MODELLING AND TRACER STUDIES
OF ATMOSPHERIC DISPERSION
AND DEPOSITION IN REGIONS
OF COMPLEX TOPOGRAPHY

by

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PREFACE

The work described in this thesis was carried out in the Isotopes and Radiation Division of the then SA Atomic Energy Board, and I would like to express my gratitude to this Institution for the opportunity afforded me in carrying out this study. The entire thesis, unless specifically indicated to the contrary in the text, is original, and the thesis has not been submitted for a degree at any other university.

I am grateful to the following persons for their scientific and technical advice and assistance in the research program discussed here and I wish to thank them:

Dr D. van As as program leader and Dr J.K. Basson, the then Director: Isotopes and Radiation Division, who initiated this program, and who offered valuable criticism with regard to this study.

Drs M. Mulholland and M.T. Scholtz and Prof E.T. Woodburn, previously of the Department of Chemical Engineering, University of Natal, who planned part of the experimental program, and Dr G.P.N. Venter, previously Head: Air Pollution Research Group, CSIR, who all gave me useful advice on certain theoretical and technical aspects of the study.

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Dr J.D. Neethling and Mr G.W.J. van der Berg who devised the computer programs used in the study (their contributions are specified in the text), and Miss E. Brümmer and Mrs E. Viljoen who did the programming.


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Mr H.N.J. Louw of the Physical Metallurgy Division of the AEB who assisted in the electron microscopy work.

I would also like to thank those involved in the preparation of the thesis: Mr F.J.P. Kroep, Miss J.M. Henchie and Mr P.E. Haskins who edited the script; Mr W.J. van Heerden, Mrs W.S.M. Boerrigter and Mrs S.B. van der Merwe who prepared the figures, and Mrs E.M. Nell, Mrs M.S. Jordaan and Miss E.H. Jacobs who did the typing of the various drafts.

C.E. Norden

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ABSTRACT

An indium tracer aerosol generating apparatus based on an alcohol/oxygen burner, and an analytical procedure by which filter samples containing tracer material could be analysed quantitatively by means of neutron activation analysis, were developed for use in atmospheric dispersion and deposition studies. A number of series of atmospheric dispersion experiments were conducted in the Richards Bay and Koeberg-Cape Town areas. The results are given, comparing the airborne tracer concentrations measured at ground level with values predicted by means of a numerical model, utilising two to three schemes, varying in sophistication, for calculating the dispersion coefficients.

The most sophisticated dispersion scheme did not give values much better than those given by a less sophisticated one, except at short distances (<5 km) in stable atmospheric conditions in the Richards Bay vicinity. In the Richards Bay work two artificially generated particulate tracers were released simultaneously at a constant rate and at more or less the same position. The two tracers, \( \text{In}_2\text{O}_3 \) and \( \text{ZnS.CdS} \) (with count-median diameters of 0.02 and 4 µm respectively), gave different normalised concentration values at samplers downwind, and these differences are used to illustrate the use of a dual-tracer approach in conjunction with a surface-depletion deposition mathematical model which was developed for this purpose. Over grassy and sandy terrain good results were obtained with this model, but a general overprediction in plume depletion was found over more highly vegetated areas.

The segmented-plume Gaussian dispersion model used in the Richards Bay area was adapted for use in the Koeberg area and this in general gave good results where the plume
trajectory could be defined. In katabatic air-flow, with marked directional wind shear near the surface, poor results were obtained. Recommendations are given regarding a dispersion model and dispersion coefficients for regular use in the Koeberg area, and ways for estimating plume trajectories.
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PART 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

The aim of this study was to develop and test experimental techniques and numerical methods to be employed in the investigation of the atmospheric behaviour of airborne effluent from the nuclear power station Koeberg, and their application in the Koeberg-Cape Town area.

The thesis is presented in four parts. The introduction is a review of dispersion and deposition models and approaches for the determination of relevant parameters. In Part Two the development and utilisation of an indium tracer generator and sampling technique (for the determination of tracer air concentrations during field experiments) and analytical procedures are discussed. Various aspects of the In$_2$O$_3$ tracer are discussed, such as filter efficiency of the sampler filters for these particles, decontamination of filter holders, etc.

In Part Three of the thesis the experimental results of a series of field tracer runs in the Richards Bay area, especially under low wind speed inversion conditions during the winters of 1975 and 1976, are investigated. The aim was partly to test the experimental techniques and partly to verify a segmented-plume dispersion model. Various approaches, depending on their degree of sophistication (the most sophisticated one based on stability length theory), for the determination of the diffusion coefficients are compared using the experimentally obtained concentration results. Results obtained from releasing two different types of tracer simultaneously, viz. In$_3$O, particles (count-median diameter - CMD -
0.02 μm) and ZnS.CdS particles (CMD 4 μm), are used to determine the applicability of a dual-tracer technique for dry-deposition studies. A surface-depletion numerical model was developed for the purpose of predicting the ratio of the concentrations of the two tracers 1 m above the surface.

In Part Four the dispersion computer program used in Part Three is adapted for use in the specific conditions prevailing in the Koeberg-Cape Town area, and the calculated concentration values compared with experimental ones from a series of tracer runs performed during 1977/78/80. The meteorological and topographical conditions in the Koeberg area are much more complex than at Richards Bay. The distances involved were larger with bigger topographical obstacles, and more complex wind fields were encountered. Especially during land- and sea-breeze conditions, directional wind shear at low levels above the surface were experienced often, causing tracer plume trajectories not expected if winds at 10 m height were considered only. Both the experimental program and numerical model for dispersion used in the Richards Bay study had to be adapted somewhat for use at Koeberg. The emphasis in the study was shifted from concentration measurements (which were still done) to plume trajectory determinations in complex wind fields, and vertical wind and temperature measurements to greater heights (500 m and more). Experimental tracer dispersion work was done to study plume trajectories and determine a suitable turbulence typing scheme and numerical approach for simulating airborne effluent behaviour, for general and emergency use in the Koeberg area. The numerical model used for simulating the Richards Bay work had to be adapted to take into account factors such as the changes in atmospheric stability.
possible as a plume moves from the coastline inland or out over the sea, and the shallow mixing layer encountered sometimes, which may cause plume material to be trapped in the lower tens or hundreds of metres of the atmosphere.

1.2 DISPERSION AND DEPOSITION STUDIES: A SURVEY

1.2.1 Numerical Approach to Turbulent Diffusion

As the dispersion of airborne effluent is strongly influenced by turbulence in the atmosphere, this is a most important variable to determine for the purposes of modelling dispersion. As the direct characterisation of turbulence is very difficult, numerical methods are based on simplified variables (mostly empirical). There is a range of such models, from the very simple where a minimum of input data (possibly from one instrument only) is necessary, to the relatively complex ones where a number of variables have to be determined, such as wind speed, temperature and the change of temperature with height, surface roughness, the depth of the mixing layer, etc.

The general equation of diffusion in three dimensions in which the diffusion coefficients, which are not necessarily equal, can vary with the three spatial coordinates $x$, $y$ and $z$, is:

$$\frac{d\bar{q}}{dt} = \frac{\partial}{\partial x}(K_x \frac{\partial \bar{q}}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial \bar{q}}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial \bar{q}}{\partial z})$$

with $\bar{q}$ the mean value of concentration and $K_i$, the eddy-diffusivity coefficient (when considering diffusion in the atmosphere).

For a stationary medium, the one-dimensional form of this
equation becomes
\[ \frac{\partial \bar{q}}{\partial t} = K \frac{\partial^2 \bar{q}}{\partial x^2} \]

Boundary conditions specifying a point source are (Gifford, 1969):

1) \( \bar{q} \to 0 \) as \( t \to \infty \) \((-\infty < x < +\infty)\)

2) \( \bar{q} \to 0 \) as \( t \to 0 \) (for all \( x \) except \( x = 0 \))

where \( \bar{q} \to \infty \) such that
\[ \int_{-\infty}^{\infty} \bar{q} \, dx = Q' \]

where \( Q' \) is the source strength (total release of \( \bar{q} \)). The solution may be obtained by various mathematical methods.

The fundamental solution of this equation, a Gaussian function (Gifford, 1969), has the form
\[ \frac{\bar{q}}{Q'} = \frac{1}{\sqrt{4\pi at}} \exp \left( -\frac{bx^2}{t} \right) \]

Integration of the instantaneous-point-source equation with respect to time gives the continuous-point-source solutions.

Combination of the Gaussian assumption with the following expression for the mean-square particle diffusion (Gifford, 1969),
\[ \bar{y}^2 = 2Kt \]

(with \( \bar{y}^2 \) the variance of the resulting distribution of
particles along the y axis and \( K \) the eddy-diffusivity coefficient), gives the following Gaussian formula for an instantaneous-point-source solution (Gifford, 1969):

\[
X(x, y, z, t) = \frac{Q}{\sqrt{2\pi \sigma_y^2}} \exp\left(-\frac{r^2}{2\sigma_y^2}\right),
\]

where \( \chi \) is concentration, \( r^2 = [(x-\bar{u}t)^2 + y^2 + z^2] \), \( \bar{u} \) is the wind speed, and where it is assumed that \( \sigma_x = \sigma_y = \sigma_z \) and \( x = \bar{u}t \) (which makes the \( \sigma \)'s functions of \( x \)). \( \sigma_x \), \( \sigma_y \), \( \sigma_z \) are respectively the standard deviations in the distribution in the \( x \), \( y \) and \( z \) directions. Keep in mind that this formula only applies in long diffusion time and for homogeneous, stationary conditions.

Where the \( \sigma \)'s are not equal,

\[
X(x, y, z) = \frac{Q}{\sigma_x \sigma_y \sigma_z} \exp\left\{-\frac{[(x-\bar{u}t)^2 + y^2 + z^2]}{2\sigma_x^2 y^2 + 2\sigma_y^2 z^2} \right\}.
\]

For obtaining a continuous-point-source diffusion formula from the latter equation, the plume is regarded as resulting from the addition of an infinite number of overlapping puffs, carried along the \( x \)-axis (Gifford, 1969). Mathematically, this corresponds to integration of the latter equation with respect to \( t \) from 0 to \( \infty \). To simplify the integration, diffusion along the \( x \)-axis is ignored (Gifford, 1969) as its effect is negligible relative to the transport by wind. After integration

\[
\bar{X}(x, y, z) = \frac{Q}{2\pi \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right],
\]

where \( \sigma_y \equiv (y^2)^{\frac{1}{2}} \) and \( \sigma_z \equiv (z^2)^{\frac{1}{2}} \), and \( Q \) is the plume release rate.

To account for the ground as a physical barrier to
diffusion, an image source to the actual source, located symmetrically with respect to the ground plane, is assumed. This results in the following much-used equation for a sampler at ground level:

\[ \bar{X} = \frac{Q}{\pi \bar{u}_0 \sigma_y \bar{u}_z} \exp \left[ - \left( \frac{y^2}{2 \sigma_y^2} + \frac{h^2}{2 \sigma_z^2} \right) \right] \]

(1-1)

where \( h \) is the source height.

The various analytical approaches for determining \( \sigma_y \) and \( \sigma_z \), divided into the "less complex schemes" and the "more complex approaches", are discussed below.

1.2.1.1 The less complex schemes

A simple scheme by Pasquill (1961) is shown by means of Table 1-1 and Fig. 1-1. The only variable to be measured instrumentally for use in the general dispersion equation (1-1) is \( \bar{u}_z \); once the turbulence category (A, B, etc.) is decided on, \( \sigma_y \) and \( \sigma_z \) are determined from Fig. 1-1.

In Table 1-1 the degree of insolation is determined from observation. A variant of this approach is proposed by Turner (1961, 1964), in which incoming solar radiation is categorised by the elevation angle and cloud amount and height.

A number of other classification schemes where the temperature difference with height is the only variable on which categorisation of stability classes depends, can be obtained from the literature. Smith (1973) gives a simple scheme where the number of stability classes is restricted to four only, viz. "very unstable", "unstable", "neutral", "stable". He gives equations for the determination of the \( \sigma \)'s, of the form \( ax^b \) (where \( x \) is
Fig. 1-1.
Curves of $\sigma_y$ and $\sigma_z$ for Pasquill's turbulence types.
Table 1-1. Meteorological conditions defining Pasquill turbulence types

A: Extremely unstable conditions
B: Moderately unstable conditions
C: Slightly unstable conditions
D: Neutral conditions*
E: Slightly stable conditions
F: Moderately stable conditions

<table>
<thead>
<tr>
<th>Surface wind speed, m.s^{-1}</th>
<th>Day-time insolation</th>
<th>Night-time conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>u &lt; 2</td>
<td>A</td>
<td>A-B</td>
</tr>
<tr>
<td>2 ≤ u &lt; 3</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>3 ≤ u &lt; 5</td>
<td>B</td>
<td>B-C</td>
</tr>
<tr>
<td>5 ≤ u &lt; 6</td>
<td>C</td>
<td>C-D</td>
</tr>
<tr>
<td>6 ≤ u</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

* Applicable to heavy overcast day or night.
** The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

the distance from the source, and a and b are constants for a particular stability category) to be applicable up to a distance of approximately 10 km downwind from the source.

A similar classification scheme is given by Carpenter et al. (1971) where the a-curves taken for a specific atmospheric condition depend on the lapse rate (potential temperature gradient) only.
One other category of turbulence classification schemes is based on the so-called Sutton parameters (Meroney and Yang, 1970). In this approach the $\sigma$'s are calculated from a set of parameters ($n$, the Sutton parameter and $C_y$ and $C_z$ the Sutton coefficients), either by having a constant $n$, $C_y$ and $C_z$ value for each stability category (Singer, 1961; Moses and Strom, 1961), or by having $n$, $C_y$ and $C_z$ determined from an empirical set of relationships in terms of lapse rate, such as the following (Venter et al., 1973):

$$n = 0.04 \frac{\delta \theta}{\delta z} + 0.37$$

$$C_y = 0.57 n + 0.106$$

$$C_z = 0.38 n + 0.112$$

where $\frac{\delta \theta}{\delta z}$ is the lapse rate in $K(100 \text{ m})^{-1}$. The $\sigma$'s are then determined from

$$2\sigma_i^2 = C_i^2 x^{2-n}$$

The discussion has thus far been centred on the use of the lapse rate, indirectly (by determining cloud cover and insolation) or directly (by measuring temperature change with height) to determine stability categories. Another way to proceed (relatively simple in terms of the mathematics involved, but instrumentally more complex) is to use the horizontal or horizontal and vertical standard deviations in wind direction.

One such classification scheme based only on the horizontal standard deviations in wind direction is the BNL scheme, originally expounded by Smith (1951). This scheme has been refined and developed by Singer, Frizzola...
and Smith (1966) and is based on the range of fluctuations of the horizontal wind-direction trace as recorded by a Bendix-Friez aerovane at 108 m above the ground. The BNL types can be categorised in the following classes (Singer and Smith, 1966):

A. Fluctuations (peak to peak) of the horizontal wind direction exceeding 90°.

B\text{.} Fluctuations ranging from 40 to 90°.

B\text{.} Fluctuations similar to A and B\text{.} but ranging from 15 to 45°.

C. Fluctuations greater than 15° and distinguished by the unbroken solid core of the trace.

D. The trace approximates a line; short-term fluctuations not bigger than 15°.

Fluctuations are recorded over a one-hour period.

This system was applied to an extensive amount of air concentration data from dispersion experiments at the BNL site (release height 108 m) and relationships for \(\sigma_y\) and \(\sigma_z\) as functions of downwind distance (x) were constructed for each of the stability classes.

Cramer (1957, 1959) classified turbulence according to the standard deviation in wind direction in both the horizontal (\(\sigma_A\)) and vertical (\(\sigma_E\)) by measurements with a bidirectional wind vane. See Table 1-2.

On the basis of studies by Cramer and others Islitzer and Slade (1969) proposed correspondences between \(\sigma_A\)
Table 1-2. Cramer's turbulence classes

<table>
<thead>
<tr>
<th>Stability description</th>
<th>$\sigma_A, \text{deg}$</th>
<th>$\sigma_E, \text{deg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely unstable</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Near neutral (rough surface; trees, buildings)</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Near neutral (very smooth grass)</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Extremely stable</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

values and the Pasquill-Gifford classes. Table 1-3 (Gifford, 1976) gives these results, as well as those from the BNL investigation.

Table 1-3. Relations among turbulence typing methods

<table>
<thead>
<tr>
<th>Stability description</th>
<th>Pasquill</th>
<th>Turner*</th>
<th>BNL†</th>
<th>$\sigma_A, \text{deg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very unstable</td>
<td>A</td>
<td>1</td>
<td>B₂</td>
<td>25</td>
</tr>
<tr>
<td>Moderately unstable</td>
<td>B</td>
<td>2</td>
<td>B₁</td>
<td>20</td>
</tr>
<tr>
<td>Slightly unstable</td>
<td>C</td>
<td>3</td>
<td>B₁</td>
<td>15</td>
</tr>
<tr>
<td>Neutral</td>
<td>D</td>
<td>4</td>
<td>C</td>
<td>10</td>
</tr>
<tr>
<td>Moderately stable</td>
<td>E</td>
<td>6</td>
<td>D</td>
<td>5</td>
</tr>
<tr>
<td>Very stable</td>
<td>F</td>
<td>7</td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Golder (1972)
†Philadelphia Electric Company (1970)
†Slade (1969)

From work by Taylor (1922) and Fuquay et al (1964), the
following relationship was devised (Islitzer and Slade, 1969) from which \( \sigma_y \) can be determined from \( \sigma_\theta \) (which is the above \( \sigma_A \); the standard deviation of lateral wind-direction distribution):

\[
\sigma_y^2 = At - \frac{A^2}{2(\sigma_\theta \bar{U})^2} \left[ 1 - \exp \left\{ - \frac{2(\sigma_\theta \bar{U})^2 t}{A} \right\} \right]
\]

where \( t \) is the travel time and \( A \) is a constant related to turbulence intensity, and is calculated from

\[ A = 13,0 + 232\sigma_\theta \bar{U}. \]

In cases where either lapse rate or \( \sigma_\theta \) is used in determining stability class it should be noted that the heights at which measurements are taken may have a radical influence on these determinations (De Marrais, 1978). \( \sigma_y \) may further be greatly underpredicted under low wind speed, and stable conditions with plume meandering (van der Hoven, 1976).

