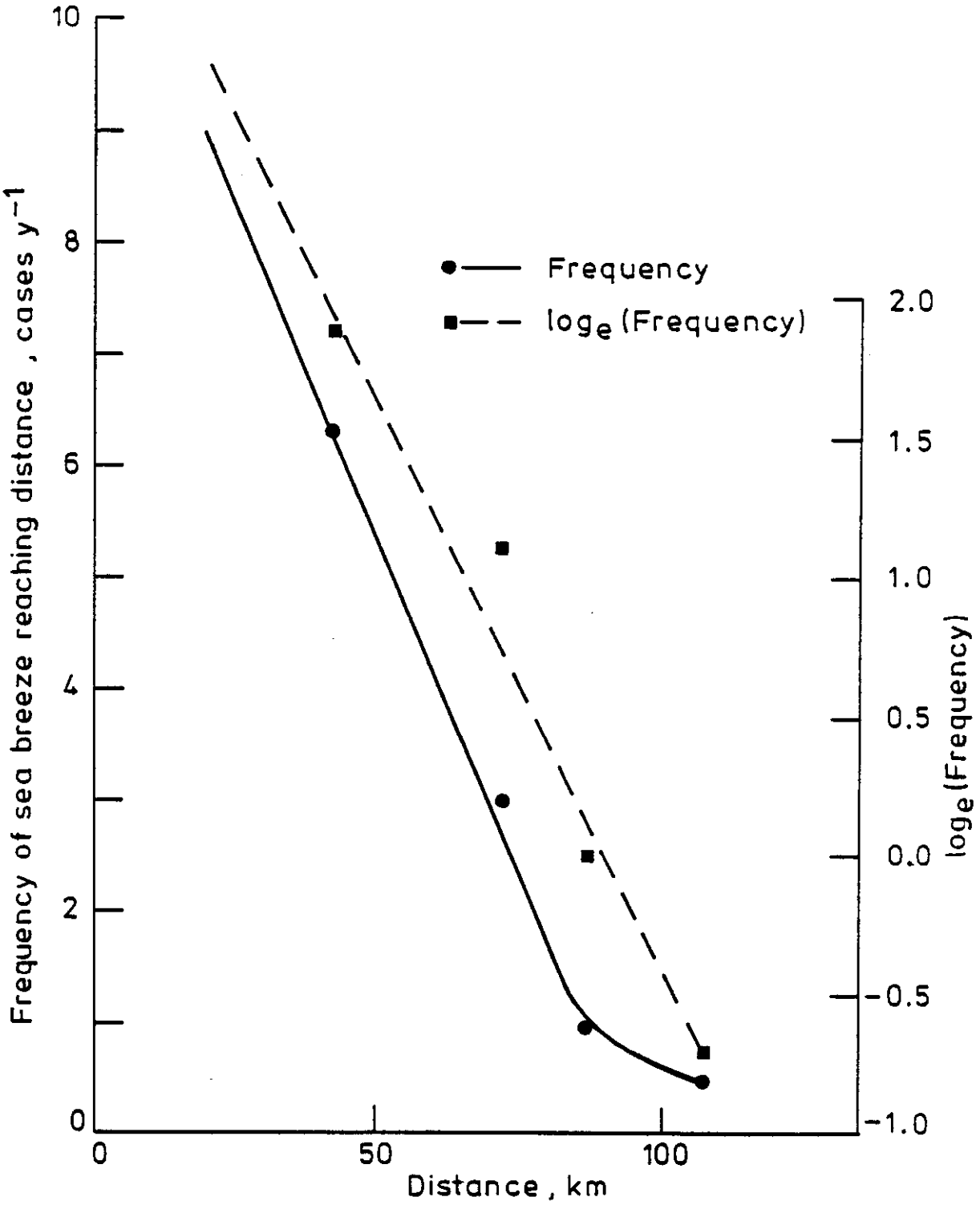
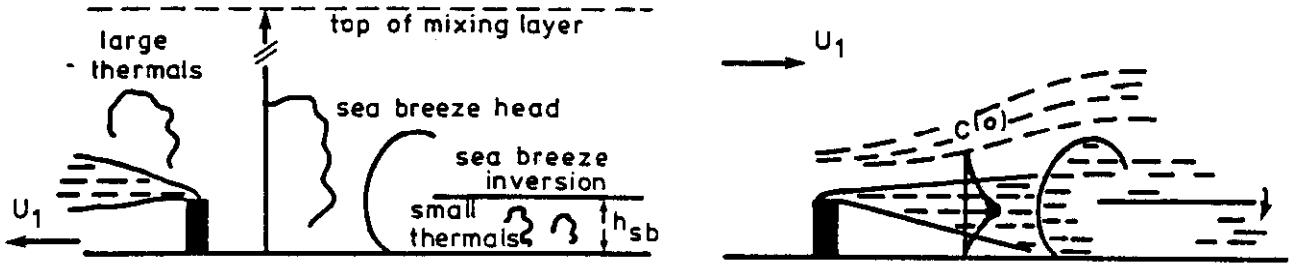


Figure A4 Probability that a sea breeze will penetrate inland

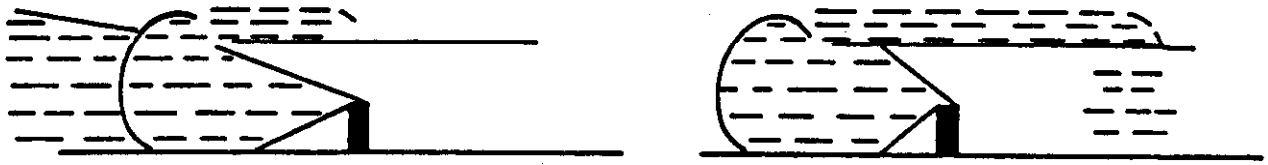
a) Before source is engulfed



i) Following wind

ii) Weak head wind

b) Just after source is engulfed



i) Following wind

(Note: In this situation an inversion may form about 10 km from the coast but a front only about 40 km inland)

ii) Weak head wind

c) Some time after source is engulfed

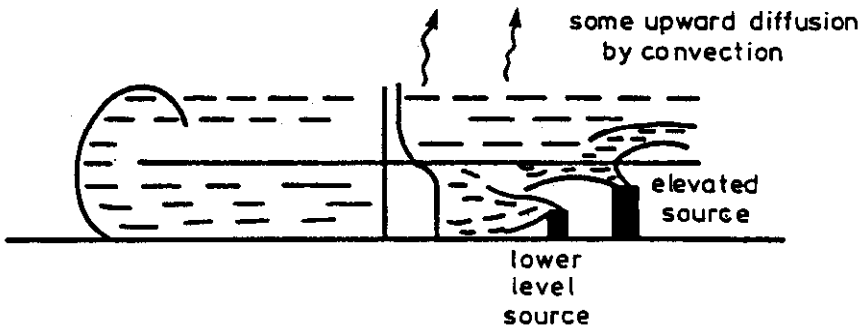


Figure A5 The effects of a sea breeze on a dispersing plume

B — PLUME RISE

B1. INTRODUCTION

Material discharged to the atmosphere may rise above its original release point if it has vertical momentum or is more buoyant than the ambient air. The buoyancy can arise because the material has a lower density than air, either because of its temperature or composition. Plumes can generate buoyancy after their release by absorbing energy generated by radioactive decay in the plume. They can gain or lose buoyancy because of chemical reactions or the latent heat of their constituent material.

The problem of predicting how far a plume will rise above its release point is extremely complex and a large number of models have been developed, many of which are reviewed by Briggs[1]. However, despite this large number of models, there is no model covering all aspects of the problem relevant to calculations for radioactive material and the Group was unable to recommend a model for all situations.

This part of the report gives the Group's conclusions on methods of modelling plume rise from isolated sources and from sources discharging into a building wake.

B2. PLUME RISE FROM AN ISOLATED SOURCE

Although a large number of models for plume rise from isolated sources have been given in the literature there are difficulties in using any of them to calculate the concentration in air at ground level, which is the quantity required in dose calculations. All the models concentrate on predicting the trajectory of the centre of the plume, making simple assumptions about the distribution of activity within the plume. Most of the models predict an infinite plume rise in a neutral atmosphere so that additional assumptions are required to limit the height of final rise. There are additional problems for buoyant plumes released at ground level with no vertical momentum, as it is not easy to decide whether such a plume will lift off the ground or diffuse as a ground-level plume. The Group's views on these problems are summarised below.

The two most comprehensive models of plume rise are those derived by Briggs[1] and Moore[2]. The Group suggests that either of these models should be used to predict the trajectory of the plume centre-line for a stack height of more than a few tens of metres. Both models have been extensively validated and Moore[2,3] has carried out an intercomparison against the same set of observational data. This intercomparison suggests that the Moore model gives a marginally more accurate prediction of plume rise than the Briggs model. This, together with its extensive validation for UK conditions, suggests that it is more appropriate to use the Moore model than the Briggs model. The equations for determining the trajectory using the Briggs and Moore models are given in Sections B2.1 and B2.2, respectively. Reasons for terminating plume rise are discussed in Section B2.3, while Sections B2.4 and B2.5 consider the calculation

of ground-level concentration and the rise of buoyant material released at ground level.

B2.1 The plume trajectory as given by Briggs

Briggs[1] gives different formulae for rise in a neutral and a stable atmosphere but does not give a formula for rise in an unstable atmosphere. The formulae for rise due to initial momentum and buoyancy are:

in a neutral atmosphere

$$z_p^3 = \frac{3F_m t}{\beta^2 u_a} + \frac{3Ft^2}{2\beta^2 u_a} \qquad \ldots\ldots \text{(B1)}$$

in a stable atmosphere with a uniform temperature and density gradient

$$z_p^3 = \frac{3}{\beta^2 u_a s'} \left[s'^{\frac{1}{2}} F_m \sin s'^{\frac{1}{2}} t + F(1-\cos s'^{\frac{1}{2}} t) \right] \qquad \ldots\ldots \text{(B2)}$$

where z_p is the rise of the plume centre-line above the release point (m)

F_m the momentum flux of the source ($m^4\ s^{-2}$) = $\frac{1}{\pi} \frac{\rho_o}{\rho_a} w_o V_o$,

with ρ_o the density of the effluent (kg m^{-3})

ρ_a the density of the atmosphere (kg m^{-3})

w_o the efflux velocity of the effluent (m s^{-1})

V_o the volume release rate ($m^3\ s^{-1}$)

F the initial buoyancy flux ($m^4\ s^{-3}$) = $\frac{g\ W}{\pi\ c_p\ \rho_a\ T_a}$ for a hot air plume,

with g the acceleration due to gravity (m s^{-2})

c_p the specific heat of air at constant pressure ($J kg^{-1}\ K^{-1}$)

T_a the temperature of the atmosphere (K)

W the heat emission rate (W)

t the travel time (s)

β an entrainment constant

u_a the wind speed averaged over the height through which the plume has risen (m s^{-1}),

and s' in a stability parameter (s^{-2}) = $\frac{g}{s_2 \theta} \gamma$,

with θ the potential temperature# of the atmosphere (K)

s_2 a dimensionless parameter

and γ the potential temperature gradient of the atmosphere (K m^{-1}).

