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

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National Radiological Protection Board

Chilton, Didcot, Oxon OX11 0RQ
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A PROCEDURE TO INCLUDE DEPOSITION IN THE MODEL FOR SHORT AND MEDIUM RANGE ATMOSPHERIC DISPERSION OF RADIONUCLIDES

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ABSTRACT

This report is the second of a series which gives practical guidance on the estimation of 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. Methods described in this report are considered suitable for including dry and wet deposition in the models suggested in the groups first report for short and medium-range dispersion.

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The following changes have been made to this report since its first publication (September 1981).

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Table 1	Column heading (5th column) corrected
Table 2	Data for "Release at 10m height" retyped as original was not legible.

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TABLES

FIGURE

As from 1 April 1978 NRPB adopted the International System of Units (SI). The relationships between the new SI units and those previously used 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 representatives of Government Departments, utilities and research organisations was held to discuss methods of calculation of atmospheric dispersion for radioactive releases. Those present agreed on the need for a review of recent developments in atmospheric dispersion modelling and an Expert Working Group was established in order to facilitate the review. The Working Group has published its first report, which gives practical guidance on the estimation of the dispersion of radioactive material in the atmosphere within a few tens of kilometres of the release for both continuous and short duration releases; the methods were specifically for radionuclides which do not deposit on the ground and are not removed from the plume by the interaction of rain.

In this report, the second by the Group, a method of extending the original model to include dry and wet deposition is described. The Group is also preparing reports describing models for long-range dispersion from both short and continuous releases. 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 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
Ms L S Fryer*	United Kingdom Atomic Energy Authority Safety and Reliability Directorate, Culcheth
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Dr S F Jagger	United Kingdom Atomic Energy Authority, Safety and Reliability Directorate, Culcheth

Dr F B Smith	Meteorological Office, Bracknell
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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
and	Dr A G Robins	Central Electricity Generating Board, Research Department, Marchwood Engineering Laboratory, Southampton

who attended primarily to advise it on other topics.

1. INTRODUCTION

The problem of predicting the distribution 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 made. The Working Group, in its first report[1], reviewed some of these models and described a model for use in assessing the dosimetric consequences of atmospheric discharges of radioactive material. That model was restricted to non-depositing radionuclides and to distances for which the meteorological and topographical conditions remain constant. This report, the second by the Group, describes methods for extending the original model to include dry and wet deposition. The Group is also preparing reports[2,3] describing models for calculating activity concentration in air and deposition rate at distances up to about a thousand kilometres from the source of both short and continuous releases.

This report contains a brief outline of the model described in the Group's first report followed by sections describing methods for the inclusion of dry and wet deposition. Sufficient results are presented to allow the model to be easily applied to determine activity concentration in air and deposition rate in the short and medium-range from any activity release.

2. THE ORIGINAL MODEL FOR SHORT AND MEDIUM-RANGE DISPERSION

In its first report the Group proposed the use of a Gaussian plume model, although it recognised that there are other more complex models which are thought to represent better the physical processes of atmospheric dispersion. However, comparisons do not provide evidence that the results of the more complex models are either suffciently different from, or more reliable than, those of the simple Gaussian model to justify the extra complexity and computational cost.

The Working Group confined the application of the first model to distances of a few tens of kilometres provided that the topographical and meteorological conditions remain unchanged throughout the dispersion, and to nuclides which do not deposit on to the ground. The model is only applicable to discharges from a source which is in a position not significantly affected by turbulence from nearby buildings.

The original model is described briefly, so that the extensions described in this report can be more easily understood. Full details of the model, together with values of the parameters for use in the absence of site specific data and comments on its range of applicability, are given in the Group's first report[1].

The model assumes that the vertical dispersion of activity may be described by a Gaussian distribution while the horizontal distribution is Gaussian for a short release, and uniform across a sector of angle α for a continuous release.

For a short duration release the activity concentration in air, C, is given by

$$C(x,y,z) = \frac{Q}{2\pi\ \sigma_y\ \sigma_z\ u_{10}} \exp\left[- \frac{y^2}{2\sigma_y^{\ 2}} \right] F\ (h,z,A) \qquad \text{.......... (1)}$$

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

u_{10} the wind speed at 10 m above the ground (m s^{-1})

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

σ_y the standard deviation of the horizontal Gaussian distribution (m)

x — along the mean wind direction (m)

y rectilinear co-ordinates — across-wind (m)

z — above ground (m)

h the effective release height (m)

A the depth of the mixing layer (m)

and

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

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

The formulation in equation (2) allows adequate inclusion of the effects of reflections from both the ground and top of the mixing layer for small values of the vertical dispersion coefficient, σ_z. As the vertical dispersion coefficient becomes large, the vertical concentration distribution becomes uniform throughout the mixing layer and the concentration is given by

$$C(x,y,z) = \frac{Q}{\sqrt{2\pi}\ u_{10}\ \sigma_y A} \exp\left[- \frac{y^2}{2\sigma_y^{\ 2}} \right] \qquad \text{.......... (3)}$$

In its first report[(1)] the Group suggested that equation (1) be used if $\sigma_z < A$, equation (3) if $\sigma_z > A$. In all cases there is no activity outside the mixing layer for a source situated within it, and no activity inside the mixing layer for a source outside it.

For a continuous release the meteorological conditions during the period of release do not remain constant and a different approach was proposed. The activity concentration in air within a specified sector, i, for each stability category, j, is given by

$$C_{ij}(r,z) = \frac{Q}{\sqrt{2\pi}\ r\ \alpha\ u_{sj}\ \sigma_{zj}} F_j(h,z,A_j) \qquad \text{.......... (4a)}$$

if $\sigma_{zj} < A_j$

and
$$C_{ij}(r,z) = \frac{Q}{r\ \alpha\ u_{sj}\ A_j} \qquad \text{.......... (4b)}$$

if $\sigma_{zj} > A_{zj}$

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

α the angular width of the sector (radians)

u_{sj} the wind speed at the effective source height or at 10 m whichever is greater (m s^{-1})

and $F_j(h,z,A_j)$ is given by equation (2)

Again it is assumed that there is no activity within the mixing layer for a source outside it, and no activity released into the mixing layer escapes from it.

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

$$C_i(r,z) = \sum_j f_{ij} \; C_{ij}(r,z) \qquad \text{.......... (5)}$$

where f_{ij} is the frequency of meteorological condition j within the ith sector.

3. THE INCLUSION OF DEPOSITION IN THE ORIGINAL MODEL

There are a number of processes which can remove activity from a diffusing plume and deposit it on the ground. Such processes include the removal of activity following its turbulent impaction on the ground, or on obstacles on it (eg, vegetation) or by chemical reaction at the air/ground surface. These processes are described as dry deposition although they occur in both dry and wet weather. Activity can also be removed as a result of the interaction between the dispersing material and rain falling through it, or by its incorporation into rain clouds. These processes are called wet deposition.