**Site-specific approaches**

A number of workers have devised empirical schemes/equations for dispersion determinations which are more site-specific than those described above. One such equation, from Haugen and Taylor (1963) and Haugen and Fuquay (1963), is

\[
\frac{X}{Q} = 0,00211 x^{-1,96} \sigma_\theta^{0,506} (\Delta T + 10)^{4,33}
\]

with \( \Delta T \) the temperature difference in °F between 54 ft (17 m) and 6 ft (1,8 m) above the surface.

**1.2.1.2 The more complex approaches**

The classification schemes where the \( \sigma \)'s are based on
or the lapse rate alone suffer from the disadvantage that certain factors which may influence turbulence such as wind speed and ground roughness (sources of mechanical turbulence) are not included.

One approach to overcome this problem is to use a simple classification scheme based on lapse rate as well as wind speed. In Table 1-1 one example was given. Other similar schemes are available from the literature (Helm and Winkler, 1973; Vogt et al, 1971).

A number of approaches exist where more complex parameters are measured for turbulence classification. Two important classes of approach are those based on the so-called Richardson number and those on the Monin-Obukhov stability length.

**The Richardson number**

The Richardson number is defined by

$$ Ri = \frac{g}{T} \frac{\partial \theta / \partial z}{(\partial u / \partial z) T} $$

where $\partial u / \partial z$ is the wind shear, $\theta$ the potential temperature, $g$ the gravitational acceleration and $T$ the absolute temperature.

More easily measured quantities are the bulk Richardson number (Lettau and Davidson, 1957; McElroy, 1969)

$$ R_B = \frac{g}{T} \frac{\partial \theta / \partial z}{u^2} \cdot z^2 $$

and the modified bulk Richardson number (Högestrom, 1964; 1968).

$$ R_s = \frac{\Delta \theta}{\Delta z} \cdot (u_f)^{-2} \cdot 10^5 $$
with $u_f$ the wind speed at 500 m height. In practice $u_f$ is replaced by a site-dependent function of $u$, where this $u$ is measured on a tower.

The modified bulk Richardson number can be used to determine $\sigma_y$ and $\sigma_z$ numerically (not discussed here) or by constructing tables with stability class vs. $R_i$ or $R_B$ or $R_s$.

**The Monin-Obukhov length**

This is a relatively accurate way of determining boundary-layer turbulence (Gifford, 1976). The Monin-Obukhov length is defined as

$$L = -\frac{(\rho C_p u^*_f)}{kgH} \quad \ldots \quad (1-2)$$

where $C_p$ is specific heat at constant pressure, $\rho$ is air density, $u^*_f$ is friction velocity, $k$ is the Von Karman constant and $H$ is vertical heat flux.

The two variables in Eq. 1-2 which have to be calculated if $L$ is to be solved, are $u^*_f$ and $H$. $u^*_f$ can be obtained in a fairly simple way by the following equation

$$\overline{u}(z) = \frac{u^*_f}{u^*_f} \frac{k}{\ln \left(\frac{z}{z_0}\right)}$$

where $\overline{u}(z)$ is the wind speed at height $z$ and $z_0$ is the roughness length. Since this relationship actually only holds under near neutral weather conditions, a more sophisticated approach is necessary. Mulholland (1977) proposed a set of equations for $u^*_f$ based on integration of

$$\frac{2u}{\phi_m(z)} = \frac{u^*_f}{kz} \phi_m(z) \quad \ldots \quad (1-3)$$
The set is:

\[
\tilde{u}(z) = \begin{cases} 
\frac{u_*}{k} \left[ 2 \tan^{-1} b - 2 \tan^{-1} b_o - \ell \ln \left( \frac{b + 1}{b_o + 1} \right) \right], & L < 0 \\
\frac{u_*}{k} \left[ \ell \ln \left( \frac{z}{Z_o} \right) + \frac{5}{L} (z - z_o) \right], & L > 0, \ z \leq L \\
\frac{u_*}{k} \left[ 5 - 5 \frac{Z_o}{L} - \ell \ln \left( \frac{Z_o}{L} \right) + 6 \ell \ln \left( \frac{Z_o}{L} \right) \right], & L > 0, \ z \geq L.
\end{cases}
\]

where

\[b = \left( 1 - 16 \frac{Z}{L} \right)^{1/6}, \quad b_o = \left( 1 - 16 \frac{Z_o}{L} \right)^{1/6}\]

These equations were deduced (Mulholland, 1977) from dimensional analysis by Monin and Obukhov (1954), Webb (1970) and Dyer (1974),

\[\phi_m = (1 - 16 \frac{Z}{L})^{-1/6}, \quad z/L < 0\]

\[\phi_m = 1 + 5 \frac{Z}{L}, \quad z/L > 0\]

and Mulholland (1977) extended the stable form of the equation for strong stability by taking

\[\phi_m \left( \frac{Z}{L} \right) = \phi_m (1), \text{ for } z > L.\]

The \(z_o\)'s in Eq. 1-3a are the integration constants from Eq. 1-3, and are termed roughness lengths.

This set of equations (1-3a) has to be solved in conjunction with the other equations to solve for \(L\). The iterative procedure is given below. \(H\) is found from the following equation:

\[H = -\rho_o C_p K_T \frac{\partial \Theta}{\partial Z} \]

\[\text{............... (1-4)}\]

with \(K_T = u_* k z / \phi_T\). Dyer (1974) proposed the following
forms for the solution of $\theta_T$:

$$\theta_T = (1 - 16 \frac{z}{L})^{-\frac{1}{2}}, \quad z/L < 0$$

$$\theta_T = 1 + 5 \frac{z}{L}, \quad z/L \geq 0$$

$$\theta_T = 6, \quad L > 0, \quad z > L. \quad \ldots \ldots \ldots (1-5)$$

An iterative procedure is used to solve for $L$: 
Eq. 1-2 can be solved by substituting any arbitrary value for $L$ into Eqs. 1-3a and 1-5 and using Eq. 1-4 solve for $u_*$ and a new $L$ (Eq. 1-2) which is again substituted into Eqs. 1-3a and 1-5; thus $L$ and $u_*$ are obtained by means of an iteration process.

Tables are available with values for $z_0$ for a number of types of surface. When an area with complex terrain is encountered, it may be found necessary to determine $z_0$ for the various surface types. For this purpose Mulholland et al (1977) had wind velocity measurements taken at two heights (2 and 11 m) on 6 masts covering an area of approximately 50 km$^2$ in the Richards Bay area (the area in which the work to be presented was done), and calculated mean values of $z_0$ from the recorded wind velocity measurements, utilising Eq. 1-3a. Table 1-4 compares the values obtained (Mulholland et al, 1977) for the areas around the masts with those from similar surfaces obtained by Sutton (1953).

To define the surface-roughness distribution over the whole Richards Bay area (approximately 200 km$^2$) the roughness length was specified (by visual evaluation, using Table 1-4) at 152 points over this area so as to define the major surface features (Mulholland et al, 1977). Values of $z_0$ were taken from 17 categories (see Table 1-5),
Table 1-4. **Surface roughness estimates at masts - Richards Bay**

<table>
<thead>
<tr>
<th>Mast</th>
<th>Upwind terrain</th>
<th>$z_o (m)$ from measurements</th>
<th>$z_o (m)$ Sutton (1953)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Sparse sugar-cane ~ 1,5 m high</td>
<td>0,2</td>
<td>&gt; 0,9</td>
</tr>
<tr>
<td>3</td>
<td>Flat sand and water</td>
<td>0,000 01</td>
<td>0,000 01</td>
</tr>
<tr>
<td>4</td>
<td>Short grass ~ 15 cm high, no obstacles</td>
<td>0,02</td>
<td>0,007</td>
</tr>
<tr>
<td>5</td>
<td>Short, sparse grass ~ 15 cm high</td>
<td>0,01</td>
<td>0,007</td>
</tr>
<tr>
<td>6</td>
<td>Flat sand and water</td>
<td>0,000 07</td>
<td>0,000 01</td>
</tr>
<tr>
<td>8</td>
<td>Thick grass ~ 40 cm high, some small bushes</td>
<td>0,2</td>
<td>0,09</td>
</tr>
</tbody>
</table>

Table 1-5. **Estimated roughness length categories for Richards Bay**

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>$z_o (m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dense forest plantation</td>
<td>0,7</td>
</tr>
<tr>
<td>2</td>
<td>Suburban houses and trees</td>
<td>0,5</td>
</tr>
<tr>
<td>3</td>
<td>Coastal bush (dense)</td>
<td>1,0</td>
</tr>
<tr>
<td>4</td>
<td>Industrial buildings</td>
<td>1,2</td>
</tr>
<tr>
<td>5</td>
<td>Sparser forest</td>
<td>0,4</td>
</tr>
<tr>
<td>6</td>
<td>Stands of trees with ~ 50 % open grass</td>
<td>0,2</td>
</tr>
<tr>
<td>7</td>
<td>Scattered trees/bushes, vlei</td>
<td>0,2</td>
</tr>
<tr>
<td>8</td>
<td>Grass and scrub (scattered)</td>
<td>0,15</td>
</tr>
<tr>
<td>9</td>
<td>Sugar cane (cultivated)</td>
<td>0,15</td>
</tr>
<tr>
<td>10</td>
<td>Coastal bush with ~ 50 % open grass</td>
<td>0,2</td>
</tr>
</tbody>
</table>
Table 1-5 (continued).

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>$z_o$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Vlei</td>
<td>0,12</td>
</tr>
<tr>
<td>12</td>
<td>Sparse grass ~ 0,3 m on flat sand</td>
<td>0,02</td>
</tr>
<tr>
<td>13</td>
<td>Open grassland (~ 0,35 m)</td>
<td>0,05</td>
</tr>
<tr>
<td>14</td>
<td>Sparse sugar-cane (~ 1,5 m) on flat sand</td>
<td>0,20</td>
</tr>
<tr>
<td>15</td>
<td>Open sea</td>
<td>0,001</td>
</tr>
<tr>
<td>16</td>
<td>Bay, lakes</td>
<td>0,000 01</td>
</tr>
<tr>
<td>17</td>
<td>Flat sand and water</td>
<td>0,000 1</td>
</tr>
</tbody>
</table>

based also on work by Lettau (1969), Priestly (1959), Sheppard (1947), Leonard and Federer (1973), Davenport (1965) and Sutton (1953).

$L$ can be used in dispersion calculations by either calculating the vertical mass eddy diffusivity ($K_z$) from which the $c$'s can be obtained, or by classifying stability type with a certain range of $L$ values.

The eddy diffusivity $K_z$ can be calculated from $L$ and $u_*$ by means of the set of equations (1-6) (Mulholland, 1977):

$$K_z(z) = \begin{cases} 
  u_* k z \left[ 1 - 16 \frac{z}{L} \right]^\frac{1}{2}, & L < 0 \\
  u_* k z \left[ 1 + 5 \frac{z}{L} \right]^{-1}, & L > 0, \quad z \leq L \\
  u_* k z / 6, & L > 0, \quad z > L. 
\end{cases} \quad (1-6)$$
\( \sigma_z \) is calculated from this:

\[
\sigma_z = \sqrt{2K_z t} \quad \ldots \ldots \quad (1-7)
\]

\( K_y \) and \( \sigma_y \) can be obtained from Mulholland (1977):

\[
K_y = K_z \left( \frac{C_y}{C_z} \right)^2 , \text{ and }
\sigma_y = \sqrt{2K_y t}
\]

where \( C_y \) and \( C_z \) are the Sutton coefficients.

Table 1-6 (Pasquill and Smith, 1970) can be used to determine the stability class from the L or Ri value. Roughness length \( z_0 \) can be incorporated in the model by referring to Fig. 1-2 (Golder, 1972).

<table>
<thead>
<tr>
<th>Pasquill type</th>
<th>Ri (at 2 m)</th>
<th>L, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-1,0 to -0,7</td>
<td>- 2 to -3</td>
</tr>
<tr>
<td>B</td>
<td>-0,5 to -0,4</td>
<td>- 4 to -5</td>
</tr>
<tr>
<td>C</td>
<td>-0,17 to -0,13</td>
<td>-12 to -15</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>( \infty )</td>
</tr>
<tr>
<td>E</td>
<td>0,03 to 0,05</td>
<td>35 to 75</td>
</tr>
<tr>
<td>F</td>
<td>0,05 to 0,11</td>
<td>8 to 35</td>
</tr>
</tbody>
</table>

A number of pages have been devoted to the Monin-Obukhov stability length, but this was deemed necessary due to the importance given to it in the mathematical modelling approaches to be investigated.
Fig. 1-2.
Curves showing Pasquill's turbulence types as a function of the Monin-Obukhov stability length and the roughness length.
The Kazanski-Monin stability

A stability parameter similar to the Monin-Obukhov stability length is the Kazanski-Monin stability \( \mu \) (Kazanski and Monin, 1960), where

\[
\mu = -\frac{gk^2H}{fC_pT_0} \alpha \frac{H}{\tau_0}
\]

with \( f \) the Coriolis parameter and \( \tau_0 \) the shear stress. \( \mu \) is thus proportional to the ratio of the two major sources of diffusive turbulence, viz. \( H \) and \( \tau_0 \) (Smith, 1979).

1.2.1.3 Numerical modelling and the accuracy expected from a turbulence classification scheme

A number of models are available for the determination of plume concentration downwind from a source, in which plume trajectory is taken into account. The more generally used of these models handle the plume as a series of puffs or a segmented plume, and the trajectory is continuously adjusted with data obtained from one or more measuring positions. Where more than one measuring position supplies data for the definition of the wind field, an interpolation scheme can be incorporated into the program to adjust plume trajectory with distance and time. There are more sophisticated models which calculate the vertical concentration profile - e.g. accounting for wind shear (Sheih, 1978; Alsmiller et al., 1977; Draxler, 1979a) or deposition at the surface (Mulholland, 1977). Another complexity taken into account by some models is topography (Hino, 1968; Sherman, 1975). A number of less sophisticated models where concentration calculations - at ground level only - are performed by means of the Gaussian plume of puff approach, have been
developed (Start and Markee, 1967; Plato et al, 1969; Ludwig et al, 1977) and used (Lamb et al, 1978; van der Hoven et al, 1973). In general, these models need less computer memory and execution time than the more sophisticated class of models mentioned above.

A number of workers have found or pointed out the large differences which may be found between observed air concentration values and those estimated by means of a mathematical model. According to Hoffman (1977), "for flat terrain and relatively steady meteorological conditions and distances of 10 km or less, the airborne concentrations for an individual case should be estimated to within about a factor of + 10 [when sampling for an hour].... For complex terrain or meteorological situations .... a few experiments have indicated departures from [this factor]."

In cases with relatively large numbers of sources and over long sampling times, the error in the predicted to experimental ratios may be much smaller. In the analyses of a series of thirty-five 24 h periods for an area of approximately 250 km² with about thirty point sources scattered over it, and a number of sampling points in the same area, Turner (1964) found that 70 % of the calculated values were within a factor 2 of the observed values. He used the simple Gaussian plume formulation with two-hourly averaged weather-data input for concentration calculations. Kretzschmar and Mertens (1980) utilised a number of generally used turbulence typing schemes to calculate average yearly ground-level concentrations around a point source. For a continuous elevated release the calculated absolute maximum values given by the schemes for a specific wind direction differed by an order of magnitude. Weil and Jepsen (1977)
found, with sampling traverses through a plume a few kilometres from its source and during neutral to unstable atmospheric conditions, the predicted to measured air-concentration ratios when classified according to stability type, having a geometric mean of roughly 0,04 to 1,24, with a geometric standard deviation of 1,7 to a few hundred, depending on stability class. Venter et al (1973) found, in dispersion experiments on the South African Highveld in Pasquill A- to D-type stability categories, and with samplers a few hundred metres from the source, calculated to observed concentration ratios ranging from 0,4 to 25,2 (65 % of the values below 4) when using derived Sutton parameters. These ratios ranged from 0,6 to 11,4 (90 % of the values below 4) when using the Pasquill categories. Mulholland (1977) used the results obtained in the Richards Bay study presented here and meteorological data (3 min averages) from a number of masts in the Richards Bay area to compare observed concentration values with simulated values from two puff models. One was relatively sophisticated and the other more simple, but both used the same meteorological data and the interpolation scheme by Wendell (1972) to estimate plume trajectory. The sophisticated model treated the plume as a series of three-dimensional puffs with diffusion and dispersion determined by roughness length and K-theory (the use of eddy diffusivity), and where wind shear and deposition velocity were included in determining plume shape and depletion. The other model used a simple Gaussian puff equation for a point source. A thirty-one-fold root mean square error was obtained between the predicted and observed concentration results when using the latter model, while the error was seventeen-fold with the more sophisticated one.

Three complicating factors when modelling dispersion in stable atmospheric conditions are:
(a) directional wind shear (Hoff and Froude, 1979), which may cause a larger than expected $\sigma_y$,

(b) topographically induced channelling of a plume, and

(c) the movement of plume material into regions with local changes in the magnitude of turbulence.

Because of these factors, Reid (1979) suggests, in discussing tracer dispersion results over mountainous terrain, that "attempts to apply Gaussian models to mountain-valley dispersion problems are futile".

Certain other factors, not only applicable to stable atmospheric conditions, should be considered when evaluating the differences between predicted and observed concentrations. These are: 1) the difficulty in estimating plume trajectory, 2) the general inaccuracy of the methods used to classify turbulence, and 3) the unrepresentativeness of stability measurements at a specific measuring point. These factors will be discussed in more detail immediately below.

When the regional pressure gradient is weak, local effects may predominate, causing changes in wind direction on a small scale (of the order of a few kilometres, for example). This is especially of importance in shoreline environments, with land and sea breezes experienced only a few kilometres on either side of the coast line, with the gradient wind predominating further inland and out over the sea, causing changes in wind direction over short distances. Furthermore, wind directions may vary continuously, causing large inaccuracies in simulated plume trajectories where only hourly or half-hourly averaged wind data are introduced into the model used.
It has been shown by a number of authors that there is generally poor agreement between lapse rate and stability class (Raynor et al, 1979; Sedefian and Bennett, 1980). One of the main reasons for this is the relatively wide range of lapse rate values to be obtained in the same atmospheric stability, depending on the measuring heights and the height interval for the determination of $\Delta T$. This factor will be further complicated by kinks in the slope of the temperature differential curve between two measuring levels. Another reason is that lapse rate alone does not determine turbulence. In general a less than 50% correspondence is to be obtained between stability classes determined by the various methods available. The utilisation of $\sigma_\theta$ and $\sigma_\phi$ estimates in the determination of stability category is proposed (Raynor et al, 1979) as giving the best results because these parameters are directly related to turbulence and plume meandering. The $\sigma_\theta$, $\sigma_\phi$ method is not preferable in a stable, low wind speed condition ($0.5 - 1 \text{ m.s}^{-1}$), when the turbulence instruments will not be adequately influenced by the wind (Raynor et al, 1979). Raynor et al (1979) proposed the use of lapse-rate values under such conditions. Instrumentation for the measurement of $\sigma_\theta$ and $\sigma_\phi$ is relatively expensive, delicate and needs more attention than more commonly used equipment. Where the wind fluctuations are used to identify stability class it must be kept in mind that such measurements are very site-specific, the magnitude of the fluctuations being largely influenced by the roughness of the surface traversed by the wind just before encountering the measuring apparatus. Stability obtained from insolation and wind speed is associated with a larger area (Anon., 1980, p. 39), and wind-speed instrumentation is relatively cheap and accurate. The degree of insolation and cloud cover may be determined visually, and records of this may
be available at a nearby weather station. On the other hand, the latter method gives only approximate values for the stability classes (Anon., 1980, p.44), and is especially inaccurate in the classification of stable situations. An important factor on the debit side is that it cannot take local effects, such as surface changes (vegetated/flat terrain, land/sea surface, etc.) and topographically induced air movement (e.g. katabatic flow), into account.