The constant β is the ratio of the rate of increase of plume radius to the

---

Potential temperature is defined in section A2.2.1.1.

plume's vertical velocity. Briggs[1] suggested that the constant β should have a value of 0.6; a value of 0.45 was used in the US Reactor Safety Study[4]. The parameter s_2 represents the retarding effect of air above the plume which has to be accelerated by the rising plume, and Briggs suggests that its value is about 2.3. He also gives formulae for the case of a zero wind speed. The formula given by Briggs for plume rise in a stable atmosphere predicts undamped oscillations of the plume and some further assumption is required to terminate these oscillations. A frequently used assumption is to terminate the rise at the point of zero buoyancy. The formula for rise in a neutral atmosphere gives an infinite rise so that an assumption must be made to terminate the rise and methods for terminating the rise are discussed in Section B2.3.

Briggs[1] discussed the way in which his equations should be extended to plumes of material other than air by modifying the definition of the momentum flux, F. He also considers an extension of his model to include plumes in which buoyancy is being generated, eg, radioactive decay. Gifford[5] has given the solution for a constant rate of buoyancy generation.

B2.2 The plume trajectory as given by Moore

Moore[2] gives a single formula applicable in unstable, neutral and stable conditions, incorporating plume break-up due to atmospheric turbulence and wind shear. This may be written as below to differentiate the effects of initial buoyancy and momentum in an emission of hot air

$$Z_p = 0.922 \frac{f}{u_1}\left(\frac{\theta'^*_o}{110}\right)^{1/8} \left\{ \frac{gQ_H}{C_p \theta_e} x^{*2} (x^* + 27d_o) + 1.5\, Q_M\, u_1\, x^* (x^* + 36d_o) \right\}^{\frac{1}{4}} \quad \ldots\ldots \text{(B3)}$$

where $x^* = x x_T / (x^2 + x_T^2)^{\frac{1}{2}}$,

with $x_T = x_1\, x_N / (x_1^2 + x_N^2)^{\frac{1}{2}}$

$x_1 = 12\, u_1 / (\gamma)^{\frac{1}{2}}$

$x_N = 1920 + 19.2\, h$ for stack height $h < 120$ m

$= 4224$ for $h > 120$ m

and x is the down-wind distance (m),

u_1 the greater of the average wind speed over the height of the plume or 0.2 ($m\ s^{-1}$)

$f = 0.16 + 0.007\, h$ for $h < 120$ m

$= 1$ for $h > 120$ m or if $\gamma / u_1^2 > 2.5\ 10^{-5}$

θ'^*_o the greater of 12 K and θ'_o (K)

θ'_o the potential temperature difference between the effluent and the atmosphere at height h (K)

θ_e the potential temperature of the air outside the plume (K)

d_o the stack exit diameter (m)

Q_H the heat emission rate (W) = $\rho_o V_o C_{p_o} \theta'$

and Q_M the momentum emission rate (kg m s^{-2}) = $\rho_o V_o w_o$.

Moore suggested that γ may be taken as 1.25 10^{-2}, 5 10^{-3}, and 8 10^{-4} K m^{-1} in stable, neutral and unstable conditions, respectively, with the ambient atmosphere being taken as very slightly stably stratified above the surface layer.

Equation (B3) applies to emissions of hot air or mixtures of gases whose molecular weight and specific heat are near to those of air. In other circumstances, proper account must be taken of the molecular weight and specific heat differences, and Moore gives a generalised form of equation (B3) for use in such cases. This equation can be used with emissions of either positive or negative buoyancy, and an extension for use with self-heating plumes is also indicated. In the form applicable to heavier-than-air emissions an initial-momentum dominated plume rise phase is followed by a (negative) buoyancy dominated 'plume droop' regime.

B2.3 Reasons for terminating plume rise

The model derived by Moore[2] includes the effects of atmospheric turbulence and wind shear in breaking up a plume and terminating its rise. The Briggs[1] model does not explicitly include any mechanism to terminate the rise in a neutral atmosphere. Plumes can be broken up by mechanical or convective turbulence in the atmosphere. Briggs[1] suggested that a plume will break up, and hence stop rising, when its turbulent energy dissipation rate becomes comparable to that of the atmosphere. He has given ways of estimating ambient and plume turbulence levels, and suggestions for calculating the final height of rise. The summary of Briggs' paper suggests the use of experimentally determined formulae for the final height of rise of a buoyant plume. He gives the final height of rise in a stable atmosphere as

$$z_p = 2.6 \left(\frac{F}{u_a s'} \right)^{1/3} \qquad \ldots\ldots \text{(B4)}$$

Briggs gives no suggestion as to the trajectory to be followed during the period of damped oscillations leading to this final height. He also suggests that a buoyant plume rising in a neutral atmosphere will be broken up by mechanical turbulence at a height given by

$$z_p = 1.2 \left(\frac{F}{u_a u_*^2} \right)^{3/5} (h + z_p)^{2/5} \qquad \ldots\ldots \text{(B5)}$$

where h is the release height (m)

and u_* the friction velocity (m s^{-1}).

In this case Briggs suggests that the plume will follow a trajectory given by equation (1) during its rise.

The formulae presented in Sections B2.1 and B2.2 were derived on the assumption that the atmospheric conditions are constant throughout the region through which the plume is rising. Changes in conditions will affect the dispersing plume, and in particular, plume rise will be inhibited by a capping inversion to the mixing layer. If a plume rises into such an inversion the amount of material in the mixing layer, and hence ground-level concentration, will be reduced. Briggs[1] discusses ways of calculating the rise of a plume into or through an elevated inversion. This effect could be included in calculations of concentration at ground level if sufficient information on the height, depth and intensity of the inversion is available.

B2.4 The calculation of ground-level concentration

In order to calculate ground-level concentration it is necessary to know not only the position of the plume centre-line but also the way in which material is distributed through the plume. A rising plume entrains air into its own volume thereby increasing its radius. It is also subject to the normal processes of turbulent diffusion which act to increase the plume size. The plume-rise models described here are derived on the assumption of a top-hat distribution of activity within the plume. However, a plume-rise model predicts the ensemble average trajectory, and there is no inconsistency in using a top-hat distribution to predict the instantaneous trajectory and a Gaussian distribution to predict the time-average ground-level concentration. The standard deviation of the distribution should allow for the effects of plume rise and passive diffusion on plume growth. The Group suggests that the standard deviation σ_z should be taken as

$$\sigma_z^2 = \sigma_{zD}^2 + r_p^2/3 \qquad \ldots\ldots \text{(B6)}$$

where σ_{zD} is the standard deviation due to passive diffusion (m)

and r_p the radius of the instantaneous top-hat distribution (m).

The value of r should be taken as equal to half the plume rise (ie, $r_p = z_p/2$). A similar formula is applicable to σ_y. The plume size in the passive diffusion phase, after plume rise has stopped, can also be obtained from this equation by using the final height of rise for z_p.

B2.5 Plume rise from sources at ground level

Moore's[2] model was derived on the assumption that the vertical wind shear is constant. This assumption is valid in the upper parts of the mixing layer but is much less valid near ground level. Therefore, the theory is not applicable to sources where the rise terminates in the lower parts of the mixing layer.

A further difficulty is in predicting whether a buoyant plume, which is initially on the ground, will lift off. If the buoyancy of a ground-level plume is low it behaves as an essentially passive plume, the peak concentration being at ground level. However, more buoyant plumes lift away from the ground, and the peak concentration is then at some height above ground. The problem has been addressed by Briggs[6] who derived a lift-off parameter, L_p, given by

$$L_p = \frac{g\, T_p \Delta\rho}{u_*^2\ \rho_a} \qquad \ldots\ldots (B7)$$

where T_p is the vertical thickness of the plume (m)

and $\Delta\rho$ the density difference between the plume and the atmosphere (kg m^{-3}).

Briggs suggested, on the basis of theory, that a critical value for L_p was about 2.5 (with a possible range of a factor of about four). Reappraising the problem at a later date, and considering some experimental work of Meroney, Briggs increased his estimate of the critical value of L_p by an order of magnitude. He assumed that if the value of L_p is much less than this then the plume will diffuse as a passive ground-level source, but if its value is much larger it will lift cleanly from the ground and rise. Recent work by Robins shows that whether or not plumes will lift-off depends on both their buoyancy and vertical momentum. In addition to passive and lifting plumes, Robins found an intermediate region of plume behaviour in which they tended to remain at ground level but had an enhanced vertical spread caused by the buoyancy. This point is considered further in Section B3.1 where the rise of a buoyant plume from a building wake is discussed.

The Group urges a user to be very cautious when utilising predictions of reduced concentration because of plume rise for a ground-level release.

B3. PLUME RISE FROM A BUILDING WAKE

The Group feels that, at present, it is not possible to give a model for plume rise from a building wake, either for plumes emitted with significant vertical momentum or with significant buoyancy. However, a formula is given in Section B3.2 for the final height of a plume emitted with vertical momentum from a source on or above the building roof.

B3.1 Buoyant plumes

Plume rise due to buoyancy is often characterised by a dimensionless buoyancy flux given by

$$F' = \frac{\pi F}{u_b^3 H_b} \qquad \ldots\ldots (B8)$$

where u_b is the wind speed at building height (m s^{-1})

and H_b the height of the building (m).

Briggs has suggested that if the plume's buoyancy is sufficiently high, the plume will lift cleanly off the ground[6], when the ground-level concentration will be very low. This lift-off was not observed in a recent preliminary experiment by Hall[7] which showed that ground-level concentration decreases smoothly as the buoyancy increases.

Data obtained by Hall[7] and by Fackrell and Robins[8] suggest that the ground-level concentration from a buoyant plume is half that from a non-buoyant plume at the same wind speed, if the value of the parameter F' is greater than about 0.05. A recent experiment by Hall suggests that ground-level concentration decreases rapidly as buoyancy increases above a value corresponding to a value for Briggs' lift-off parameter of about 30.

The Group suggests, therefore, that buoyancy effects be ignored if the parameter F' has a value below 0.05, and that wind tunnel studies be considered if it is necessary to utilise predicted concentrations for higher values of F'. Note that high values of F' may be produced either by high values of buoyancy flux, F, or low values of wind speed, u_b, so that consideration of low enough wind speeds will always involve significant plume-rise effects.

B3.2 Plumes with vertical momentum

Plume rise due to vertical momentum can be characterised by a dimensionless momentum flux, F'_m, given by[8]

$$F'_m = \frac{\rho_o w_o^2 A_s}{\rho_a u_b^2 H_b^2} \qquad \ldots\ldots (B9)$$

where A_s is the area of the source.

This can be expressed in terms of Briggs' parameter as

$$F'_m = \frac{F_m}{\pi u_b^2 H_b^2}$$

where F_m is the momentum flux of the source ($m^4 s^{-2}$) = $\pi \frac{\rho_o}{\rho_a} w_o v_o$.

The final height of rise, z'_p, of a plume emitted at roof level or above, provided it is outside the separated region and w_o is greater than u_b, can be obtained from two essentially equivalent formulae

$$z'_p = 3.4\ F'^{\frac{1}{2}}_m H_b \quad \text{(Robins and Castro[8])} \qquad \ldots\ldots (B10)$$

$$z'_p = 3 d_o w_o / u_b \quad \text{(Thompson and Lombardi[9])} \qquad \ldots\ldots (B11)$$

The rise z'_p refers to differences between the position of the plume centre-line and the position of the streamline passing through the source. This streamline will not travel over the building and its wake at a constant height. The behaviour of the streamline passing through the source will also depend on the position of the source relative to the building roof. The formula should only be used if the behaviour of this streamline can be specified (see Section C). The critical value of efflux velocity for a plume to rise as specified above requires comment. Other references quote critical values of typically one to two times the wind speed at a reference height. There is no clear transition from a passive to rising plume as efflux velocity increases. However, the Group considers that a critical value of efflux velocity equal to the wind speed at the height of the building represents the best simple criterion to divide the two types of behaviour.