This section describes the methods recommended by the Group for including deposition processes in the models given in its original report. The models for dry and wet deposition are described in separate sub-sections. In both cases the models enable calculations to be undertaken of both the fraction of the original material remaining in the plume at any distance, which affects the activity concentration in air, and the deposition rate of activity on to the ground at that point. The models can be applied for any release duration although there are limitations, described in Section 3.2.2, on the use of this wet deposition model for short releases.

3.1 Dry deposition

The Group proposes that the dry deposition rate should be calculated using the concept of a deposition velocity, V_g, defined by Chamberlain as the ratio of total activity deposited per unit area to the time integrated activity concentration in air at ground level[4]. The dry deposition rate or its time integral, D_D, is then given by

$$D_D = V_g C \qquad \text{.......... (6)}$$

where C is the activity concentration in air at ground level or its time integral, respectively.

The depletion process can affect the concentration at a point in two ways - by altering the vertical profile of activity within the plume and by reducing the effective source strength. The concentration used in equation (6) is that calculated allowing for these effects.

Several models have been proposed to calculate the concentration in plumes subject to dry deposition. The models can be divided into two groups; source depletion models[5], in which the effective source strength is reduced while the Gaussian vertical profile is assumed to be unaffected by the deposition process, and surface depletion models, in which not only is the effective source strength reduced but the vertical profile is affected by deposition. This latter category includes both eddy-diffusivity models[6,7] and modified Gaussian models[8,9].

Dry deposition occurs at the ground surface, so the plume vertical profile is modified because the processes of atmospheric dispersion cannot immediately replace this material. Source depletion models assume that the vertical Gaussian profile is maintained, therefore following deposition of material they tend to predict too large a value for activity concentration in air at ground level. This then leads to a higher depletion of the plume but leaves less material to travel downwind. As a consequence of these two aspects, prediction of both activity concentration in air at ground level and deposition rate should be more accurate than predictions of the amount of material remaining in the plume, which is underestimated.

In a number of studies[7-10] the predictions of surface depletion models have been compared with results from the simpler source depletion model. The general conclusion from these comparisons is that, for most values of deposition velocity and wind speed in both unstable and neutral atmospheric stability, the models give similar predictions of both activity concentration in air and total activity in the plume over large distances. In stable conditions the agreement between the models is better when predicting activity concentration in air at ground level than when predicting the amount of material remaining in the plume. The main area in which the models differ is at distances greater than about 10 km for releases from relatively low stacks in stable conditions. However, such conditions persist on average for only a few hours[2], and the Group considers that the agreement between the models is sufficiently good for the chosen model to be used at all distances for which the original stable conditions persist.

3.1.1 The suggested model for dry deposition

The Group suggests the use of the source depletion model for including dry deposition. As this model is well known, the derivation of the plume depletion factors are not given here and may be found, for example, in reference 5.

The activity concentration in air is given by equations (1) to (5), as appropriate, but the source strength, Q, is replaced by a modified source strength, $Q^*(x)$, given by

$$Q^*(x) = Q\left[\exp F_D(x)\right]^{V_g/u} \qquad \text{.......... (7)}$$

where

$$F_D(x) = -\sqrt{\frac{2}{\pi}}\int_o^x \frac{1}{\sigma_z}\left\{\exp\left[-\frac{h^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(h+2A)^2}{2\sigma_z^2}\right]\right.$$

$$\left. + \exp\left[-\frac{(h+2A)^2}{2\sigma_z^2}\right]\right\}dx' \qquad \text{.......... (8a)}$$

while $\sigma_z(x) < A$

and $$F_D(x) = F_D(x_c) - \frac{x-x_c}{A} \qquad \text{.......... (8b)}$$

while $\sigma_z(x) > A$

and where x_c is such that $\sigma_z(x_c) = A$

These equations apply for any release duration. The integrals specified in equation (8a) cannot in general be evaluated analytically and must therefore be evaluated numerically.

The integral in equation (8a) can only be evaluated if values of σ_z are specified at distances less than 100 m, the lowest distance for which they are given in the Group's first report(1). However, values at distances less than 100 m can be obtained with sufficient accuracy for this purpose by back extrapolation from the values given at distances of a few hundred metres. Values obtained in this way should not, however, be used to estimate concentrations at distances within 100 m of a source.

The Group suggests that when calculating deposition rate from equation (6) the activity concentration in air at ground level (ie, that obtained by using z = 0 in equations (3) to (5), should be used. This is a small approximation as deposition velocities are usually determined at a reference height of a few metres. The approximation is considered to be adequate in this model.

3.1.2 Results

The fraction of material remaining in the plume, $Q^*(x)/Q$, for a range of effective release heights in all stability conditions considered is given in Tables 1 and 2 for a deposition velocity of 10^{-2} m s^{-1}. Table 1 contains values applicable to a short release and is calculated using the windspeed at 10 m given in the Group's first report(1). Table 2 contains values applicable to a continuous release and is calculated using the windspeed at stack height, given in the table. Values for other deposition velocities or windspeeds can be derived by appropriate scaling. It is seen from equation (7) that

$$\frac{Q^*(x,V_g,u)}{Q} = \left(\frac{Q^*(x,V_{gT},u_T)}{Q}\right)^{V_g u_T/V_{gT} u} \qquad \text{.......... (9)}$$

where $Q^*(x,\ V_g,\ u)/Q$ is the fraction of activity remaining in the plume at distance x, for a deposition velocity V_g and wind speed u. V_{gT} and u_T are the values of deposition velocity and wind speed for which the tabulated values were calculated. Equation (9) enables the plume depletion factor to be obtained for values of deposition velocity or windspeed differing from those used in deriving Tables 1 and 2.

This process involves a small approximation if the tabulated value for $Q^*(x, V_{gT}, u_T)/Q$ is equal to 1.0 and the value of $V_g u_T / V_{gT} u$ is greater than 1.0. The approximation is however considered adequate. The tables are given for a deposition velocity of 10^{-2} m s^{-1} to reduce the number of cases for which the tabulated value of Q^*/Q is 1.0.

3.1.3 <u>The value of the deposition velocity</u>

The value of deposition velocity depends on the physical and chemical form of the depositing nuclide, the nature of the surface on which it is depositing and to a lesser extent on the wind speed and atmospheric stability. The Working Group has yet to consider the values of deposition velocity which should be used but two recent reviews of the parameter are suitable for reference [11,12].

Because of the difficulty of specifying a value for deposition velocity the Group suggests that a sensitivity analysis should be carried out to investigate the effect of changes in the assumed value.