Sedefian and Bennett (1980) found, when analysing the percentage of simultaneous occurrences of turbulence classes by a number of methods, that $\sigma_0$ (measured at 10 m) will predict the same class as will the Richardson number from 9 % (class C) to 70 % (class D) of the time, while this correspondence between $\sigma_0$ (measured at 10 m) and $\sigma_0$ (measured at 50 m) is from 54 % (class E) to 96 % (class A) in a five-class scheme. Draxler (1979b) found, when comparing $\sigma_0$ (bivane) data with $\sigma_0$ (calculated via K-theory) data, a correlation coefficient of 0.46, and that in 82 % of the cases the corresponding values differ within a factor 2. These are two of the most sensitive approaches for determining turbulence.

An important point to consider when investigating dispersion in a complex area such as a coastal site is the representativeness of stability type determined at one point in a specific area surrounding this point. This phenomenon was not considered in detail in the Richards Bay study, but it needs consideration at Koeberg because of the more complex weather patterns to be found in the latter area, and the longer distances involved.

Lalas et al (1979) found, when comparing a large number of simultaneously determined stability classes for two localities 8 km apart (the one on the coast and the other
that in only 32% of the cases did the two stations possess identical categories. Slade (1962) found, with a number of measurements of $\sigma_0$ in a coastal area, on the average, a 50% reduction in $\sigma_0$ and a 25% increase in off-shore wind speed after 7 miles of over-water travel. Munn (1964) suggested that estimates of $\sigma_0$ should not be made from observations at a single point when terrain varies markedly, such as with on-shore flow. In air movement from over-water to over-land, diffusion becomes characterised by the surface under the plume; a comparison of over-water to over-land plume concentrations may give a ratio of 3 when the water surface temperature is lower than air temperatures over the land (van der Hoven, 1967). Raynor et al. (1978) observed that a smoke plume released from a boat on water, is dispersed much more slowly than one released from an island (size 800 m x 175 m), with $\sigma_y$ 1.5 to 4 times bigger for the latter plume (the biggest difference during stable periods). Raynor et al. (1979) also reported on dispersion results in on-shore winds, where $\sigma_0$ increased from 6.6 to 48.1° and $\sigma_\phi$ from 1.6 to 15.1° from the coast to an inland site. Draxler (1979b) compared stability classes (4800 hourly observations) as found at two sites, 20 km apart. He found 65% more stable periods at the one site relative to the other. During these times the wind speeds were 20 - 30% greater at the site experiencing the more neutral (fewer stable) periods.

From this discussion one can see how any dispersion model is limited in accuracy by a number of factors, such as the inherent inaccuracy in all the approaches for determining stability class and plume trajectory, and the difficulty in having measuring apparatuses in optimum positions in the area under study. Care must be taken to employ the most appropriate model and turbulence classification.
scheme, or combination of schemes, for a specific site.

1.2.2 Deposition of Aerosols and Gases

Deposition of airborne effluent is important mainly in two respects, viz. the depletion of the airborne cloud, thus minimising air concentration (this effect may become marked over tens of kilometres); and increase of the ground contamination, which is especially important for radioactive fallout.

"It has been recognized for some years that radiological hazards are more likely to arise from deposited material than from the initial airborne cloud ..." (Marley, 1966). Thus it is found that released radioactive iodine is taken up by a human being via his food chain by a factor of roughly 5 times as high as that from airborne activity.

The immediate effect of dry deposition on the depletion of airborne gaseous or particulate effluent is not as marked as that of wet deposition (i.e. by rainout and washout). However, for chronic daily releases of radioactive contaminants to the atmosphere, the effect of dry deposition (in many areas) may, on a long-term basis, be more important with respect to average radiation caused by deposited radioactive effluent. Wet deposition may be important when considering large radioactive releases accompanied by rain.

1.2.2.1 Dry deposition

Factors influencing deposition

(1) Characteristics of the aerosol or gas. An aerosol or gas is removed dry from the air by the following
main means: gravitational settling, and diffusion and impaction onto obstacles.

Gravitational settling, eddy diffusivity and inertial impaction are effective for particles with diameters > ~ 10 μm, but will also influence the removal of particles < 10 μm over distances of a few tens of kilometres. Brownian diffusion starts to play a more significant role in the deposition of particles < 0.1 μm, and in the case of gases. The electrostatic properties of submicron particles coupled with the marked vertical wind profile in the air layer of a few micrometre thickness next to a solid surface, causes a very low resuspension probability from such a surface for these smaller particles, even in very strong winds (Corn and Stein, 1967). Five micrometre mica particles on a smooth glass surface, for example, exposed to a wind of 150 m.s⁻¹, showed a loss of 5% after 3 min. For 26 μm particles the loss was > 80% (Corn and Stein, 1967).

The role of sedimentation on larger particles and of diffusion on smaller ones results in a minimum deposition velocity for particles between 0.1 and 1 μm, and an increase from this range for particles smaller than 0.1 μm and bigger than 1 μm. See Fig. 1-3 (Chamberlain, 1962).

Gases are largely removed by their chemical/biological properties, e.g. water solubility and sorption by plants. Thus it was found that the maximum uptake of SO₂ by a forest occurs near noon - about two times higher than during the morning and evening - when the stomatal resistance of the canopy is at a minimum and when the solubility of the SO₂ in water is at a maximum (Murphy et al, 1975). Furthermore, the deposition velocity of
Fig. 1-3.
Deposition of particles on vertical plane surfaces.

Fig. 1-4.
Comparison of experimental deposition velocities for surfaces with different roughness.
SO₂ on grass is ~ 3 times higher in summer than in autumn (Shephard, 1974).

(ii) Topography and wind speed/turbulence. Various types of obstacles on the surface over which particles move, may have an effect on their deposition velocities. Larger obstacles (i.e. in the size range of millimetres to metres) may have quite a large effect on the deposition of larger (> 10 μm) particles, especially in higher wind speeds, where these particles will find it more difficult to follow the trajectory of the wind around such larger obstacles. Both larger and smaller particles will be removed by smaller obstacles such as a patch of grass; the larger ones more by direct impaction and the smaller ones more by Brownian diffusion and impaction.

Fig. 1-3 may be misleading in the sense that it does not show the effect of the type of obstacles or wind speed and turbulence. It appears as if a particle of 0.05 μm diameter will be deposited at the same rate as a particle of ~5 μm, but the latter will be deposited to a lesser extent relative to the former in the presence of higher turbulence and in the absence of large obstacles. Fig. 1-4 (Sehmel and Schwendiman, 1970) throws some light on deposition velocities of different particle sizes under the influence of different wind speeds and with surface effects superimposed.

Turbulence will cause plumes consisting of larger particles (say, > ~ 10 μm), with deposition velocity more dependent on gravitational settling, to decrease their depletion rates (although the actual deposition velocities may increase or stay unaltered) due to a decreased concentration near the surface. On the other hand, a plume consisting of smaller particles (or a gas) with a
negligible settling velocity, which under stable conditions may be depleted to a limited extent only due to the smaller fraction of such a plume near ground level, may have a larger portion deposited under more turbulent conditions when its concentration at ground level is increased.

Experimental determination of deposition and plume depletion

There are various ways in which one can determine deposition, such as the direct measurement of deposited effluent in environmental samples. In this way the activity of radioactive isotopes, for example, can be determined on vegetation after an accidental release (or long-term planned releases) at a nuclear reactor, such as after the Windscale accident in 1957 (Chamberlain and Dunster, 1958; Stewart and Crooks, 1958; Martin and Doury, 1960). This method, although suitable for continuous or accidental releases, is not always sensitive enough in the case where relatively small quantities of tracer are artificially generated. Another similar method is to use artificial surfaces (together, perhaps, with air concentration measurements). One effective method proposed by Israel (1977), is the use of static limed filter paper samplers (which were found to be more effective scavengers than certain vegetation types) for the collection of particulate fluorine compounds. Flat surfaces (such as filters), though perhaps easier to operate than artificial grass, for example, will be less accurate, due mainly to:

(1) the air-flow pattern over such a surface which is different from that over irregular surfaces, and

(2) the fact that deposition velocity varies with, inter alia, vegetation density and friction velocity.
In order to determine plume depletion, a method used by Raynor (1967) and also reported by Gifford and Pack (1962) is the following: The mass flux of the plume with distance is determined by the integration of the measured concentration in both the horizontal (y-axis) and the vertical, and comparing this with expected values. A disadvantage of this technique is that a relatively dense sampling grid is needed in both horizontal and vertical planes, thus limiting its value for long-distance work. Nickola and Clark (1974) used a somewhat similar approach, releasing two tracers, one having zero deposition velocity, simultaneously from the same height, at a constant and known rate, and also having samplers extending in the y and z planes. The comparison between the concentration values obtained can be used to determine the deposition velocity and plume depletion of the one tracer. Dual-tracer techniques have been suggested by Wedin et al (1959), Eggleton and Thompson (1961), and Dietz et al (1976). Enger and Högstrom (1979) used the results from dispersion experiments where inert SF$_6$ tracer was released simultaneously with SO$_2$ to determine the SO$_2$ to sulphate transformation rate.

A simple single-tracer technique by which deposition velocities can be determined, is the so-called flux-gradient or profile model, proposed by Sheppard (1958) and Droppo and Hales (1974), and used, inter alia, by Markee (1967a). Tracer or pollutant concentration is measured at two or more heights above the surface and close to it; and the concentration profile is used to solve for $v_d$ (deposition velocity) in the equation

$$K \frac{\partial X}{\partial z} = v_d X_0$$

where $X_0$ is the air concentration at the interface.
Extrapolating deposition effects determined at a specific distance to other distances is difficult. Preferential deposition of certain size ranges of particulates at certain distance ranges will cause $v_d$ to change with distance. At relatively large distances the gas or particulates may even change their physical form due to chemical reactions (oxidation, decomposition, etc.) and sorption onto the same or other particulates in the air. It has been found in dispersion experiments with $SO_2$ that the concentration of $SO_2$ at longer distances (distances not specified) increases with increasing wind speed. This was explained by the authors as due to the shorter time available in strong winds for the conversion of the $SO_2$ to other compounds (Zeedijk and Velds, 1973).

There are also problems in extrapolating deposition values obtained over certain surface types to other types.

It is a major problem to estimate the deposition velocity of particles moving through a forest. For individual trees or clumps of trees and hedges one can still make an estimate from experimental data, e.g. those by Clough (1975). He found no significant difference between deposition velocity of ZnS.CdS particles (CMD ~ 5 μm) on wet relative to dry surfaces, but a marked difference (an order of magnitude) between a horizontal relative to a vertical surface of the same type (moss). Fig. 1-5 shows his results (the moss bags are the vertical surfaces). Owers and Powell (1974) found with measurements of the deposition velocity of $SO_2$, in a 5 m.s$^{-1}$ wind, that $v_d$ increased about two-fold when moving through a loosely packed hedgerow 1.7 m high and 0.6 m thick, relative to the value for $v_d$ on the grass upwind from this hedge. To cope with single objects in a vertical plane such as the abovementioned, estimated values for $v_d$ may
Fig. 1-5. The effect of particle size on deposition to moss trays \((u^* = 37 \text{ cm.s}^{-1})\) and moss bags \((u^* = 300 \text{ cm.s}^{-1})\).
be used, taking the volume or surface area of the whole obstacle (or the frontal part, depending on the type of obstacle) into consideration. But, once one has to calculate the effect of forests on plume depletion, matters become more complex. Firstly, with trees in depth downwind, the wind-profile becomes distorted (Raynor, 1967). Dispersion experiments with pollen (~20 μm diam.) as tracer (Raynor, 1967) indicated that particles tended to penetrate a forest at tree trunk height or to rise above the canopy, following the wind pattern. Particles did not seem to penetrate the crown area. An initial sharp decrease in particle concentration was found in the first 10-20 m of the forest, caused largely by impaction on the foliage due to the still higher wind speed.

Deposition velocity on grass is dependent on the mass of grass per unit area. Under some conditions this relationship may not hold, e.g. where the vegetation becomes too dense and where wind movement may not penetrate such a patch.

Another complex situation for deposition measurements is that over the sea. Surface "roughness" is a function of wind speed (Sutton, 1953). For winds below 6-7 m s⁻¹ the sea surface can be regarded as aerodynamically smooth; for stronger winds, the value for $z_o$ will change (Sutton, 1953).

Mathematical approach to plume depletion

Although the measurement of plume material deposition is relatively simple, its relation to total plume depletion is more complicated and requires a computational approach.
Gravitational settling

The formulation for gravitational settling will not be discussed in detail as it is not very important in the size ranges and travel distances concerned in this study, and will most probably not be important in dealing with deposition of airborne effluent from a nuclear reactor.

A plume consisting of particles with a significant settling velocity can be seen as having its centreline tilted downwards. This can be treated by replacing the constant release height \( h \) in the Sutton dispersion equation by a variable (van der Hoven, 1969):

\[
X(x,y,z) = \frac{2Q}{\pi C_y C_z} \exp \left[ - \frac{x^n - z^n}{2} - \frac{(h-xv/u)^2}{2} \right]
\]

where \( v_s \) is the settling velocity. \( h \) in the original equation is substituted by \( h - xv/\bar{u} \).

Dry deposition

A formula proposed by Chamberlain (1953), which is a modification of Sutton's equation, gives plume depletion for a continuous ground level source as

\[
\frac{Q_x'}{Q_o'} = \exp \left[ - \frac{4v_d x^{n/2}}{n \bar{u} C_z} \right]
\]

with \( Q_o' \) the original source strength, \( Q_x' \) the depleted source strength and \( v_d \) the deposition velocity. This expression for \( Q_x' \) can be substituted for the release rate \( Q \) in Sutton's diffusion equation.

For a continuous point source at height \( h \), the Gaussian diffusion formula can be modified to incorporate plume depletion in the following way:
\[ w(x,y) = v_d \cdot x(x,y,o) \]

where \( w \) is the total amount of particles deposited per unit area per unit time at point \((x,y)\) on the ground.

Then \( w(x,y) = \frac{v_d Q'}{\pi \sigma y z \bar{u}} \exp \left[ -\frac{1}{2} \left( \frac{y^2}{\sigma y} + \frac{h^2}{\sigma z} \right) \right] \).

The depletion of the plume per unit distance is given by van der Hoven (1969):

\[ \frac{\partial Q'_x}{\partial x} = - \int_{-\infty}^{\infty} w(x,y) \, dy \]

\[ = - \left( \frac{2}{\pi} \right)^{\frac{1}{2}} \frac{v_d Q'_x}{\sigma z \bar{u}} \exp \left[ -\frac{h^2}{2\sigma z} \right] \, \frac{dx}{\sigma z \bar{u}} \exp \left( \frac{h^2}{2\sigma z} \right) \]

This can be rearranged to give

\[ \int_0^x \frac{dQ'_x}{Q'_x} = \left( \frac{2}{\pi} \right)^{\frac{1}{2}} \frac{v_d}{\bar{u}} \int_0^x \frac{dx}{\sigma z \exp \left( \frac{h^2}{2\sigma z} \right)} \]

If \( Q'_x \) is taken \( Q_0' \) at \( x = 0 \), then

\[ \ln \frac{Q'_x}{Q_0'} = - \left( \frac{2}{\pi} \right)^{\frac{1}{2}} \frac{v_d}{\bar{u}} \int_0^x \frac{dx}{\sigma z \exp \left( \frac{h^2}{2\sigma z} \right)} \]

Therefore,

\[ \frac{Q'_x}{Q_0'} = \left[ \exp \int_0^x \frac{dx}{\sigma z \exp \left( \frac{h^2}{2\sigma z} \right)} \right]^{-\left( \frac{2}{\pi} \right)^{\frac{1}{2}} \cdot \frac{v_d}{\bar{u}}} \quad \ldots \quad (1-9) \]

Similar source-depletion models, where the total plume depletion rate is directly related to the rate of ground-level air-concentration reduction, are utilised by Brook (1968), Tadmore (1971), Tveten (1975), Jensen (1980), Miller et al (1978), Skibin (1980) and Hosker (1973). The
main disadvantage in using this source-depletion approach is that it assumes an unaltered Gaussian concentration distribution in the vertical, which is not the case as the concentration reduction will be felt most markedly at lower levels, especially under stable atmospheric conditions. (Markee, 1967b), and where the transported material has a high deposition velocity.

A more realistic approach is to have deposition affect only that part of the plume in contact with a surface, and to have it affect higher levels eventually by diffusion - a so-called surface-depletion approach.

Surface-depletion deposition models have been proposed and utilised by a number of authors, such as Draxler and Elliott (1977), Ermak (1977), Horst (1977), Scriven and Fisher (1975), Doran (1979), Reid and Crabbe (1980), Fisher (1975), and Carmichael et al (1980). Comparisons between the results using surface- and source-depletion models (Prahm and Berkowicz (1978); Miller and Hoffman (1979)) have shown the advantages in the former approach.

1.2.2.2 Wet deposition

This type of deposition can be divided into two main categories, viz. (i) in-cloud scavenging by water droplets of the particles or gas molecules inside a cloud, normally before raining starts, and while the cloud is forming; and (ii) below-cloud scavenging by falling raindrops. The latter type is normally the most important mechanism for ground-based pollutant sources and for particles and molecules which have travelled for a few tens of kilometres only.