The Group suggests that plume rise should be ignored if F'_m is less than 0.05[8,10]. As before, higher values of F'_m may be produced by either increased source momentum or low wind speed. If it is necessary to utilise predicted concentrations for higher values of F'_m, then wind tunnel studies should be used.

B4. REFERENCES

1. Briggs, G M, Plume rise predictions. IN Lectures on Air Pollution and Environmental Impact Analyses, sponsored by American Meteorological Society, Boston, MA, USA. Air Turbulence and Diffusion Laboratory Contribution, File No. 75/15 (1975).

2. Moore, D J, Lectures on plume rise. IN Atmospheric Planetary Boundary Layer Physics, Development in Atmospheric Sciences, 11 (Longhetto, A, ed.). Amsterdam, Elsevier (1980).

3. Moore, D J, Reply to discussion on 'A comparison of the trajectories of rising buoyant plumes with theoretical empirical models (Moore, D J, Atmos. Environ., 8, 131 (1974))', Atmos. Environ., 9, 457 (1975).

4. Rassmussen, N, The Reactor Safety Study, Appendix VI. USAEC Report, WASH-1400 (1977).

5. Gifford, F A, The rise of strongly radioactive plumes. J. Appl. Meteorol., 6, 644 (1967).

6. Briggs, G A, Lift-off of buoyant gas initially on the ground. Air Turbulence and Diffusion Laboratory Contribution, File No. 87 (1973).

7. Hall, D J, Barrett, L F and Simmonds, A C, Wind tunnel model experiments on a buoyant emission from a building. Warren Spring Laboratory, Report LR 355 (AP) (1980).

8. Fackrell, J E and Robins, A G, Dispersion of releases from an AGR site. Central Electricity Generating Board, Report RD/M/1172/R81 (1981).

9. Fackrell, J E and Robins, A G, Laboratory studies of dispersion near buildings. IN Proceedings CEC Seminar on Radioactive Releases and their Dispersion in the Atmosphere Following a Hypothetical Reactor Accident, Riso, April 1980. Luxembourg, CEC, Doc. No. V/4111/80 (1980).

10. Fackrell, J E, Wind tunnel tests of dispersion from the proposed PWR. Central Electricity Generating Board, Report TPRD/M/1289/R82 (1982).

C — THE EFFECTS OF BUILDINGS ON THE DISPERSION OF A NON-BUOYANT MATERIAL

C1. INTRODUCTION

This part of the report describes the general features of air flow around buildings. It identifies those regions in which mathematical models or empirical rules can be used to estimate concentrations from sources close to a building, and also the concentration on a building face from sources upwind of the building. Simple models are unable to describe all features of the air flow round buildings and so a series of models, applicable in particular regions, is described, together with a brief discussion of some of the situations not amenable to simple modelling.

This report provides only a fairly brief survey of dispersion near buildings. A more extensive review has recently been published by Hosker[1]. Fackrell[2] has described the air flow around rectangular buildings and given suggestions for determining the flow in a specific case.

C2. AIR FLOW AND DIFFUSION AROUND BUILDINGS

Figure C1 (taken from Robins and Fackrell[3]) is a sketch of the main aspects of the flow over a building which influence dispersion. This includes an approach flow, with given mean velocity profile and turbulence characteristics, which is rolled up in front of the building to form a complex recirculation zone. The vorticity associated with this region is bent around the building and stretched in a longitudinal direction producing the so-called 'horseshoe' vortex shape. The flow over the building separates, forming a highly turbulent recirculating flow in the near wake immediately downstream of the building. The paths of the streamlines in the wake region are shown in Figure C2. Hunt et al[4] show that this region is not a closed bubble, as was once thought, but that material carried into this region over the top of the building is rolled up and ejected laterally. Whether flow which separates at the upstream edge of the building reattaches on the roof, or whether one continuous recirculating region is formed, depends on the geometry of the building[2] and details of the approach flow and this feature can greatly influence the behaviour of emissions on or near the roof. Above the recirculating zone is a region in which flow streamlines are significantly deflected by the zone beneath, thus altering plume trajectories. Downstream of the recirculating zone is a wake region, characterised by a velocity deficit and higher turbulence compared to the approach flow. These decay with distance downstream as the wake spreads and entrains material from the external flow (for more details see Counihan et al[5]). Two contra-rotating trailing vortices can be formed within the wake, with the flow downwards at the centre, which would cause a plume to move towards the ground. This is particularly true for a building with leading roof-top edges at an angle to the wind, when the separating shear layers from the leading edges are rolled up over the roof into relatively intense vortices (eg, see Castro and Robins[6]). Persistent trailing vortices have also been observed for a hemisphere[7] and for

long cuboids at an angle to the wind direction. The rate at which these vortices decay with downstream distance depends on the intensity of turbulence, which tends to destroy the vortices and the degree of stable stratification of the flow which can increase them.

The mean height of material released from sources above a building decreases over a few building heights downwind as the air flow descends and is entrained into the wake. Thereafter the plume is mixed through the wake and, as the wake itself is growing, the mean height of material in the plume eventually begins to increase, ie, the plume spreads upwards. Downflow is markedly increased when the wind is not perpendicular to the face of a cuboid building, due to the strong trailing vortices generated on the roof[8].

Material released on or above the roof of a building may be entrained into the recirculating wake, where the concentration distribution is approximately uniform. This material will eventually disperse out of the recirculating wake as if from a broad, low-level source. Released material which was not entrained in the near wake will have a much narrower spatial distribution. Therefore, the concentration distribution down-wind from the near wake can exhibit a double plume structure (eg, see Robins and Castro[8], and Thompson and Lombardi[9]). In the main wake the development of plumes is largely controlled by the enhanced turbulence and mixing motions within the wake, together with any trailing vortex motions which may exist.

C3. MODELS FOR DIFFUSION NEAR A BUILDING

Because of the complexity of the air flow near a building it is not possible to recommend a single model which is applicable in all the situations for which a model is required. The regions for which models have been considered are illustrated in Figure C3, and are listed below.

(i) Sources upwind of the building and sufficiently low that the plume can impinge on the building.

(ii) Sources on or just above the building roof, or within the recirculating wake.

(iii) Sources above the building roof, or upwind of the building and above roof height.

(iv) Sources in or above the main wake.

(v) Sources on the upwind face, or on or adjacent to the sides of the building.

The following sections consider what the Group believes to be the best available models for these situations. In some cases the Group felt that it was not possible to recommend a general model.

C4. SOURCES UPWIND

As the wind blows towards a building there are streamlines which impinge directly on to the front face of the building. If a source is located near such a streamline then material can diffuse on to the building, either directly or via

the recirculating wake. The maximum concentration on the upwind face of the building can be taken to be equal to the maximum concentration at that distance from the source in the absence of a building[10]. If the source is close to the building this can be much greater than the ground-level concentration. Plumes should be assumed to impinge on the building if the vertical separation between the source and the building is less than σ_z at the distance of the building, and the cross-wind distance between source and building is less than σ_y at the distance of the building.

Material released into the upwind recirculation region can spread a significant distance upwind of the building (of order one to two times the building height) before being swept around it and then affected by the near and main wake flows. Plume structure downwind of the building varies considerably with source height and location, building geometry, and wind direction.

Sources upwind of the building and sufficiently high that the plume does not impinge on the building face can be considered using the methods of Section C6.

C5. SOURCES ON OR JUST ABOVE THE ROOF, OR WITHIN THE RECIRCULATING WAKE REGION

Material released on or just above the roof of a building can be entrained into the near wake. However, the fraction entrained is a complex function of source location, building geometry and wind direction[11]. The Group suggests that it can be assumed that all the emitted material is entrained when:

$$(h - H_b)/(|x_s| + H_b/10) < 0.1 \qquad \ldots\ldots \text{(C1)}$$

where h is the source height above ground

H_b the building height

and x_s the distance of the source from the down-wind building edge.

For cuboid buildings with reattached roof flow and with the approach flow normal (< 15°) to the front face, equation (C1) represents a reasonable limit to source height. However, for rectangular plain buildings of more extreme shape, roof level emissions may be little entrained for wind directions normal to the small face[11]. Further, should the flow over the roof be fully or intermittently separated, or the building be at significant incidence to the approach flow (ie, > 15°), then material released from higher sources may also be fully entrained. Although an assumption of full entrainment is pessimistic in the near-wake region, it need not be further downwind, particularly if plume impingement on elevated receptors is of concern. Guidance on the character of the flow over the roof is given by Fackrell and Pearce[12].

The Group suggests that the concentration within the recirculating wake can be estimated using a formula developed from the work of Vincent[13,14], ie,

$$\chi_w = B(T_r/\lambda_r) \qquad \ldots\ldots \text{(C2)}$$

where χ_w is the normalised concentration = Cu_bA/Q,

with C the actual concentration

u_b the wind speed at building height

and A the cross-sectional area of the building,

Q the release rate

B a shape factor, typically about 0.5

T_r the normalised residence time in the building wake = $u_b\tau/H_b$,

with τ the actual residence time,

and λ_r the normalised wake length = L_r/H_b,

with L_r the actual wake length.

Values of the necessary parameters, derived from wind tunnel studies, are given in Fackrell and Pearce[12] for a range of building shapes and flow conditions. The results presented there can be well represented by the formulae

$$\lambda_r = \frac{1.8\ W_b/H_b}{(H_L/H_b)^{0.3}\ (1 + 0.24\ W_b/H_b)} \qquad \ldots\ldots (C3)$$

$$T_r = \frac{11(W_b/H_b)^{1.5}}{1 + 0.6(W_b/H_b)^{1.5}} \qquad \ldots\ldots (C4)$$

where W_b is the building width

and H_L the building length.

Fackrell and Pearce suggest that equation (C3) should only be used in the range $0.3 < H_L/H_b < 3$. The value of λ_r is assumed not to change for variation of H_L/H_b outside this range. The studies concentrated on buildings orientated normal to the approach flow. For buildings of significant incidence, less is known concerning the behaviour of T_r and λ_r. However, available evidence suggests that the results and data correlations given in Fackrell and Pearce[12] remain valid provided that the effective building dimensions are used, and L_r is measured from the nearest building face mid-point[2] (see Figure C4 for clarification). The width of the recirculating wake, b_r, has been examined by Fackrell[15] who found that its maximum value is well predicted by

$$b_r = 0.6\ H_b + 1.1\ W_b \qquad \ldots\ldots (C5)$$

This expression is considered appropriate for all building lengths. The expression was derived from studies which did not consider tall narrow buildings and, therefore, it should not be used for buildings with $W_b/H_b \lesssim 0.2$. The width of the wake for a wind direction at an angle to the building should be obtained from equation (C5) using effective building dimensions as illustrated in Figure C4. The Group suggests that the recirculating wake be taken to be rectangular, with length L_r and width b_r placed symmetrically down-wind of the building.

The Group suggests that parameter B of equation (C2) should be taken to equal 0.5.

Equation (C2) is based on an assumption of comparatively uniform concentration within the near wake, which is reasonable for cases of distributed sources within the near wake, or cases in which material is entrained into the wake from sources outside. However, for point sources located in the near wake, particularly near the ground, the assumption is a poor one. In such cases the near-wake concentration field displays a complex structure which is a function of source location, building shape and orientation. Concentrations considerably in excess of those predicted by equation (C2) may be experienced in the vicinity of the source. Hall has found that the peak concentration is at roof level for a source emitting uniformly over the down-wind building face[16].

