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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

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Chilton, Didcot, Oxon OX11 0RQ
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ABSTRACT

This report is the third in a series giving practical guidance on the estimation of the dispersion of radioactive material 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 a method considered suitable to extend the models described in the first and second reports for dispersion and deposition at short and medium range to long range for continuous releases.

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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)	$1\ Bq \sim 2.7 \times 10^{-11}\ Ci$

FOREWORD

In December 1977 a meeting of representative of Government Departments, utilities and research organisations was held to discuss methods of calculation of atmospheric dispersion for radioactive releases. Those present agreed on the need for a review of recent developments in atmospheric dispersion modelling and a Working Group was established in order to facilitate the review. The Working Group has published its first report giving practical guidance on the estimation of 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 refers specifically to nuclides which do not deposit on the ground and are not removed from the plume by an interaction with rain. The Group has also published its second report describing methods for including dry and wet deposition in the models given in its first report.

This report, the third by the Group, describes a method for extending the models given in the first and second reports to a range of about a thousand kilometres for continuous releases. The Group is also preparing its fourth report describing a model for calculating air concentration and deposition rate at a few hundred kilometres from the release point for a short duration release. Other topics under consideration by the Group include building effects, effects of topography including coastal sites, plume rise, dispersion of large particles, and appropriate values for deposition velocity and washout coefficient.

The membership of the Working Group for most of the time during which 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
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Dr J A Jones (Secretary)	National Radiological Protection Board

The Group received considerable assistance from

Dr J C R Hunt	Department of Applied Mathematics and Theoretical Physics, Cambridge University
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who attended primarily to advise it on other topics.

1. INTRODUCTION

The problem of predicting the dispersion of airborne material released from a source is commonly approached by solving the diffusion-transport equation. Several models are available to solve the equation depending on the boundary conditions imposed and simplifying assumptions used. The Working Group, in its first report(1), reviewed some of these models and proposed a model for use when calculating activity concentrations in air for both short and continuous releases of radioactive material to atmosphere. That model was restricted to non-depositing material and to distances for which the topographical and meteorological conditions remain constant. The Group has prepared further reports describing methods for extending its original model to include dry and wet deposition(2) and describing a model for long-range dispersion for a short release(3).

This report is the third by the Group and describes a model for calculating activity concentrations in air and deposition rates at long range from a continuous release. This report contains a brief outline of the models for continuous releases in the Group's first and second reports as these models form the basis of the proposals given here.

2. THE ORIGINAL MODEL FOR A CONTINUOUS RELEASE

In its first report the Group proposed the use of a Gaussian plume model. The Group was aware of more complex models which give a physically more realistic description of the dispersion process, but considered that there was insufficient evidence that the results of these models are either sufficiently different from or more reliable than those of Gaussian models to justify their greater complexity and the increased computer time required. A further reason for choosing the simple Gaussian model was the relative ease with which it can be extended to include other effects, such as deposition of activity on to the ground and long-range dispersion.

This section gives a brief description of the original model for a continuous release, derived for a non-depositing material, and the method of including deposition in that model. The range of applicability of the model was for distances over which the meteorological conditions remain constant. The equations of the original model were considered by the Working Group to be suitable for use in its model for dispersion at long range.

The model assumed that the vertical distribution of activity is Gaussian, modified by reflections at both the ground and the top of the mixing layer at short distances, and becomes uniform at greater distances from the source; the horizontal distribution is assumed to be constant across a sector of angular width α. The concentration C for a non-depositing nuclide in a particular sector i and atmospheric condition j is then given by

$$C_{ij}(r,z) = \frac{Q}{\sqrt{2\pi}\ r\ \alpha\ u_j\ \sigma_{zj}}\ F_j(h,z,A_j) \qquad \text{..........} \ (1a)$$

if $\sigma_z < A_j$

and $$C_{ij}(r,z) = \frac{Q}{r \alpha u_j A_j} \quad \text{.......... (1b)}$$

$$\text{if} \quad \sigma_{zj} > A_j$$

where r is the horizontal distance from the source (m),

z is the height above ground (m)

α is the angular width of the sector (radians)

u is the wind speed ($m\ s^{-1}$)

σ_z is the standard deviation of the vertical Gaussian distribution (m)

h is the effective release height (m)

A is the depth of the mixing layer (m)

Q is the release rate (unit s^{-1})

and where

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

$$\exp\left[-\frac{(2A-z+h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(2A+z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(2A+z+h)^2}{2\sigma_z^2}\right]$$

The annual average concentration in the ith sector may then be obtained by summing the activity concentration in air obtained for each set of atmospheric conditions weighted by the fractional occurrence of those conditions, ie,

$$C_i(r,z) = \sum_j f_{ij}\, C_{ij}(r,z) \quad \text{.......... (2)}$$

where f_{ij} is the frequency of atmospheric condition j within the ith sector, such that $\sum_{ij} f_{ij} = 1$

The activity concentration in air of a nuclide subject to dry deposition is given by equations (1) and (2) when the release rate Q is replaced by the amount of material remaining in the plume at a given distance $Q^*(r)$, given by

$$Q_j^*(r) = Q\left[\exp F_{Dj}(r)\right]^{V_g/u_j} \quad \text{.......... (3)}$$

where V_g is the deposition velocity ($m\ s^{-1}$)

and

$$F_{Dj}(r) = -\sqrt{\frac{2}{\pi}} \int_o^r \frac{1}{\sigma_{zj}} \left\{\exp\left[-\frac{h^2}{2\sigma_{zj}^2}\right] + \exp\left[-\frac{(h+2A_j)^2}{2\sigma_{zj}^2}\right]\right.$$

$$\left. + \exp\left[-\frac{(h-2A_j)^2}{2\sigma_{zj}^2}\right]\right\} dr'$$

while $\sigma_z(x) < A$

$$\text{and } F_{Dj}(r) = F_{Dj}(r_{cj}) - \left(\frac{r - r_{cj}}{A_j} \right)$$

$$\text{if } \sigma_{zj} > A_j$$

and where r_{cj} is such that $\sigma_{zj}(r_{cj}) = A_j$

The dry deposition rate, D_D, in sector i and stability category j, is then obtained from

$$D_{Dij}(r) = V_g \, C_{ij}(r, z = 0)$$

$$D_{Di}(r) = \sum_j f_{ij} \, D_{Dij}(r) \qquad \text{.......... (4)}$$

$$= V_g \, C_i(r, z = 0)$$

The activity concentration in air and deposition rate of a material subject to wet deposition are obtained by a further modification of the equation in which the release rate Q is replaced by the amount of material remaining in the plume because of wet depletion. The term Q in equation (1) or (3) must be replaced by Q'(t) given by

$$Q'(t) = \frac{Q}{m_1 - m_2} \left[(m_1 + \Lambda f_w) e^{m_2 t} - (m_2 + \Lambda f_w) e^{m_1 t} \right] \qquad \text{.......... (5)}$$

where $m_1 = -\frac{1}{2} \left\{ P_D + P_W + \Lambda - \sqrt{(P_D + P_W + \Lambda)^2 - 4 \Lambda P_D} \right\}$

$m_2 = -\frac{1}{2} \left\{ P_D + P_W + \Lambda + \sqrt{(P_D + P_W + \Lambda)^2 - 4 \Lambda P_D} \right\}$

t is the travel time given by r/u_j

P_D and P_W are the probabilities that dry and wet weather, respectively, will stop in unit time (s^{-1})

Λ is the washout coefficient (s^{-1})

f_w is the fraction of the time for which rain falls in each category, given by $f_w = \frac{P_D}{P_D + P_W}$

The wet deposition rate, D_W, is given by

$$D_{Wij}(r) = \frac{f_{ij} \Lambda \, Q_{wj}(t)}{r \, \alpha \, u_j} \qquad \text{.......... (6)}$$

$$D_{Wi}(r) = \sum_j f_{ij} \, D_{Wij}(r)$$

$$\text{where } Q_w(t) = \frac{f_w Q}{m_1 - m_2} \left[(m_1 + \Lambda) e^{m_2 t} - (m_2 + \Lambda) e^{m_1 t} \right] \qquad \text{.......... (7)}$$

If the material is also subject to dry deposition these equations must be corrected by multiplying $O'_j(t)$ and $Q_{wj}(t)$ by $Q^*_j(r)/Q$ derived from equation (3)

3. THE MODEL FOR DISPERSION AT LONG RANGE FROM A CONTINUOUS RELEASE

3.1 Dispersion at long range

The two main difficulties in modelling long-range dispersion are changes in the wind direction and atmospheric stability condition during the travel time of the plume. The mean duration of a particular stability category is only a few hours and changes in stability category during a plume's travel can affect the rate at which material disperses. As material travels along it disperses vertically and, if conditions remain constant for long enough, will uniformly fill the turbulent mixing layer. Changes in the vertical distribution subsequently reflect changes in the depth of the mixing layer caused by atmospheric stability changes. The depth of the mixing layer during daytime in unstable conditions can be up to a few kilometres, while during the night, when stable conditions occur, it can be as small as a few tens of metres. Material released under stable conditions will initially be retained within the shallow mixing layer. However, the depth of the mixing layer increases when the stable conditions break up and the material then rapidly diffuses throughout the new, deeper layer. When the mixing layer depth reduces in a transition to stable conditions, material can be trapped in the layers above the new mixing layer and prevented from diffusing to the ground. In this situation the concentration at ground level is similar to that found while the layer was much deeper. Material left outside a decreasing mixing layer may be returned to the mixing layer when its depth subsequently increases.