Although ordinary diffusion and impaction mechanisms play
a role in in-cloud scavenging, some complicating factors, such as the solubility of gases, wettability of particles, the fact that droplets containing particles may evaporate, leaving the particle or cluster of particles to be taken up by other droplets, etc., have made the formulation for this type of scavenging relatively difficult.

Equilibrium solubility is one of the most important physical variables in the scavenging of a gas, as it limits the maximum amount of gas to be absorbed by water droplets. Thus I₂ can be taken up to a concentration ~ 600 times that of CH₃I into falling water drops (Postma, 1970).

From a theoretical treatment by Pemberton (1961) non-wettable particles of 2 μm diam. in a rain of 2.5 mm/h will be depleted by ~ 25% in a few hours time, while for wettable particles of the same size and under the same conditions this figure is ~ 90%.

Another complicating factor is the location of the part of the plume in contact with the forming cloud, which can more easily be controlled under lab. conditions, but not in the open, where the exact position of the plume after tens of kilometres of travel distance may not be known (especially in a vertical plane). This factor may especially influence in-cloud scavenging and its estimation.

Washout (below-cloud scavenging) seems to be more easily dealt with, as the most important mechanisms are diffusion and impaction.

Washout by rain (below-cloud scavenging)

Scavenging can be treated mathematically as an exponential
decay process:

\[ X = X_0 \exp(-\Lambda t) \quad \text{............... (1-10)} \]

where \( X \) is the measured concentration of the airborne effluent after time \( t \) (dispersion excluded), while \( X_0 \) is the initial concentration and \( \Lambda \) is the so-called washout coefficient.

Scavenging efficiency (\( E \)) for a raindrop is considered a function of the following variables: \( E = f(a^2 \rho, D) \) where \( a \) is the particle radius, \( \rho \) is the particle density and \( D \) is the obstacle (raindrop) diameter (Engelmann, 1969).

With \( E \) known as a function of drop size, \( \Lambda \) can be determined (Engelmann, 1969) for a particular aerosol size and density:

\[ \Lambda = \int^\infty_0 P E a dD \]

where \( \Lambda \) is the cross-sectional area of drops of diameter \( D \), and \( P \) is their flux density (drops per unit area - time-diameter interval).

For particles < 0.1 \( \mu \text{m} \), electrical charges on raindrops may have a significant effect on scavenging. Deposition velocities exceeding 1 cm.s\(^{-1}\) (which corresponds to the gravitational settling of 15-20 \( \mu \text{m} \) particles) are imposed on particles below 0.1 \( \mu \text{m} \), even if they carry a charge of only a few electrons, in fields of 1 000 V.cm\(^{-1}\) or less (Davies, 1967). Other important factors are Brownian motion (already mentioned) and diffusiophoresis. Under normally encountered conditions in the atmosphere, Brownian diffusion is probably more important in washout than the combined effects of charges and other factors (Hagen, 1967). Two problems due to the effects of charge, increase the complexity of calculating scavenging:
(i) insufficient information exists for the safe extrapolation of the effect of existing charge values to other charges, and

(ii) insufficient information exists on charges existent in rain and clouds (Engelmann, 1969).

Fig. 1-6 (McCormack and Hilliard, 1970) shows the different effects on scavenging superimposed to give collection efficiencies for particles < 0.01 μm to 10 μm.

Although, under controlled experimental conditions, some good results were obtained in comparing the experimental results of washout of particles > 1 μm with calculated ones (Engelmann, 1969), A is dependent upon so many possible changing factors, that "... it is easier and generally as accurate to begin the solution of a problem by adjustment or modification of previously measured or predicted coefficients than with the more basic variable" (Engelmann, 1969).

Washout coefficients may be obtained from generalised charts such as in Fig. 1-7, reproduced from Engelmann (1969).

Scavenging of gases

Scavenging of a gas can be predicted by using its molecular diffusion and taking into account solubility of the gas and drop size.

For very soluble gases the scavenging coefficients are nearly proportional to their diffusion coefficients in a rain of given flux density. Experimental work by Brooker (1965) on the washout of deuterated and tritiated water vapour and bromine gas confirmed the theoretical predictions. For iodine gas, however, washout coefficients of one to two orders of magnitude lower were
Fig. 1-6.
Single-drop collection efficiency measured in CSE spray tests. Particle density taken as 1 g.cm⁻³. Lines are calculated for 250 °F (121 °C). Saturated atmosphere, 1200 μm drops.

Fig. 1-7.
Washout coefficients for unit density particles vs. rainfall rate and ρ (ρ = density of particle material in g.cm⁻³).
obtained. In the latter case the coefficients obtained experimentally showed no relation to precipitation rate.

The lower coefficients in snow compared to rain is one reason to suspect that scavenging depends more on the reaction rate with water than on solubility (Engelmann, 1969).

**In-cloud scavenging**

An equation similar to Eq. 1-10 can be used (Engelmann, 1969):

\[
\frac{X}{X_0} = \exp (-\Psi t),
\]

where \( \Psi \) is the rainout coefficient.
PART 2

TRACER GENERATING, SAMPLING AND ANALYSING TECHNIQUES

2.1 INTRODUCTION

The study of atmospheric behaviour of releases from particular sites or stacks often requires the use of artificial tracers in order to make measurements of dispersion, deposition or washout parameters. Various tracers have been used and are described in the literature. Among the gaseous tracers, the use of radioactive gases $^{85}$Kr (Nickola et al., 1970), $^{4}$Ar and $^{133}$Xe (Eggleton and Thompson, 1961), molecular gases freon (Johnson et al., 1975), SF$_6$ (Dietz et al., 1976), I$_2$ and Br$_2$ (Engelmann and Hagen, 1966), has been reported. Airborne particulates have the complication that particle size distribution could affect their behaviour. This is not an important factor with particles below 1 μm in diameter. However, they have the great advantage that high air volumes can be sampled for extended time periods. Furthermore, certain phenomena such as deposition cannot be studied by means of the inert gases only.

The various particulate tracers that have been used include pollen and spores (Clough, 1975), as well as fluorescent materials such as fluorescein (Nickola, 1971), uranine (Dickson et al., 1969), rhodamine B (Dana, 1971) and ZnS.CdS (Venter et al., 1973), particles containing elements which are rare in the atmosphere but which can be detected to very low concentrations. Of this latter group, elements with high neutron cross-section and which transform, under neutron irradiation, to γ-emitting isotopes which can be detected with high sensitivity, such as La, Au (van As et al., 1970), In, Dy, Sb (Haines et al., 1957), have been used by other
workers. These particles can be generated by several means, e.g. released as the dry powder, or by atomising, by means of a nozzle, a solution or slurry containing the element. Another approach is to heat the compound above its evaporation point, resulting in the condensation of small particles which are released as such.

This heating can be done pyrotechnically in a flare or by pumping a solution containing the element into a furnace at a suitable temperature. Some examples are dysprosium- (Kühn et al, 1976), or indium-containing particles from a flare (Dingle, 1968), indium in an alcoholic solution in an oil burner (Dahl et al, 1970), and the burning in air of acetone-hexane solutions containing various elements (Thomas et al, 1973).

Important properties of an ideal tracer are that it should have a unique origin (and, therefore, not be a normal constituent of the atmosphere), a controllable and stable release rate, a known particle-size distribution and a low limit of detection.

For the particular application of studying dispersion under stable atmospheric conditions at a coastal site and over distances between 1 and 50 km, indium (In) was selected as tracer. It is extremely rare in nature and the natural concentration in air is less than $5 \times 10^{-11}$ g per kg air. Due to the extremely high neutron capture cross-section of $^{115}$In, the element can be detected down to levels of $10^{-11}$g by means of neutron activation analysis. In practice, however, the short half-life of the activation product $^{116m}$In (54 min) may present a problem, due to interference by longer-lived neutron-induced isotopes of the more abundant elements present in the atmosphere. These elements include Na,
Cl and Mn. A simple chemical separation of In after irradiation of the filter with the sample, however, results in a lower limit of detection of $5 \times 10^{-11}$ g (Norden and van As, 1977).

For experiments lasting 20-40 h and with an air-sampling apparatus using sampling rates of 1-2 m³.h⁻¹, release rates of approximately 20 g.h⁻¹ are practical and dispersion factors of the order of $10^{-8}$ g.m⁻³ per g.s⁻¹ can be determined. For experiments of short duration, increased release rates will facilitate the measurement of dispersion factors as low as $10^{-9}$ g.m⁻³ per g.s⁻¹.

2.2 DEVELOPMENT OF A TRACER TECHNIQUE

Initially indium was to be atomised as an aqueous solution by means of a pneumatic nozzle. This solution was obtained by dissolving indium metal in hot concentrated hydrochloric acid and then, just before a tracer run, the pH of the solution was adjusted to a value between 4 and 7 by means of ammonium hydroxide, resulting in a colloidal suspension of indium hydroxide. At the concentrations used (in the order of 10 g In/l) this colloid remained stable for a number of weeks. A cascade impactor with gelatine-covered slides was used to determine the particle-size distribution immediately on exit from the nozzle. Although count-median diameters for the droplets on exit ranged from 0.6 to 2.0 μm at the specific nozzle types, and solution- and air-flows used, the high $\sigma_g$ values (3.0 to 3.5) caused high mass-median diameters, viz. 30-80 μm. This tracer-dispensing technique was scrapped mainly because the pneumatic nozzles on trial could not produce a sufficiently fine aerosol.

It was thus decided to develop a furnace for the high-
temperature evaporation of indium and the subsequent release of submicron-sized particles.

2.2.1 The Indium Furnace

The production of submicron particles is based on a combustion process which results in temperatures in excess of 850°C (volatilisation point of In$_2$O$_3$) and, thus, releases fumes of In$_2$O$_3$ which rapidly condense to form submicron particles. The fuel for the combustion process is a solution of In in ethyl alcohol which is atomised with either air or oxygen, injected into a high-temperature furnace and ignited.

2.2.1.1 Furnace

The furnace consists of a stainless steel sheath (33 cm long by 7 cm diam.) with an inner quartz liner which surrounds the atomising nozzle to inhibit corrosion of the sheath. The nozzle, made of nickel-plated brass, is a pneumatic type where spray formation (and, thus, the mixing of the alcohol and oxygen) occurs outside the nozzle. A conical brass collar surrounding the nozzle acts as a shield against draughts. The top end or exit of the furnace consists of a honeycomb of quartz tubes, each 1.5 cm x 6 mm diam. (8 mm OD), which serves to increase the temperature inside the furnace, and to intercept and evaporate droplets of In solution which do not ignite in the furnace and which may form large unwanted particles. A port just above the nozzle contains a filament of Ni-Cr wire which could be heated by remote activation and serves as ignitor to the burner. A schematic drawing of the furnace is shown in Fig. 2-1.

The optimum temperature inside the furnace in the quartz honeycomb is in the range of 900°C. This temperature ensures that the In$_2$O$_3$ evaporates and is also high enough
HONEYCOMB OF QUARTZ TUBES (8 mm OD AND 6 mm ID) MELTED TOGETHER AND TO THE INSIDE OF THE LARGER TUBE

In/ETHANOL SOLUTION

Fig. 2-1. Indium furnace.
to ensure auto-ignition in case the flame is extinguished due to wind or air bubbles in the liquid supply line. When atomising with air, high flow rates are needed to reach the required temperature. This often results in a flame which "jumps" and burns above the furnace (outside the honeycomb) where it is easily extinguished by wind. When using pure oxygen to atomise the ethyl alcohol mixture, high temperatures are reached at low gas flow rates, and this results in overheating of the nozzle, which in turn causes bubble formation in the liquid supply to the nozzle and the formation of large droplets. The optimum temperature and stable operating conditions were achieved by using an 80% ethyl alcohol 20% aqueous mixture atomised through the correct nozzle combination, using pure oxygen.

Various combustible mixtures of In in ethyl alcohol, with additions of methyl alcohol, acetone, toluene and nitromethane, were investigated. Ethanolic solutions containing 5-15% of these were found to have little effect on flame performance.

2.2.1.2 Generation of In$_2$O$_3$ aerosol

The In solution is prepared by dissolving indium metal in HCl. Approximately 1 g In is dissolved in 3 ml hot concentrated HCl. The solution is then adjusted to pH 2 with NH$_4$OH. Depending on the In release rate required, this solution may be further diluted with water before mixing one part aqueous solution with four parts 96% ethyl alcohol. With the particular nozzle combination used (Spraying Systems 64/2850) a liquid flow rate between 2 and 4 l.h$^{-1}$ was optimum (see also Section 2.2.1.3). The solution is supplied to the elevated burner by means of a diaphragm constant-displacement pump at a constant
rate. The burner is ignited by applying 24 V to the ignitor at low O₂ flow rate. As the burner heats up, the O₂ is increased to the optimum which was 15-20 ℓ.min⁻¹ for this combination.

When the temperature measured at the honeycomb decreases below 850°C, In is deposited on it, and also inside the furnace on the lower end of the quartz tube and around the nozzle. At temperatures in excess of 860°C the deposition of In becomes significant only after extended periods (longer than 40 h at release rates of > than ~ 20 g.h⁻¹).

2.2.1.3 Operational experience

During field operations over a period of five years much experience was gained and the following remarks might prove useful.

(i) As the In solution is more corrosive to aluminium than to brass or stainless steel, the former material should not be used in parts exposed to the solution.

(ii) The position of the flame in relation to the nozzle is determined by the rate of liquid and gas flow. At a liquid flow rate of 2.2 ℓ.h⁻¹, the optimum temperature was achieved with an oxygen flow of ~ 15 ℓ.min⁻¹, while at a liquid flow of 3.3 ℓ.h⁻¹ an oxygen flow of ~ 17 ℓ.min⁻¹ was required for optimum temperature. The resultant corrosion on the nozzle of these two operating conditions is shown in Fig. 2-2.

Apart from the nozzle tip (which is replaceable) the rest of the nozzle and other parts of the
(a) Unused nozzle tip.

(b) Nozzle tip used for 25 h at 3.3 l.h⁻¹ liquid flow, 17 l.min⁻¹ O₂ flow.

(c) Same as for (b), but 2.2 l.h⁻¹ liquid and 15 l.min⁻¹ O₂ flow

Fig. 2-2.
Corrosion of furnace nozzle tips due to various flame 'speeds'.

Fig. 2-3.
Windshield for furnace.
furnace were capable of withstanding at least a few hundred hours of operation. Depending on the amount of rough handling, the glass parts may need replacement more often.

With a liquid flow rate of 3 \( l.h^{-1} \), much less deposition of In\(_2\)O\(_3\), was found and, therefore, less maintenance was required than with flow rates of the order of 2 \( l.h^{-1} \). It is recommended that a liquid flow rate of at least 3 \( l.h^{-1} \) be used to reduce nozzle corrosion and In deposition.

(iii) If installed with its axis normal to the wind direction and with liquid flow rates of 3-4 \( l.h^{-1} \), the furnace can be used in winds of up to 10 m.s\(^{-1}\). A cylindrical aluminium wind-shield was constructed around the furnace, which allowed it to be used in winds up to 20 m.s\(^{-1}\) (see Fig. 2-3). Less than 2% of the In\(_2\)O\(_3\) released is deposited on the inside surface of this wind-shield in wind speeds of the order of 5 m.s\(^{-1}\).

(iv) Liquid supplies to the furnace should be stable and, for efficient operation, any pulsing by the pump in the liquid supply should be eliminated. The supply line must be secured (e.g. not left dangling in the wind) to prevent erratic burning.

(v) The dimensions of the quartz tubes in the honeycomb are critical; if they are too long or narrow, a part of the flame is forced out through the bottom of the furnace, causing deposition in this area, as well as overheating of the nozzle, which leads to erratic burning. If they are too short and/or too wide, it is more difficult to heat the
inside of the furnace to higher temperatures, causing more deposition of $\text{In}_2\text{O}_3$ on it and also causing small air bubbles in the liquid supply to extinguish the flame (this is not serious in the optimum setup, thanks to auto-ignition of the alcohol after the air bubble has passed).

(vi) The furnace operated effectively with alcohol mixtures containing up to 30% water. Variations in oxygen flow of $\pm$ 20% could be tolerated.

2.2.1.4 Particle size analyses

Size distributions of In particles produced by the furnace were determined by collecting $\text{In}_2\text{O}_3$ particles on a thin carbon film with an electrostatic precipitator and using an electron microscope for the analyses. The precipitator used was a point-to-plane electrostatic precipitator as devised by Morrow and Mercer (1962). The microscopes used were an Hitachi 100 UB and a Jeol mod. JSEM 200 scanning transmission electron microscopes, run at 100 kV with magnification ranging from 67 000 to 93 000. For each of the three sets of samples taken (one set of samples was taken for each set of generating conditions - see below), one sample was selected, and a number of fields (fourteen for sample (i), sixteen for (ii) and twenty five for (iii)) were photographed at random over the whole sample, from one edge to the other. No loss of particles was observed in the electron beam. Unfortunately, samples (i) and (ii) were taken at a distance of ~ 20 cm from the generator and relatively high particle densities were obtained on the carbon films. Size separation along the deposits may have occurred. However, as larger agglomerates occurred at places with higher particle density, it is difficult to say whether this increase in size occurs due to an increase in the particle concentration.
on parts of the grid or to changes in the potential field over the area of concern, causing a size separation. To remove the uncertainty, the third set of samples (iii) was taken - 2 m from the source and for a shorter time period; a much lower particle density on the carbon film was obtained. Size separation along the deposits seemed to be insignificant. The size distribution for sample (iii) (see Fig. 2-4) yields a curve fairly similar to that for the other samples. The difference may be partly due to the fact that only 170 particles were included in the size analysis of sample (iii).

Samples were taken 20 cm to 2 m from the furnace for periods from 1 to 5 s during the following release conditions.

Sample (i). Liquid flow: $2.8 \text{ L.h}^{-1}$ (28 g In/h), $\text{O}_2$ flow: ~16 $\text{ L.min}^{-1}$ (temperature at the top of the honeycomb: 870°C).

Sample (ii). As above but $\text{O}_2$ flow: ~24 $\text{ L.min}^{-1}$ (temperature 1 050°C).

Sample (iii). Liquid flow: $3.3 \text{ L.h}^{-1}$ (27 g In/h), $\text{O}_2$ flow: ~20 $\text{ L.min}^{-1}$.

The particle-size distribution is shown in Fig. 2-4. Sizing was done, using the projected-area diameter, on individual particles as well as on whole agglomerates. Electron micrographs of sample (iii) (x 93 000) are shown in Fig. 2-5. Very little difference was noticed when analysing the distributions from the first two samples.