This model for concentration in the near wake predicts the concentration averaged over a period of some tens of minutes. If the average concentration over longer periods is required then allowance must be made for the change in the position of the wake as the wind direction changes. The range of wind directions for which a particular receptor lies within the wake can be determined assuming that the width of the wake is given by equation (C5). The concentration (C) at a particular point in direction θ_p, for an arbitrary wind direction θ_w, is then given by equation (C2) if the point is within the wake, and is zero otherwise. The concentration for a longer averaging time is given by

$$C'(T,\theta_p) = \int_0^{2\pi} P(T,\theta_w)\, C(\theta_w)\, d\theta_w \qquad \ldots\ldots (C6)$$

where T is the release duration in hours

$P(T,\theta_w)$ the probability of the wind direction lying within θ_w and $\theta_w + d\theta_w$ during the release

and $C(\theta_w)$ the receptor concentration, being zero or the short-term near-wake concentration.

For release durations up to a few hours, P may be taken to be a Gaussian distribution about the mean wind direction, with a standard deviation σ_θ given by

$$\sigma_\theta = 0.065\ (7\ T/u_{10})^{\frac{1}{2}} \qquad \ldots\ldots (C7)$$

as given in the Group's first report. In practice this could be adequately approximated by

$$P = \frac{1}{2(3)^{\frac{1}{2}}\sigma_\theta} \quad \text{for } \left| \theta_w - \bar{\theta}_w \right| < (3)^{\frac{1}{2}}\sigma_\theta,$$

$$= 0 \text{ otherwise.}$$

This process can be extended to the calculation of annual average concentration by using windrose data for the distribution of wind directions.

Fackrell has reviewed a number of simple models for calculating the concentration within the main wake for release from the roof or down-wind side of a building and compared their predictions with experimental data[17]. Although there were no great differences between the predictions of the models reviewed, the Group feels that the virtual-source model, as modified by Barker[18], is as good as any, and may therefore be used to calculate concentrations within the main wake from fully entrained releases.

The concentration C is then given by

$$c(x,y,z) = \frac{Q}{2\pi u_{10}\sigma'_y\sigma'_z} \exp\left[-\frac{y^2}{2\,\sigma'^2_y}\right]\left\{\exp\left[-\frac{(z-h_e)^2}{2\,\sigma'^2_z}\right]+\exp\left[-\frac{(z+h_e)^2}{2\,\sigma'^2_z}\right]\right\} \qquad \ldots\ldots (C8)$$

where x is the rectilinear co-ordinate along the wind direction

y the across-wind rectilinear co-ordinate

z the vertical rectilinear co-ordinate

u_{10} the wind speed (at 10 m)

σ'_y, σ'_z the standard deviation of the horizontal and vertical Gaussian distributions of activity

and h_e the effective height of release.

The effective height of release, h_e, should be taken as $H_b/3$ to give the best prediction of the concentration distribution observed near buildings. The dispersion parameters σ'_y and σ'_z are modified to allow for the effects of the building by assuming that the building produces a rapid initial spread of the plume so that

$$\sigma'_z(x = o) = H_b/3$$

and $\qquad \ldots\ldots (C9)$

$$\sigma'_y(x = o) = W_b/3$$

where x is measured from the down-wind edge of the building.

The dispersion parameters at a distance x from the edge of the building are then obtained from

$$\sigma'_y(x) = \sigma_y(x + x_{vy})$$
$$\sigma'_z(x) = \sigma_z(x + x_{vz}) \qquad \ldots\ldots (C10)$$

where σ is the value of plume spread appropriate to a point source

$\sigma_y(x_{vy}) = W_b/3$

and $\sigma_z(x_{vz}) = H_b/3$.

In general x_{vy} is not equal to x_{vz}. The formulation of σ_y recommended in the Group's first report differentiated between spread due to atmospheric turbulence, designated σ_{yt}, and spread due to wind direction fluctuations, designated σ_{yw}. The modifications to σ_y given above relate only to the turbulence term so that

the full plume spread for a release of more than a few minutes duration is given by

$$\sigma'^2_y(x) = \sigma^2_{yt}(x + x_{vy}) + \sigma^2_{yw}(x) \quad \ldots\ (C11)$$

Barker[18] describes the way in which the model is extended to calculate annual average concentrations. He recommends a procedure similar to that given in the Group's first report. The concentration in a given sector and stability category is given by

$$C(r) = \frac{Q}{(2\pi)^{\frac{1}{2}}\sigma_z r\,\alpha\,u_{10}}\left\{\exp\left[-\left(\frac{z-h_e}{2\,\sigma'^2_z}\right)^2\right] + \exp\left[-\left(\frac{z-h_e}{2\,\sigma'^2_z}\right)^2\right]\right\} \quad \ldots\ (C12)$$

where r is the distance from a continuous source (m)

and α the sector width (radians).

The annual average concentration is then obtained as the sum of the concentration in each category, weighted by the frequency of occurrence of the category.

By using the smallest value of W appropriate to a building, rather than the effective value, this model should produce estimates of ground-level concentration which are pessimistic with respect to measured data for all wind directions (by up to a factor of two to three). However, the model should not be used with the effective building width to study the variation of concentration with wind direction, since the variation produced would be incorrect. The model also cannot be used to assess variations with source position.

In general, the main-wake model does not match correctly with the near-wake model as x becomes small. It is suggested that in the region between $x = L_r$ and $x = 3$ to $5H_b$ a linear interpolation should be performed between the concentrations predicted by equation (C2), at $x = L_r$, and equation (C8), at $x = 3$ to $5H_b$. The limitations of the near-wake model have been briefly mentioned and those of the main-wake model are discussed by Barker[18]. Hunt[19] has suggested that the virtual-source model may be improved by varying the virtual-source locations according to down-wind distance, though this concept has not yet been developed into a working model.

C6. SOURCES WELL ABOVE THE BUILDING ROOF

The simple models described in the previous section are suggested for use when a large fraction of the released material is entrained into the recirculating wake down-wind from the building. As the stack height is increased, less material is entrained into the recirculating wake and so the concentration at ground level near the building becomes lower. However the dispersing material is carried down towards the ground into the main wake so that the effective release height is lower than the actual stack height. Huber and Snyder[20] have investigated the horizontal and vertical spreading of plumes released above roof height. Their results show decreasing entrainment into the wake as the stack height is increased.

The model described in Section C5 could be very pessimistic near the building if applied where only part of the released material is entrained. If a more realistic calculation is required then a more complex model must be used. In this case the group suggests that the model developed by Hunt and Robins[21] should be used. This model estimates the reduction in effective release height caused by down-wash into the main wake and allows for partial entrainment of the released material into the recirculating wake. The model is too complex for a full specification of the equations to be given in this report; users should refer to the original report[21] for further details. In some circumstances this model may also be used for upwind sources above the height of the building and for down-wind sources.

The extensions of the model to cover cases of fully separated roof flow or persistent trailing vorticity in the wake have yet to be undertaken and, as with all the models discussed in this report, application is restricted to effectively isolated buildings of simple shape. Within these limitations the model is capable of predicting realistic variations of concentration levels with source location, wind direction and building shape. The absolute accuracy in some of these applications may, however, be uncertain.

A number of simple methods have been suggested to calculate the effective height of a stack on a building roof. The Group believes that these methods do not give an adequate prediction of the concentration close to the building. However, the method given by Hunt et al[22] may be used to determine the effective stack height for use in calculating concentrations beyond the wake region.

C7. SOURCES ABOVE OR WITHIN THE BUILDING MAIN WAKE

The enhanced turbulence, reduced wind speed and trailing vorticity generated by a building can persist for a long distance down-wind. When trailing vorticity effects are pronounced (eg, a cuboid at significant incidence) the dispersion of material emitted down-wind of the building may be considerably affected. For example, Barrett et al[23] observed increased maximum ground-level concentrations for sources of various heights (up to $2H_b$) located up to $20H_b$ down-wind of a cube at 45° to the approach flow. There are no simple models available for use in these circumstances. In the absence of trailing vorticity effects (eg, normally orientated cuboids) the model developed by Hunt and Robins[21] may be used.

Hunt et al[22] have considered sources in and above the wake of obstacles which are very large in the cross-wind direction. Some simple results, obtained from their work, are summarised in Figure C5 which is taken from their paper. The left-hand part of this figure shows the path of the streamlines passing over the building while the right-hand part allows the position and magnitude of the peak concentration at ground level to be estimated.

C8. SOURCES ON THE UPWIND FACE, OR ON OR ADJACENT TO THE SIDE FACES OF A BUILDING

Material emitted from the lower part of a front face normal to the approach

flow will enter the upwind recirculation region (Section C4). In other cases, emissions will tend to be swept up and around the front faces, generally forming a deep, broad plume down-wind, and the models of Section C5 will overestimate resulting plume centre-line concentrations, but underestimate plume dimensions. The same is likely to be true for emissions from a generally porous building. Side-face emissions, and adjacent ground-level emissions, behave in quite complex manners and no simple predictive models can be recommended. The ground-level emission adjacent to a building behaves somewhat analogously to an elevated emission. Part of the emission may be entrained into the near-wake, the remainder forming a relatively compact adjacent plume with high centre-line concentrations[24]. Small-scale features of building geometry can have a considerable effect in such circumstances.

Empirically defined upper bounds to concentrations on the surface of the emitting building, at a given distance from the source, may be obtained from the work of Wilson and Britter[10] for a neutrally buoyant material. Care should be exercised in the use of such predictions if, for example, ventilation air quality is being studied and the possibility exists for recirculation of emitted material.

C9. STABILITY AND SITE LAY-OUT EFFECTS

Of the models presented, those of Barker[18], for entrained emissions, and Hunt and Robins[21], for elevated emissions, include effects of stability; the near-wake model[12] and the building-surface concentration model[10] do not. This roughly accords with available observational evidence, though the evidence is by no means comprehensive.

In strongly stable conditions roof-level emissions have been observed to travel down-wind without entrainment into the near-wake[25], suggesting that equation (C1) may need modification in such circumstances. For low-level emissions from, or close to, a building the effects of source location, wind direction and building geometry appear to dominate those of flow stability, insofar as concentrations close to the building are concerned. Clearly, the more remote a source is from nearby buildings the more important the effects of stability are likely to be and, even for sources on or very close to buildings, stability must obviously re-assert itself sufficiently far down-wind. The evidence also suggests that in the near field, at least, the influence of small-scale features of real sites can be profound[24]. For elevated emissions, or further down-wind, these effects become less important. However, care must be exercised in choosing the relevant building dimensions for use with the virtual-source model.

C10. THE NEED FOR PHYSICAL MODELLING

It is clear from the foregoing account that there are many circumstances in which it is not possible to put forward mathematical models, or the use of the

proposed models is very questionable. This is not surprising, as the flow and the dispersion of emitted material in the vicinity of an industrial site can be very complex. Some of the problems have been identified in this report, though the list is by no means comprehensive. Physical modelling, either in air or water, offers the prospect of realistic solutions to many of these problems, provided the modelling is properly performed and the limitations of the techniques employed are fully acknowledged[26]. Included in such studies can be the effects of emission buoyancy[27] and momentum, the investigation of unsteady emissions, and the measurement of extreme short-term concentration levels[24]. The effects of buoyancy and momentum are considered in more detail in the plume-rise section of this report.

C11. REFERENCES

1. Hosker, R P, Methods for estimating wake flow and effluent dispersion near simple block-like structures. NOAA, Technical Memorandum ERL-ARL-108 (1981).

2. Fackrell, J E, Flow behaviour near isolated rectangular buildings. Central Electricity Generating Board, Report TPRD/M/1254/N82 (1982).