Changes of atmospheric stability before the dispersing material has spread uniformly through the mixing layer affect the subsequent dispersion in two ways. Firstly, the depth of the mixing layer changes allowing material to disperse throughout the new mixing layer. Secondly, the change of stability alters the rate at which the plume increases in size.

The plume, dispersing vertically throughout the mixing layer, is carried along by the wind with a speed which increases with height above the ground. Therefore, as the plume disperses the effective wind-speed will increase.

Changes in wind direction could have only a small effect on the annual average concentration at great distances in a given sector for two reasons. Firstly, the reduction in concentration caused by wind direction changes taking material from one sector will be partly balanced by similar changes in adjacent sectors bringing material into the sector. Secondly, the concentration at great distances is mainly determined by neutral conditions in which the trajectories are likely to be approximately straight. The average trajectory length to points within about 1000 km of a release has been estimated to be only 15% greater than the straight line distance to the points(4).

There is a range of models of differing degrees of complexity available for calculating concentrations and deposition rates at long range from a continuous source. All dispersion models may be considered to consist of the prediction of a plume's trajectory and the calculation of the dispersion along that trajectory. Two model types have been used to predict the plume trajectory. The simpler one assumes that the plume travels in a straight line along the wind direction at the time of release. The more complex method predicts the trajectory using a meteorological data base covering a wide area. Several methods have been used to predict the spread of the plume around its trajectory. The simplest method is to assume that the stability category experienced throughout the period of travel of the material is that occurring when it was discharged. The most complex method is to use a stability category at each point of the plume's trajectory derived from meteorological data bases. A method of intermediate complexity has also been used in which the sequence of atmospheric conditions affecting the plume has been assumed to be that occurring at the release point. In all but the simpler methods it is necessary to represent a continuous release as a series of short releases.

In reaching its conclusions on a model for long-range dispersion from a continuous release, the Group considered the results of studies described below comparing concentrations and deposition rates predicted by a range of models.

One of the studies(5) compared concentrations and deposition rates calculated using Gaussian models allowing for changes of stability during plume travel, with those calculated from a complex trajectory model MESOS. The MESOS code uses a meteorological data base for the whole of Europe to predict dispersion of a continuous release throughout a year by following individual trajectory sequences. Results from this study suggest that a Gaussian model with unchanging categories predicts concentrations at distances of a few hundred kilometres which are about a factor of three higher than those obtained from the trajectory model, while much better agreement is obtained if account is taken of changing categories in the Gaussian model.

A second study(6) compared concentrations, deposition rates and collective exposures predicted by a Gaussian model using several methods of representing a change in stability category during dispersion with those predicted assuming the original stability persisted throughout the plume's travel. The results of this study are briefly described here, as they were an important factor in the Group's choice of model for calculating dispersion at long range from a continuous release.

The study was based on the assumption that the sequence of category changes affecting a dispersing plume could be simplified by considering a single change of category, which was always to neutral stability. The final neutral stability should therefore be considered as a means of averaging over all stabilities. The earlier discussion on the effects on concentration of changes in mixing layer depth suggests that, at great distances from a source, the concentration is determined more by the maximum mixing layer depth encountered during previous travel along the trajectory than at the point at which concentrations are required. In modelling changes from stable to neutral conditions, the mixing layer depth was assumed to increase instantaneously to a value typical of neutral conditions. However, in modelling changes from unstable to neutral conditions, there was assumed to be no reduction in the depth of the mixing layer. As neutral stability can occur for any value of wind-speed there was assumed to be no change in wind-speed during the plume's dispersion even though the stability was changed to neutral.

The interpretation to be placed on the duration of a category in this model needs to be considered and two possible definitions were used in the study. In one the duration of the initial category was taken to be the time until the atmospheric stability becomes more neutral than its initial value, while in the other the duration of the original category was taken to be the time until neutral stability occurred. The probabilities of a category persisting, based on these interpretations of category duration, and obtained from UK meteorological data, are given in Figures 1 and 2.

Different representations of the distribution of duration of the original stability category were also used. In some cases the original category was assumed to change to neutral after persisting for its mean duration, while in others it was divided into a series of sub-categories with differing durations and appropriate frequencies of occurrence.

Concentrations and deposition rates at specific distances from the release point were evaluated for category distribution near the extremes of the range found in the UK, and corresponding to 50% and 80% frequency of category D with other categories as given in the Group's first report. Collective doses for four hypothetical release points in the UK with differing population distributions were calculated for both stability category distributions. The sites were representative of two remote nuclear sites, a site with a large nearby population and a hypothetical site in an urban area. The release was assumed to be from a height of 100 m; results were obtained using the wind-speed at that height. In all cases calculations were undertaken for material which does not deposit and for material subject to dry and wet deposition with a dry deposition velocity of 3.10^{-3} m s^{-1} and a washout coefficient of 10^{-4} s^{-1}. The extreme cases of only-dry or only-wet deposition were also considered, as was the effect of radioactive decay.

Some of the results of this study are given in Tables 1 to 5.

Table 1 gives activity concentration in air and deposition rate at a number of distances calculated using four ways of describing a change of stability category during the plume's travel and also assuming that the initial conditions persist throughout. The following points can be made about the results given in Table 1.

- The concentration or deposition rate calculated assuming that each category persists for a range of times is not sensitive to whether the category duration is taken to be the time before a change towards neutral or the time to reach neutral stability.

- The concentration or deposition rate calculated, assuming that each category persists for its mean duration, is within 10 - 20% of that calculated assuming a range of durations of the original category, with the agreement improving as distance increases. The agreement is, however, likely to be worse than 20% near those distances at which the categories are assumed to change.
- The concentration calculated assuming that each category persists throughout the plume's travel can be up to a factor of three greater than that calculated assuming a change of category. The discrepancy is greatest for a non-depositing nuclide.
- The deposition rate calculated assuming that each category persists throughout the plume's travel is, however, lower than that predicted assuming a category change, because of the different assumptions about the fraction of time that rain falls.
- The concentration and deposition rate calculated assuming only neutral stability but with a range of windspeed and mixing layer depths appropriate to that after a category change is generally within about 20% of that calculated assuming a change of category other than at the shorter distances.
- The concentration and deposition rate calculated assuming only category D tends to be somewhat less than those predicted assuming a change of category.

Table 2 gives a quantity, expressed in units of population multiplied by activity concentration in air, proportional to collective exposures for a continuous discharge of material, which does not deposit to the ground, calculated using different approximations to describe the change in stability category during plume dispersion. Similar results are given in Tables 3 and 4 for a material subject to wet and dry deposition, for collective exposures based on activity concentration in air and deposited activity. The following points can be made about the results given in Tables 2 -4.

- The collective exposure calculated, assuming each category persists for a range of times, is not sensitive to whether category duration is taken to be the time before a change towards neutral or the time to reach neutral stability.
- The collective exposure calculated, assuming the mean duration of each category, is generally within 10% of that calculated assuming a range of duration of the original category.
- The collective exposure calculated, assuming that each category persists throughout the plume's travel, generally overestimates that predicted assuming a change of category. The overestimate is usually less than a

factor of two but is greater for a remote site and for a non-depositing material.

- The collective exposure calculated, assuming only neutral stability but with a range of wind-speeds and mixing layer depths appropriate to that after a category change, is generally within 20% of that calculated using a model explicitly considering the category change.
- The collective exposure calculated assuming only category D tends to underestimate that predicted using a changing category model by up to 40%.

Table 5 gives collective exposures calculated for releases of a non-depositing material from the two remote sites as a function of radioactive half-life. These results show similar features to those identified above for a non-decaying material. The differences between the predictions of the different models become less as the half-life reduces. Similar results were found for depositing material which also decays radioactively.