The count-median diameter (CMD) and geometric standard deviation $\sigma_g$ are deduced from these curves and are,
(i) Liquid flow 2.8 l/h (28 g ln/h); O\textsubscript{2} flow ~16 l/min (Temp. 870°C)
(ii) Liquid flow 2.8 l/h (28 g ln/h); O\textsubscript{2} flow ~24 l/min (Temp. 1050°C)
(iii) Liquid flow 3.3 l/h (27 g ln/h); O\textsubscript{2} flow ~24 l/min

Fig. 2-4.
Particle-size distribution of aerosol from indium furnace.

Fig. 2-5.
In\textsubscript{2}O\textsubscript{3} particles from furnace (x 33000).
respectively, 0.02 µm and 1.9 for samples (i) and (ii) and 0.03 µm and 1.7 for sample (iii). The standard deviation in $\ln \sigma_g$ for samples (i) and (ii) is of the order of 0.025 and for sample (iii) 0.030, and that in $\ln \text{CMD}$ is, respectively, 0.03 and 0.04. From the CMD and $\sigma_g$ values the mass-median diameter (MMD) was calculated, using the following equation:

$$\log_{10} \text{MMD} = \log_{10} \text{CMD} + 6.9 \left( \log_{10} \sigma_g \right)^2.$$ 

The MMD was found to be 0.07 µm for samples (i) and (ii) and 0.06 µm for sample (iii).

The results of the furnace particle-size distribution do not compare well with those of Dingle (1968) who used a pyrotechnic flare to generate In$_2$O$_3$ particles. He obtained a CMD of 0.18 µm. On the other hand, the size distribution obtained by Dahl et al (1970) for In$_2$O$_3$ from an oil burner has a range of $5 \times 10^{-3}$ to $7 \times 10^{-2}$ µm, whereas particles from the furnace used here were in the range $4 \times 10^{-3}$ to $9 \times 10^{-2}$ µm, if the smallest 1% and largest 1% of the particles are left out.

### 2.2.1.5 Conclusions

The tracer generator described has been proved to be reliable under different environmental conditions. Constant release rates can be maintained over extended periods and under adverse weather conditions. The particle-size distribution approximates gaseous behaviour and no significant plume depletion due to gravitational settling of large particles was experienced. There is a possibility that the size distribution may be markedly influenced by coagulation over longer travel distances. One sample of particles from the generator taken at ~50 m from the source showed them to be in the
same size range, more or less, as those in samples (i) to (iii) above. Only a qualitative observation was made as there were nil to two particles per field. One can expect that even at the ranges involved (up to 50 km), coagulation may have a significant effect only on the smaller particles in the size spectrum obtained in this study (Sheih, 1977).

The technique could be used in remote areas as only low power consumption (~ 700 W) is required. Oxygen consumption is low (~ 1 m³.h⁻¹) and allows the use of ordinary gas cylinders for the supply of oxygen.

The release rates that can be maintained make possible the measurement of dispersion factors over distances of 50 km.

The advantages of the indium tracer and generator were discussed above (Sects. 2.1, 2.2.1). A popular tracer type used or proposed by many workers and reported on in recent publications is inert gases such as SF₆ and the freons. Other gases such as SO₂, Br₂, and I₂ are relatively unstable and not as suitable in long-distance studies. The advantages of the inert gases are that almost unlimited release rates are possible (not so with the particle generator) and that sensitive analytical methods are available (gas chromatography/electron capture, for example) for quantitative determinations. On the other hand, sampling is more difficult than with particulate tracers, and much smaller sampling rates for shorter time periods can be achieved. Instrumentation for the analysis of a gas is expensive; means for neutron activation were readily available at the time when work was started on the tracer generator. The particulate tracer has the further advantage that deposition phenomena can be studied with it. Initially this was an important
consideration. In the line of particulate generators a furnace (or similar device for the evaporation of an element) is the only practical way to get particles as small as were obtained here.

2.3 TRACER SAMPLING

2.3.1 Sampling Apparatus

The air samplers consist of rotary carbon-vane air pumps driven by electric motors (10 samplers used in the Koeberg work used mains supply while the other 10 could be operated from either mains or car battery), each motor mounted in a metal box with an integrating flow-meter to determine total air volume pumped. The filter head with a membrane-type filter (0.45 and 0.8 μm pore diameter filters were used) is mounted approximately 1 m above ground on a stem on the sampler box. Air sucked through the filter (at 15-30 l.min⁻¹) is then passed through the flow-meter and pump. Sample volumes normally consisted of 1 to 10 m³ of air.

2.3.2 Filter Efficiency and Apparatus Decontamination

(a) The collection efficiency (i.e. the percentage of tracer retained by a filter during sampling) of membrane filters of two pore sizes was tested for the In₂O₃ aerosol. The filters tested were Millipore filters of 47 mm diameter and pore sizes of 0.45 and 0.8 μm. Two filters of the same pore size were set up in series for each test, 5-10 m from the tracer generator; sampling rate was varied: 12-24 l.min⁻¹. Filter efficiency is calculated from

\[ E = 1 - \frac{A_2}{A_1} \]

where E is the efficiency and A₂ and A₁ respectively the
tracer concentration on the second and first filters in the series. The filter efficiency was found to be better than 99.9% for the 0.45 μm pore size filters and better than 99.7% for the 0.8 μm pore size.

(b) For the purposes of recovery of In from the filters and the decontamination of materials such as filter holders, a number of tests were performed on the solubility of In₂O₃ in hydrochloric acid. Millipore membrane filters (two for each acid strength) bearing the tracer aerosol and spiked with radioactive ¹¹⁶ᵐIn were tested in 1 M, 6 M and concentrated (33%) HCl. After a few hours the two filters in 1 M HCl at room temperature (RT) still had 10 and 40% respectively of the original In₂O₃ not in solution. The filters in 6 M HCl had respectively 0.9 and 0.5% left after 1.5 h at RT; both had 0.1% after 5 h at RT, and 0.005% and 0.02% when the same filters were kept in the acid at boiling point for 1 min. In concentrated HCl, after 1.5 h at RT, 0.1 and 0.05% tracer, respectively, were left on the filters.

2.4 QUANTITATIVE DETERMINATION OF INDIUM TRACER SAMPLES

Sample concentrations were determined by neutron activation followed by dissolving the filter load in hydrochloric acid and the subsequent solvent extraction of InI⁻ into ether; this phase is γ-counted.

Neutron activation of air-filter samples produces a host of other gamma emitters, amongst which ⁵⁶Mn, ²⁴Na and ³⁸Cl interfere with the quantitative analyses of low levels of ¹¹⁶ᵐIn. Due to the short half-life of ¹¹⁶ᵐIn (54 min.), it is necessary to separate it rapidly from the bulk of the interfering nuclides before it can be analysed by means of gamma spectrometry.

If high resolution spectrometry, with a Ge(Li) detector,
is used, the separation of In from other elements need not be perfect, provided the In is quantitatively recovered. The separation serves to reduce the total activity and thereby reduces the dead time of the multichannel analyser, which increases the accuracy of counting.

The low levels of In which have to be determined, demand extreme care during pre-irradiation handling to prevent contamination with, or losses of, In.

Various methods are described in the literature for the quantitative precipitation of In, e.g. as $\text{In}_5(\text{IO}_6)_3$ (Verdizade and Mekhtiev, 1971) and $\text{In}_2\text{S}_3$ (Taimni and Salaria, 1954; Busev, 1962). A method that was used for some time in this laboratory is hydroxide precipitation of In from aqueous solution. In this way Cl and most of the Na was removed, but the Mn and a small portion of the Na included in the precipitate was enough to cause a dead time which was sometimes significantly higher than 10 % on the gamma spectrometer.

Sulphide precipitation is time-consuming and inconvenient when $\text{H}_2\text{S}$ is used, while Mn is co-precipitated when $(\text{NH}_4)_2\text{S}$ is used. Precipitation of $\text{In}_5(\text{IO}_6)_3$ was not investigated.

Several methods for In separation are possible using ion-exchange columns. In acid medium both cation (Strelow et al, 1965; Strelow et al, 1969) and anion exchange (Klakl and Korkisch, 1969) reactions are available. The disadvantages of these methods are as follows:

(i) in certain cases Cl will be eluated with In;
(ii) the large volume of the eluant results in low
counting efficiencies and therefore requires an additional precipitation step; and,

(iii) the long time required for the flow of large volumes through the column.

Solvent extraction is rapid and appears promising as a means of indium separation. In can be extracted from 6 M HBr with 0.05 M tributylphosphine in benzene (Mieczkowska, 1970) or as InI₄ from H₂SO₄ medium into diethyl ether (Irving and Rossotti, 1952). As the In₂O₃ cannot be dissolved in H₂SO₄, this latter process was investigated for an HCl medium, and the extraction of In from the aqueous medium by ether.

2.4.1 Neutron Activation Procedure

Indium is naturally present as ¹¹⁵In, with an abundance of 100%. When irradiated with thermal neutrons, the reaction ¹¹⁵In(n,γ)¹¹⁶mIn leads to the production of the 54 min ¹¹⁶mIn, decaying with the emission of three intense gamma rays with energies 417.0 (36 %); 1 097.1 (53 %); and 1 293.4 (80 %) keV (Bolotin, 1964). The saturation irradiation time for In at a flux of 3 x 10¹³ n.cm⁻²s⁻¹ is approximately five hours. However, the optimum irradiation time is determined by the physical condition of the membrane filter. It was experimentally found that a 20 min irradiation in the above flux resulted in a filter sample that could still be handled and transferred quantitatively for chemical separation. Higher exposures resulted in the embrittlement of the filter (which prevented quantitative recovery) and could also result in high levels of radiation from the sample which would require remote handling.

Standards were prepared by micro-pipetting standard In
solution onto blank filters. These standards were irradiated with the samples and treated in the same way as the latter. Quantitative determination of In was achieved by the comparison of counts between samples and standard, with the consideration of differences in decay time of them.

Individual filters were contained in polyethylene bags. Four to six bags together with two standards were irradiated in the pneumatic facility of the SAFARI-1 reactor.

2.4.2 Chemical Procedure

The conditions for maximum In yield from an aqueous solution were determined by investigating the role of carrier concentration, HCl volume, KI mass, total solution volume and ether contact time, with $^{115m}$In ($T_1/2 = 50$ d) as a tracer. Extractions were performed in a 250 ml separating funnel by vigorous shaking with 35 ml diethyl ether. The relative yields of single extractions with various combinations of these parameters are shown in Table 2-1.

Table 2-1. Percentage yield of In extraction under various conditions

<table>
<thead>
<tr>
<th>Mass In$^{3+}$ carrier added (mg)</th>
<th>Volume 6 M HCl added (mL)</th>
<th>Mass KI added (g)</th>
<th>Total volume solution (mL)</th>
<th>Contact time (min)</th>
<th>% Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>10</td>
<td>50</td>
<td>200</td>
<td>2</td>
<td>98.8</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>30</td>
<td>150</td>
<td>2</td>
<td>94.7</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>10</td>
<td>150</td>
<td>2</td>
<td>92.4</td>
</tr>
<tr>
<td>0.005</td>
<td>30</td>
<td>50</td>
<td>150</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>50</td>
<td>150</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 2-1 (continued).

<table>
<thead>
<tr>
<th>Mass In$^{3+}$ carrier added (mg)</th>
<th>Volume 6 M HCl added (ml)</th>
<th>Mass KI added (g)</th>
<th>Total volume solution (ml)</th>
<th>Contact time (min)</th>
<th>% Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>50</td>
<td>50</td>
<td>250</td>
<td>2</td>
<td>95.9</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>50</td>
<td>180</td>
<td>2</td>
<td>98.8</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>50</td>
<td>150</td>
<td>2</td>
<td>100</td>
</tr>
</tbody>
</table>

2.4.3 Determination of Quantitative Yields

With In concentrations in excess of $10^{-8}$ g or with samples with a low background activity it is possible to determine the In directly by means of instrumental neutron activation analysis without separation from interfering nuclides. To determine possible losses during the dissolution and subsequent chemical treatment, filters were labelled with known quantities of In and irradiated in duplicate or triplicate for 20 min at $3 \times 10^{13}$ n.cm$^{-2}$s$^{-1}$. The $^{116m}$In activity of one or two chemically treated filters was compared with the activity on the filter of the set which was analysed by direct gamma spectrometry, and counted in the same geometry as the treated samples by dissolving the filter in acetone. The areas under the three most intense $\gamma$-peaks were summed to give the total observed count. The results of these yield determinations are shown in Table 2-2. On the $\gamma$-spectrometer used (with a 60 cc Ge(Li) crystal), the count rate was found of the order of 2 000 cpm.ng$^{-1}$ one hour after irradiation.

2.4.4 Discussion of Analytical Procedure

The optimum conditions for rapid separation and a high yield of In in the extraction process led to the following procedure for sample treatment:

1. Six filters and two standards contained in individu=
Table 2-2. Percentage yield of samples subjected to the In separation procedure compared with untreated (standard) samples

<table>
<thead>
<tr>
<th>Standard mass (ng)</th>
<th>Treated filter mass (ng)</th>
<th>Yield %</th>
</tr>
</thead>
<tbody>
<tr>
<td>13,9</td>
<td>13,16</td>
<td>105 ± 1,8*</td>
</tr>
<tr>
<td>12,07</td>
<td>12,09</td>
<td>99 ± 1,8</td>
</tr>
<tr>
<td>12,07</td>
<td>0,121</td>
<td>93 ± 5,8</td>
</tr>
<tr>
<td>11,10</td>
<td>12,09</td>
<td>101 ± 1,8</td>
</tr>
<tr>
<td>11,59</td>
<td>11,59</td>
<td>97 ± 0,7</td>
</tr>
<tr>
<td>10,62</td>
<td>11,0</td>
<td>102 ± 1,3</td>
</tr>
<tr>
<td></td>
<td>0,102</td>
<td>110 ± 3,2</td>
</tr>
<tr>
<td></td>
<td>0,120</td>
<td>105 ± 3,5</td>
</tr>
</tbody>
</table>

* % error calculated from the total counts of standard and treated filter

All polyethylene bags are irradiated simultaneously for approximately 20 min in a flux of 3 x 10^{13} \text{n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}. After allowing 15 min for the decay of short-lived impurities, the irradiated filters are transferred from the polyethylene bags to individual 250 ml conical flasks.

2. The In is dissolved by boiling for 1 min in 30 ml 6 M HCl containing 5 mg In^{3+} carrier. The solution is filtered under suction and the conical flask washed with 20 ml 6 M HCl and 10 ml H_{2}O respectively.

3. 50 g KI dissolved in 30-40 ml H_{2}O is added.

4. The solution (~ 180 ml) is transferred to a 250 ml
separating funnel and ~ 35 ml diethyl ether added. This is vigorously shaken for about one minute, and 5-10 min is allowed for the separation of the phases. The organic phase is quantitatively collected in a screw-top polyethylene container and the level of the solution adjusted to a standard height.

5. The sample is sealed to prevent evaporation, and transferred to a gamma spectrometer. The time at the start of the count is noted.

The total processing time from the end of irradiation to the start of counting of the first sample is approximately one hour. Four to six filters can be handled simultaneously.

The reproducibility of the method was determined by treating 10 filters labelled at the one nanogram level. Without special precautions such as double washing of the flasks or accurate levelling of the solution in the counting vial, the standard deviation of the replicate analyses was 3.4%.
PART 3

DISPERSION AND DEPOSITION STUDIES IN THE RICHARDS BAY AREA

3.1 DISPERSION STUDIES

3.1.1 Introduction

A series of atmospheric dispersion experiments was conducted during the winter months of 1975 and 1976 in the vicinity of Richards Bay, South Africa (Scholtz and Brouckaert, 1978). This investigation was primarily aimed at studying the behaviour and dispersion of tracer materials released under stable atmospheric conditions with katabatic winds, and was part of a larger program for investigating the air pollution potential of the planned industrial area. The tracer dispersion experiments were run mainly in the gravity (katabatic) winds, because of the many uncertainties in plume trajectory and dispersion under such conditions.

The main aim of this section (3.1) is to see how well a segmented-plume dispersion model incorporating a simple wind-field interpolation scheme, and wind data obtained from about ten 10 m masts over an area of roughly 100 km², would predict tracer trajectories and air concentrations at ground level. Data obtained from the experiments in the Richards Bay area were used to see how the relative sophistication of the approach with which the diffusion coefficients are determined, will influence the accuracy of concentration predictions.

In the model presented here, using a segmented-plume approach, dispersion and air concentrations downwind from the source were calculated by means of the simple,
generally used, Gaussian dispersion equation for a continuous point source. Three diffusion schemes, ranging from a very simple one to a relatively sophisticated one, were incorporated in the computer program and any one can be used on demand.

A relatively unsophisticated numerical model was chosen as such a model was deemed more suitable (less computer time needed) for subsequent real-time mini-computer use for operational purposes at a nuclear installation. A segmented-plume instead of a puff approach was used so that the diffusion coefficients \( \sigma_y \) and \( \sigma_z \), as determined by the turbulence typing schemes, could be used in the conventional equation for a continuous point source. These schemes were used for the determination of the diffusion coefficients; the simplest one has only one category for stable atmospheric conditions; the second, based on experimental results of a large number of recent dispersion studies, has two stable categories; the third is based on stability length theory. An investigation was done into the relative accuracy by which these schemes could predict dispersion, especially in a stable atmosphere.

**Meteorological and topographical factors**

The terrain over which the experiments were conducted is fairly flat; the highest point is 40 m above sea level, sloping gradually towards the bay. The tracer release point was on top of a 25 m mast, erected on this rise. The average surface obstacle heights for the area are shown in Fig. 3-2. In the sector SW to SE from the release point, vegetation consisted of either grass and short shrubbery or changed to bare sand at the shores of the bay, while the sector SE to
NNE had grass, coastal bush and intermittent clumps of trees.

The most important sector in which dispersion took place under stable gravity wind conditions proved to be SW to SE from the release point, while during higher wind speed and less stable conditions the sector ESE to NNE became dominating. The ground-based inversion heights at the release point varied from approximately 200 to 700 m, with a total difference in temperature of 2-15°C (Scholtz and Brouckaert, 1976; Scholtz et al., 1978). The latter was obtained by means of pilot balloon/radiosonde trackings. The temperature difference at the release point, \( T(24\, \text{m}) - T(3\, \text{m}) \), varied from +5.5 to -1.5°C (Mulholland et al., 1977).

The ground level inversion broke up between 08h00 and 09h00 in the mornings.