3. Robins, A G and Fackrell, J E, Paper presented at CEC seminar on 'Radioactive releases and their dispersion in the atmosphere following a hypothetical reactor accident' at RISO, Denmark, April 1980.

4. Hunt, J C R, Abell, C J, Peterka, J A and Woo, H, Kinematical studies of the flows around free or surface mounted obstacles, applying topology to flow visualisation. J. Fluid Mech., 86, 179 (1978).

5. Counihan, J, Hunt, J C R and Jackson, P S, Wakes behind 2-dimensional surface obstacles in turbulent boundary layers. J. Fluid Mech., 64, 529 (1974).

6. Castro, I C and Robins, A G, The flow around a surface-mounted cube in uniform and turbulent streams. J. Fluid Mech., 79, 307 (1977).

7. Mansen, A C, PhD Thesis, Colorado State Univ. (1975).

8. Robins, A G and Castro, I C, A wind tunnel investigation of plume dispersion in the vicinity of a surface mounted cube, Part 1. Flow field. Atmos. Environ., 11, 291 (1977).

9. Thompson, R S and Lombardi, D J, Dispersion of roof-top emissions from isolated buildings – a wind tunnel study. EPA-600/4-77-006 (January 1977).

10. Wilson, D J and Britter, R E, Predicting maximum building surface concentrations from nearby point source emissions. Presented at the Air Pollution Aerodynamics Symposium, American Society of Civil Engineers Fall Convention, St Louis, Missouri, October 1981.

11. Robins, A G, The dispersion of fume cupboard emissions in the atmosphere. Central Electricity Generating Board, Report TPRD/M/1221/N82 (1982).

12. Fackrell, J E and Pearce, J E, Parameters affecting dispersion in the near wake of buildings. Central Electricity Generating Board, Report RD/M/1179/N81 (1981).

13. Vincent, J H, Model experiments on the nature of air pollution transport near buildings. Atmos. Environ., 11, 765 (1977).

14. Vincent, J H, Scalar transport in the near aerodynamic wakes of surface mounted cubes. Atmos. Environ., 12, 1319 (1978).

15. Fackrell, J E, Flow behaviour near isolated rectangular buildings. Central Electricity Generating Board, Report 7PRD/M/1254/N82 (1982).

16. Hall, D J, Private communication.

17. Fackrell, J E, An examination of simple models for building influenced dispersion. Central Electricity Generating Board, Report RD/M/1194/N81 (1981).

18. Barker, C D, The application of the virtual source entrainment model in nuclear safety calculations. Central Electricity Generating Board, Report RD/B/5238/N82 (1982).

19. Hunt, J C R, Mechanism for dispersion of pollution around buildings and vehicles. IN Proceedings BMFT/TUV Colloquium on Exhaust Gas Air Pollution Caused by Motor Vehicle Emissions, Cologne, Oct 1981. To be published.

20. Huber, A H and Snyder, W H, Wind tunnel investigations of the effects of a rectangular shaped building on dispersion of effluents from short adjacent stacks. Atmos. Environ., 16, 2837 (1982).

21. Hunt, J C R and Robins, A G, The dispersion of passive emissions near buildings. Central Electricity Generating Board, Report TPRD/M/1285/N82 (in press).

22. Hunt, J C R, Britter, R E and Puttock, J S, Mathematical models of dispersion of air pollution around buildings and hills. IN Mathematical Modelling of Turbulent Diffusion in the Environment (Harris, J, ed.). London, Academic Press (1979).

23. Barrett, C F, Hall, D J and Simmonds, A C, Paper presented at NATO/CCMS 9th International Meeting on Air pollution Modelling and its Applications, Toronto, Canada, August 1978.

24. Fackrell, J E and Robins, A G, Dispersion of releases from an AGR site. Central Electricity Generating Board, Report RD/M/1172/R81 (1982).

25. Start, G E, Cate, J H, Dickson, C R, Ricks, N R, Ackerman, G R and Sagendorf, J R, Rancho Seco building wake effects on atmospheric dispersion. NUREG/CR-0456 (1978).

26. Snyder, W H, Guidelines for fluid modeling of atmospheric diffusion. EPA-600/8-81-009, 1981.

27. Hall, D J, Barrett, L F and Simmonds, A C, Wind tunnel model experiments on a buoyant emission from a building. Warren Spring Laboratories, Report LR 355 (AP) (1980).

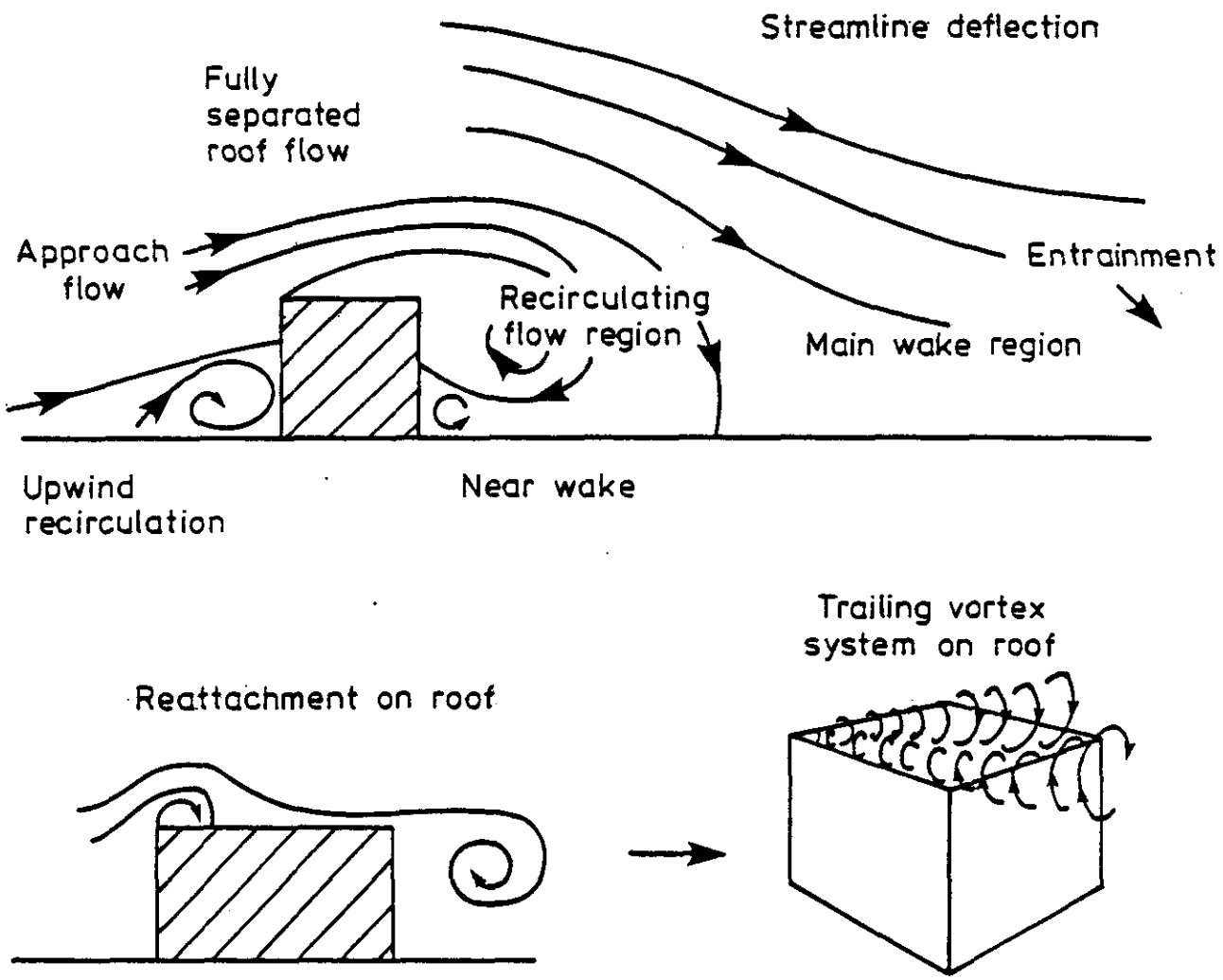


Figure C1 Important aspects of the flow around a building

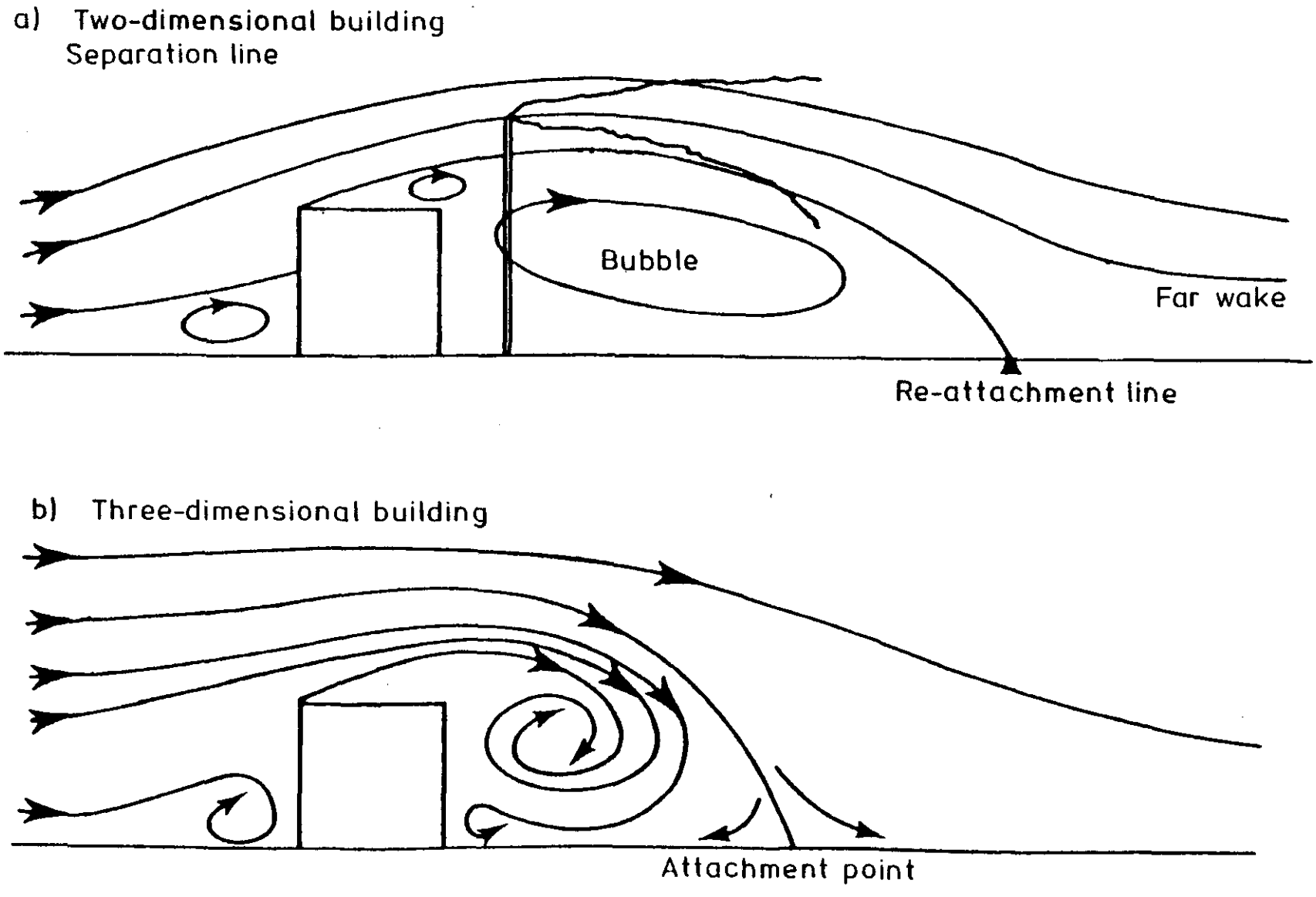


Figure C2 Streamlines in the wake regions specified after Hunt et al.(Reference 4)