3.2 The proposed model

The Group considers that the models considered in the studies(5,6) described above give results which are not significantly different from each other. However, the Group notes that it has not been possible to undertake comparisons between results of these models and experimental data; therefore the proposed model had to be selected on the basis only of the results of model intercomparisons. Nonetheless, the Group suggests that long-range dispersion should be evaluated assuming that all releases occur in neutral stability, but allowing for a range of wind-speeds. This decision represents a compromise between the complexity and costs of a physically more realistic model which explicitly includes changes of stability category, the accuracy required from a model and the unreasonableness of assuming that the original conditions can persist for extended travel times. The distances at which this model, rather than that described in the Group's first report, should be applied are discussed in Section 3.2.1.

The Group recommends that a simplification can be made to the model used in the study(6) described in Section 3.1. That study assumed that the depth of the mixing layer in the final neutral stability reflected that in the original category. Thus the depth of the mixing layer used to represent releases in categories A to D were 1300, 900, 850 and 800 m respectively. However, the difference in concentrations predicted using mixing layer depths of 900, 850 and 800 m is not likely to be significant while category A, for which a mixing layer depth of 1300 m is appropriate, occurs usually for less than 2% of the time. Therefore, the Group suggests that a mixing layer depth of 800 m be assumed for all conditions.

The Group's suggested model for calculating activity concentration in air and deposition rate at large distances from the source is, therefore, to

- evaluate activity concentrations in air using equations (1) and (2)
- correct for plume depletion due to dry deposition using equation (3)
- correct for plume depletion due to wet deposition using equation (5)
- evaluate deposition rates using equations (4) and (6) corrected for wet and dry depletion.

Equations (1) and (2), as used in the Group's first report, referred to an averaging procedure over different atmospheric stability categories. The model suggested by the Group for long-range dispersion does not consider different stability categories, but rather different wind-speeds in the same stability category (ie, neutral). These wind-speed classes define the set of atmospheric conditions over which a weighted sum is required.

3.2.1 The region of applicability of the proposed model

The concentration predicted using the models and parameters described in this report does not represent a homogeneous extension to longer distances of that obtained using the model proposed in the Group's first report. Furthermore, there is no clearly defined distance at which either model becomes unacceptable.

The model described in this report is only valid after each category has changed to neutral stability. The duration of the stability categories is shown in Figures 1 and 2 from which the mean duration is seen to be 2 - 3 hours, although on a small percentage of occasions any category can persist for up to about 10 hours. This implies that the model described in this report may not be strictly applicable at distances less than 100 km. However, the model described in the Group's first report is only applicable while the initial stability conditions persist. As shown in Figures 1 and 2, there is a significant probability that a category will persist for less than 2 hours, corresponding to a travel distance of only a few kilometres in some categories. Therefore the model given in the first report should not be used at distances beyond about 10 km.

Therefore the Group suggests that, when calculating concentrations, the original model should be used at distances of less than 50 km and the model described in this report at greater distances, but notes that this procedure implies that concentrations at distances between 10 and 100 km will be predicted with less accuracy than at longer or shorter distances.

The Group suggests that collective exposures should be calculated using the model described in this report, unless the population distribution or half-life of the nuclide considered is such that a significant fraction of the collective exposure is received at distances less than about 50 km, when the model given in the first report should be used.

3.2.2 Choice of values for the dispersion parameters

a) Windspeed and frequency distribution in different directions, u and f_{ij}

Material travelling over great distances will be spread throughout the mixing layer and will be carried along at a speed representing an effective average throughout the layer. This effective wind-speed is more easily related to the geostrophic wind-speed than to the wind-speed at a defined, low height in the mixing layer. The Group proposes that the geostrophic wind-speed should be used when evaluating concentrations at long range although recognising that the effective wind-speed is probably about 10% lower than the geostrophic wind-speed.

The Group suggests that the fraction of time the wind blows into a particular sector should be determined from the geostrophic windrose. This does not vary significantly over the UK and is similar to that which has been measured at about 400 m above a point in the UK. A representative windrose, given in Table 6 and taken from the data base for the MESOS program, can be used in the application of this model.

b) The vertical standard deviation of the plume, σ_z

The Group's first report gave a method of evaluating σ_z at distances up to 100 km from the release point based on the work of Smith(7). In some cases it is necessary to treat the plume as a reflected Gaussian at distances greater than 100 km. An extrapolation of the original graph of σ_z is given in Figure 3. It is the original graph of Smith at distances up to 100 km extrapolated by assuming that Hosker's formula(8) to fit Smith's graph can be used at distances greater than those for which it was derived. Corrections for other roughness lengths given in the first report for a distance of 100 km should be used at longer distances.

c) The depth of the mixing layer

The value chosen for the depth of the mixing layer should reflect the depth of the mixing layer averaged over all conditions. The value of 800 m, used in the Group's first report for neutral conditions, is appropriate in this model.

d) Deposition velocity and washout coefficient

The value of deposition velocity depends on the physical and chemical form of the dispersing material and the nature of the underlying surface. It may also be a function of atmospheric stability and wind-speed. Values of deposition velocity have been widely reviewed, two recent reviews being by Slinn(9) and Sehmel(10).

The value of washout coefficient also depends on the physical and chemical form of the dispersing material and on the rainfall rate and size of the raindrops. The Group suggests that a value appropriate to the average rainfall rate (approximately 1 mm per hour) should be used. Values of washout coefficient have recently been reviewed(9) and the Group is undertaking a review of suitable values for deposition velocity and washout coefficient.

Because of the difficult in choosing representative values for the washout coefficient and deposition velocity, the Group suggests that users should carry out a sensitivity analysis to determine the importance of the chosen values for these parameters.

e) The probability of dry and wet weather stopping, P_D and P_W

The difficulty of specifying a value for these parameters is discussed in the Group's second report(2). The problem identified there, of rain falling in only one category, is not relevant here where only one average dispersion category is considered. However, the other difficulties identified are equally relevant to long range dispersion. The values suggested in the Group's second report are considered equally applicable for use in a long range dispersion model.

3.3 Presentation of results

The average concentration as a function of distance is given in Figure 4 for a range of effective release heights, assuming a uniform windrose and a roughness length of 30 cm. The concentrations given there are normalised with respect to wind-speed.

The fraction of material remaining in the plume due to dry deposition Q*(r)/Q (equation (3)) is given in Table 7 for a deposition velocity of 10^{-2} m s^{-1} and a wind-speed of 10 m s^{-1}. Values appropriate to other deposition velocities and wind-speeds can be derived from

$$\frac{Q^*(r,V_g,u)}{Q} = \left[\frac{Q^*(r,V_{gT},u_T)}{Q}\right]^{V_g u_T/V_{gT} u} \qquad \text{..........} \quad (8)$$

where $Q^*(r,V_g,u)$ is the fraction of material remaining in the plume at a distance r, for a deposition velocity V_g and a wind-speed u

V_{gT} and u_T are the values of deposition velocity and wind-speed for which the tabulated values were calculated.

The fraction of material remaining in the plume and the fraction travelling in wet conditions Q'(t)/Q and $Q_W(t)/Q$ (equation (5)) are plotted in Figure 5 as a function of travel time for a range of washout coefficients.

3.4 Precision of the model

The model described in this report was chosen after considering the results of two studies in which predictions of models were compared(5,6), since there is very little experimental data available to validate models for dispersion over hundreds of kilometres.

One study(6) compared collective doses predicted by a range of modified Gaussian models of different degrees of complexity and showed that the model described here predicts collective exposures within a factor of two of those obtained from a more complex model in which the change of category is explicitly modelled.

The study also compared the activity concentration in air at a given point predicted using a range of models and showed larger differences between model predictions of up to a factor of four.

The other study(5) showed that predicted concentrations compare well with the results of the more complex trajectory model, MESOS, for which validation has been attempted against the Windscale release of 1957.

4. SUMMARY

In this report a method has been described for extending atmospheric dispersion calculations to long ranges for continuous releases. The method is based on a review of existing models. The model chosen represents a compromise beween those giving a good description of the physical processes involved and those which are simple to use.

Sufficient results are included to allow the model to be applied.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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 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).

4. Smith, F B, Private communication (1979).

5. ApSimon, H M and Crompton, S, Modelling longer range exposure from continuous releases. London, Imperial College, Report SAF 021 of the Environmental Safety Group, Nuclear Power Section (1979).

6. Jones, J A, The importance of including changes in atmospheric stability in predicting the dispersion and collective doses from continuous releases of radionuclides. To be published.