Apart from the fact that the temperature differential between the land and the sea provided an additional driving force for the stable land winds, the study was not greatly influenced by the land-sea interface, as the tracer release point was situated well inland with the sampler positions near enough to the release point. Plume trajectory and dispersion can thus be taken as a function of mainly the gradient wind, katabatic air flow (i.e. the movement of cold, more dense air from topographically higher to lower levels) and certain surface properties such as the surface temperature over the bay and surroundings (see Figs. 3-1, 3-2 and 3-3). Certain other phenomena caused or influenced by the land-sea interface, such as the sea breeze and the return flow of pollutants previously transported to the sea, back to the land, were not investigated. Most tracer work was done in winds moving from the release point on
Fig. 3.1.
Topography of Richards Bay area.
Fig. 3-2.
Estimated effective mean height of surface obstacles in the Richards Bay area (July - August 1976) (measurements in metres).

Fig. 3-3.
Air sampler and weather mast positions in Richards Bay area.
land towards the coastline.

Figs. 3-1, 3-2 and 3-3 give, respectively, (i) the general topography of the area, (ii) the estimated effective mean height of surface obstacles, and (iii) the tracer release point, air sampler and meteorological mast positions. Note that at the time of the experiments, the only built-up areas of significance were Arboretum and Meerensee, and that the "surface obstacles" referred to in Fig. 3-2 indicate grass, trees, etc.

3.1.2 Experimental

The greater part of the experimental program (weather mast and sampler positions, details of meteorological measuring apparatuses, ZnS.CdS tracer generator, particle-counting system and radiosonde system) was planned by Scholtz and Brouckaert (1978) and Mulholland (1977). Air samplers and the indium tracer generating and analysis techniques were developed by Norden and van As (1977, 1979).

For the purpose of the study, tracers were released continuously at a constant rate and height, with the release points of the two tracer generators about 1.5 m apart, and for periods ranging from 5 to 16 h. As tracers for this study, the materials In$_2$O, and ZnS.CdS were used, with count-median diameters of 0.02 and 4 μm respectively. Sampling of the tracers was done by means of air pumps at distances ranging from about 1 to 8 km from the release point, and with sampling periods of 1-10 h. The air samplers (a total of 10-12) were moved, depending on the wind direction, to strategic positions for covering the plume (sectors of 5°-20°).
The meteorological conditions (wind and temperature) during an experimental run were characterised by a system of 10 masts covering the area of study which was roughly 100 km². Data were collected continuously at these masts by means of a wind direction sensor at 10 m, and air temperature sensors and anemometers at both 2 m and 10 m. The data were averaged for three-minute intervals and sent by telemetry to the main station for recording. See Appendix A for a description of the telemetry system. The tracers were released from the top of a 25 m mast which also carried temperature sensors at 3 and 24 m and a Lambrecht wind recorder at 8 m. During typical dispersion runs, five to eight of the masts could be relied on to produce useful data. It was essential to measure the wind field over the total area traversed by the plume due to the many variations in wind direction with distance from the release point during conditions of low wind-speed katabatic air movement. Shown in Fig. 3-3 are the positions of the various masts of the wind-field system, as well as air sampler positions. Sixteen mast positions are given, representing all the positions used during both years of the study.

3.1.3 The Dispersion Model

3.1.3.1 A semi-real-time dispersion model

The dispersion model utilises the basic Gaussian diffusion equation (Eq. 1-1) for atmospheric dispersion from a continuous point source. The values for variables fed into the dispersion program every half-hour are the usual, viz. average wind speed (\( \bar{u} \) in the equation is obtained by dividing the total plume travel distance to a sampler by the total time taken for this travel) and direction and lapse rate.
Furthermore, release height, release rate and the coordinates of the release point and sampler and mast positions are entered initially. For this purpose a grid system is superimposed over the area of interest. When stability length theory is used for the computation of $\sigma_z$, average values for air temperature at ground level and roughness length are also entered. The lapse-rate value entered is an average of the values obtained from the masts covering the area traversed by the plume during a specific half-hour.

The total plume formed during a release of tracer/pollutants is taken as a composite of shorter five-minute length "sub-plumes". (This is the time period used here, other suitable periods can be used.) Each set of half-hourly averaged wind directions and velocities is used to direct a new set of six consecutive five-minute length sub-plumes from the release point, as well as to give new directions of movement (based on an interpolation scheme, explained below) to each of the other five-minute length sub-plumes already on the grid system. Each set of new half-hourly averaged wind directions which are entered into the program is compared with the previous set and the sector traversed by the wind during the half-hour is divided into smaller sectors of equal size. Thus, if for example, the previous half-hourly averaged wind direction was 300° and the new one is 330°, then the 30° sector (330° - 300°) is divided into 6 x 5° sectors. The first direction imposed on all (five-minute length) sub-plumes will be (300° + 5° =) 305° for the first five minutes of this half-hour, the second direction 310°, etc. ... and the sixth (and last) 330°. See Fig. 3-4 as well as the explanation of Figs. B-1, 2 and 3 in Appendix B. This approach gives one the same values
Fig. 3-4.
Plume development during one period into six consecutive sub-plumes, with wind speeds and directions at all measuring points the same. (See text.)
(more or less) as would be the case if five minute average wind data had actually been used; the problem is that five-minute averaged weather data are not always easily available, therefore half-hourly values are rather divided into five-minute averaged values (naturally, not as accurate). The direction and length of each sub-plume is therefore adjusted every five minutes by means of the five-minute averaged weather data for that five-minute interval. The wind speed and direction imposed on each sub-plume are those due to the "total" effect of the speed and direction from all the masts in the area under consideration. For this purpose an interpolation scheme is used in which the effect of each mast on each sub-plume is dependent on the inverse of the square of the distance between this mast and the specific sub-plume. This approach has been used by other workers, such as Wendell (1972) and Scholtz and Brouckaert (1976):

\[ P(x, y) = \frac{\sum_{i=1}^{n} \frac{P_i}{r_i^2}}{\sum_{i=1}^{n} \frac{1}{r_i^2}} \]

where \( P(x, y) \) is the interpolated value at point \((x, y)\); \( P_i = P(x_i, y_i), i = 1, 2, \ldots, n \), the values from the measurement points \((x_i, y_i), i = 1, 2, \ldots, n\); \( r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}, i = 1, 2, \ldots, n \).

A simulated plume may shift through a relatively large sector in a half-hour (or even in five minutes) due to a large change in average wind direction, and during such a shift may move over a sampling position from a position where it may have a relatively small or no effect on the concentration calculated at this sampler.
to a position past the sampler where the simulated plume may again have a small or no effect on the concentration calculated at the sampler concerned. Zero concentration may thus be calculated at such a sampler, although the plume has passed over it. Thus, for a more accurate assessment of the average calculated concentration at a sampler, a step was brought into the program whereby the concentration at a sampling point, calculated for each sub-plume which affects this sampler during a five-minute period, is calculated for ten (or another suitable value) consecutive equidistanced steps of the sub-plume during this five-minute period, and the average concentration value taken. See note 7 in Appendix B.

The average concentrations calculated at all specified sampler positions are printed every 15 min during a simulated tracer run.

The dispersion model which was programmed in Fortran, for execution by an IBM-370, has the capability (by means of six separate subroutines) to utilise one of six diffusion classification schemes as obtained from the literature. The flow-diagram of the program is given in Appendix B.

3.1.3.2 Diffusion classification schemes

The computer simulations for this study used three alternative methods to calculate the $\sigma$'s, chosen for their degrees of sophistication:

Subroutine 1: This is based on the more recent scheme by Briggs (1974), having six stability classes, including two for stable atmospheric conditions. See Table 3-1.
Subroutine 2: $\sigma_y$ is determined in the same way as in Subroutine 1, but $\sigma_z$ is calculated by means of the Monin-Obukhov stability length.

$$\sigma_z = \sqrt{2K_z t}.$$  

$K_z$ is determined at $z = 10$ m.

Table 3-1. Formulas recommended by Briggs (1974) for $\sigma_y(x)$ and $\sigma_z(x)$; $10^2 < x < 10^4$ m, open-country conditions

<table>
<thead>
<tr>
<th>Pasquill type</th>
<th>$\sigma_y, m$</th>
<th>$\sigma_z, m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$0.22x(1+0,000 \ 1x)^{-\frac{1}{3}}$</td>
<td>$0.20x$</td>
</tr>
<tr>
<td>B</td>
<td>$0.16x(1+0,000 \ 1x)^{-\frac{1}{3}}$</td>
<td>$0.12x$</td>
</tr>
<tr>
<td>C</td>
<td>$0.11x(1+0,000 \ 1x)^{-\frac{1}{3}}$</td>
<td>$0.08x(1+0,000 \ 2x)^{-\frac{1}{3}}$</td>
</tr>
<tr>
<td>D</td>
<td>$0.08x(1+0,000 \ 1x)^{-\frac{1}{3}}$</td>
<td>$0.06x(1+0,001 \ 5x)^{-\frac{1}{3}}$</td>
</tr>
<tr>
<td>E</td>
<td>$0.06x(1+0,000 \ 1x)^{-\frac{1}{3}}$</td>
<td>$0.03x(1+0,000 \ 3x)^{-1}$</td>
</tr>
<tr>
<td>F</td>
<td>$0.04x(1+0,000 \ 1x)^{-\frac{1}{3}}$</td>
<td>$0.016x(1+0,000 \ 3x)^{-1}$</td>
</tr>
</tbody>
</table>

To simplify computation, each sampler position was allotted a specific $z_o$ value, depending on the surface type(s) the tracer plume had to traverse from the source to this position during a tracer run. $z_o$ values were obtained from Table 1-5 in Section 1.2.1.2.

Subroutine 3: This approach uses the stability classification scheme by Smith (1973) and has four stability classes (of which only one is for stable conditions), viz. "very unstable", "unstable", "neutral" and "stable". Equations of the form $ax^b$ (with $x$ the distance from the source) are used to determine the
3.1.4 Results

The experimental results from six tracer runs are compared with the corresponding computer runs in Figs. 3-5(a) and (b). Tracer release rates were all normalised to 1 kg.s⁻¹. Each tracer run was divided (where applicable) into time periods covering roughly the stability ranges encountered. Where more than one sample was taken at one position during such a period, the average air concentration was taken for this position for this period. Only run 1975-G used the In₂O₃-tracer results; the rest of the runs used the ZnS.CdS tracer concentration results (Mulholland, 1977).

Histograms are shown for the experimental values and for those obtained from Subroutine 1 only; values obtained from the other two subroutines are indicated by symbols only. The sampler positions (except position 111) are on the horizontal axis in the figures, separated by distances roughly equivalent to the sectors covered, and treated as if equidistant (5 000 m) from the release point. Wind directions observed at the release point only (mast 9), and average wind-speed and lapse-rate values, are given in the figures.

Predicted and measured air concentrations are compared in Figs. 3-6 and 3-7. Where the one value is on or below 0.01 ng In/m³ or one particle ZnS.CdS/m³, the comparison point is marked on the appropriate axis.

Unfortunately, the lapse-rate values varied quite significantly from the release point to positions near the coast line and over the bay, the atmosphere being less stable in general over the bay during the night, and more stable than at mast 9 after sunrise. Thus,
Fig. 3-5(a).

Richards Bay atmospheric study tracer concentration results, runs 1975 G and 1976 A.
Fig. 3-5(b).
Fig. 3-6.
Comparison of predicted and measured mean concentrations for runs in stable atmospheric conditions.

Fig. 3-7.
Comparison of predicted and measured mean concentrations for runs in unstable atmospheric conditions.
while mast 9 gave, on occasion during the night, a lapse rate of +10 to 20 K/(100 m)^{-1}, masts 5 and 6 gave from small negative to small positive values for the lapse rate.

When comparing the values of the calculated and experimental results, the error in the latter should be kept in mind. Where the average concentration values approach 0.1 \times 10^{-8} only 5-10 particles were counted on a filter. The effects of deposition and gravitational settling are ignored. The error due to deposition in the sector SW to SE from the release point should have made a difference of less than 50% - see Sections 3.1.6.3 and 3.2 (samplers 107 to 118 in Figs. 3-5) - while it could have been a factor 5 at the samplers more to the east and NE of the release point.

The results from the different tracer runs will not be discussed separately, except for the following cases:

1. During the stable period of three of the runs (viz. 1975-G, 1976-C and 1976-D) a significant "shift" to higher experimental values occurred towards the harbour mouth (samplers 118 and 119). A curvature in the wind-field trajectory could have been expected due to partial drainage of gravity wind through this gap in the coastal dunes, and the simulated plume did not follow this curvature well enough.

2. The results from the simulated runs during less stable conditions normally compared fairly well with experimental results. One significant exception occurred for the second period of run 1976-C when
no tracer was collected at positions 120 and 124, while the wind directions indicated that the plume should have moved in these general directions. This was most probably due to wind-shear effects.

To evaluate the diffusion schemes used, the averages of the ratios of calculated to experimental values for a number of the runs are given in Table 3-2. This is of little value in cases where the calculated and actual plume trajectories differed much, and especially in the cases where some values have a zero corresponding to a non-zero value (in such cases where one value is a zero the ratios are left out when averaging). Another way of comparing the results is to calculate, for each subroutine as well as for the experimental values, the integral $\frac{1}{B} \int_{0}^{B} X dy$ (or arc-wise integrated concentration) with $B$ the length of arc with radius 5 000 m (and the release point the centre of the arc), over which the tracer was detected. This is achieved by firstly normalising all concentrations so as to have values as if the samplers were all at the same distance (here 5 000 m) from the release point (by calculating what the concentrations would have been if $x = 5 000$ m), and dividing the distance between each set of adjacent samplers in two. The sum of the two half-distances on both sides of each sampler is multiplied by its normalised concentration value, and all these values (from one period) are summed to give the integral. The results of the comparisons are given in Table 3-2.

3.1.5 Discussion and Conclusions

The results obtained in about half of the cases using this model in stable atmospheric conditions were not very good. The main problem lies in determining the plume trajectory. Because of local effects the trajec-
<table>
<thead>
<tr>
<th>Run no.</th>
<th>Period no.</th>
<th>Experimental Average ratio calculated and standard deviation</th>
<th>$\left[ \frac{1}{B} \int_0^B \chi dy \right]<em>{\text{calc.}} / \left[ \frac{1}{B} \int_0^B \chi dy \right]</em>{\text{exp.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sub. 1 exp. Sub. 2 exp. Sub. 3 exp. &amp; σ</td>
<td>Sub. 1 Sub. 2 Sub. 3  &amp; σ</td>
</tr>
<tr>
<td>1975-G</td>
<td>1</td>
<td>18,5 30 10,0 17 20,4 33,6</td>
<td>7,1 3,8 7,5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2,1 2,7 3,5 2,7 0,67 0,60</td>
<td>- - -</td>
</tr>
<tr>
<td>1976-A</td>
<td>1</td>
<td>7,0 9,6 4,3 7,9 4,5 6,2</td>
<td>2,7 2,2 2,7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2,3 1,8 3,6 2,7 4,9 5,0</td>
<td>3,0 4,5 6,4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,2 1,3 2,2 2,3 0,63 0,72</td>
<td>- - -</td>
</tr>
<tr>
<td>1976-C</td>
<td>1</td>
<td>- - - - -</td>
<td>3,0 3,6 4,2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>- - - - -</td>
<td>- - -</td>
</tr>
<tr>
<td>1976-D</td>
<td>1</td>
<td>- - - - -</td>
<td>12,4 9,0 14,5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1,2 1,0 - - 1,4 1,4</td>
<td>- - -</td>
</tr>
<tr>
<td>1976-F</td>
<td>1</td>
<td>75,4 128 73,5 127 79,6 138</td>
<td>8,9 9,0 8,7</td>
</tr>
<tr>
<td>1976-G</td>
<td>1</td>
<td>- - - - -</td>
<td>2,9 1,3 2,9</td>
</tr>
</tbody>
</table>
tory may deviate on a smaller scale than indicated by
the meteorological masts. This could allow certain
local concentration maxima to occur between two samplers,
or, alternatively, permit a local maximum to influence
a specific sample only. This problem is partly over-
come by taking samples over a period of at least a few
hours. Smaller sectors should be covered by air
samplers during such stable conditions. A factor which
may account partly for the observed discrepancy between
calculated and observed results is directional wind
shear with a relatively shallow gravity wind and the
gradient wind just above the surface. Another factor
which may cause inaccuracies in predicting a trajectory
is the fact that half-hourly averaged wind data were
used in the wind-field interpolations, while the area
generally had continuously changing wind-field patterns
during the stable periods. Under the atmospheric
conditions encountered during this series of tracer
experiments a significant number of plume-trajectory
changes occurred in the time period of a few hours.
Thus, in nearly all the runs (under both stable and
unstable conditions) the tracer was detected during
periods ranging from five to fifteen hours at samplers
covering an arc between 80° and 180°.

At the distances at which samples were taken during
stable atmospheric conditions, it may appear that any
improvement achieved by using Subroutine 2 is practically
neutralised by the inaccuracy in determining plume
trajectory. The integral $\frac{1}{B} \int_{0}^{B} x dy$ gives some idea of
the subroutine which can be used to achieve the most
accurate results under these conditions. Subroutine 2,
utilising the stability length (L), generally seems to
be the best choice, as it calculated the best estimates
for $\sigma_z$ (see below). Subroutine 3, on the other hand,
with only one "stable" category, fared the worst, due to the lower $a_y$ values calculated by this subroutine in stable conditions. Subroutine 3 normally produced the highest ground concentration values, as well as the lowest (the latter seen only a few times (see Fig. 3-5) as this normally occurred when all three subroutines gave values below $0.1 \times 10^{-8}$ kg.m$^{-3}$). Subroutine 1 gave the best results during neutral to unstable conditions. The difference between the results given by the three subroutines may not be significant enough to warrant the use of Subroutine 2, bearing in mind that it is more expensive in terms of computer time. Thus, the CPU time on an IBM-370, using Subroutines 1 and 3 for a run lasting 17 h, is approximately 8 min, whereas using Subroutine 2 it is approximately 15 min.