3.1.4 <u>Restrictions on the use of the suggested model</u>

The conditions for which the Group considers the Gaussian plume model to be suitable for a non-depositing material are described in the Group's first report. Further caveats are imposed when modelling the dispersion of a depositing material. As described above, the source depletion model does not necessarily represent the physical distribution of activity in the atmosphere but it is simple to use and gives results which are considered sufficiently reliable for use in assessing the dosimetric consequences of radioactive discharges. The principal area in which the model breaks down is for dispersion from a low stack in stable conditions (especially categories F and G). The user is advised to treat results of this model with caution if a significant fraction of material is predicted to be removed from the plume in these conditions. The inclusion of a value for the fraction remaining in the plume in Tables 1 and 2 does not imply that the source depletion model is considered adequate for a deposition velocity of 10^{-2} m s^{-1} at all distances up to 100 km.

A further restriction is that the model makes no allowance for gravitational settling and should not be applied to particles with a settling velocity greater than a few centimetres per second. This implies a restriction in use to aerosols of activity median aerodynamic diameter* less than about 10 μm.

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* Aerodynamic diameter of a particle is the diameter of a unit density sphere with the same settling velocity as the particle. Activity median aerodynamic diameter of an aerosol is the median of the distribution of activity against aerodynamic diameter

3.2 Wet deposition

Wet deposition is the removal of activity from a plume by the action of rain and includes two distinct removal processes; rain falling through the plume, which is termed washout, and removal of activity incorporated in the rain cloud, known as rainout. The model described below includes both these removal processes. Activity can also be removed from a plume by the action of snow, usually referred to as snowout. This can be described by the model given below for removal by rain. There is considerable current research effort in this area aimed at studying the removal process and removal rate during rainfall and the probability that a dispersing plume will encounter rain. It is possible therefore that the model described below could be improved within a few years.

There are two separate aspects of the problem of calculating wet deposition rates from a dispersing plume, namely calculating the deposition rates in those sections of the plume subject to rain and describing the intermittent nature of rainfall, in both time and space.

Rain falling through a plume removes material throughout the whole of the plume volume. The wet deposition rate is therefore a function of the total activity throughout the depth of the plume being rained on rather than the activity concentration in air at ground level. The Group suggests that the wet deposition rate during rainfall be calculated using the washout coefficient, Λ, defined as the fraction of material within the plume removed by rain in unit time. The total amount of material Q remaining in a plume subject to continuous rainfall at a constant rate is given by

$$\frac{dQ'}{dt} = -\Lambda Q' \qquad \text{.......... (10)}$$

where t is the time from the start of the rain. Similar coefficients can be derived for rainout and snowout.

The Group considered three models which describe the intermittent nature of rainfall and lead to the calculation of the fraction of the time that a dispersing plume from a continuous release is subject to rainfall. These models can be briefly outlined as follows.

1. That fraction of activity discharged during conditions of rain experiences rain continuously during dispersion downwind while the remaining activity is discharged in dry conditions and travels downwind entirely in dry conditions (ie, unchanging meteorology).
2. All activity discharged experiences rain for a fraction of its travel time to any distance, the fraction being equal to the fraction of time for which rain falls at a given point.
3. A model in which the passage of activity between periods of wet and dry conditions is explicitly included.

There are difficulties associated with each of these models, although at short range the predictions of the three models are identical. However, the Group is also preparing a report on long-range dispersion and has decided to select a wet deposition model applicable at long range, where the predictions of the three models differ. The first model predicts essentially no wet deposition at distances beyond about a hundred kilometres from the release point as the vast majority of the activity which can be affected by rain has been deposited at shorter distances. This does not agree with observed deposition patterns and was considered unacceptable for use in a long-range dispersion model. The second model corresponds to physically unreasonable assumptions about the time distribution of rainfall. The main difficulty with the third model is to represent the sequences of passages of activity between wet and dry conditions.

A comparison has been carried out of activity concentrations in air, deposition rates and collective doses calculated using these models(13). In this comparison rain was assumed to occur only in categories C and D. The study showed that, for a washout coefficient of 10^{-4} s^{-1} and rain falling for 10% of the duration of category C and D, the wet deposition rate predicted by the third model described above is not very sensitive to the choice of parameters in the model. The combined wet and dry deposition rate in these categories, calculated for a washout coefficient of 10^{-4} s^{-1} and deposition velocity of 10^{-3} m s^{-1}, predicted by the three models differed by up to a factor of five at distances between 100 and 1000 km. For a given discharge the collective dose to the UK population was calculated for three locations representative of remote and semi-urban nuclear sites and a built-up area. The collective doses predicted by the models from routes such as inhalation, based on activity concentration in air, were found to differ by only a few tens of percent for any one site, while the collective doses from routes such as external irradiation, based on deposited activity, differed by up to a factor of three, but usually by much less.

The Group recognises that the models are unlikely to give signifcantly different predictions when applied to continuous releases but feels that the third model should be used as it is physically more realistic and not much more complicated to apply when compared with the other two models. The Group also considers it is sufficient that rainfall should only be assumed to occur in category D conditions. The model was selected primarily for application to a continuous release; its applicability to a short release is considered in Section 3.2.4.

3.2.1 <u>The suggested model for wet deposition</u>

A model for wet deposition must be able to predict the activity concentration in air and deposition rate at any distance downwind of the source. It must therefore predict Q', the total amount of material from a continuous release remaining in the plume at a given travel time (or distance) allowing for earlier depletion processes. It must also predict that component of Q', ie, Q'_W, which is the amount of material remaining in the plume at a given travel time, provided it is raining at that time. This is the amount which contributes to the wet deposition rate at that point. Because of the intermittent nature of rainfall in both time and space, these two quantities are not simply related. They can be evaluated from[14,15]

$$\frac{d\,Q'_D}{dt} = -\,P_D\,Q'_D + P_W\,Q'_W$$

$$\frac{d\,Q'_W}{dt} = P_D\,Q'_D - P_W\,Q'_W - \Lambda\,Q'_W \qquad \text{.......... (11)}$$

where Q'_D is the amount of material remaining at a given travel time assuming it is not raining at that time, such that $Q' = Q'_D + Q'_W$ and where P_D and P_W are the probabilities of dry and wet weather, respectively, stopping in unit time. The solution of equation (11) can be expressed as[16]

$$Q'(t) = \frac{Q}{m_1 - m_2}\left[\,(m_1 + \Lambda\,f_w)e^{m_2 t} - (m_2 + \Lambda\,f_w)e^{m_1 t}\,\right] \qquad \text{.......... (12a)}$$

$$Q'_W(t) = \frac{Q\,f_w}{m_1 - m_2}\left[\,(m_1 + \Lambda)e^{m_2 t} - (m_2 + \Lambda)e^{m_1 t}\,\right] \qquad \text{.......... (12b)}$$

with $2m_1 = -\,(\Lambda + P_D + P_W) - \sqrt{(\Lambda + P_D + P_W)^2 - 4\,\Lambda\,P_D}$

$2m_2 = -\,(\Lambda + P_D + P_W) + \sqrt{(\Lambda + P_D + P_W)^2 - 4\,\Lambda\,P_D}$

where $f_W = \dfrac{P_D}{P_D + P_W}$ is the fraction of the time for which rain falls in category D

The solutions given in equation (12) refer only to category D as this is the only category in which rain is assumed to fall. The equations were derived assuming that

$$Q'_W(t{=}0) = f_W\,Q$$

and that P_D and P_W are constants, independent of the previous pattern of precipitation. Activity concentrations in air are then obtained using equations (1) - (5) as appropriate, but replacing Q by $Q'(t)$ in category D.