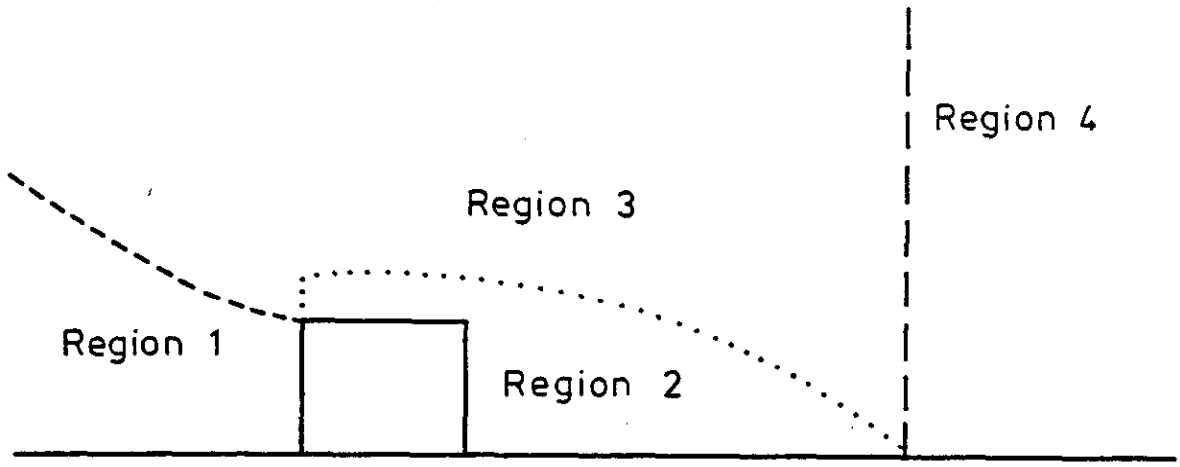
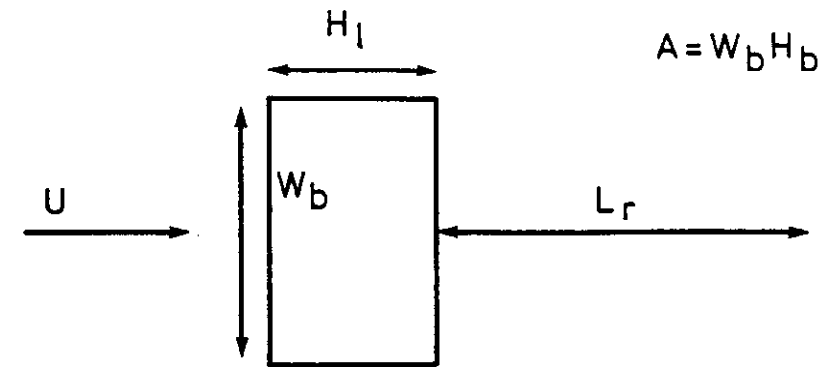
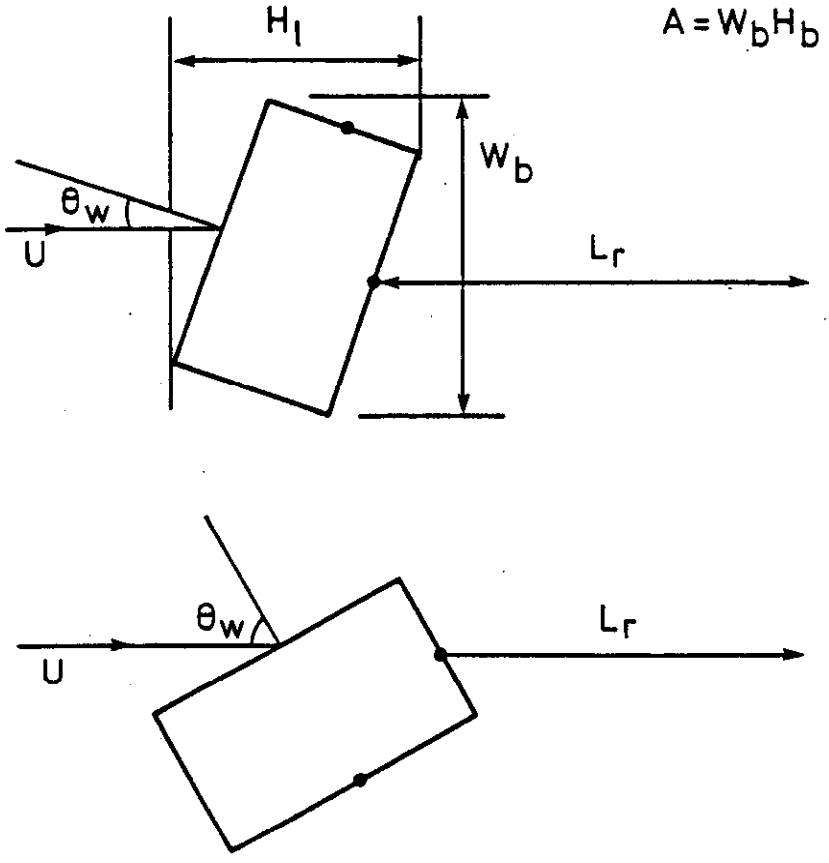


Figure C3 Source regions considered

(Note: Region 5 includes the upwind and side faces and spaces adjacent to the latter)

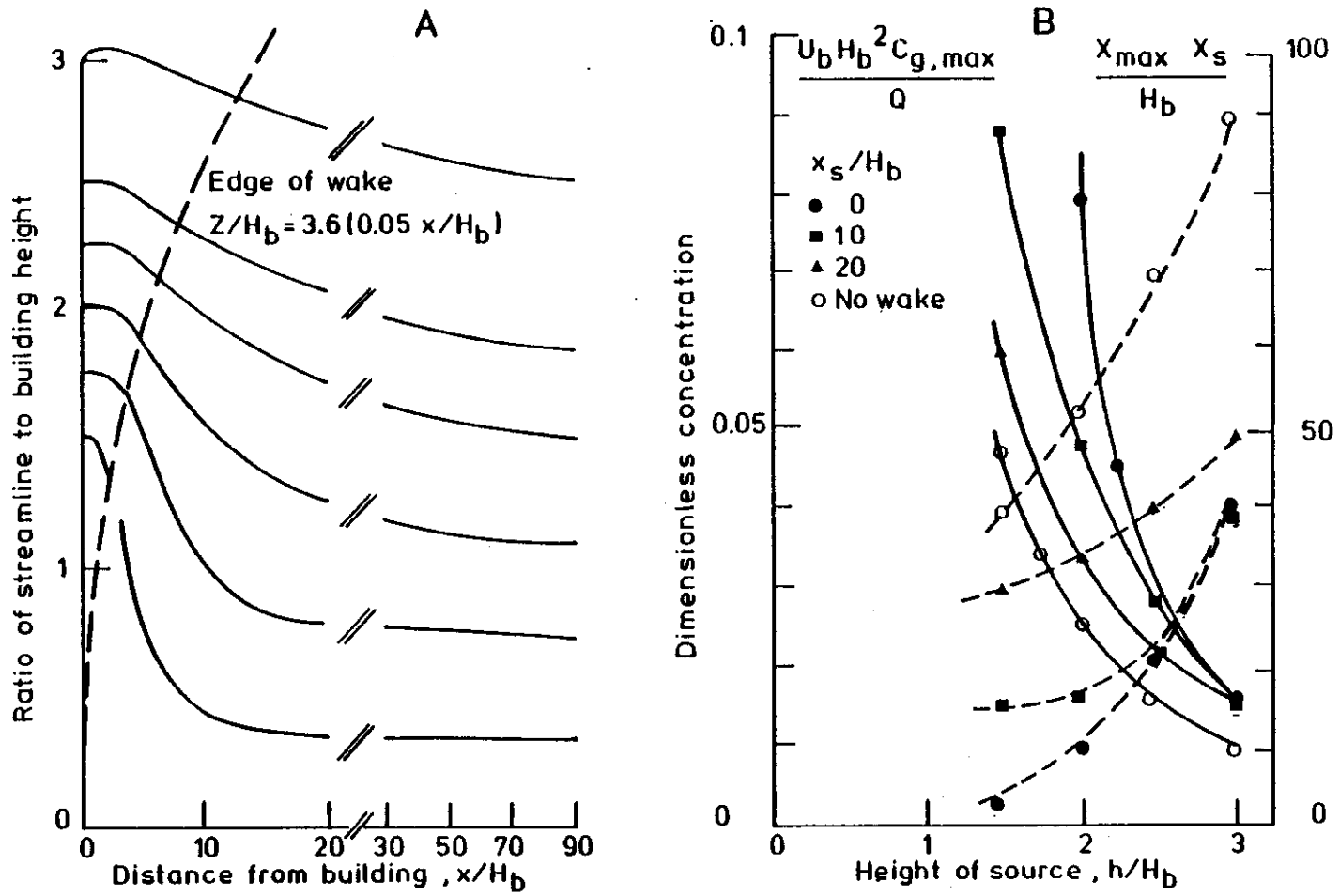


a) Building normally orientated



b) Building incidence θ_w
(W_{be}, H_l - effective dimensions)

Figure C4 Definitions of effective dimensions, wind direction and recirculation region length



a Downwind path of main streamlines

b The value $C_{g,max}$ and position X_{max} of the maximum ground level concentration as a function of the ratio of the height (h) of the source to the height (H_b) of the obstacle, and of the distance of the source downwind of the obstacle, x_s (theoretical estimation)

Figure C5 A typical wake behind a two-dimensional bluff surface obstacle in a turbulent boundary layer

D — GUIDANCE ON THE VALUE OF DEPOSITION VELOCITY AND WASHOUT COEFFICIENT

D1. INTRODUCTION

The Working Group, in its second report[1], described models for calculating dry and wet deposition rates and methods of allowing for plume depletion when calculating concentrations of pollutants in air. However, it did not give any guidance on the values of the parameters for use in the models suggested, referring the user of the models to recent reviews[2,3]. The Group has now considered the information from these reviews and other sources. This report represents the Group's guidance on the values of the parameters to be used in its models.

The Group draws the attention of users of this report to the considerable uncertainty involved in specifying values of deposition velocity and washout coefficient appropriate to a specified situation. The values given in this report represent the best judgement of the Group on the topics concerned and are subject to the caveats given in the report. However, the Group expects a user of its models to undertake sensitivity studies to investigate the importance of accurately specifying deposition velocity and washout coefficient in any particular situation.

D2. DRY DEPOSITION

In its second report[1] the Working Group suggested that dry deposition rates be calculated using the deposition velocity V_g defined[4] as

$$\text{deposition velocity} = \frac{\text{total activity deposited per unit area}}{\text{time integrated air concentration per unit volume}}$$

with the concentration measured at some convenient height. Most available measurements of deposition velocity are based on concentration measurements at a height of about 1 metre above the surface. The Group believes that, when using the model in its second report, it is sufficient to calculate the deposition rate using a deposition velocity appropriate to a height of a few metres and the concentration calculated from the Gaussian model at ground level (ie, $z = 0$).

