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The Fourth Report of a Working Group on Atmospheric Dispersion

A Model for Long Range Atmospheric Dispersion of Radionuclides Released Over A Short Period

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National Radiological Protection Board

Chilton, Didcot, Oxon OX11 0RQ
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A MODEL FOR LONG RANGE ATMOSPHERIC DISPERSION OF RADIONUCLIDES RELEASED OVER A SHORT PERIOD

J A Jones

Secretary of the Working Group

ABSTRACT

This report is the fourth in a series which gives 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 model considered suitable for calculating dispersion at long range from releases of short duration.

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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 a Working Group was established in order to facilitate the review. The Working Group published a first report giving practical guidance on estimating the dispersion of radioactive releases in the atmosphere within a few tens of kilometres of the release. This guidance applies for both continuous and short duration releases for nuclides which do not deposit on the ground and are not removed from the plume by the interation of rain.

The Group has published two other reports: its second report describes methods for including dry and wet deposition for both continuous and short duration releases in the original model; its third report describes an extension of the models in the first two reports to predict long-range dispersion from continuous releases. This report, the fourth by the Group, describes a model for calculating the activity concentration in air and the deposition rate for a short duration release at distances of a few hundred kilometres from the release point. The model is typically for use in submissions under Article 37 of the Euratom Treaty. Other topics under consideration by the Group include building wake effects, plume rise, effects of topography including coastal sites, the dispersion of large particulate material, and appropriate values for deposition velocity and washout coefficients.

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
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 D J Moore	Central Electricity Generating Board, Research Department, Central Electricity Research Laboratory, Leatherhead
Dr F B Smith	Meteorological Office, Bracknell
Dr M L Williams	Department of Industry, Warren Spring Laboratory, Stevenage
Dr J A Jones (Secretary)	National Radiological Protection Board

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.

CONTENTS

FIGURES

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} ~ 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 ~ 2.7 x 10^{-11} Ci

1. INTRODUCTION

The problem of predicting the distribution of airborne material released from a source is often approached by solving the diffusion-transport equation. A range of models is available to solve the equation depending on the boundary conditions imposed and simplifying assumptions made. The Working Group reviewed some of these models and suggested methods for calculating activity concentration in air for a non-depositing material at short and medium range for short and continuous releases[1]. The Group has prepared other reports describing methods to include wet and dry deposition in the original model[2] and to extend it to long range for a continuous release[3].

The present report describes a model for the calculation of activity concentrations in air at distances of a few hundred kilometres from a short release. The model was developed primarily for use in the context of submissions to the Commission of the European Communities made under Article 37 of the Euratom Treaty. Amongst other things, submissions include a calculation of doses to the populations of other Member States of the European Communities following an accidental release of radioactive material from nuclear installations. The Working Group considered that the models for short releases described in its first report were inappropriate for use when calculating activity concentrations at distances of a few hundred kilometres from the release point. The Group considered that there must be a probabilistic element in the calculations to allow for the changes in atmospheric conditions that can occur for plumes travelling as far as several hundred kilometres. The model proposed is outlined in this report.

2. REQUIREMENTS OF THE MODEL

Any comprehensive methodology for dealing with hypothetical accidental releases must be based on a probabilistic method. Probability distributions could be specified for wind direction at the time of the release, for stability category both at the time of the release and during the plume's travel, for changes in wind direction both for a release with a duration of several hours and in the plume's subsequent travel, and for rain starting and stopping during the plume's travel. These probability distributions are likely to be strongly correlated. The result of such an analysis would be the overall probability distribution of activity concentration at given points.

In studies of the consequences of accidental releases it is the dose to those people who are irradiated which is of concern; in this situation the direction in which the plume is travelling is irrelevant. The problem is then slightly simplified to that of calculating the probability distribution of activity concentration along the nominal plume trajectory.

Submissions made under Article 37 of the Euratom Treaty usually consider doses to two groups of individuals resulting from accidental releases of activity. The first group to be considered is those people living close to the

source of the release; the second consists of the nearest group of people living in another Member State of the European Communities. The models described in the Group's first report[1] are applicable for calculating doses to people living within 100 km of the release point with caveats given in that report. This report describes a model for use when calculating doses to people living at greater distances.

The model described here is intended to provide a simple procedure for estimating the activity concentration which will be exceeded with a given probability as a function of distance along the direction of travel of a plume released over a short period. The requirements of a model for use in Article 37 submissions, as described above, are such that the Working Group did not consider it necessary to constrain the model described here to be a continuous extension of its original model to longer distances.