The wet deposition rate per unit time D'_W is obtained from equation (10) as

$$D'_W(t) = \Lambda\,Q'_W(t) \qquad \text{.......... (13)}$$

and the wet deposition rate per unit area D_W for a continuous release, as

$$D_W = \frac{\Lambda\,Q'_W(t)}{r\,\alpha\,u_s} \qquad \text{.......... (14)}$$

and for a short release as

$$D_W = \frac{\Lambda\,Q'_W(t)}{\sqrt{2\pi}\,u_{10}\,\sigma_y}\exp\left[\,-\,y^2/2\sigma_y^{\,2}\,\right] \qquad \text{.......... (15)}$$

The travel time, required to evaluate $Q'_W(t)$ in equations (14) and (15), can be taken to be distance divided by wind speed.

3.2.2 The values of the probabilities P_D and P_W

If the probability of dry weather stopping in unit time, P_D, is assumed to be independent of the length of time that it has been dry then it can be regarded as the reciprocal of the mean duration of dry weather. Similarly, P_W can be regarded as the reciprocal of the mean duration of wet weather. The duration of dry or wet weather conditions as used in equation (11) should strictly be the durations as observed by the plume during category D conditions. There are no available measurements of these quantities. However the distribution of duration of wet and dry conditions at meteological stations in the UK is available(17).

The mean duration of periods of dry weather is in the region of 60-70 hours. However, the distribution of dry periods is not consistent with a single value of P_D. Rain is more likely to start in a given time after a short period of dry weather than after a long period. To some extent this may reflect the movement of air masses over fixed points on the ground and the mean duration of dry weather as applied to a plume may be consistent with the single value of P_D quoted above.

The distribution of the duration of wet periods as seen at fixed points on the ground is consistent with a single value of P_W corresponding to a mean duration of about 3 hours. For moving air masses the mean duration of wet weather may well be greater. If the mean duration of dry weather is taken to be 60 hours and rain is assumed to fall for about 10% of the time(17), then the implied mean duration of wet weather is 6 hours.

Because of the difficulties in specifying values for the mean durations of wet and dry conditions a sensitivity study was undertaken(13). The mean duration of dry weather was varied from 54 to 200 hours while the mean duration of wet weather was chosen to correspond to rain falling for 10% of the time. The washout coefficient was taken to be 10^{-4} s^{-1}. The wet deposition rate at any point within 1000 km of the source, in the absence of dry deposition, was found to vary by at most a factor of 2.5. If dry deposition is also taken into account the total deposition rate is less sensitive to the choice of values for the mean duration of weather conditions, as is the activity concentration in air.

As a result of this study, the Group suggests that the values of P_D and P_W should be taken as 4.6×10^{-6} s^{-1} and 4.6×10^{-5} s^{-1} corresponding to mean durations of dry and wet weather of 60 and 6 hours respectively.

3.2.3 The value of the washout coefficient

The value of washout coefficient depends on the physical and chemical form of the dispersing nuclide, the size distribution of the rain drops and the rainfall rate. The Group has yet to consider values of washout coefficient for use in the model, but a recent review of the parameter has been described by Slinn(11). However, its value cannot be specified with any reliability and a sensitivity study should be carried out.

When using the model for rainout, appropriate coefficients should be selected. The form of the solution given in this report will overestimate wet deposition due to rainout at short distances where the plume has not spread through the mixing layer.

3.2.4 Applicability of the proposed model

The model is appropriate for application to a continuous release. Because of its probabilistic nature, the model is only appropriate for application to short releases when a large number of short releases in category D are considered, or when average consequences are being calculated. The model cannot be applied to calculate concentrations and deposition rates from a single, specific release, since in that case the actual sequence of periods of wet and dry conditions will determine the concentrations. The solution given in equation (12) is appropriate only if a fraction, f_W, of the releases are assumed to occur in wet weather. Solutions of equation (11) can be obtained for other initial conditions, such as all releases in dry weather or all releases in wet weather.

3.2.5 Presentation of results

The functions $Q'(t)/Q$ and $Q'_W(t)/Q$ (derived from equation (12)), are plotted for different values of washout coefficient as functions of travel time in Figure 1. Values applicable to a particular distance can be obtained by assuming that distance equals the product of wind speed and travel time, using the wind speed at stack height for a continuous release and at 10 m for a short release.

3.3 The calculation of activity concentration in air and deposition rates

Activity concentration in air can be calculated from equations (1) - (5) as appropriate, provided that the release rate, Q, is replaced by the amount of material remaining in the plume, allowing for plume depletion. For the case of dry deposition only, Q is replaced by Q* obtained using equations (7) - (9); in the case of wet deposition only, Q is replaced by $Q'(t)$, obtained from equation (12). The correction factors for calculating the amount of material remaining in a plume subject to both dry and wet deposition are multiplicative so that Q must be replaced by $Q^* \, Q'(t)/Q$.

The dry deposition rate is given by equation (6), in which concentration is evaluated as described above. The wet deposition rate is given by equations (13) - (15) but correcting Q'_W for the effect of plume, depletion due to dry deposition, Q'_W is replaced by $Q'_W \, Q^*/Q$.

The activity concentration in air and deposition rate are given by the following equations.

For a short release :

$$\left.\begin{aligned} C(x,y,z) &= \frac{Q^*(x)}{2\pi\, \sigma_y\, \sigma_z\, u_{10}} \; \frac{Q'(t)}{Q} \; \exp\left[- \frac{y^2}{2\sigma_y^{\,2}} \right] F(h,z,A) \quad \text{if } \sigma_z < A \\ C(x,y,z) &= \frac{Q^*(x)}{\sqrt{2\pi}\, \sigma_y\, u_{10}\, A} \; \frac{Q'(t)}{Q} \; \exp\left[- \frac{y^2}{2\sigma_y^{\,2}} \right] \quad \text{if } \sigma_z > A \end{aligned}\right\} \quad \ldots (16)$$

$$D_W(x,y) = \frac{\Lambda\ Q^*(x)}{\sqrt{2\pi}\ u_{10}\ \sigma_y} \frac{Q_w'(t)}{Q} \exp\left[-\frac{y^2}{2\sigma_y^2}\right]$$

$$D_D(x,t) = V_g\ C(x,y,z) \qquad \ldots\ldots\ldots\ldots (17)$$

$$D(x,y) = D_D(x,y) + D_W(x,y)$$

For a continuous release:

$$C_{ij}(r,z) = \frac{Q^*(r)}{\sqrt{2\pi}\ r\ \alpha\ u_{sj}\ \sigma_{zj}} \frac{Q'(t)}{Q} F_j(h,z,A_j) \quad \text{if } \sigma_{zj} < A_j$$

$$C_{ij}(r,z) = \frac{Q^*\ (x)}{r\ \alpha\ u_{sj}\ A_j} \frac{Q'(t)}{Q} \quad \text{if } \sigma_{zj} > A_j \qquad \ldots\ldots\ldots (18)$$

$$C_i(r,z) = \sum_j f_{ij}\ C_{ij}\ (r,z)$$

$$D_{Wij}(r) = \frac{f_{ij}\Lambda\ Q^*(r)Q_w'(t)}{r\ \alpha\ u_{sj}\ Q}$$

$$D_{Dij}(r) = V_g\ C_{ij}(r,z=0) \qquad \ldots\ldots\ldots\ldots (19)$$

$$D_i(r) = \sum_j f_{ij}\ (D_{Wij} + D_{Dij})$$

where $Q^*(x)$ is given by equations (7) - (9)