7. Smith, F B, A scheme for estimating the vertical dispersion of a plume from a source near ground level. IN Proceedings 3rd Meeting of an Expert Panel on Air Pollution Modelling, Paris, October 1972. Brussels, NATO-CCMS Report 14 (1973).

8. Hosker, R P, Estimates of dry deposition and plume depletion over forests and grasslands. IN Proceedings Symposium on Physical Behaviour of Radioactive Contaminants in the Atmosphere, Vienna, November 1973. Vienna, IAEA, p291 (1974).

9. 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, No 2 (1978).

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

7. SYMBOLS USED

A	Depth of mixing layer
$C(r,z)$	Air concentration for a continuous release at radius r ($Bq\ m^{-3}$)
D_D	Dry deposition rate or its time integral ($Bq\ m^{-2}\ s^{-1}$ or $Bq\ m^{-2}$)
D_W	Wet deposition rate per unit area ($Bq\ m^{-2}\ s^{-1}$)
f_{ij}	Frequency distribution of wind direction and weather category in the ith sector and jth category
f_W	The fraction of the time for which rain falls
F	A term defined in equation (2) giving the vertical distribution of activity in the plume
F_D	Term defined by equation (8)
h	Effective release height (m)
i	Subscript denoting sector
j	Subscript denoting category
P_D	Probability of a dry period ending in unit time (s^{-1})
P_W	Probability of a wet period ending in unit time (s^{-1})
Q	Release rate ($Bq\ s^{-1}$)
Q'	The amount of material remaining in a plume affected by wet deposition
Q*	The amount of material remaining in a plume affected by dry deposition
r	Distance from the release point for a continuous release (m)
r_c	Distance from the source at which $\sigma_z = A$
t	Travel time or time (s)
T	Subscript indicating the value used in tables
u	Wind speed ($m\ s^{-1}$)
V_g	Deposition velocity ($m\ s^{-1}$)
α	Angular width of a sector (radians)
Λ	Washout coefficient (s^{-1})
σ_z	Standard deviation of the vertical Gaussian plume profile (m)

Table 1

Activity concentration in air and deposition rate averaged over categories predicted by a range of modified Gaussian models

Model[1]	2.10^4 m		5.10^4 m		10^5 m		10^6 m	
	50% D^2	80% D^2	50% D^2	80% D^2	50% D^2	80% D^2	50% D^2	80% D^2
Air concentration - no deposition								
1 a	$3.7\ 10^{-9}$	$2.5\ 10^{-9}$	$1.1\ 10^{-9}$	$7.0\ 10^{-10}$	$4.1\ 10^{-10}$	$2.8\ 10^{-10}$	$3.0\ 10^{-11}$	$2.4\ 10^{-11}$
b	$4.2\ 10^{-9}$	$2.6\ 10^{-9}$	$1.3\ 10^{-9}$	$7.3\ 10^{-10}$	$4.5\ 10^{-10}$	$2.9\ 10^{-10}$	$3.1\ 10^{-11}$	$2.4\ 10^{-11}$
2 a	$4.6\ 10^{-9}$	$2.7\ 10^{-9}$	$8.2\ 10^{-10}$	$6.5\ 10^{-10}$	$3.5\ 10^{-10}$	$2.7\ 10^{-10}$	$3.1\ 10^{-11}$	$2.4\ 10^{-11}$
b	$4.4\ 10^{-9}$	$2.7\ 10^{-9}$	$1.6\ 10^{-9}$	$8.0\ 10^{-10}$	$3.4\ 10^{-10}$	$2.7\ 10^{-10}$	$3.1\ 10^{-11}$	$2.4\ 10^{-11}$
3	$4.4\ 10^{-9}$	$2.7\ 10^{-9}$	$1.7\ 10^{-9}$	$8.0\ 10^{-10}$	$8.7\ 10^{-10}$	$3.6\ 10^{-10}$	$8.8\ 10^{-11}$	$3.3\ 10^{-11}$
4	$3.3\ 10^{-9}$	$2.5\ 10^{-9}$	$8.9\ 10^{-10}$	$6.7\ 10^{-10}$	$3.7\ 10^{-10}$	$2.8\ 10^{-10}$	$3.1\ 10^{-11}$	$2.4\ 10^{-11}$
5	$2.3\ 10^{-9}$	$2.3\ 10^{-9}$	$6.1\ 10^{-10}$	$6.1\ 10^{-10}$	$2.5\ 10^{-10}$	$2.5\ 10^{-10}$	$2.2\ 10^{-11}$	$2.2\ 10^{-11}$
Air concentration - wet and dry deposition[3]								
1 a	$3.5\ 10^{-9}$	$2.4\ 10^{-9}$	$9.5\ 10^{-10}$	$6.3\ 10^{-10}$	$3.1\ 10^{-10}$	$2.4\ 10^{-10}$	$9.1\ 10^{-12}$	$9.6\ 10^{-12}$
b	$4.0\ 10^{-9}$	$2.5\ 10^{-9}$	$1.1\ 10^{-9}$	$6.5\ 10^{-10}$	$3.4\ 10^{-10}$	$2.5\ 10^{-10}$	$9.3\ 10^{-12}$	$9.6\ 10^{-12}$
2 a	$4.3\ 10^{-9}$	$2.5\ 10^{-9}$	$7.3\ 10^{-10}$	$5.9\ 10^{-10}$	$2.9\ 10^{-10}$	$2.4\ 10^{-10}$	$9.3\ 10^{-12}$	$9.6\ 10^{-12}$
b	$4.1\ 10^{-9}$	$2.5\ 10^{-9}$	$1.3\ 10^{-9}$	$7.0\ 10^{-10}$	$2.8\ 10^{-10}$	$2.3\ 10^{-10}$	$9.3\ 10^{-12}$	$9.6\ 10^{-12}$
3	$4.1\ 10^{-9}$	$2.5\ 10^{-9}$	$1.4\ 10^{-9}$	$7.0\ 10^{-10}$	$5.2\ 10^{-10}$	$2.8\ 10^{-10}$	$1.1\ 10^{-11}$	$1.1\ 10^{-11}$
4	$3.1\ 10^{-9}$	$2.4\ 10^{-9}$	$7.7\ 10^{-10}$	$6.1\ 10^{-10}$	$2.9\ 10^{-10}$	$2.4\ 10^{-10}$	$8.9\ 10^{-12}$	$9.4\ 10^{-12}$
5	$2.2\ 10^{-9}$	$2.2\ 10^{-9}$	$5.6\ 10^{-10}$	$5.6\ 10^{-10}$	$2.2\ 10^{-10}$	$2.2\ 10^{-10}$	$9.6\ 10^{-12}$	$9.6\ 10^{-12}$
Deposition - wet and dry deposition[3]								
1 a	$1.4\ 10^{-11}$	$1.3\ 10^{-11}$	$4.2\ 10^{-12}$	$3.6\ 10^{-12}$	$1.6\ 10^{-12}$	$1.4\ 10^{-12}$	$7.1\ 10^{-14}$	$6.8\ 10^{-14}$
b	$1.5\ 10^{-11}$	$1.3\ 10^{-11}$	$4.4\ 10^{-12}$	$3.6\ 10^{-12}$	$1.7\ 10^{-12}$	$1.4\ 10^{-12}$	$7.4\ 10^{-14}$	$6.9\ 10^{-14}$
2 a	$1.6\ 10^{-11}$	$1.3\ 10^{-11}$	$3.4\ 10^{-12}$	$3.4\ 10^{-12}$	$1.6\ 10^{-12}$	$1.4\ 10^{-12}$	$7.3\ 10^{-14}$	$6.9\ 10^{-14}$
b	$1.6\ 10^{-11}$	$1.3\ 10^{-11}$	$5.0\ 10^{-12}$	$3.7\ 10^{-12}$	$1.5\ 10^{-12}$	$1.4\ 10^{-12}$	$7.3\ 10^{-14}$	$6.9\ 10^{-14}$
3	$1.6\ 10^{-11}$	$1.3\ 10^{-11}$	$5.2\ 10^{-12}$	$3.7\ 10^{-12}$	$1.9\ 10^{-12}$	$1.4\ 10^{-12}$	$5.2\ 10^{-14}$	$6.2\ 10^{-14}$
4	$1.8\ 10^{-11}$	$1.4\ 10^{-11}$	$4.7\ 10^{-12}$	$3.9\ 10^{-12}$	$1.8\ 10^{-12}$	$1.5\ 10^{-12}$	$6.9\ 10^{-14}$	$6.7\ 10^{-14}$
5	$1.3\ 10^{-11}$	$1.3\ 10^{-11}$	$3.7\ 10^{-12}$	$3.7\ 10^{-10}$	$1.4\ 10^{-12}$	$1.4\ 10^{-12}$	$6.6\ 10^{-14}$	$6.6\ 10^{-14}$

Notes:

1. Models used
   1. All initial categories change to neutral at a range of times.
   2. All initial categories change to neutral after mean duration.
   3. Initial categories do not change.
   4. Category D only but with a range of wind-speeds and mixing layer depths (chosen model).
   5. Category D only.

   a. Category duration defined as until a change towards neutral.
   b. Category duration defined as until neutral is reached.