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

3.1 Dispersion at long range

The two main difficulties in modelling long-range dispersion are changes in wind direction and atmospheric stability category during the plume's travel. These difficulties can increase with increasing release duration.

Changes in stability category during the plume's travel can affect the rate at which the material disperses vertically and horizontally. As the material is carried along by the wind it diffuses upwards until the turbulent mixing layer is uniformly filled. Changes in the vertical distribution are subsequently affected by changes in the depth of the mixing layer caused by changes in atmospheric stability. The daytime depth of the mixing layer is, typically, up to a few kilometres, while during the night it can be as low as a few tens of metres. Dispersion of material released during the night will originally be restricted to within the shallow nocturnal mixing layer. However, when the depth of the mixing layer increases as the sun rises, the material is free to diffuse throughout the deeper mixing layer and spreads rapidly in the vertical direction. On the other hand as the sun sets, the depth of the mixing layer is reduced and material can be trapped above the new nocturnal mixing layer, thus being prevented from diffusing to ground level. The ground level concentration in this situation with a shallow mixing layer is then similar to that during the day when the mixing layer is much deeper.

To a large extent, changes in wind direction during the travel of a plume can be ignored and the model predictions must then be interpreted as giving activity concentration in air as a function of distance along the trajectory rather than along the original plume direction. This approach is adequate for those studies in which the objective is to calculate the maximum activity concentrations at a particular distance or at a particular point, when it is reasonable to assume that a plume will have travelled in a straight line to the point.

The horizontal distribution of activity within the plume reflects the combined effects of two processes. For relatively short release durations the average spread of the plume around the mean wind direction is determined by turbulent diffusion and fluctuations of instantaneous wind direction, termed turbulent spread for convenience, Θ_t. On a time scale of a few tens of hours, the lateral spread of the plume, Θ_w, is determined by systematic changes of wind direction. Therefore, for release durations up to a few tens of hours it is logical simply to add the two components of horizontal spread and assume that the horizontal distribution of activity is uniform across that angle. The time-integrated activity concentration, C, at a distance x (m) from the release is given by

$$C(x) = \frac{Q}{u\Theta xA} \qquad \ldots\ldots\ldots (1)$$

where Q is the total activity released

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

Θ the total width of the plume (radians)

$= \Theta_t + \Theta_w$

and A the depth of the mixing layer (m)

3.2 Choice of values of the parameters

3.2.1 The value for plume width, Θ

The plume width is the sum of two components, because of turbulent spreading, Θ_t, and systematic changes of wind direction, Θ_w. The suggested values of Θ_w are based on a recent study[4] of the angle between the locations at which trajectories starting at different times cross circles of given radius centred at the release point. The results of this study give the probability that plume width is less than a given angle as functions of release duration and distance from the source, averaged over all weather conditions. Simple formulae have been obtained to give the angles less than that experienced by 10, 50 and 90% of the trajectories considered. The formulae are

$$\left.\begin{aligned} \Theta_w &= 2.2\ 10^{-2}\ T^{1.16}\ x^{-0.125} && \text{10\% of the time} \\ \Theta_w &= 1.9\ 10^{-1}\ T^{0.85}\ x^{-0.125} && \text{50\% of the time} \\ \Theta_w &= 1.1\ T^{0.64}\ x^{-0.125} && \text{90\% of the time} \end{aligned}\right\} \qquad \ldots\ldots\ldots (2)$$

where Θ_w is the angle (radians)

T is the release duration (h)

and x is the distance (m)

The angle Θ_w for these three probabilities is plotted in Figure 1 as a function of release duration for four distances.

Values of Θ_w corresponding to other probabilities can be obtained from Figure 2 which is applicable at a distance of 500 km.

Values applicable at other distances can be obtained from those appropriate to 500 km by using equation (3).

$$\Theta_w(x) = \Theta_w\,(5.10^5\ \text{m})\ \left(\frac{x}{5.10^5}\right)^{-0.125} \qquad \ldots\ldots\ldots\ (3)$$

If equation (2) or (3) is used to predict values of Θ_w for large distances, long release durations and high probabilities, a value in excess of π or even 2π radians can be obtained. Equation (1) clearly cannot be used for values of Θ greater than 2π radians. The equation is valid for angles greater than π radians but should then be used with caution as it was not always possible to distinguish between angle of Θ_w and $(2\pi-\Theta_w)$ radians as Θ_w approached π in the trajectory study.