$Q'(t)$ and $Q'_W(t)$ are given by equation (12)

Q is the initial discharge or discharge rate

F(h,z,A) is given by equation (2)

D is the total deposition rate

D_D and D_W are the dry and wet deposition rates and the subscripts i and j denote sector and category, respectively.

Note that as rain falls only in category D, $Q'(t) = Q$ and $Q'_W(t) = 0$ in all categories other than D.

4. SUMMARY

In this report a method has been proposed for including wet and dry deposition in atmospheric dispersion calculations. No new models have been developed but existing models have been reviewed. The models chosen represent a compromise between those giving a good description of the physics of atmospheric dispersion and those which are simple to use.

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

5. ACKNOWLEDGEMENTS

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7. SYMBOLS USED

A	Depth of mixing layer
C(r,z)	Air concentration for a continuous release at radius r (Bq m^{-3})
C(x,y,z)	Air concentration or its time integral for a short release (Bq m^{-3} or Bq s 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})
$D_{W'}$	Wet deposition rate per unit time (Bq 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 or total activity released (Bq s^{-1} or Bq)
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
Q_D	The amount of material remaining in a plume at a given time if it is not raining at that time
Q_W	The amount of material remaining in the plume at a given time if it is raining at that time
r	Distance from the release point for a continuous release (m)
t	Travel time or time (s)
T	Subscript indicating the value used in tables
u	Wind speed (m s^{-1})
u_s	Wind speed at the effective stack height (m s^{-1})
u_{10}	Wind speed at a height of 10m (m s^{-1})
V_g	Deposition velocity (m s^{-1})
x)	(along the mean wind direction
y)	Rectilinear co-ordinates (horizontally at right angles to the
z)	(mean wind direction vertically
x_c	Distance from the source at which $\sigma_z = A$ (m)
α	Angular width of a sector (radius)
Λ	Washout coefficient (s^{-1})
σ_y	Standard deviation of the cross-wind Gaussian plume profile (m)
σ_z	Standard deviation of the vertical Gaussian plume profile (m)

Table 1

The fraction of material remaining in the plume due to dry deposition for a short release and a deposition velocity of 10^{-2} m s^{-1}