2. Frequencies of other categories taken from reference 1.

3. Deposition velocity 10^{-3} m s^{-1}, washout coefficient 10^{-4} s^{-1}.

Table 2

UK collective exposure averaged over stability categories for a long-lived nuclide which does not deposit[1]

Model used	Collective exposure (man Bq m^{-3} per Bq s^{-1}) Site A[2]	Site B[2]	Site C[2]	Site D[2]
50% category D				
1 a	$1.1\ 10^{-2}$	$1.8\ 10^{-2}$	$3.9\ 10^{-2}$	$9.0\ 10^{-2}$
b	$1.2\ 10^{-2}$	$2.0\ 10^{-2}$	$4.3\ 10^{-2}$	$9.6\ 10^{-2}$
2 a	$1.0\ 10^{-2}$	$1.8\ 10^{-2}$	$4.0\ 10^{-2}$	$9.4\ 10^{-2}$
b	$1.1\ 10^{-2}$	$1.9\ 10^{-2}$	$4.6\ 10^{-2}$	$9.7\ 10^{-2}$
3	$2.6\ 10^{-2}$	$3.6\ 10^{-2}$	$6.0\ 10^{-2}$	$1.1\ 10^{-1}$
4	$1.1\ 10^{-2}$	$1.7\ 10^{-2}$	$3.7\ 10^{-2}$	$1.1\ 10^{-1}$
5	$7.5\ 10^{-3}$	$1.2\ 10^{-2}$	$2.5\ 10^{-2}$	$7.2\ 10^{-2}$
80% category D				
1 a	$8.3\ 10^{-3}$	$1.3\ 10^{-2}$	$2.8\ 10^{-2}$	$7.6\ 10^{-2}$
b	$8.4\ 10^{-3}$	$1.3\ 10^{-2}$	$2.9\ 10^{-2}$	$7.8\ 10^{-2}$
2 a	$8.2\ 10^{-3}$	$1.3\ 10^{-2}$	$2.8\ 10^{-2}$	$7.7\ 10^{-2}$
b	$8.3\ 10^{-3}$	$1.3\ 10^{-2}$	$2.9\ 10^{-2}$	$7.8\ 10^{-2}$
3	$1.1\ 10^{-2}$	$1.6\ 10^{-2}$	$3.1\ 10^{-2}$	$8.0\ 10^{-2}$
4	$8.3\ 10^{-3}$	$1.3\ 10^{-2}$	$2.8\ 10^{-2}$	$8.0\ 10^{-2}$
5	$7.5\ 10^{-3}$	$1.2\ 10^{-2}$	$2.5\ 10^{-2}$	$7.2\ 10^{-2}$

Notes:

1. The models and the stability category distribution used are identified in Table 1.
2. Sites A and B are remote nuclear sites, site C has a large population close in and site D is in a built-up area.

Table 3

UK collective exposure based on air concentration averaged over stability categories for a nuclide subject to wet and dry deposition[1,2]

Model used	Collective exposure (man Bq m^{-3} per Bq s^{-1})			
	Site A	Site B	Site C	Site D
50% category D				
1 a	$8.3\ 10^{-3}$	$1.5\ 10^{-2}$	$3.5\ 10^{-2}$	$8.6\ 10^{-2}$
b	$8.9\ 10^{-3}$	$1.6\ 10^{-2}$	$3.8\ 10^{-2}$	$9.1\ 10^{-2}$
2 a	$8.1\ 10^{-3}$	$1.5\ 10^{-2}$	$3.6\ 10^{-2}$	$9.0\ 10^{-2}$
b	$8.5\ 10^{-3}$	$1.6\ 10^{-2}$	$4.0\ 10^{-2}$	$9.2\ 10^{-2}$
3	$1.2\ 10^{-2}$	$2.0\ 10^{-2}$	$4.5\ 10^{-2}$	$9.5\ 10^{-2}$
4	$8.2\ 10^{-3}$	$1.4\ 10^{-2}$	$3.3\ 10^{-2}$	$1.0\ 10^{-1}$
5	$6.3\ 10^{-3}$	$1.0\ 10^{-2}$	$2.3\ 10^{-2}$	$7.0\ 10^{-2}$
80% category D				
1 a	$6.8\ 10^{-3}$	$1.1\ 10^{-2}$	$2.5\ 10^{-2}$	$7.4\ 10^{-2}$
b	$6.9\ 10^{-3}$	$1.1\ 10^{-2}$	$2.6\ 10^{-2}$	$7.5\ 10^{-2}$
2 a	$6.7\ 10^{-3}$	$1.1\ 10^{-2}$	$2.6\ 10^{-2}$	$7.5\ 10^{-2}$
b	$6.8\ 10^{-3}$	$1.2\ 10^{-2}$	$2.7\ 10^{-2}$	$7.5\ 10^{-2}$
3	$7.6\ 10^{-3}$	$1.2\ 10^{-2}$	$2.7\ 10^{-2}$	$7.6\ 10^{-2}$
4	$6.7\ 10^{-3}$	$1.1\ 10^{-2}$	$2.5\ 10^{-2}$	$7.7\ 10^{-2}$
5	$6.3\ 10^{-3}$	$1.0\ 10^{-2}$	$2.3\ 10^{-2}$	$7.0\ 10^{-2}$

Notes:

1. Collective dose based on air concentration for a nuclide with deposition velocity 3.10^{-3} m s^{-1} and washout coefficient 10^{-4} s^{-1}.

2. The models and stability category distributions used are identified in Table 1. The sites used are identified in Table 2.

Table 4

UK collective exposure from deposited activity averaged over stability categories for a nuclide subject to wet and dry deposition[1,2]

Model used	Collective exposure (man Bq m^{-2} per Bq s^{-1}			
	Site A	Site B	Site C	Site D
50% category D				
1 a	$4.4\ 10^{-5}$	$7.1\ 10^{-5}$	$1.5\ 10^{-4}$	$3.5\ 10^{-4}$
b	$4.6\ 10^{-5}$	$7.5\ 10^{-5}$	$1.6\ 10^{-4}$	$3.7\ 10^{-4}$
2 a	$4.5\ 10^{-5}$	$7.2\ 10^{-5}$	$1.5\ 10^{-4}$	$3.7\ 10^{-4}$
b	$4.6\ 10^{-5}$	$7.5\ 10^{-5}$	$1.7\ 10^{-4}$	$3.7\ 10^{-4}$
3	$4.7\ 10^{-5}$	$7.7\ 10^{-5}$	$1.7\ 10^{-4}$	$3.7\ 10^{-4}$
4	$4.9\ 10^{-5}$	$8.2\ 10^{-5}$	$1.9\ 10^{-4}$	$5.3\ 10^{-4}$
5	$3.8\ 10^{-5}$	$6.3\ 10^{-5}$	$1.4\ 10^{-4}$	$3.8\ 10^{-4}$
80% category D				
1 a	$3.9\ 10^{-5}$	$6.2\ 10^{-5}$	$1.4\ 10^{-4}$	$3.6\ 10^{-4}$
b	$3.9\ 10^{-5}$	$6.3\ 10^{-5}$	$1.4\ 10^{-4}$	$3.6\ 10^{-4}$
2 a	$3.9\ 10^{-5}$	$6.2\ 10^{-5}$	$1.4\ 10^{-4}$	$3.6\ 10^{-4}$
b	$3.9\ 10^{-5}$	$6.3\ 10^{-5}$	$1.4\ 10^{-4}$	$3.7\ 10^{-4}$
3	$3.8\ 10^{-5}$	$6.2\ 10^{-5}$	$1.4\ 10^{-4}$	$3.6\ 10^{-4}$
4	$4.1\ 10^{-5}$	$6.8\ 10^{-5}$	$1.5\ 10^{-4}$	$4.2\ 10^{-4}$
5	$3.8\ 10^{-5}$	$6.3\ 10^{-5}$	$1.4\ 10^{-4}$	$3.8\ 10^{-4}$

Notes:

1. Collective dose based on deposition rate for a nuclide with deposition velocity 3.10^{-3} m s^{-1} and washout coefficient 10^{-4} s^{-1}.
2. The models and stability category distributions used are identified in Table 1. The sites used are identified in Table 2.