There could be circumstances in which significantly better results might be obtained when using Monin-Obukhov length $L$, rather than the other approaches, for example when calculating air concentrations after short-distance plume travel and/or higher release height, as well as in areas where relatively strong positive lapse rates occur. In one example during run 1976-G, for a certain sampler 5400 m from the release point, during a period with a lapse rate of $+10.5 \text{ K}(100 \text{ m})^{-1}$, the $\sigma_z$ was 12 m when using Subroutine 2 while with Subroutine 1 it was 33 m and with Subroutine 3 27 m. These values are significant, owing to the release height of 25 m (with a $\sigma_z$ of 12 m, a smaller concentration would be predicted at ground level than with a $\sigma_z$ of 27 m). The average ground-level concentrations during this quarter-hour period for this sampling position and these three subroutines (2, 1 and 3) were $1.14, 3.85$ and $3.93 \times 10^{-6}$ kg.m$^{-3}$ respectively. As can be seen from the results, Subroutine 2 fared the best
during this run. Also, illustrating the effect of distance from the release point, during run 1975-G period 1, when Subroutine 1 gave concentration values at the longer distances (> 4 500 m) of less than twice the values given by Subroutine 2, the values at position 212 (x = 3 500 m) were 103, 27.9 and 97.2 x 10^-8 for Subroutines 1, 2 and 3 respectively, while the experimental value was 21.0 x 10^-8 kg.m^-3. Similar examples emerged during the other runs for positions 107 and 111 (not all the results are given in the figures).

From these results it may appear to be well-founded, when developing a dispersion model for use in a specific location, to use parts of different suitable turbulence typing schemes for concentration predictions in the various stability types. Thus, use of the Monin-Obukhov stability length to calculate σ_z for stable atmospheric conditions may be better than simpler methods, for example, for cases where short-period releases may be important and air concentrations of effluent at short distances from the release point are required. A scheme such as that by Briggs (Subroutine 1) can be used for less stable conditions. This scheme is cheaper in computer time and in this set of tracer runs gave better results.

In order to minimise computer time, the surface roughness and stability length were not used rigorously in Subroutine 2; significant errors may have arisen through taking average values for z_0 over heterogeneous terrain when the concentration at a specific sampler was calculated (Peterson, 1971). Another potential source of inaccuracy, as discussed earlier, was the use of an "average" value for the temperature profile, while
in fact the plume might have been released in stable conditions in the direction of samplers in neutral to slightly unstable conditions. This point also arises in Section 3.2.

3.1.6 Differences in the Observed Surface Concentration Results for the Two Tracers In$_2$O$_3$ and ZnS.CdS

3.1.6.1 Introduction

In this series of atmospheric dispersion experiments where the two tracers, viz. submicron-sized In$_2$O$_3$ (mass-median diameter 0.07 μm), and ZnS.CdS (count-median diameter ~ 4 μm), had been released simultaneously and at fairly constant rates, relatively large differences were obtained in the dilution factors (normalised concentrations) for the two tracers. The possible reasons for this discrepancy were investigated.

The various possible sources of experimental errors and the error margins of the contributing factors were investigated, and a study was undertaken of anisokinetic effects on sampling and the effect of deposition and relative plume heights on the representativeness of samples.

3.1.6.2 Experimental results

The results obtained are given in Figs. 3-8 and 3-9. Only those results were considered in which the total indium mass on a filter exceeded 0.4 ng, as the indium mass on filter blanks was of the order of 0.001 to 0.2 ng, due to contamination at some stage of sample handling. The samples taken at 1000 m and nearer (Fig. 3-8) were taken near the plume axis and under neutral to unstable atmospheric conditions, while most
WEATHER CONDITION:
- STABLE
- NEUTRAL TO UNSTABLE
- WIND SPEED > 3 m.s⁻¹

**Fig. 3-8.**
Comparison of the dilution factors of the two tracers In₂O₃ and ZnS CadS over relatively flat, obstruction-free terrain.

**Fig. 3-9.**
Comparison of the dilution factors of the two tracers In₂O₃ and ZnS CadS over relatively uneven, bushy terrain.
of the other samples were obtained in stable or near-stable conditions.

As deposition may significantly influence the observations, the samples were divided into two classes, viz. those where the plume travelled mostly over flat terrain with little or no vegetation (Fig. 3-8), and those where vegetation may play a significant role in deposition (long grass, shrubbery, coastal bush and intermittent clumps of trees) (Fig. 3-9). The dilution factor \( K \) in the figures is

\[
\frac{\text{concentration in } \text{g.m}^{-3} \text{ or } \text{particles.m}^{-3}}{\text{release rate in } \text{g.s}^{-1} \text{ or } \text{particles.s}^{-1}}
\]

The coefficient of correlation for the In to ZnS.CdS dilution factor ratios in Fig. 3-8 (excluding those taken at 1 km and nearer) is calculated to be \( \pm 0.07 \), which has very little significance for statistical purposes (e.g. for investigating any tendencies in plume behaviour with distance). The average In/ZnS.CdS ratio is found to be 1.03 when the single high value is omitted, with a standard deviation of 0.56, while a straight-line least-squares fit has the equation

\[
y = 0.90 + 0.025x
\]

The average In/ZnS.CdS ratio over the densely vegetated terrain (Fig. 3-9) is about 5. The results in Fig. 3-9 will not be considered further because the effects of all other factors influencing the differences in the In and ZnS.CdS results have been swamped by the deposition effects.

3.1.6.3 Discussion

Statistical and random errors
The various errors in the experimental work which might have had an effect on results obtained for the ZnS.CdS tracer are the following (Niemeyer and McCormick, 1967):

(i) Statistical/analytical error - < 10 % if more than 100 particles are counted, and > 30 % if less than 10 particles are counted.

(ii) Sampling error due to, for example, anisokinetic effects - certain errors should be negligible as both tracers were simultaneously sampled by the same sampler.

(iii) Inaccuracy in release rate.

(iv) The stability of the ZnS.CdS may be influenced by UV radiation from the sun, and loss of tracer can be approximately 5 % per hour (travel time).

A number of stoppages occurred during the tracer experiments. On average, one or another of the release mechanisms (normally the ZnS.CdS one) would stop once during a 12 h period for 5 to 15 min. When it took longer than 10 min to start again, the other tracer generator was also stopped. An investigation of the influence of stoppage on the magnitude of the In$_2$O$_3$ to ZnS.CdS ratio during such a period did not show any significant difference.

An important source of error may be in tracer losses due to filter handling. Although tests have shown that the particles of both tracers are not easily removed by rough handling or relatively high wind speeds (membrane filters with tracer material were subjected to shocks, rubbing actions and strong air flows to assess loss of the tracer from the filters), loss may depend on the amount of dust and other particulates on a filter.
As only samples with at least 50-100 ZnS.CdS particles were considered, the statistical/analytical error could be of the order of 10-15 % if a loss of 5-10 % due to deposition is included. The error in the analytical indium determination could be 5-10 %. The error in the release rates for each tracer was also of the order of 5 %. Thus one could expect a standard deviation in the error of approximately 20 % when comparing the results of the two tracers. This figure (20 %) is too low to explain the 56 % obtained in the standard deviation of the In:ZnS.CdS ratios over flat terrain.

Sources of systematic variance

Anisokinetic sampling effects

As the sampling speed and sampler orientation were not regulated during the experiments an investigation was made into the effect that this could have had on the representativeness of samples. According to one source in the literature (Watson, 1954), a sampler at isokinetic flow with an angle of 90° between the inlet tube and the wind direction will give a value of approximately 30 % too low for particles with a 4 μm diameter, and a value of approximately 50 % if the angle is 180°. On the other hand, if the sampling tube faces directly into the wind, and if the ratio of wind speed to inlet air speed is two, the obtained air concentration will be approximately 5 % too high for 4 μm particles. The ratio of wind speed to inlet air speed varied from 5 to 50 during experimental work, while the angle of the sampler inlet to wind direction was approximately 90°. This could therefore have a significant effect, especially on the larger ZnS.CdS particles.

A series of tests was done in the beginning of the first
series of dispersion experiments at Richards Bay. These tests comprised the simultaneous release at a constant rate of the two tracers at a height of 3.5 to 5 m from the same spot (approximately 500 mm apart), under neutral to slightly unstable weather conditions, and wind speeds of 1 to 5 m.s\(^{-1}\). Sampling was done at a height of 1.5 to 2 m above ground level at downwind distances 150 to 1 000 m from the release point. Samplers were kept in the plume axis. Simultaneous samples were collected with filters orientated at different angles to the wind direction, and with linear sampling speeds varying between 0.05 and 0.15 m.s\(^{-1}\). Sampling periods varied from 0.5 to 1 h for a single set of filters.

The sampling heads consisted of a plastic filter-holder with a 47 mm diameter membrane filter (0.45 \(\mu\)m pore size), as shown in Fig. 3-10.

The results are given in Tables 3-3 and 3-4, and also in Fig. 3-8. (Some of the samples are given in the latter figure, e.g. those at the distances of 250 m and 1 000 m.) Note that the experimental error in these tests is decreased by having large samples (1 000–10 000 particles per filter in general). Unexpectedly, orientation seems to become a problem only at angles larger than 90° (180° here). The relatively small error at 90° may be due to the aerodynamic shape of the filter-holder. (See Fig. 3-10.)

It should further be noted (Table 3-4) that the In:ZnS.CdS ratios (excluding samples taken with the filter-holder at a 180° orientation and those taken at 1 000 m where the samplers were not continuously under the plume centreline) have a standard deviation of 2-11 %, which is more or less as expected when taking all the random errors into consideration (see above). The generally higher ZnS.CdS
Table 3-3. Effect of sampler orientation and sampling speed on the collection of ZnS, CdS and In$_2$O$_3$ particles (at wind speeds 1-5 m.s$^{-1}$, sampling distances 150-250 m)

<table>
<thead>
<tr>
<th>Sampler orientation and sampling speed relative to a standard orientation and speed</th>
<th>No. of samples taken</th>
<th>Sampler yields, relative to standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$ - slow (0.04 m.s$^{-1}$)</td>
<td>4 of each (&quot;slow&quot; and &quot;fast&quot; respectively)</td>
<td>In$_2$O$_3$ ($\sigma$)</td>
</tr>
<tr>
<td>$0^\circ$ - fast (0.16 m.s$^{-1}$)</td>
<td></td>
<td>0.96 (2.6 %)</td>
</tr>
<tr>
<td>$90^\circ$ (both 0.16 m.s$^{-1}$)</td>
<td>5 of each</td>
<td></td>
</tr>
<tr>
<td>$180^\circ$ (both 0.16 m.s$^{-1}$)</td>
<td>4 of each</td>
<td></td>
</tr>
</tbody>
</table>

* Standard deviation

Table 3-4. Comparison of dilution factors for In$_2$O$_3$ relative to ZnS, CdS (sampling speeds were all of the order of 0.15 m/s$^{-1}$)

<table>
<thead>
<tr>
<th>Distance of samplers from point of release (m)</th>
<th>Wind speed (m.s$^{-1}$)</th>
<th>Re=lease height (m)</th>
<th>Average In$_2$O$_3$/ZnS, CdS normalised concentration ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sampler orientation $0^\circ$</td>
</tr>
<tr>
<td>150</td>
<td>4-5</td>
<td>3,5</td>
<td>0,78</td>
</tr>
<tr>
<td>250</td>
<td>1-4</td>
<td>5</td>
<td>0,90</td>
</tr>
<tr>
<td>1 000</td>
<td>1-2</td>
<td>3,5</td>
<td>0,77</td>
</tr>
</tbody>
</table>
Fig. 3-7.
Comparison of predicted and measured mean concentrations for runs in unstable atmospheric conditions.

Fig. 3-10.
Air sampler filter-holder.
normalised concentrations at 1000 m may be due to a marked lowering of this plume due to the higher gravitational settling velocity of these particles.

These results show that anisokinetic effects played a minor role in causing the discrepancy between the In and ZnS.CdS results.

Effective release height

Although the release apparatuses of the two tracers were at the same height, 25 m above ground level, an important factor which might have resulted in a difference in effective release height is buoyancy. The In$_2$O$_3$ is generated in a flame with a temperature of 1000°C. As the speed of exit of the plume from this generator was visibly low, momentum rise may be excluded from the calculation.

One can use the equations by Briggs (1970) to calculate the distance from the source of maximum plume rise ($x_3$) and the maximum rise ($H(x)$), respectively,

$$x_3 = \frac{\pi u s^{-1}}{s}, \text{ and}$$

$$H(x) = 2.9 \left(\frac{F}{us}\right)^{1/3}$$

where $u$ is the wind speed (m.s$^{-1}$), $s$ a stability parameter

$$s = \frac{g}{T_0} \cdot \frac{\partial B}{\partial z}$$

and $F$ the buoyancy flux (m$^4$.s$^{-3}$).

For conditions where $T(z = 24 \text{ m}) - T(z = 3 \text{ m})$ varies from $0^\circ \text{C}$ to $+2^\circ \text{C}$, $u = 1-2 \text{ m.s}^{-1}$, $x_3$ is found to vary from 5 to 20 m, and $H(x)$ from 1 to 3 m.
For a release height of 25 m this difference in effective release heights may have a significant effect on concentration differences measured between the two tracers in stable conditions. Thus, one could expect lower values for the In$_2$O$_3$ tracer at shorter distances, as were found. (See Table 3-4.) The differences in the values when the concentrations of the two tracers are compared are not as marked in the results given in Table 3-4 as they are in the results in Fig. 3-8, as these runs were performed in a neutral to unstable atmosphere where the release height varied from 3.5 to 5 m and sampling height from 1.5 to 2 m. An important factor in the long-distance runs under stable conditions is the low vertical spread of the plumes, coupled with the relatively high release height.

Deposition

The effect of gravitational settling and dry deposition might have been an important factor in depleting the one tracer relative to the other. Wet deposition did not play a role during the tracer runs, but mist might have caused particle nucleation and thus higher fallout rates in certain areas for some of the runs.

Due to the flatness of the terrain (samples in Fig. 3-8), the lack of vegetation and the fact that highly stable conditions were not obtained over the bay (where samples are marked "stable" in Fig. 3-8 it refers to the atmospheric conditions at the release point), one could expect a relatively small (< 30 %) reduction in the ZnS.CdS particle concentration at ground level. (See the results for samplers S and R in Table 3-5.) This effect should in any case only reduce the latter particle type relative to the In$_2$O$_3$, and not vice versa.
The effect of deposition on the ZnS.CdS plume is much more visible where the plume moves over areas with denser vegetation (Fig. 3-9).

Although a larger proportion of ZnS.CdS is lost relative to the In tracer than is apparent in Fig. 3-8, due to dry deposition, the plume axis of the ZnS.CdS is lower than that of the other tracer and this partly compensates or overcompensates for this (deposition) effect.
Coupled with the lowering of the ZnS.CdS plume axis of about 2-3 m by gravitational settling (sedimentation velocity approximately $1.5 \times 10^{-3}$ m.s$^{-1}$), is the increased effective release height of the In aerosol caused by buoyancy.

Peak-to-mean concentration ratios

If one considers the plumes of the two tracers with their axes at different heights, one may expect that, especially at distances where the plumes are still not well-mixed down to ground level, the plumes would give different concentration values at a point on the ground. The shorter the distance between such a point and the release point, and the smaller the vertical diffusion, the bigger the difference between the two concentration values. The relative concentration values may fluctuate at this point with the tracers giving peak values at different times. This effect may have an influence on the relative values of the ground-level air concentrations of the two plumes.

From various sources in the literature, experimental results on atmospheric dispersion work show that, even at longer distances and with relatively long sampling times, high local concentration peaks at certain samplers
relative to those at nearby sampling points can be expected to be observed. Thus van der Hoven (1976) found for one-hour measurements under stable weather conditions that with a one-kilometre sampling arc "numerous spikelike peaks are determined by three adjacent samplers .... often [the concentration at a sampler is] about a factor of 10 higher than the measurements on either side ...." It has been found by Gifford (1960) (for an elevated source) and Hinds (1969) that peak-to-mean (P/M) concentration ratios may be between 10 : 1 and 50 : 1 if the ratio of total sampling time (T) to the smoothing interval over which the peak concentration was observed (t) is 200 : 1. Furthermore, Hinds (1969) found that this P/M ratio depended on cross-wind distance from the plume centre-line; thus, for $0 < y/\sigma_y < 0.7$ and a T/t ratio of 20, P/M was found to be ~ 4, while for $2.1 < y/\sigma_y < 2.8$ and the same T/t ratio, P/M was ~ 20.

This description was given to illustrate how the ground-level air concentration of a plume may fluctuate with time, and how the horizontal concentration distribution normal to the plume axis may differ from a true normal distribution. The differences in the concentration results for the two tracers discussed here, may seem to be partly due to the deposition velocity difference and relative plume heights. Although one can expect the size of the larger ZnS.CdS particles to be small enough to follow the smaller eddy movements of the air and one can expect similar travel times for the particles of the two tracers, differences in the heights of the centre-lines of the two tracer plumes may have an effect on the times of occurrence of peak concentrations. This effect may be small on the plume axis, especially at the release height, but with the large
variations in $y/\sigma_y$ values possible at air samplers at ground level, large peak-to-mean ratios for both plumes, but at different time-scales, may be possible. This effect may be enhanced under stable conditions with a strongly meandering plume and where $\sigma_y$ and $\sigma_z$ are both relatively small, and may thus especially influence positions near the release point under such atmospheric conditions. The relatively weaker correspondence between concentration values for the two tracers 2-4 km from the soni (Fig. 3-8) when compared to values obtained at longer distances, may be indicative of this factor.

3.1.6.4 Conclusions

From these experiments and the comparison between concentration results for the two tracers, it may seem as if the differences in the In$_2$O$_3$ and ZnS.CdS results may be due mainly to the particle-size difference (and thus deposition) and the initial buoyancy of the In aerosol plume; and that experimental sources of error and anisokinetic effects play a minor role. A difference in height between the centre-lines of the two plumes is established due to the initial buoyancy of the hot In$_2$O$_3$ plume and the downward movement of the heavier ZnS.CdS particles causing this plume to "bend down". Super-imposed on these effects is the depletion of the plumes, at different rates, by dry deposition at ground level, and the small $\sigma_z$ relative to release height values.

As a result, the ZnS.CdS and In$_2$O$_3$ particles will come under the influence of different wind eddies, and thus generate peak concentrations at different times at a fixed point on the ground.

Dry deposition seems to be the prime factor in causing
the discrepancy between the concentrations of the two tracers where the plumes have been transported over bushy terrain, over-shadowing all other factors.

Observations bore no clear relationship to wind speed.

Although these conclusions may be uncertain to some extent, the results show that care is necessary in evaluating the results of atmospheric tracer studies, and that effective release height and the "real" height of the plume axis may be important parameters for consideration with an elevated release, especially during stable atmospheric conditions.