Stack height	Fraction left in plume at various distances									
	1.10^2m	2.10^2m	5.10^2m	1.10^3m	2.10^3m	5.10^3m	1.10^4m	2.10^4m	5.10^4m	1.10^5m
Category A (wind speed 1 m s^{-1})										
5.0	9.42E-01	9.17E-01	8.93E-01	8.59E-01	8.31E-01	7.92E-01	7.56E-01	6.99E-01	5.55E-01	3.78E-01
10.0	9.69E-01	9.44E-01	9.10E-01	8.84E-01	8.56E-01	8.16E-01	7.79E-01	7.20E-01	5.72E-01	3.89E-01
20.0	9.83E-01	9.68E-01	9.35E-01	9.08E-01	8.80E-01	8.38E-01	8.00E-01	7.40E-01	5.87E-01	4.00E-01
30.0	9.96E-01	9.81E-01	9.49E-01	9.23E-01	8.94E-01	8.52E-01	8.13E-01	7.52E-01	5.97E-01	4.06E-01
50.0	1.00E+00	9.94E-01	9.68E-01	9.42E-01	9.13E-01	8.70E-01	8.30E-01	7.68E-01	6.10E-01	4.15E-01
70.0	1.00E+00	9.98E-01	9.79E-01	9.55E-01	9.26E-01	8.83E-01	8.42E-01	7.79E-01	6.19E-01	4.21E-01
100.0	1.00E+00	1.00E+00	9.89E-01	9.69E-01	9.40E-01	8.97E-01	8.56E-01	7.92E-01	6.29E-01	4.28E-01
150.0	1.00E+00	1.00E+00	9.97E-01	9.82E-01	9.56E-01	9.14E-01	8.72E-01	8.07E-01	6.40E-01	4.36E-01
200.0	1.00E+00	1.00E+00	9.99E-01	9.90E-01	9.67E-01	9.26E-01	8.84E-01	8.18E-01	6.49E-01	4.42E-01
Category B (wind speed 2 m s^{-1})										
5.0	9.66E-01	9.46E-01	9.16E-01	8.92E-01	8.65E-01	8.22E-01	7.85E-01	7.36E-01	6.22E-01	4.71E-01
10.0	9.85E-01	9.67E-01	9.37E-01	9.12E-01	8.84E-01	8.41E-01	8.02E-01	7.52E-01	6.36E-01	4.82E-01
20.0	9.97E-01	9.85E-01	9.59E-01	9.34E-01	9.06E-01	8.62E-01	8.22E-01	7.71E-01	6.52E-01	4.94E-01
30.0	1.00E+00	9.94E-01	9.72E-01	9.48E-01	9.20E-01	8.75E-01	8.35E-01	7.83E-01	6.62E-01	5.02E-01
50.0	1.00E+00	9.99E-01	9.87E-01	9.66E-01	9.39E-01	8.94E-01	8.53E-01	8.00E-01	6.77E-01	5.13E-01
70.0	1.00E+00	1.00E+00	9.94E-01	9.78E-01	9.52E-01	9.08E-01	8.67E-01	8.13E-01	6.87E-01	5.21E-01
100.0	1.00E+00	1.00E+00	9.99E-01	9.88E-01	9.66E-01	9.23E-01	8.82E-01	8.27E-01	7.00E-01	5.30E-01
150.0	1.00E+00	1.00E+00	1.00E+00	9.96E-01	9.81E-01	9.42E-01	9.02E-01	8.46E-01	7.16E-01	5.42E-01
200.0	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.90E-01	9.57E-01	9.17E-01	8.62E-01	7.29E-01	5.52E-01
Category C (wind speed 5 m s^{-1})										
5.0	9.86E-01	9.75E-01	9.59E-01	9.45E-01	9.28E-01	9.01E-01	8.75E-01	8.42E-01	7.73E-01	6.91E-01
10.0	9.95E-01	9.86E-01	9.70E-01	9.56E-01	9.39E-01	9.12E-01	8.86E-01	8.53E-01	7.88E-01	7.00E-01
20.0	9.99E-01	9.95E-01	9.83E-01	9.69E-01	9.52E-01	9.25E-01	8.98E-01	8.65E-01	7.99E-01	7.10E-01
30.0	1.00E+00	9.90E-01	9.90E-01	9.77E-01	9.61E-01	9.33E-01	9.07E-01	8.73E-01	8.06E-01	7.17E-01
50.0	1.00E+00	1.00E+00	9.97E-01	9.87E-01	9.72E-01	9.45E-01	9.19E-01	8.35E-01	8.17E-01	7.26E-01
70.0	1.00E+00	1.00E+00	9.99E-01	9.93E-01	9.80E-01	9.54E-01	9.29E-01	8.94E-01	8.26E-01	7.34E-01
100.0	1.00E+00	1.00E+00	1.00E+00	9.97E-01	9.88E-01	9.65E-01	9.39E-01	9.05E-01	8.36E-01	7.43E-01
150.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.95E-01	9.77E-01	9.53E-01	9.19E-01	8.51E-01	7.56E-01
200.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.98E-01	9.85E-01	9.64E-01	9.32E-01	8.63E-01	7.67E-01
Category D (wind speed 5 m s^{-1})										
5.0	9.87E-01	9.73E-01	9.49E-01	9.29E-01	9.03E-01	8.62E-01	8.22E-01	7.71E-01	6.80E-01	5.81E-01
10.0	9.97E-01	9.87E-01	9.66E-01	9.46E-01	9.20E-01	8.78E-01	8.38E-01	7.95E-01	6.93E-01	5.93E-01
20.0	1.00E+00	9.98E-01	9.84E-01	9.65E-01	9.41E-01	8.98E-01	8.57E-01	8.04E-01	7.09E-01	6.07E-01
30.0	1.00E+00	1.00E+00	9.93E-01	9.78E-01	9.54E-01	9.13E-01	8.71E-01	8.17E-01	7.21E-01	6.17E-01
50.0	1.00E+00	1.00E+00	9.99E-01	9.91E-01	9.72E-01	9.33E-01	8.92E-01	8.37E-01	7.39E-01	6.33E-01
70.0	1.00E+00	1.00E+00	1.00E+00	9.97E-01	9.84E-01	9.49E-01	9.08E-01	8.54E-01	7.55E-01	6.46E-01
100.0	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.93E-01	9.66E-01	9.28E-01	8.75E-01	7.75E-01	6.65E-01
150.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.83E-01	9.53E-01	9.04E-01	8.05E-01	6.92E-01
200.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.93E-01	9.70E-01	9.26E-01	8.31E-01	7.17E-01
Category E (wind speed 3 m s^{-1})										
5.0	9.82E-01	9.54E-01	9.00E-01	8.50E-01	7.91E-01	6.95E-01	6.07E-01	5.01E-01	3.44E-01	2.13E-01
10.0	9.98E-01	9.86E-01	9.42E-01	8.94E-01	8.34E-01	7.34E-01	6.41E-01	5.30E-01	3.64E-01	2.25E-01
20.0	1.00E+00	9.99E-01	9.82E-01	9.45E-01	8.88E-01	7.86E-01	6.87E-01	5.59E-01	3.91E-01	2.42E-01
30.0	1.00E+00	1.00E+00	9.95E-01	9.72E-01	9.23E-01	8.24E-01	7.24E-01	6.00E-01	4.14E-01	2.56E-01
50.0	1.00E+00	1.00E+00	1.00E+00	9.94E-01	9.67E-01	8.83E-01	7.83E-01	6.55E-01	4.54E-01	2.82E-01
70.0	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.87E-01	9.24E-01	8.32E-01	7.04E-01	4.93E-01	3.07E-01
100.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.98E-01	9.64E-01	8.90E-01	7.69E-01	5.49E-01	3.46E-01
150.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.92E-01	9.52E-01	8.56E-01	6.38E-01	4.10E-01
200.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.82E-01	9.18E-01	7.17E-01	4.73E-01
Category F (wind speed 2 m s^{-1})										
5.0	9.90E-01	9.47E-01	8.34E-01	7.22E-01	5.94E-01	4.09E-01	2.72E-01	1.48E-01	3.23E-02	2.65E-03
10.0	1.00E+00	9.95E-01	9.35E-01	8.35E-01	7.00E-01	4.89E-01	3.27E-01	1.79E-01	3.90E-02	3.20E-03
20.0	1.00E+00	1.00E+00	9.94E-01	9.50E-01	8.43E-01	6.21E-01	4.26E-01	2.37E-01	5.18E-02	4.25E-03
30.0	1.00E+00	1.00E+00	1.00E+00	9.89E-01	9.28E-01	7.33E-01	5.22E-01	2.97E-01	6.54E-02	5.37E-03
50.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.91E-01	8.89E-01	6.97E-01	4.23E-01	9.44E-02	7.75E-03
70.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.63E-01	8.24E-01	5.32E-01	1.21E-01	9.90E-03
100.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.91E-01	8.96E-01	6.04E-01	1.39E-01	1.14E-02
Category G (wind speed 1 m s^{-1})										
5.0	1.00E+00	9.78E-01	7.64E-01	4.87E-01	2.43E-01	6.16E-02	1.36E-02	1.50E-03	1.36E-05	2.51E-08
10.0	1.00E+00	1.00E+00	9.77E-01	8.13E-01	5.04E-01	1.54E-01	3.69E-02	4.34E-03	4.23E-05	3.18E-08
20.0	1.00E+00	1.00E+00	1.00E+00	9.92E-01	8.84E-01	4.48E-01	1.44E-01	2.16E-02	2.73E-04	5.39E-07
30.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.87E-01	7.42E-01	3.41E-01	7.18E-02	1.36E-03	4.25E-06
50.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.75E-01	7.66E-01	3.32E-01	1.74E-02	1.18E-04
70.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.53E-01	6.79E-01	9.17E-02	1.34E-03
100.0	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.96E-01	8.99E-01	2.26E-01	5.62E-03

Table 2

The fraction of material remaining in the plume due to dry deposition for a continuous release and a deposition velocity of 10^{-2} m s^{-1} for each Pasquill category A–G