Table 5

Collective exposure from a non-depositing material of different half-lives[1]

Model	Collective exposure for a half-life of (hours) (man Bq m^{-3} per Bq s^{-1})					
	1	2	3	5	10	∞
Site A						
1 a	$1.0\ 10^{-3}$	$2.1\ 10^{-3}$	$3.1\ 10^{-3}$	$4.6\ 10^{-3}$	$6.6\ 10^{-3}$	$1.1\ 10^{-2}$
b	$1.0\ 10^{-3}$	$2.2\ 10^{-3}$	$3.3\ 10^{-3}$	$4.9\ 10^{-3}$	$7.1\ 10^{-3}$	$1.2\ 10^{-2}$
2 a	$1.0\ 10^{-3}$	$2.1\ 10^{-3}$	$3.0\ 10^{-3}$	$4.3\ 10^{-3}$	$6.2\ 10^{-3}$	$1.0\ 10^{-2}$
b	$1.1\ 10^{-3}$	$2.2\ 10^{-3}$	$3.2\ 10^{-3}$	$4.7\ 10^{-3}$	$6.6\ 10^{-3}$	$1.1\ 10^{-2}$
3	$1.1\ 10^{-3}$	$2.6\ 10^{-3}$	$4.2\ 10^{-3}$	$7.1\ 10^{-3}$	$1.2\ 10^{-2}$	$2.6\ 10^{-2}$
4	$1.1\ 10^{-3}$	$2.2\ 10^{-3}$	$3.1\ 10^{-3}$	$4.5\ 10^{-3}$	$6.4\ 10^{-3}$	$1.1\ 10^{-2}$
5	$1.1\ 10^{-3}$	$2.2\ 10^{-3}$	$3.0\ 10^{-3}$	$4.1\ 10^{-3}$	$5.4\ 10^{-3}$	$7.5\ 10^{-3}$
Site B						
1 a	$3.4\ 10^{-3}$	$5.8\ 10^{-3}$	$7.5\ 10^{-3}$	$9.8\ 10^{-3}$	$1.3\ 10^{-2}$	$1.8\ 10^{-2}$
b	$3.6\ 10^{-3}$	$6.2\ 10^{-3}$	$8.1\ 10^{-3}$	$1.1\ 10^{-2}$	$1.4\ 10^{-2}$	$2.0\ 10^{-2}$
2 a	$3.6\ 10^{-3}$	$6.1\ 10^{-3}$	$7.7\ 10^{-3}$	$9.8\ 10^{-3}$	$1.2\ 10^{-2}$	$1.8\ 10^{-2}$
b	$3.7\ 10^{-3}$	$6.5\ 10^{-3}$	$8.4\ 10^{-3}$	$1.1\ 10^{-2}$	$1.4\ 10^{-2}$	$1.9\ 10^{-2}$
3	$3.8\ 10^{-3}$	$7.0\ 10^{-3}$	$9.6\ 10^{-3}$	$1.4\ 10^{-2}$	$2.0\ 10^{-2}$	$3.6\ 10^{-2}$
4	$3.4\ 10^{-3}$	$5.6\ 10^{-3}$	$7.2\ 10^{-3}$	$9.2\ 10^{-3}$	$1.2\ 10^{-2}$	$1.7\ 10^{-2}$
5	$3.2\ 10^{-3}$	$5.1\ 10^{-3}$	$6.3\ 10^{-3}$	$7.8\ 10^{-3}$	$9.4\ 10^{-3}$	$1.2\ 10^{-2}$

Note:

1. The models used are identified in Table 1. The sites used are identified in Table 2. The stability category distribution is that given in the Group's first report for 50% category D.

Table 6

A representative windrose for use in long-range dispersion calculation

Speed		Direction[1] (degrees from North)												
Range m s^{-1}	Representative value m s^{-1}	11-40	41-70	71-100	101-130	131-160	161-190	191-220	221-250	251-280	281-310	311-340	341-10	
		Percentage of the time that the wind is from a given direction with given speed												TOTAL
5	2.5	1.58	1.82	2.07	1.72	1.92	2.07	1.67	1.48	2.07	2.07	1.97	2.02	22.46
5-10	7.5	1.77	1.72	1.43	2.12	1.33	2.66	1.87	5.07	3.84	2.91	3.50	4.53	32.75
10-15	12.5	1.43	0.94	0.98	0.39	0.84	0.59	1.33	1.92	3.99	2.27	2.41	3.35	20.44
15	20.0	1.08	0.84	0.69	0	0	2.46	2.22	2.81	4.97	3.84	2.86	2.56	24.33
TOTAL		5.86	5.32	5.17	4.24	4.09	7.78	7.09	11.28	14.88	11.09	10.74	12.46	100.00

Note:

1. Direction, in degrees clockwise from north, from which the wind is blowing.

Table 7

The fraction of material remaining in a plume subject to dry deposition[1,2]

Stack height	Fraction remaining in the plume at a distance of				
	10^4 m	3.10^4 m	10^5 m	3.10^5 m	10^6 m
5[3]	0.905	0.855	0.761	0.588	0.245
10	0.916	0.866	0.771	0.595	0.248
20	0.926	0.875	0.779	0.601	0.251
30	0.933	0.882	0.785	0.607	0.253
50	0.944	0.893	0.796	0.615	0.256
70	0.953	0.902	0.804	0.621	0.259
100	0.963	0.914	0.815	0.630	0.263
150	0.976	0.930	0.832	0.643	0.268
200	0.985	0.943	0.847	0.656	0.273

Notes:

1. Calculated for a wind-speed of $10\ m\ s^{-1}$, a deposition velocity of $10^{-2}\ m\ s^{-1}$ and a roughness length of 0.3 m.

2. Fractions appropriate to other values can be derived using the procedure given in the Group's second report(2). The fractions are tabulated to 3 significant figures to facilitate this process and not because of their implied accuracy.