D2.1 Processes affecting dry deposition

Dry deposition is a very complex process. The deposition rate is affected by the state of the atmosphere, the state of the surface and the state of the depositing material. Sehmel[3] has given a list of about 50 quantities which may affect the deposition velocity. The processes which give rise to dry deposition also occur during wet conditions. However, the deposition rates to wet and dry surfaces could be different.

Transport between the reference height used in defining the deposition velocity and the ground can be considered in terms of three processes, ie, transport through the turbulent boundary layer, transport through the viscous

boundary layer on grass, leaves, etc, and an interaction with the surface itself. Despite the complexity of the deposition process, dominant mechanisms can be identified for each of these stages and are summarised in Table D1[5]. The deposition velocity can be expressed in terms of the resistance to transfer through these layers and to the surface as

$$V_g^{-1} = r_a + r_b + r_s \qquad \ldots\ldots (D1)$$

where r_a, r_b and r_s are as identified in Table D1.
The quantities r_a and r_b are identified separately in this equation for consistency with other reports; however, only their sum is considered in this report.

The dominant transfer processes through the turbulent and laminar boundary layers are fairly well understood and the appropriate resistances can be calculated[2,5,6]. They depend on the surface roughness and atmospheric stability conditions. Typical values, applicable to gases, are given in Figure D1. The resistance to transfer in the lowest layers of the atmosphere imposes an upper limit on the value of the deposition velocity. In stable conditions this value is of the order of 10^{-2} m s^{-1}.

D2.2 Deposition velocity to grass in neutral conditions

Values of the deposition velocity suggested by the Group for four types of material are given in Table D2. The values are appropriate to neutral stability and for deposition to grass. The variation of deposition velocity with particle size is shown in Figure D2[2]. The variation with particle size is such that for an aerosol with a broad size distribution it may be necessary either to choose a different value, or to consider portions of the aerosol to have different deposition velocities. The user should undertake sensitivity studies on this point.

The values quoted for reactive gases are intended primarily for elemental iodine and are for use at short distances from the release. There is some evidence that the deposition velocity of elemental iodine decreases with increasing travel distance, perhaps because the chemical form of the iodine changes. There are a number of other gases, such as methyl iodide, carbonyl sulphide and hydrogen sulphide, for which these values are not appropriate.

The Group has only been able to propose a range of values for the deposition velocity. Values outside the range given here have been reported in the literature. Judgement has been applied to specify what the Group considers to be a realistic range of values. No clear definition can be given of what the extremes of the range represent in terms of the probability of the true value of deposition velocity being within the range. A number of workers have reported values for deposition velocity of elemental iodine in excess of 10^{-2} m s^{-1}. The Group considers that these results may be unrepresentative of general conditions. The user of dispersion models must select a value by considering the ranges

specified here or elswhere in the literature. The value chosen will depend on the purpose of the calculation being undertaken (eg, a pessimistic value would be chosen if the objective is to demonstrate compliance with dose limits, but a realistic value would be used for optimisation studies).

D2.3 Deposition velocity for other conditions

A number of reviews of deposition velocity have been undertaken, the most comprehensive being those by Slinn[2] and Sehmel[3]. Garland[5] has given a description of the reasons why deposition velocity varies with surface and atmospheric conditions.

Variation of $(r_a + r_b)$ with surface roughness has been investigated for vegetation, and typical results are shown in Figure D1. For some reactive gases r_s is higher for tall vegetation, compensating for the lower $(r_a + r_b)$, so that V_g varies little with vegetation height. For urban areas there are some reasons to suggest that r_b should be large, although direct evidence is lacking. Although iodine is absorbed readily by some building materials it is likely that deposition is no higher in towns than it is on pasture. Information on the deposition of particles to tall vegetation (other than forest canopies) and urban areas is also very sparse and the little evidence that exists suggests that the deposition velocity is not much greater than for grassland. What little evidence is available for deposition of particles to smooth surfaces, such as water, suggests that the deposition velocity may be somewhat lower than to grass.

Variation of $(r_a + r_b)$ with atmospheric conditions is largely determined by its variation with wind speed, as shown in Figure D1. In stable conditions with a low wind speed the value of $(r_a + r_b)$ is greater than that at higher wind speed. Therefore, the deposition velocity in stable conditions could be lower than that given in Table D2. The surface component r_s depends on the plant stomata and could be different at night than in daylight.

D3. WET DEPOSITION

In its second report[1] the Working Group described a model intended for use when calculating long-term average deposition rates in any form of precipitation. The model used the concept of a wet removal coefficient, defined as the fraction of material in the plume removed by the precipitation per unit time. This section gives guidance on the values to be used for the removal coefficient. The model given for predicting the amount of material left in the plume in the Group's second report is based on a statistical treatment of the sequence of wet and dry conditions affecting a dispersing plume. Therefore, it is not appropriate for use with a specific short release. However, the concept of a wet removal coefficient is applicable to short releases and comments are made on the choice of a value for use in calculations relating to short releases.

D3.1 Processes affecting wet deposition

Wet deposition is a very complex process but can, at least partially, be considered as the sum of two components, washout and rainout. Washout is the removal of material from a plume by rain falling through it, while rainout is the removal of material which has been carried into the rain-cloud itself. Similar processes can be identified for removal by snow.

Washout is affected by the size distribution of the rain drops as well as by properties of the diffusing material. Rainout is governed by condensation processes within the cloud and by the rate at which diffusing material is swept into a rain-cloud. It is very difficult to separate contributions due to rainout and washout, so guidance is given on the value of a wet removal coefficient incorporating the effects of both processes. Its use at short distances will tend to overestimate the deposition rate, as rainout does not occur while the plume is contained in the lower parts of the mixing layer.

D3.2 Sources of information on the wet removal coefficient

Washout coefficients can be estimated theoretically by considering the size distribution of raindrops and the collection efficiency of the dispersing material. Calculations suggest that, at a rainfall rate of 1 mm h^{-1}, the washout coefficient of 1 μm particles is about 4 10^{-5} s^{-1} while that for 20 μm particles is about 3 10^{-4} s^{-1}[4,7]. Wet removal coefficients can also be derived from washout ratios; these are defined as the ratio of activity concentration per unit mass of rain-water to the activity concentration per unit mass of air[2]. A number of experiments have been carried out to measure wet removal coefficients, some of which are reviewed by Slinn[2], and by Brenk and Vogt[8].

D3.3 Value of the wet removal coefficient

Suggested values of the wet removal coefficient are given in Table D2 for four types of material. The values are applicable to a rainfall rate of 1 mm h^{-1}, and reflect the combined effects of washout and rain-out. They are intended for use in the Group's recommended model for wet deposition, which was derived for continuous releases and is only applicable to short releases in a limited range of circumstances.

Two comments should be made on the use of a washout coefficient for reactive gases. Firstly, gas removed from the plume is dissolved in the raindrops, which could become saturated and so unable to remove any more material from the plume. This effect is unlikely to modify the removal rate other than for very large accidental releases. Secondly, processes whereby reactive gases are removed by rain are reversible. Therefore, material could evaporate from raindrops which have fallen through an elevated plume while they are falling through the low-concentration regions below the plume. This could have the effect of reducing the effective height of part of the dispersing material. This process is only likely to be important at distances shorter than that of the maximum ground-level concentration.

As with the deposition velocity, a range of values for the wet removal coefficient has been specified. The user must choose an appropriate value for his own purposes, preferably after carrying out a sensitivity study.

D3.4 The variation with rainfall rate and particle size

The variation of washout coefficient with rainfall rate is not very large. The washout coefficient has been found to be proportional to rainfall rate to a power between 0.5 and 1.0[7,8]. The Group considers that it is adequate to ignore the variation of washout coefficient with rainfall rate, and to assume that all rain falls at a rate of 1 mm h^{-1}, close to the UK average rainfall rate, when calculating long-term average deposition rates.

Although the values for the wet removal coefficient given in this report are intended for use in modelling deposition from continuous releases, a few comments on the value for short releases are included for completeness. When calculating wet deposition rates from a short release the type and intensity of the precipitation must be considered. The relative removal efficiencies of rain, hail and snow are uncertain. The spatial and temporal extent of the rain must also be considered. Localised showers may effectively punch holes in a large cloud of dispersing material; thunderstorms can act rather like giant vacuum cleaners pulling in air from the mixing layer in a strong convergence and removing the pollutant in rain as it is carried up in the thunder cell, possibly leading to very high deposition over a localised area. Frontal rain, however, tends to be fairly uniform along a broad frontal zone. Material in the boundary layer ahead of the front does not easily penetrate the frontal zone into the cloud and so is affected by washout only. Rainfall intensity is often correlated with the spatial and temporal extent of the rain. These features of wet-deposition models have not been considered by the Group, which considers its recommendation to be appropriate for average conditions and continuous releases.

Calculations suggest that at rainfall rates of a few millimetres per hour the washout coefficient of particles increases rapidly with particle size and that the removal processes for 1 μm particles are not particularly efficient. Experimental data generally support the calculations for large particles but suggest that small particles are washed out more efficiently than the theory suggests. This could be a result of small particles collecting on water droplets in the air if the humidity is high.

D4. THE INTERCEPTION OF DEPOSITS FROM ATMOSPHERE BY PLANTS

The values given in this report for deposition velocities and washout coefficients represent deposition on to the total ground area, and an additional factor is required to determine the amount of material which is deposited on the edible parts of plants. The amount of airborne contamination which is captured and retained by plants is determined by various complex physical mechanisms and much depends on particle size, wind speed and the nature of the plant surface[9].

The interception and retention of particulates on plants is often represented by a combination of two parameters; the interception factor, ie, the fraction of the total deposit which is initially intercepted by the plant, and the retention half-life, which represents losses by physical and biological processes.

The interception of airborne materials on the portions of pasture grass eaten by grazing animals has been well studied. Chamberlain has reviewed the available experimental data and found that the interception factor, p_i, is related to the herbage density by the following expression[10]

$$1 - p_i = \exp(-\mu w)$$

where w is the herbage density, dry weight (kg m^{-2})

and μ the uptake coefficient (m^2 kg^{-1}).

Values of μ for a variety of different contaminants on pasture grass were found to be in the range 2.3–3.3 m^2 kg^{-1}[10]. From the expression given above, for the average herbage density in the UK of 0.1 kg m^{-2} (dry weight), the interception factor p_i is between 0.20 and 0.28. The value of 0.25 commonly used in generic modelling studies is in the middle of this range of values. It seems reasonable to assume that the interception factor will vary with the state of the grass, eg, wet grass might reduce particle bounce and so increase the interception. However, the expression above was found to give a reliable prediction of interception factor for a wide range of conditions.

For crops consumed directly by man fewer experimental data are available and the situation is complicated by the need to know the concentration of material on the plant at harvest, which will vary depending on when deposition occurred relative to the growing cycle of the plant. It is not, therefore, possible to recommend interception factors for crops, such as green vegetables and grain, for use in generic studies particularly for single deposits. In a recent review[11] representative values of interception factor and retention half-time have been derived, for leafy vegetables and grain, for use when there is continuous deposition from atmosphere.

D5. REFERENCES

1. Jones, J A, The second report of a Working Group on Atmospheric Dispersion: A procedure to include deposition in the model for short and medium range atmospheric dispersion of radionuclides. Chilton, NRPB-R122 (1981) (London, HMSO).

2. Slinn, W G N, Parameterizations for resuspension and for wet and dry deposition of particles and gases for use in radiation dose calculations. Nucl. Saf., 19, 205 (1978).