	Windspeed at stack height, m s^{-1}	Fraction left in plume									
		1.10^2m	2.10^2m	5.10^2m	1.10^3m	2.10^3m	5.10^3m	1.10^4m	2.10^4m	5.10^4m	1.10^4m
Release at ground level											
A	1.00E+00	9.42E-01	9.17E-01	8.83E-01	8.58E-01	8.51E-01	7.92E-01	7.56E-01	6.99E-01	5.55E-01	3.78E-01
B	2.00E+00	9.66E-01	9.46E-01	9.16E-01	8.92E-01	8.65E-01	8.22E-01	7.85E-01	7.36E-01	6.22E-01	4.71E-01
C	5.00E+00	9.86E-01	9.75E-01	9.59E-01	9.45E-01	9.28E-01	9.01E-01	8.75E-0_	8.42E-01	7.78E-01	6.91E-01
D	5.00E+00	9.87E-01	9.73E-01	9.49E-01	9.28E-01	9.03E-01	8.62E-01	8.22E-01	7.71E-01	6.80E-01	5.81E-01
E	3.00E+00	9.82E-01	9.54E-01	9.00E-01	8.50E-01	7.91E-01	6.95E-01	6.07E-01	5.01E-01	3.44E-01	2.13E-01
F	2.00E+00	9.90E-01	9.47E-01	8.34E-01	7.22E-01	5.94E-01	4.09E-01	2.72E-01	1.48E-01	3.23E-02	2.65E-03
G	1.00E+00	1.00E+00	9.78E-01	7.64E-01	4.87E-01	2.43E-01	6.16E-02	1.36E-02	1.50E-03	1.36E-05	2.51E-08
Release at 10m height											
A	1.00E+00	9.69E-01	9.44E-01	9.10E-01	8.84E-01	8.56E-01	8.16E-01	7.79E-01	7.20E-01	5.72E-01	3.89E-01
B	2.00E+00	9.85E-01	9.67E-01	9.37E-01	9.12E-01	8.84E-01	8.41E-01	8.02E-01	7.52E-01	6.36E-01	4.82E-01
C	5.00E+00	9.95E-01	9.86E-01	9.70E-01	9.56E-01	9.39E-01	9.12E-01	8.86E-01	8.53E-01	7.88E-01	7.00E-01
D	5.00E+00	9.97E-01	9.87E-01	9.66E-01	9.46E-01	9.20E-01	8.78E-01	8.38E-01	7.85E-01	6.93E-01	5.93E-01
E	3.00E+00	9.98E-01	9.86E-01	9.42E-01	8.94E-01	8.34E-01	7.34E-01	6.41E-01	5.30E-01	3.64E-01	2.25E-01
F	2.00E+00	1.00E+00	9.95E-01	9.35E-01	8.35E-01	7.00E-01	4.89E-01	3.27E-01	1.79E-01	3.90E-02	3.20E-03
G	1.00E+00	1.00E+00	1.00E+00	9.77E-01	8.13E-01	5.04E-01	1.54E-01	3.69E-02	4.34E-03	4.23E-05	3.18E-08
Release at 20m height											
A	1.19E+00	9.91E-01	9.73E-01	9.45E-01	9.22E-01	8.96E-01	8.63E-01	8.29E-01	7.77E-01	6.40E-01	4.64E-01
B	2.39E+00	9.97E-01	9.88E-01	9.65E-01	9.44E-01	9.20E-01	8.83E-01	8.49E-01	8.04E-01	6.99E-01	5.54E-01
C	5.97E+00	1.00E+00	9.96E-01	9.85E-01	9.74E-01	9.60E-01	9.36E-01	9.14E-01	8.85E-01	8.28E-01	7.50E-01
D	5.97E+00	1.00E+00	9.98E-01	9.87E-01	9.71E-01	9.50E-01	9.14E-01	8.79E-01	8.33E-01	7.50E-01	6.58E-01
E	3.58E+00	1.00E+00	9.99E-01	9.85E-01	9.55E-01	9.05E-01	8.17E-01	7.30E-01	6.23E-01	4.55E-01	3.04E-01
F	2.39E+00	1.00E+00	1.00E+00	9.95E-01	9.58E-01	8.67E-01	6.71E-01	4.69E-01	2.99E-01	8.37E-02	1.03E-02
G	1.19E+00	1.00E+00	1.00E+00	1.00E+00	9.93E-01	9.02E-01	5.10E-01	1.97E-01	4.02E-02	1.03E-03	6.44E-06
Release at 30m height											
A	1.32E+00	9.97E-01	9.86E-01	9.62E-01	9.41E-01	9.19E-01	8.86E-01	8.55E-01	8.06E-01	6.77E-01	5.06E-01
B	2.65E+00	1.00E+00	9.95E-01	9.79E-01	9.60E-01	9.39E-01	9.04E-01	8.73E-01	8.31E-01	7.32E-01	5.94E-01
C	6.62E+00	1.00E+00	9.99E-01	9.92E-01	9.83E-01	9.70E-01	9.49E-01	9.29E-01	9.02E-01	8.50E-01	7.77E-01
D	6.62E+00	1.00E+00	1.00E+00	9.95E-01	9.83E-01	9.65E-01	9.33E-01	9.01E-01	8.58E-01	7.81E-01	6.94E-01
E	3.97E+00	1.00E+00	1.00E+00	9.97E-01	9.79E-01	9.41E-01	8.64E-01	7.83E-01	6.80E-01	5.13E-01	3.57E-01
F	2.65E+00	1.00E+00	1.00E+00	1.00E+00	9.91E-01	9.45E-01	7.91E-01	6.12E-01	4.00E-01	1.27E-01	1.93E-02
G	1.32E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.90E-01	7.98E-01	4.44E-01	1.37E-01	6.82E-03	8.73E-05
Release at 50m height											
A	1.51E+00	1.00E+00	9.96E-01	9.79E-01	9.61E-01	9.41E-01	9.12E-01	8.84E-01	8.39E-01	7.20E-01	5.58E-01
B	3.01E+00	1.00E+00	9.99E-01	9.91E-01	9.78E-01	9.59E-01	9.29E-01	9.00E-01	8.63E-01	7.72E-01	6.42E-01
C	7.54E+00	1.00E+00	1.00E+00	9.98E-01	9.91E-01	9.82E-01	9.63E-01	9.45E-01	9.22E-01	8.75E-01	8.09E-01
D	7.54E+00	1.00E+00	1.00E+00	9.99E-01	9.94E-01	9.82E-01	9.55E-01	9.27E-01	8.89E-01	8.19E-01	7.38E-01
E	4.52E+00	1.00E+00	1.00E+00	1.00E+00	9.96E-01	9.78E-01	9.20E-01	8.50E-01	7.55E-01	5.92E-01	4.32E-01
F	3.01E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.94E-01	9.25E-01	7.87E-01	5.65E-01	2.09E-01	3.98E-02
G	1.51E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.83E-01	8.38E-01	4.81E-01	6.81E-02	2.47E-03
Release at 70m height											
A	1.64E+00	1.00E+00	9.99E-01	9.87E-01	9.72E-01	9.54E-01	9.27E-01	9.01E-01	8.59E-01	7.46E-01	5.91E-01
B	3.28E+00	1.00E+00	1.00E+00	9.97E-01	9.86E-01	9.71E-01	9.43E-01	9.16E-01	8.81E-01	7.96E-01	6.72E-01
C	8.21E+00	1.00E+00	1.00E+00	9.99E-01	9.96E-01	9.88E-01	9.72E-01	9.55E-01	9.34E-01	8.90E-01	8.28E-01
D	8.21E+00	1.00E+00	1.00E+00	1.00E+00	9.98E-01	9.90E-01	9.68E-01	9.43E-01	9.08E-01	8.43E-01	7.67E-01
E	4.93E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.92E-01	9.53E-01	8.94E-01	8.07E-01	6.50E-01	4.88E-01
F	3.28E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.77E-01	8.89E-01	6.81E-01	2.76E-01	6.02E-02
G	1.64E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.71E-01	7.90E-01	2.34E-01	1.78E-02
Release at 100m height											
A	1.80E+00	1.00E+00	1.00E+00	9.94E-01	9.82E-01	9.66E-01	9.41E-01	9.17E-01	8.78E-01	7.72E-01	6.24E-01
B	3.60E+00	1.00E+00	1.00E+00	9.99E-01	9.93E-01	9.81E-01	9.57E-01	9.33E-01	9.00E-01	8.20E-01	7.03E-01
C	8.99E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.93E-01	9.80E-01	9.66E-01	9.46E-01	9.05E-01	8.48E-01
D	8.99E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.96E-01	9.81E-01	9.59E-01	9.28E-01	8.68E-01	7.97E-01
E	5.40E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.80E-01	9.37E-01	8.54E-01	7.16E-01	5.54E-01
F	3.60E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.95E-01	9.41E-01	7.56E-01	3.34E-01	8.31E-02
G	1.80E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.98E-01	9.42E-01	4.37E-01	5.61E-02
Release at 150m height											
A	1.99E+00	1.00E+00	1.00E+00	9.98E-01	9.91E-01	9.78E-01	9.56E-01	9.34E-01	8.98E-01	8.00E-01	6.60E-01
B	3.99E+00	1.00E+00	1.00E+00	1.00E+00	9.98E-01	9.91E-01	9.71E-01	9.49E-01	9.20E-01	8.46E-01	7.36E-01
C	9.97E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.98E-01	9.88E-01	9.76E-01	9.59E-01	9.22E-01	8.69E-01
D	9.97E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.92E-01	9.76E-01	9.50E-01	8.97E-01	8.31E-01
E	5.98E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.96E-01	9.75E-01	9.25E-01	7.98E-01	6.40E-01
Release at 200m height											
A	2.15E+00	1.00E+00	1.00E+00	1.00E+00	9.95E-01	9.85E-01	9.65E-01	9.44E-01	9.11E-01	8.18E-01	6.84E-01
B	4.29E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.95E-01	9.80E-01	9.61E-01	9.33E-01	8.63E-01	7.58E-01
C	1.07E+01	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.93E-01	9.83E-01	9.68E-01	9.33E-01	8.84E-01
D	1.07E+01	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.97E-01	9.86E-01	9.65E-01	9.17E-01	8.57E-01
E	6.44E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	9.99E-01	9.91E-01	9.61E-01	8.57E-01	7.05E-01