3. These values should be applied for all lower stack heights.

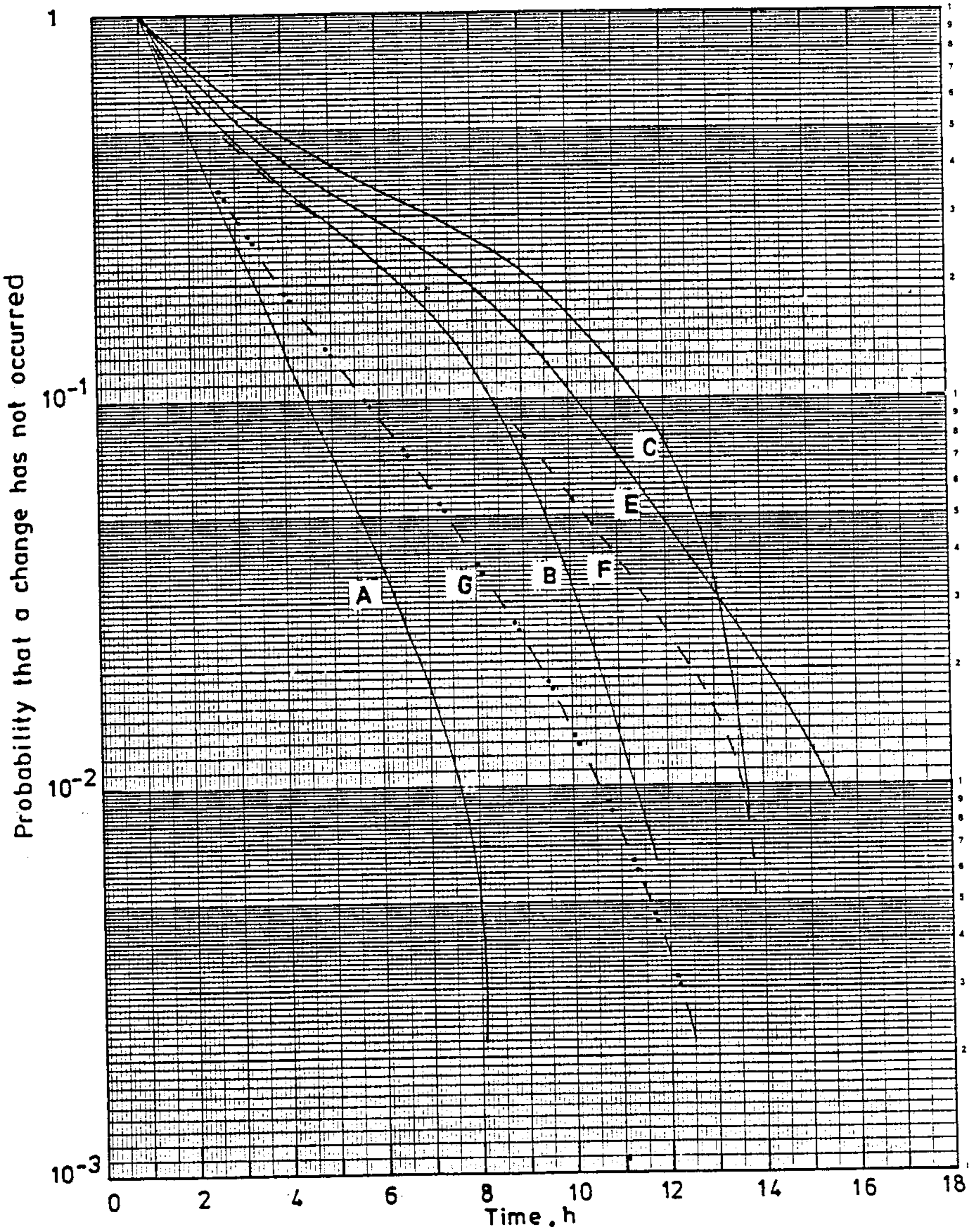

Figure 1 The duration before a category change towards neutral stability.