The study used to derive Figures 1 and 2 and equations (2) and (3) was restricted to release durations between 12 and 100 hours. Values for shorter release durations may be obtained by scaling the 12-hour value

$$\Theta_w\,(T < 12) = \Theta_w\,(T = 12)\,\frac{T}{12} \qquad \ldots\ldots\ldots\ (4)$$

The angle Θ_t representing the spread of the plume due to turbulence is given in radians by

$$\Theta_t = 1.0\ x^{-0.16} \qquad \ldots\ldots\ldots\ (5)$$

where x is the distance (m).

This formulation is based on an extension to greater distances of the formulation given in the Group's first report for horizontal spreading of the plume from a short release and is applicable to a release duration of about one hour. There are theoretical reasons, but little experimental evidence, to suggest that this may slightly overestimate the angle and underestimate the concentration. However, in many cases Θ_t is small compared to Θ_w so the effect is not likely to be important.

3.2.2 The value for mixing layer depth, A

As described in Section 3.1 the activity concentration at ground level at great distances is determined not by the depth of the mixing layer at that distance, but rather by the maximum mixing layer depth encountered by the plume during its travel. As those atmosphere conditions with a shallow mixing layer are unlikely to persist for travel distances beyond 100 km, the Group considers it sufficient to use a single value of 1000 m for depth of the mixing layer. This value is somewhat larger than the average value of mixing layer depth which could be derived from the Group's first report[1].

3.2.3 The value for windspeed, u

There is a correlation between wind speed and wind direction persistence, strong winds having a greater tendency to maintain their direction than light winds. This means that the product of wind speed and plume width ($u\Theta$) in equation (1) is largely independent of wind speed. Therefore, when using equation (1) to calculate concentrations it is sufficient to use a value for the

wind speed representative of the average for the weather conditions and over the depth of the mixing layer. A single value of 8 m s^{-1} is suggested for this[4].

3.3 The probability predicted

The simple model described here does not incorporate the full statistical variation of all the relevant meteorological parameters for the time-integrated activity concentration in air. Probability distributions of many parameters, for example, plume width and windspeed, are likely to be strongly correlated. Variability in plume width can be incorporated using equation (2) for the lateral spread parameter Θ_w. Note that if the plume width is less than Θ_w with a probability, p, the corresponding time integrated activity concentration is exceeded with a probability p. However, because of the incomplete treatment of other parameters, the probabilities derived in this way are likely to be only approximately valid but the Group considered them adequate for the purposes of this report.

3.4 The inclusion of deposition

Dry and wet deposition rates can be calculated using the methods described in the Group's second report[2].

The time-integrated dry deposition D_D is given by

$$D_D(x) = V_g \; C(x) \qquad \ldots\ldots\ldots (6)$$

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

and the time-integrated wet deposition D_w is given by

$$D_w(x) = \frac{\Lambda Q}{u\Theta x} \qquad \ldots\ldots\ldots (7)$$

where Λ is the washout coefficient (s^{-1})

These formulae for time-integrated deposition do not include the effects of plume depletion during the plume's travel from its source to the point at which the deposition is being calculated. There may be applications in which it is acceptable to assume, pessimistically, that there has been no plume depletion during travel. Where necessary, plume depletion can be estimated using the methods described in other reports by the Group[2,3] and included in the model described here.

The Working Group has not yet given values for the deposition velocity and washout coefficient. However, recent comprehensive reviews of their values have been made by Slinn[5] and Sehmel[6].

4. PROBABLE PRECISION OF THE MODEL

There are very few sets of data available with which to attempt to validate the model described in this report. Therefore the only way to obtain indications of the precision of the model predictions is by comparing results of this and other models. Such a comparison can be treated in two ways, because of the probabilistic nature of models for dispersion following a short release.

The model can be used to calculate the time-integrated activity concentration which will be exceeded with a specified probability. This time-integrated activity concentration can be compared with that predicted by other models for the same situation. An alternative approach is to derive the probability according to other more complex models, in which the activity concentration exceeds that for the specified probabilities given by this model. Such a comparison has been undertaken for an inert non-depositing material between the results of this model and of the trajectory model MESOS[7].

In general, the probability of exceeding a given time-integrated activity concentration deduced from the cumulative probability distribution given by the MESOS code is less than that predicted by the model in this report. Thus, if the Group's model is used to evaluate time-integrated activity concentrations which will be exceeded 10, 50 and 90% of the time, then MESOS indicates that these time-integrated concentrations are likely to be exceeded on about 5 to 20%, 10 to 30% and 30 to 60% of occasions respectively. The model in this report seems therefore, in general, to be slightly conservative as it predicts higher concentrations at a given probability.