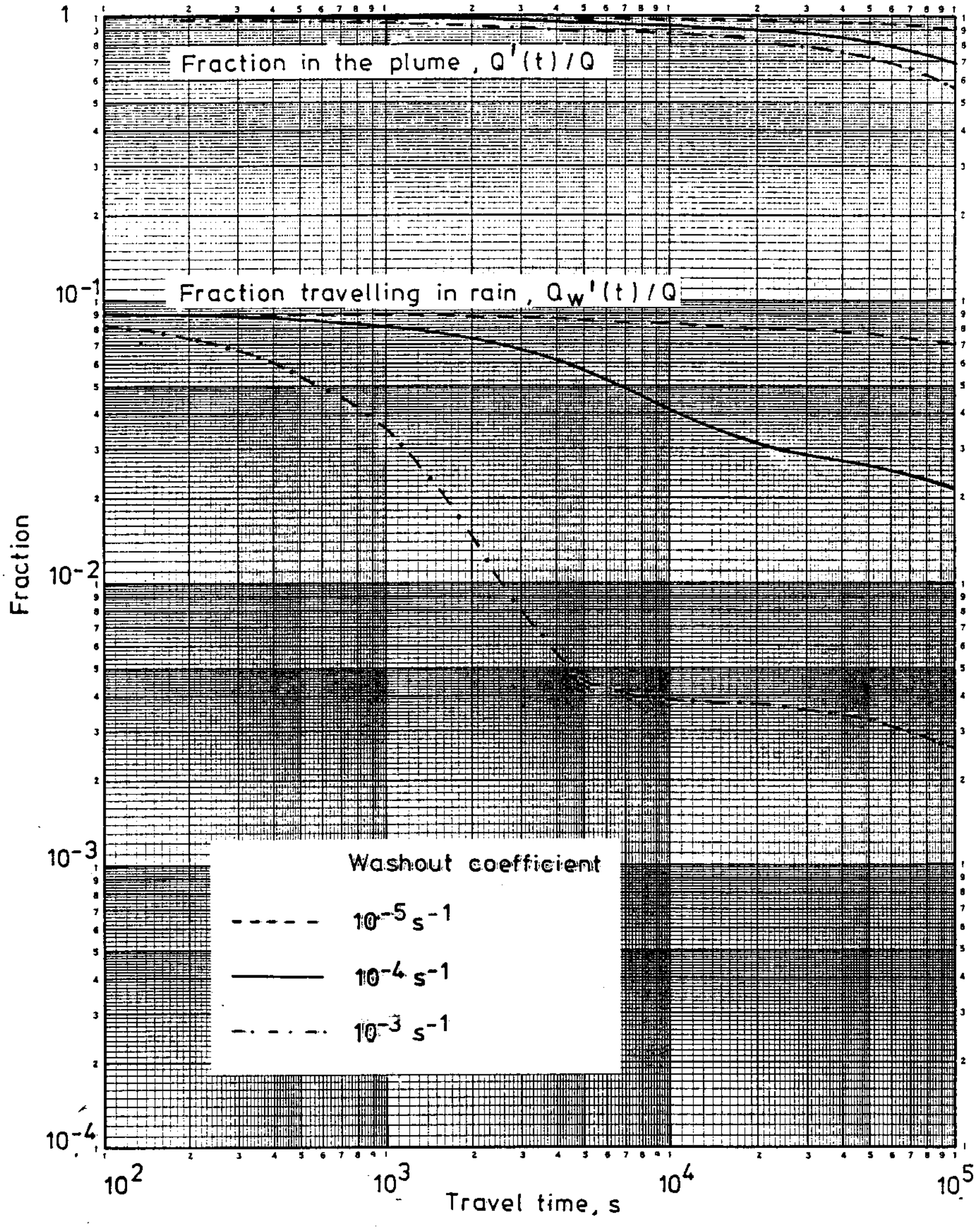

Figure 1 Fraction of material remaining in a plume subject to wet deposition and the fraction travelling in wet weather in Category D