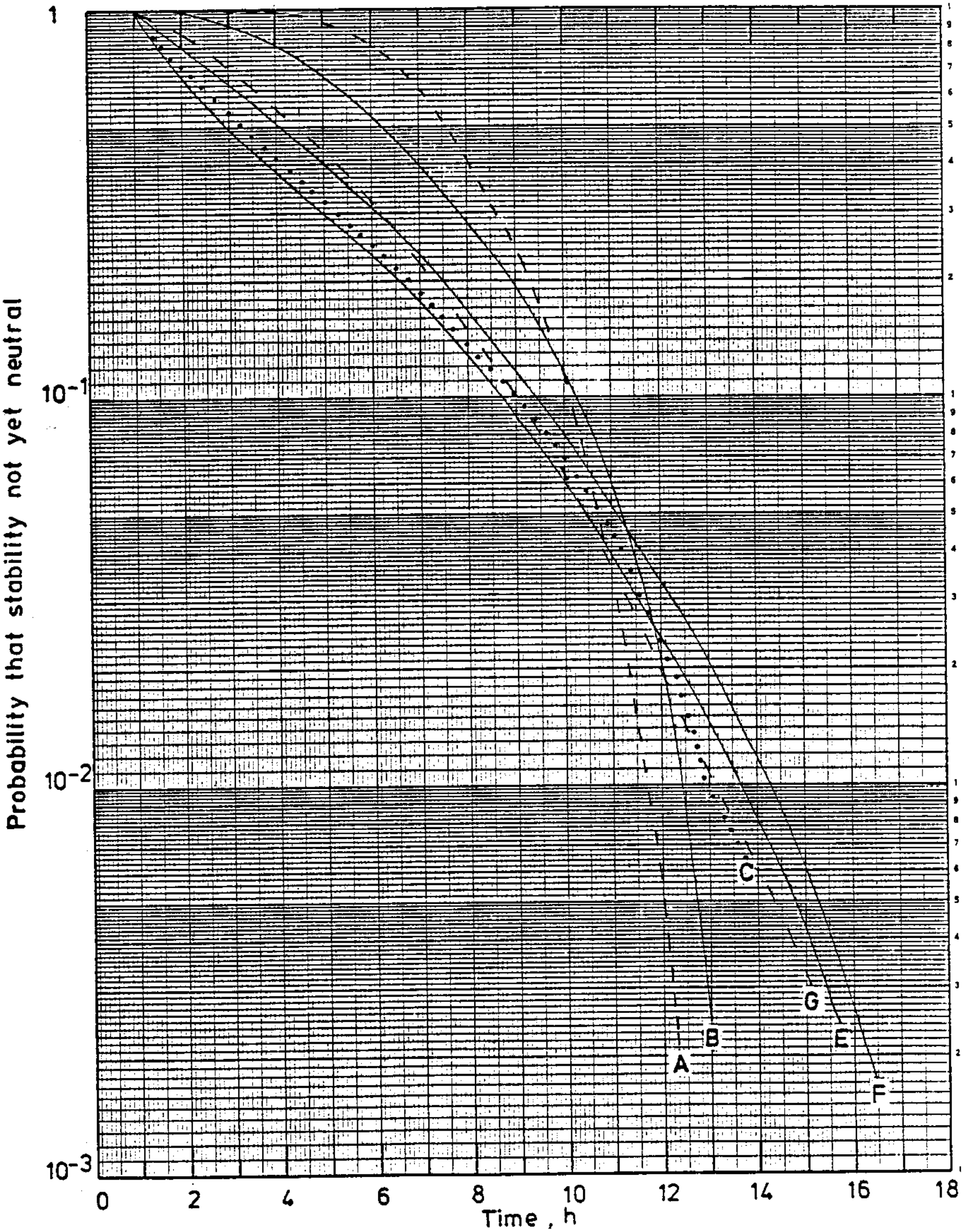

Figure 2 Duration of periods from each category to neutral stability

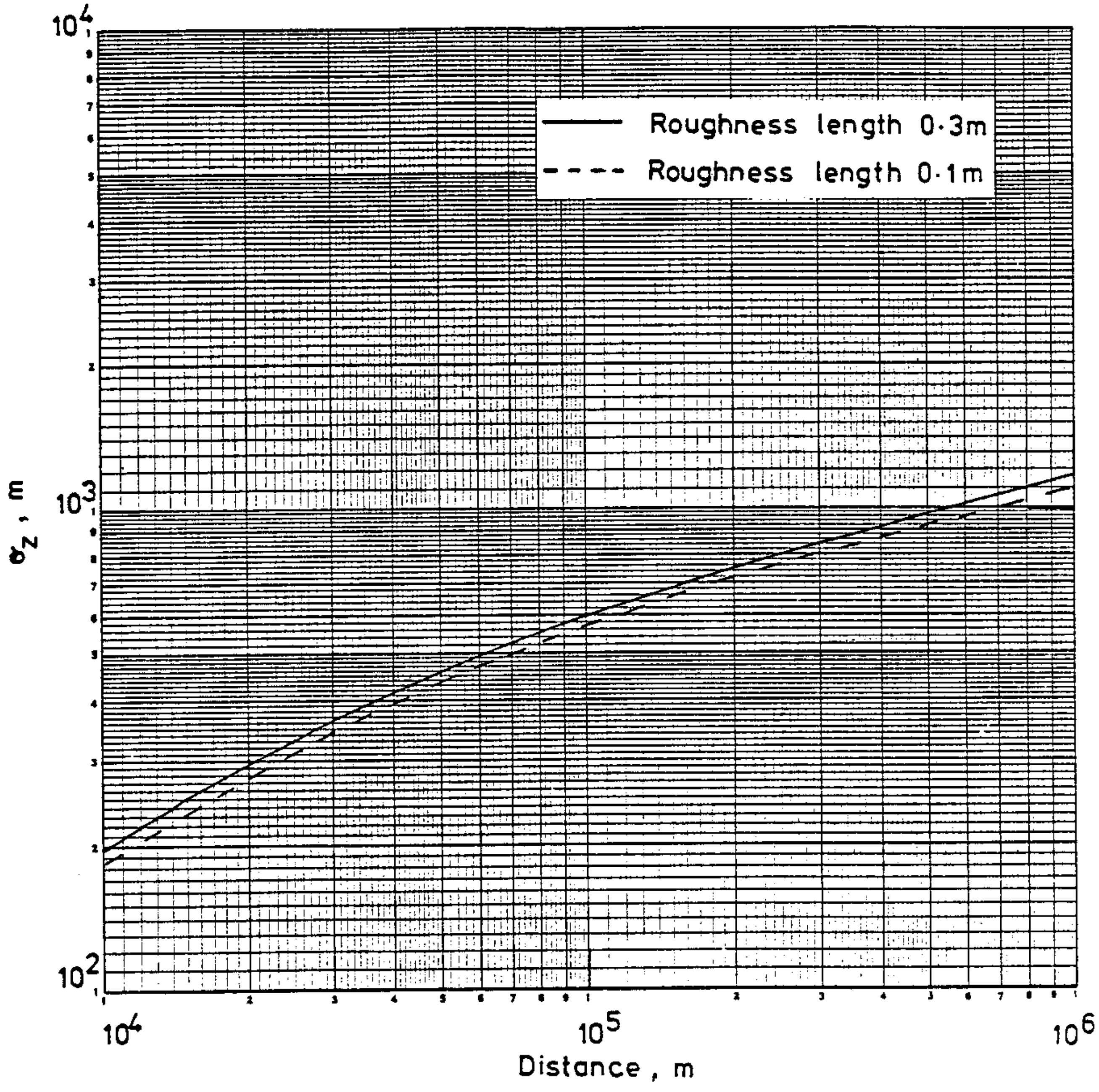

Figure 3 The vertical standard deviation σ_z as a function of distance

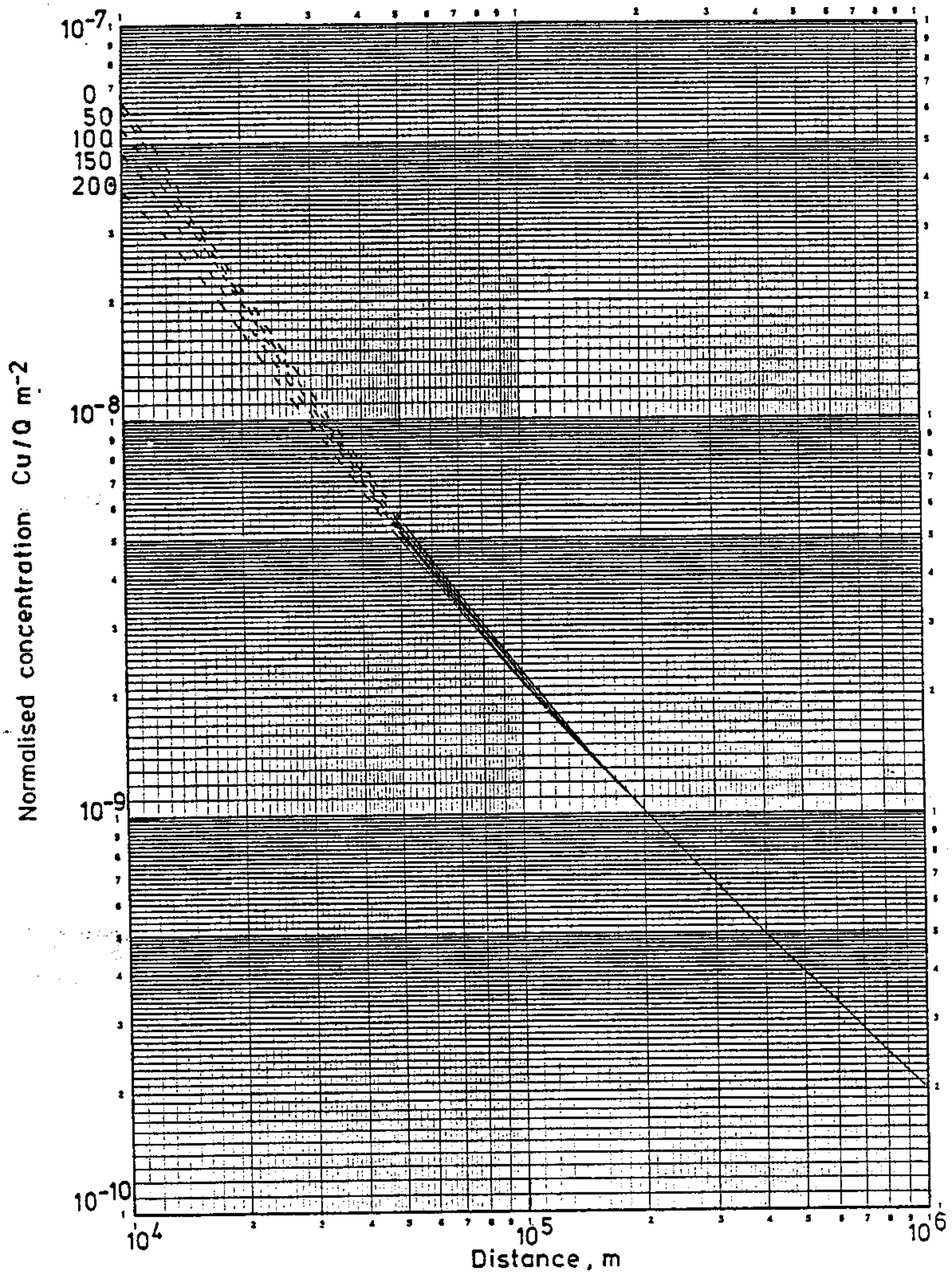

Figure 4 The normalised air concentration for a release from a range of stack heights in neutral stability conditions for a uniform wind rose

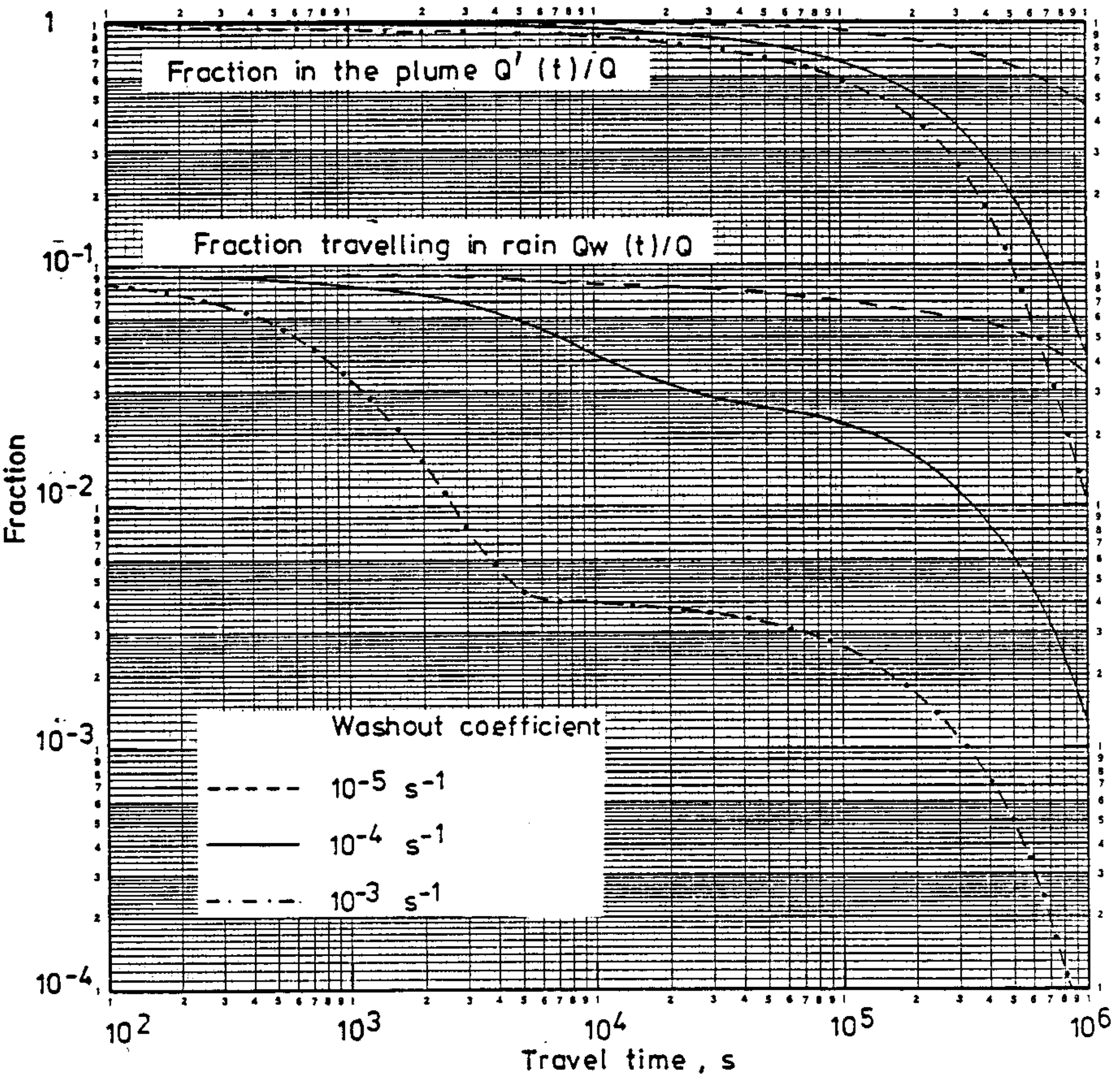

Figure 5 Fraction of material remaining in the plume due to wet deposition and the fraction travelling in rain