5. SUMMARY

This report describes the model suggested by the Working Group for calculating activity concentrations and deposition rates at great distances following a short duration release. The model is applicable to those situations in which the activity concentrations are required only at long distances.

6. ACKNOWLEDGEMENTS

Both the author and the chairman of the Working Group would like to thank all members of the Working Group for their assistance in the preparation of this document.

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8. SYMBOLS USED

C	Time-integrated air concentration (Bq s m^{-3})
D_D	Total dry deposition (Bq m^{-3})
D_w	Total wet deposition (Bq m^{-2})
Q	Activity released (Bq)
T	Release duration (h)
u	Wind speed (m s^{-1})
V_g	Deposition velocity (m s^{-1})
x	Distance from the source (m)
Λ	Washout coefficient (s^{-1})
Θ	Total width of the plume (radians)
Θ_t	Width of the plume due to turbulence (radians)
Θ_w	Width of the plume due to wind direction changes (radians)

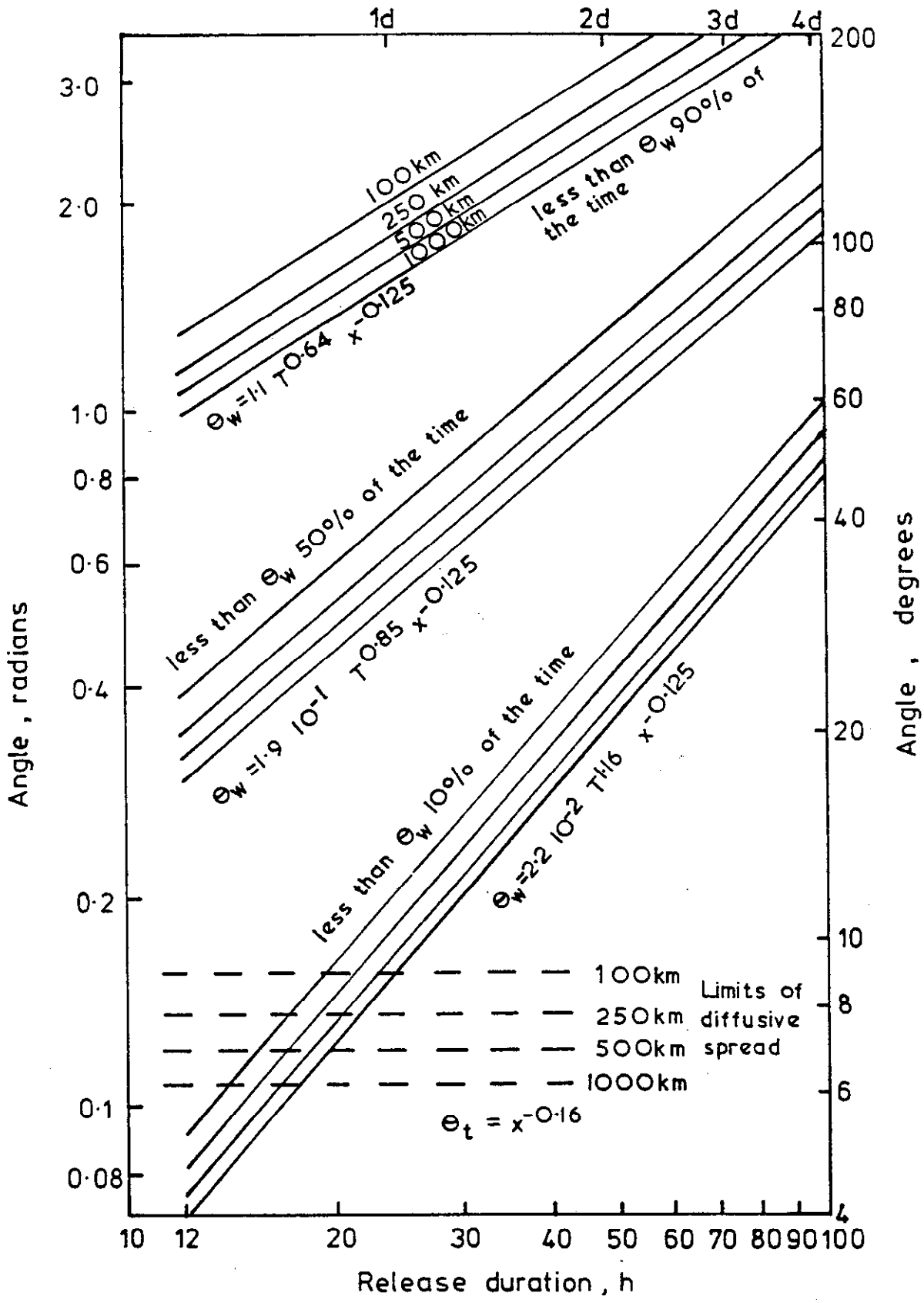

Figure 1 Plume width as a function of distance from the source and release duration for different probabilities