3. Sehmel, G A, Particles and gas dry deposition: a review. Atmos. Environ., 14, 983 (1980).

4. Chamberlain, A C, Aspects of travel and deposition of aerosol and vapour clouds. Harwell, UKAEA, AERE-HP/R1261 (1953).

5. Garland, J A, Surface deposition from radioactive plumes. IN Proceedings CEC Seminar on Radioactive Releases and their Dispersion in the Atmosphere following a Hypothetical Reactor Accident, Riso, April 1980. Luxembourg, CEC, Doc. No. V/4111/80 (1980).

6. Fisher, B E A, Long range transport and deposition of sulphur oxide. IN Sulphur in the Environment (Nriagu, J O, ed.). New York, Wiley-Interscience (1978).

7. Engelman, R J, The calculation of precipitation scavenging. IN Meteorology and Atomic Energy, 1968 (Slade, D H, ed.). USAEC, Report TID-24190 (1968).

8. Brenk, H D and Vogt, K J, The calculation of wet deposition from radioactive plumes. Nucl. Saf., 22, 362 (1981).

9. Chamberlain, A C and Little, P, Transport and capture of particles by vegetation. IN Plants and their Atmospheric Environment. Proceedings of the British Ecology Society Symposium, Edinburgh (1979).

10. Chamberlain, A C, Interception and retention of radioactive aerosols by vegetation. Atmos. Environ., 4, 57 (1970).

11. Simmonds, J R and Linsley, G S, Parameters for modelling the interception and retention of deposits from atmosphere by grain and leafy vegetables. Health Phys., 43, 679 (1982).

Table D1

Summary of processes operating in transfer of gases and particles to rough surfaces

Resistance Component	Region	Dominant transfer processes		
		Gases	Sub-micron particles	Particles of approximate size 1.0 μm
r_a	Turbulent boundary layer	Turbulent transport	Turbulent transport	Turbulent transport + sedimentation
r_b	Laminar sub-layer	Molecular diffusion	Brownian motion	Inertial impaction
r_s	Surface	Chemical properties controlling diffusion through stomato may be important	Particles adhere on contact	Interception bounce-off may be important

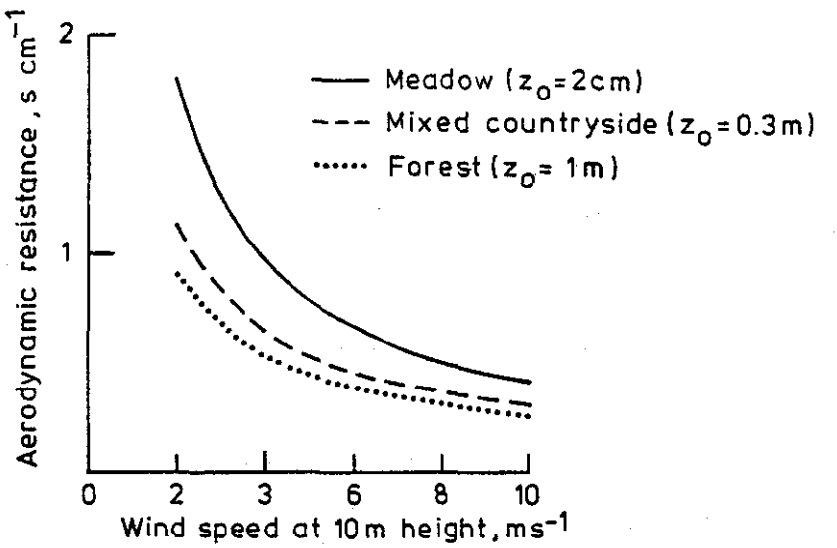
Table D2

Suggested values of deposition velocity and the wet removal coefficient

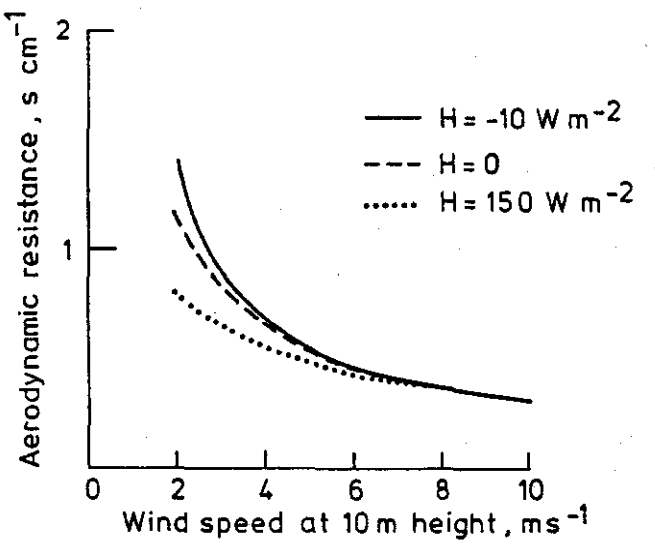
Type of material	Deposition velocity[1] $m\ s^{-1}$	Wet removal coefficient[2] s^{-1}
Noble gas	0	0
Reactive gas	10^{-3} to 10^{-2}	3.10^{-5} to 3.10^{-4}
Particles ~ 1 μm AD	10^{-4} to 10^{-3}	3.10^{-5} to 3.10^{-4}
Particles ~ 10 μm AD	10^{-2} to 3.10^{-2}	3.10^{-5} to 3.10^{-4}

Notes:

1. Applicable to neutral stability and deposition to grass.
2. For a rainfall rate of 1 mm h^{-1}.



a) Variation of aerodynamic resistance for iodine vapour at various surfaces in neutral conditions



b) Variation of aerodynamic resistance for iodine vapour with wind speed for mixed countryside (z_o =0.3 m), showing the effect of surface heat flux in conditions of moderate daytime heating (H = 150 W m^{-2}), neutral and moderate nocturnal cooling (H =-10 W m^{-2})

Figure D1 The effects of wind speed and surface roughness (a) and of surface heat flux (b) on the aerodynamic resistance for deposition of iodine vapour to terrestrial surfaces

Papers quoted in Figure D2

Chamberlain, A C, Transport of gases to and from grass and grasslike surfaces. Proc. R. Soc. London, Ser. A, 290, 236 (1966).

Clough, W S, Transport of particles to surfaces. J. Aerosol Sci., 4, 227 (1973).

Sehmel, G A and Suther, F C, Particle deposition rates on a water surface as a function of particle diameter and air velocity. J. de Rech. Atmos., 8, 911 (1974).

Möller, U and Schumann, G, Mechanisms of transport from the atmosphere to the earth's surface. J. Geophys. Res., 75, 3013 (1970).

Sehmel, G A, Hodgson, W H and Sutter, S L, Dry deposition of particles. IN Pacific Northwest Laboratory Annual Report for 1973 to the USAEC Division of Biomedical and Environmental Research, Part 3, Atmospheric Sciences. USAEC Report BNWL-1850 (Pt 3), p157, Battelle Pacific Northwest Laboratories, NTIS (1974).

Sehmel, G A, Sutter, S L and Dand, M T, Dry deposition processes. IN Pacific Northwest Laboratory Annual Report for 1972 to the USAEC Division of Biomedical and Environmental Research, Volume II, Physical Sciences, Part 1, Atmospheric Sciences. USAEC Report BNWL-1751 (Pt 1), p43, Battelle Pacific Northwest Laboratories, NTIS (1973).

Weseley, M L, Hicks, B B, Dannevik, W P, Frisella, S and Husar, R B, An eddy-correlation measurement of particulate deposition from the atmosphere. Atmos. Environ., 11, 561 (1977).

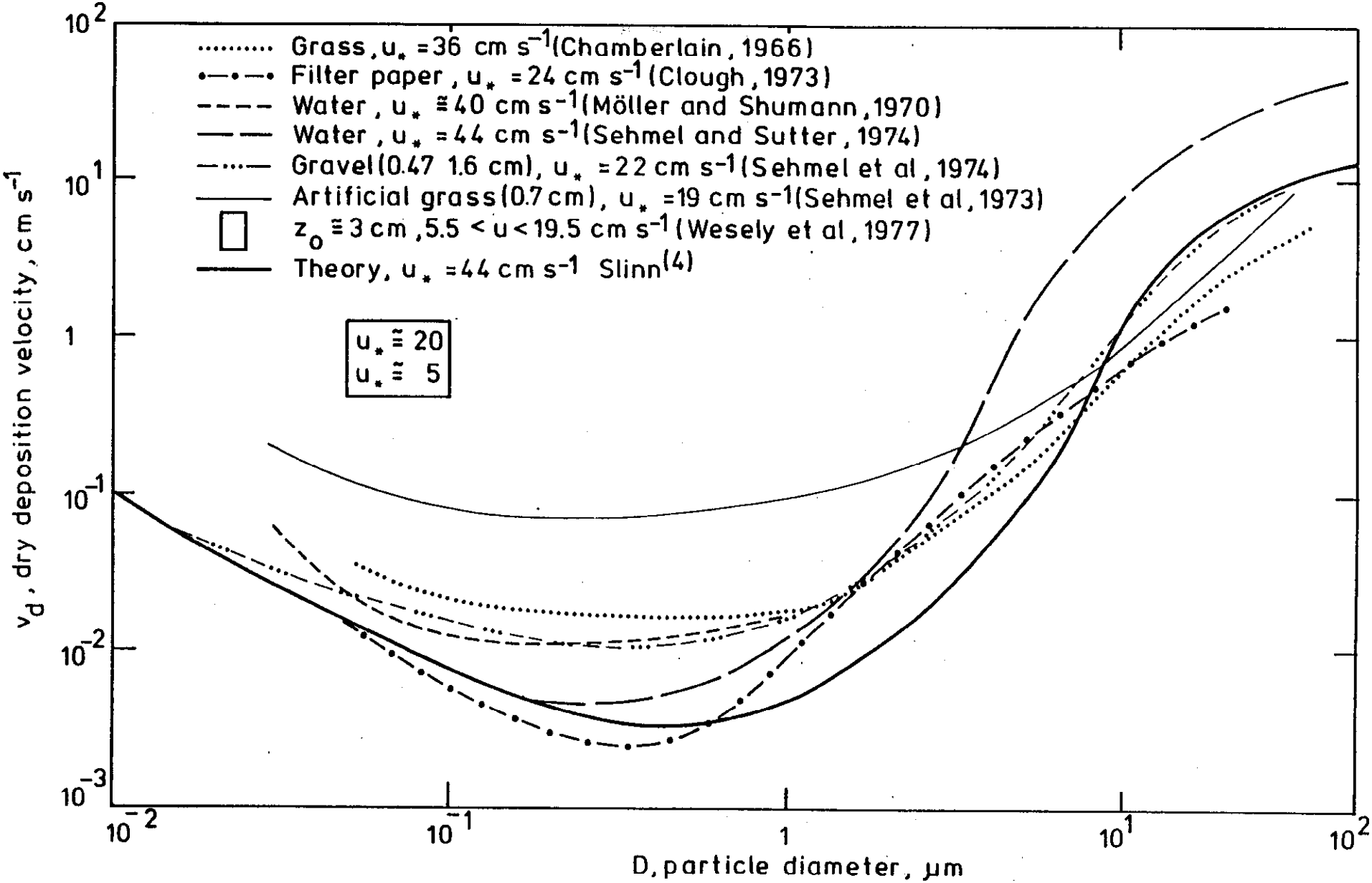


Figure D2 The variation of deposition velocity with particle size and underlying surface (Taken from reference 4)