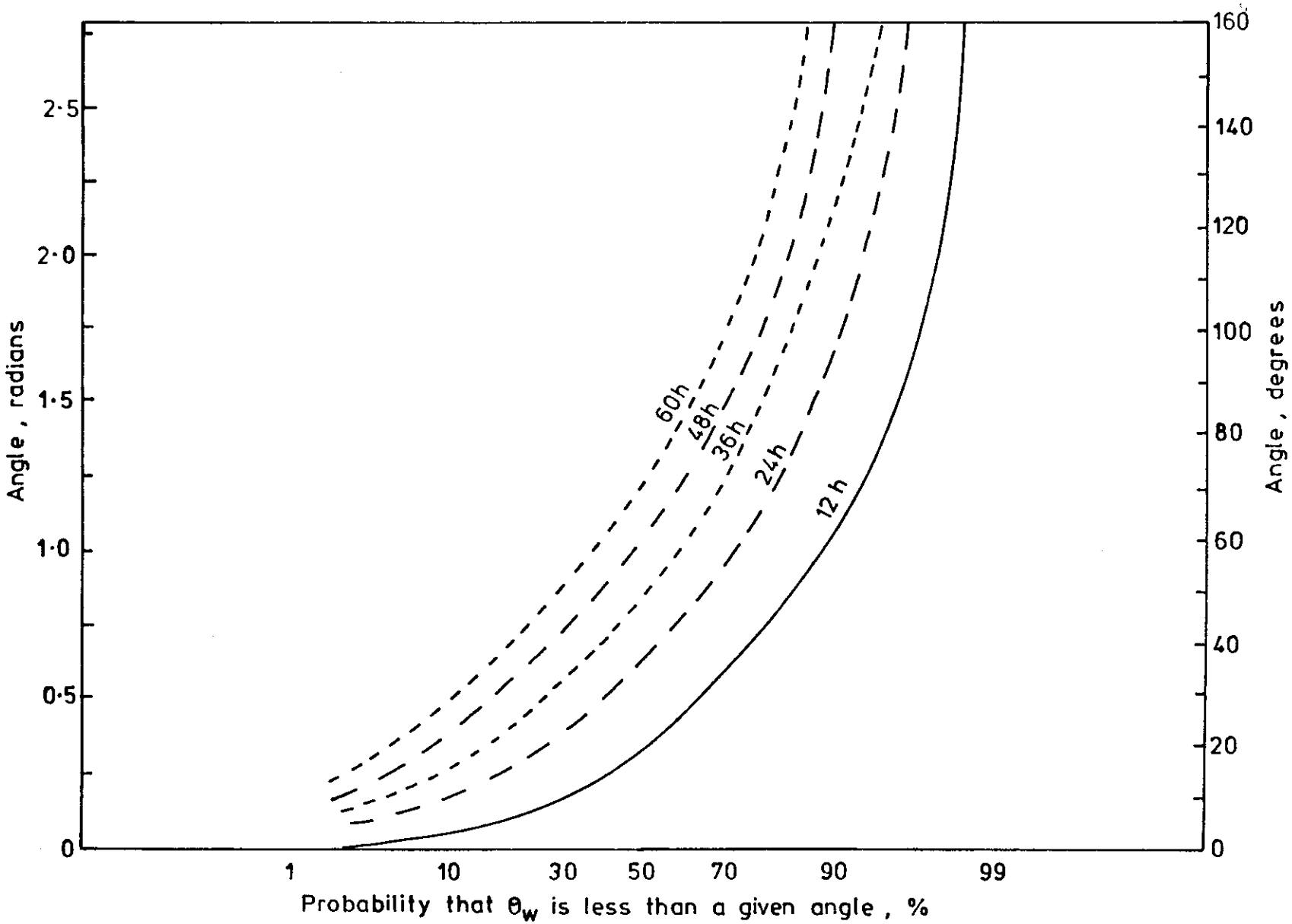

Figure 2 Cumulative probability distribution of angular spread θ_w for various sampling times T measured at a range of 500 km