3.2 DEVELOPMENT OF A DEPOSITION/PLUME DEPLETION MODEL

3.2.1 Introduction

The ground-level air-concentration results from a series of atmospheric dispersion studies where the two tracers - In\textsubscript{2}O, particles with a mass-median diameter (MMD) of 0.07 μm and a count-median diameter (CMD) of 0.02 μm and ZnS.CdS with a CMD of 4 μm - were released simultaneously, indicated that the concentration of the tracer with the higher deposition velocity became markedly reduced relative to that of the other tracer, over relatively short distances (1-5 km). This effect did not seem marked over flat terrain with sparse or no vegetation, but became significant where the vegetation was denser.

Mass- and count-median diameters were used for the two types of tracer respectively, as concentration of the first type is quantitatively determined by determining its total mass on a filter, and the concentration of the
second type by the counting of individual particles on a filter. A measured loss, of, for example, 50 % in the latter particle-type aerosol air concentration will thus mean that 50 % fewer particles will be counted, while a measured loss of 50 % in the In$_2$O particle concentration will mean a 50 % loss by weight (although this may mean a reduction in the total number of particles of perhaps 90 %).

Experimental results were compared with the results from a two-dimensional mathematical dispersion model (the numerical solution and computer program were devised by J D Neethling), taking into account (in the model) removal in that part of the plume in contact with obstacles, and allowing adjustment of deposition velocities and other variables with distance travelled by the plume. In this model the mixing layer is divided into a set of horizontal layers, each of which has part of its total mass of tracer continuously moved into neighbouring layers by diffusion. The model used here only accounts for scavenging in those layers where removal of tracer actually takes place - therefore a surface-depletion model. Since lateral diffusion is not incorporated in the model, only vertical concentration profiles are provided by the program. The model is based on the solution of a set of differential equations based on K-theory, where diffusivity is determined by means of stability length theory (Section 1.2.1.2), and with a removal term to take deposition into account.

A surface-depletion model is proposed here which uses the results of a dual-tracer technique to determine the effects of surface type on deposition and plume depletion. As mentioned before (Section 1.2.2.1), a number of surface-
depletion models had been developed by other workers such as Draxler and Elliott (1977), Ermak (1977), Horst (1977) and Scriven and Fisher (1975). These were all for use on a larger scale and were not taking local surface changes into account. The model presented here takes such changes into account and dry deposition can be simulated in more than one layer in the vertical. Furthermore, the estimated deposition rate over a certain surface type can be adjusted (by an iterative procedure, if necessary) by using the results from a dual-tracer technique. The model is especially applicable to the evaluation of surface effects on deposition and plume depletion on a meso-scale.

3.2.2 The Model

3.2.2.1 The profiles of relative concentration

A computer program was devised which could simulate a plume for which the concentration in the y-direction is integrated, thus resolving the plume into two dimensions (x and z). The concentration profile in the z-direction (vertical) was then divided into sections of equal thickness, the optimum value of which was determined by factors discussed later, up to a chosen height. In the model, removal of material from a layer was treated in such a way that the process initially affects only the relevant layer and its immediate neighbours. As lateral diffusion is not dependent on absolute concentration and is assumed to be the same for both tracers, relative values of concentration (or concentration ratios) are independent of y-diffusion, and the depletion rate can be considered equal over the total width of the plume.

The rate of movement of plume material from one layer to adjacent ones, and vice versa, is determined by K-theory,
with $K_z$ dependent on height. A set of differential equations was constructed to govern diffusion, with boundaries at ground level and at a specified upper height (which was taken as 500 m in this study; the upper inversion lid was actually much higher, but this was seen as unimportant as the total distances involved were always less than 7 km, and runs were performed normally under stable to neutral conditions). The depletion rates at a specific distance interval were equal for all layers specified (in which deposition took place), and were adjusted depending on the terrain over which the plume moved. To determine depletion of the total plume and the reduction of the concentration at specific measuring heights above ground level, the concentration profiles of plume material are computed after specified travel times; comparison of the concentration values in these profiles with those of a simultaneously run plume without depletion will give the desired depletion ratios. The total content of material in the plume traversing a point of reference per unit time is determined by summation of all the concentration values in the profile, multiplied by the wind speed and layer thickness.

The initial concentration profile used in the main program (at a short distance from the source, before any significant reduction in total plume material could have taken place - in this study after one-second plume travel) is calculated for each layer height using Eq. 3-1:

$$
\chi(z,t) = \frac{Q}{2\sqrt{\pi K_z t} \Upsilon(z_s)} \left[ \exp\left(\frac{-(z-z_s)^2}{4K_z t}\right) + \exp\left(\frac{-(z+z_s)^2}{4K_z t}\right) \right]
$$

... (3-1)
taking $Q = 1$. Values for $K_z$ at each layer height are calculated using $L$ (Monin-Obukhov) and $u_*$ values determined from average values of $\bar{u}$, $T_0$, $6^9/\delta z$ and $z_0$, one value of each for the duration of the run and for the whole distance. The trajectory from the source to the sampler is divided into distinct terrains over which specific deposition velocities for each tracer hold.

After the initial "seeding" of the plume, the main program continues to do the profile calculations at the specified time intervals, taking deposition into account.

### 3.2.2.2 Determination of deposition velocity

Various errors are inherent in the model and experimental procedures involved, e.g. analytical and statistical errors; long sampling times which may cause errors due to the averaging of a number of meteorological parameters; errors in the averaging of $z_0$; residence time of the tracer when moving through vegetation is not considered; inaccurate values available for wind speed close to the surface, etc. Therefore a number of smaller approximations may be tolerated.

Sophisticated relationships containing complex variables exist for the determination of deposition velocities. Markee (1967a) has established an empirical relationship to calculate $v_d$ for iodine vapour, where this is directly proportional to vegetation density and the friction velocity squared and inversely proportional to wind speed. But even this relationship may not hold under all circumstances, such as where the vegetation becomes very dense. Heinemann et al (1975) found the deposition velocity of elemental iodine to depend on biological and meteorological parameters, amongst others, and they express $v_d$ by a semi-empirical equation
containing the dry weight of vegetation per unit area, the friction velocity, relative humidity and a biological factor reflecting certain qualities of the vegetation.

Sehmel and Schwendiman (1971) found that \( v_d \) as a first approximation can be correlated to friction velocity. Clough (1975) found, in deposition experiments with various particle types (particle diameter ranging from 0.08 \( \mu \)m to 30 \( \mu \)m), a linear relationship between \( v_d \) and \( u^* \) on a flat (horizontal) grass surface. This result is confirmed by Chamberlain (1967) for 0.08 and 1 \( \mu \)m particles. Clough (1975) found a linear relationship between \( v_d \) and \( u^* \) for the 0.08 to 30 \( \mu \)m particles, using moss bags, the scavenging surfaces of which were set up vertically. After an extensive literature survey on this subject, McMahon and Denison (1979) came to more or less the same conclusion, viz. that "deposition velocity is approximately a linear function of wind speed and friction velocity".

The re-entrainment (after deposition) of the smaller particles was investigated by Sehmel and Schwendiman (1971) who observed no re-entrainment from grass surfaces for particles smaller than 28 \( \mu \)m in diameter at wind speeds up to 13 m.s\(^{-1}\) (30 mph). Clough (1975) did not experience any loss of particles (0.08 - 30 \( \mu \)m) during 15 h on grass and moss surfaces at a wind speed of 7 m.s\(^{-1}\). Re-entrainment is therefore not considered in further calculations.

From the data by Clough (1975) and Sehmel and Schwendiman (1971), and assuming the linear relationship between \( u^* \) (and \( u \)) and \( v_d \), the following relationships are postulated for the tracers \( \text{In}_2\text{O}_3 \) and \( \text{ZnS.CdS} \) used in this
study:

In$_2$O$_3$, tracer

- flat terrain: $v_d = 0.0008u_*$
- grassy terrain: $v_d = 0.002u_*$
- trees and other "vertical" obstacles: $v_d = 0.0012u + 0.0001$

ZnS.CdS tracer

- flat terrain: $v_d = 0.013u_*$
- grassy terrain: $v_d = 0.05u_*$
- trees and other "vertical" obstacles: $v_d = 0.05\bar{u} + 0.002$

The deposition rate is the fraction of tracer deposited in one layer per second. For "flat" and "grassy" terrain the deposition rate is given by $v_d/\Delta z$ for the horizontal layers of concern, where $\Delta z$ is the layer thickness. For layers having "vertical" obstacles the total area onto which deposition can take place has to be considered. As a first approximation a tree is considered as a cylindrical object where only the total outer surface is effective in tracer scavenging. The deposition rate ($r_z$) then becomes

$$v_d \cdot \frac{[\text{average area in layer effective in scavenging}]}{\Delta z \cdot [\text{above a horizontal surface of 1 m}^2]}$$

or, $v_d/\Delta z \cdot A$, where $A$ is unity for a "horizontal" surface without large vertical scavenging obstacles like trees. $u_*$ is obtained from

$$\bar{u}/u_* = \frac{1}{k} \ln \left( \frac{z}{z_o} \right)$$
where a different value of $z_o'$ (roughness length) is used at each new surface type traversed by the plume.

The use of the total outer surface areas of trees in the deposition rate calculations may result in large errors. However, because of the simplicity of this approach it was preferred to the use of vegetation density as a parameter in the calculation of deposition rate.

3.2.2.3 The numerical solution of the diffusion equation

The theory is discussed in detail in Appendix C.

The following basic equation is used, considering diffusion as a function of time, and only in the vertical:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left( K_z \frac{\partial c}{\partial z} \right) - r_z c$$

$$c = c(z,t) \quad \ldots \ldots \quad (1)$$

(where $c$ is the concentration, $r_z$ the depletion rate and $K_z$ the mass diffusivity), with the following boundary values:

$$c_z(0,t) = c_z(Z_T,t) = 0.$$ 

$$c(z,0) = f(z).$$ 

$$\ldots \ldots \quad (3)$$

Eq. 2 expresses reflection on the ground ($z = 0$) and at an upper layer $z = Z_T$. The initial plume concentration is given by:

A finite difference solution was carried out using a generalisation of Douglas' method (Mitchell, 1969).

The substitution
c(z,t) = \frac{v(z,t)}{h_k(z)}

transforms (1) into

\frac{\delta v}{\delta t} = K_z \frac{\delta^2 v}{\delta z^2} + \left[ \frac{1}{4} \left( \frac{K_z'}{K_z} \right)^2 - \frac{1}{2} K_z'' - \frac{1}{2} r_z \right] v, \quad \ldots \ldots \quad (1a)

with boundary conditions

K_z(0)v_z(0,t) - K_z'(0)v(0,t) = 0, \quad \ldots \ldots \quad (2a)

K_z(Z_T)v_z(Z_T,t) - K_z'(Z_T)v(Z_T,t) = 0,

and initial condition

v(z,0) = \sqrt{K_z(z)} \cdot f(z). \quad \ldots \ldots \quad (3a)

The discretisation of (1a) with respect to time was done in the usual way (Mitchell, 1969, p. 25), whereas for \( \frac{\delta^2}{\delta z^2} \) the high-order approximation (Mitchell, 1969, p. 26)

\[ \frac{\delta^2}{\delta z^2} \approx \frac{1}{(\Delta z)^2} \frac{\delta^2 v}{\delta z^2} \quad \ldots \ldots \ldots \ldots \quad (4) \]

was used. Since the customary handling of the boundary values leads to numerical instability (Mitchell, 1969, p. 44), a third-order Taylor polynomial was used to approximate (2a), the order being chosen to match (4) under the supposition that

\[ \frac{\Delta t}{(\Delta z)^2} \approx 1. \]

Thus, in discretised form:

\[ v(0 + \Delta z, t) \approx v(0, t) + \Delta z v_z(0, t) + \frac{1}{2} (\Delta z)^2 v_{zz}(0, t) + \]
\[ \frac{1}{6} (\Delta z)^3 v_{zzz}(0,t). \]

\( v_{zz} \) and \( v_{zzz} \) were eliminated from this using (1a) and its z-derivative, \( v_{tz} = v_{zt} \) being eliminated by the t-derivative of (2a), \( v_z \), by (2a). The usual Thomas algorithm was used in double precision to solve the tridiagonal system of equations that arose.

No investigation was done into an optimum stepsize (\( \Delta t \)). A value of one second was used throughout the study, and was dictated by computer time on the one hand (runs simulated used 3 to 15 min CPU time) and accuracy on the other. Accuracy was checked having the computer print out the total amount of tracer in the plume per unit time (if no deposition took place) at the end of the distance travelled by the simulated plume.

3.2.3 Experimental, Results and Discussion

The shorter-distance tracer runs (1976-A, 1976-H, 1976-I and 1976-J, see Table 3-5) were especially set up for these dual-tracer deposition experiments. The other samples were obtained during ordinary dispersion study runs.

Plumes were assumed to travel in straight lines from the source to the samplers. The types of terrain over which experiments were conducted are shown diagrammatically in Figs. 3-11 (a) to (i). The terrain types and the areas covered by them were obtained from aerial maps and on-location inspection. Where terrain types traversed by the plume were not homogeneous the terrain type of most consequence is indicated. The roughness lengths (\( z_p \)) of terrains were selected from examples given by Mulholland et al (1977). See Table 1-5.
Table 3-5: Comparison of dual-tracer concentration results with surface-depletion model results

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Distance (m)</th>
<th>Travel time (s)</th>
<th>$u_0$ (general) (m/s)</th>
<th>$u_1$ (m/s)</th>
<th>$\tau_{o}$ (K)</th>
<th>$L$ (m)</th>
<th>$u_2$ (m/s)</th>
<th>% of In tracer left at 1 m</th>
<th>% of In tracer left in total</th>
<th>% of ZnS tracer left at 1 m</th>
<th>% of ZnS tracer left in total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976-J</td>
<td>25</td>
<td>1 100</td>
<td>220</td>
<td>0.15</td>
<td>5.0</td>
<td>0.90</td>
<td>292</td>
<td>405</td>
<td>0.489</td>
<td>99</td>
<td>84</td>
</tr>
<tr>
<td>1976-I</td>
<td>4</td>
<td>200</td>
<td>40</td>
<td>0.2</td>
<td>5.0</td>
<td>1.9</td>
<td>295</td>
<td>212</td>
<td>0.535</td>
<td>93</td>
<td>97</td>
</tr>
<tr>
<td>1976-A</td>
<td>25</td>
<td>2 800</td>
<td>1 330</td>
<td>0.02</td>
<td>2.1</td>
<td>2.9</td>
<td>285</td>
<td>20.4</td>
<td>0.9563</td>
<td>97</td>
<td>100</td>
</tr>
<tr>
<td>1976-H</td>
<td>4</td>
<td>800</td>
<td>80</td>
<td>0.2</td>
<td>10</td>
<td>0.048</td>
<td>293</td>
<td>1.02</td>
<td>95</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Sampler K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-1</td>
<td>25</td>
<td>4 800</td>
<td>2 400</td>
<td>0.3</td>
<td>2.0</td>
<td>1.5</td>
<td>288</td>
<td>76.8</td>
<td>0.194</td>
<td>93</td>
<td>98</td>
</tr>
<tr>
<td>K-2</td>
<td>25</td>
<td>4 800</td>
<td>3 200</td>
<td>0.3</td>
<td>1.5</td>
<td>2.0</td>
<td>288</td>
<td>34.5</td>
<td>0.121</td>
<td>92</td>
<td>98</td>
</tr>
<tr>
<td>K-3</td>
<td>25</td>
<td>4 800</td>
<td>1 600</td>
<td>0.3</td>
<td>3.0</td>
<td>5.8</td>
<td>289</td>
<td>46.3</td>
<td>0.264</td>
<td>94</td>
<td>98</td>
</tr>
<tr>
<td>Sampler G</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G-1</td>
<td>25</td>
<td>4 200</td>
<td>560</td>
<td>0.02</td>
<td>7.5</td>
<td>0.048</td>
<td>289</td>
<td>9 360</td>
<td>0.481</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>G-2</td>
<td>25</td>
<td>4 200</td>
<td>3 500</td>
<td>0.02</td>
<td>1.2</td>
<td>8.1</td>
<td>285</td>
<td>3 05</td>
<td>0.0281</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Sampler L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-1</td>
<td>25</td>
<td>6 400</td>
<td>3 200</td>
<td>0.02</td>
<td>2.0</td>
<td>4.3</td>
<td>283</td>
<td>12.8</td>
<td>0.0787</td>
<td>97</td>
<td>99</td>
</tr>
<tr>
<td>L-2</td>
<td>25</td>
<td>3 800</td>
<td>1 000</td>
<td>0.4</td>
<td>3.8</td>
<td>11</td>
<td>288</td>
<td>46.4</td>
<td>0.357</td>
<td>96</td>
<td>98</td>
</tr>
</tbody>
</table>
Fig. 3-11(a). Calculated depletion at ground level of the tracers $\text{In}_2\text{O}_3$ and $\text{ZnS.CdS}$ for sample 1976 H.

Fig. 3-11(b). Calculated depletion at ground level of the tracers $\text{In}_2\text{O}_3$ and $\text{ZnS.CdS}$ for sample 1976 J.

Fig. 3-11(c). Calculated depletion at ground level of the tracers $\text{In}_2\text{O}_3$ and $\text{ZnS.CdS}$ for sample 1975 L.

Fig. 3-11(d). Calculated depletion at ground level of the tracers $\text{In}_2\text{O}_3$ and $\text{ZnS.CdS}$ for sample 1976 A.
Calculated depletion at ground level of the tracers In\(_2\)O\(_3\) and ZnS.CdS for sampling position K.
Fig. 3-11(f).
Calculated depletion at ground level of the tracers In$_2$O$_3$ and ZnS:CdS for sampling position S.

Fig. 3-11(g).
Calculated depletion at ground level of the tracers In$_2$O$_3$ and ZnS:CdS for sampling position R.
Fig. 3-11(a)
Calculated depletion at ground level of the tracers In_{2}O_{3} and ZnS: CdS for sampling position L.

Fig. 3-11(b)
Calculated depletion at ground level of the tracers In_{2}O_{3} and ZnS: CdS for sampling position G.
The heights of trees and bushes are indicated and the densities of trees in the plume trajectory were determined and used in the calculation of the depletion rate ($r_z$) in the 1 m layers specified (those layers from ground level and higher, affected by scavenging surfaces). In the figures the concentration of In and ZnS.CdS tracers in the plume calculated at 1 m above ground level is shown as a fraction of the concentration which would have existed had no removal of tracer occurred from the plume, and as a function of terrain type and travel time. The $r_z$-values given in the figures represent the depletion rates ($s^{-1}$) for each surface type in each 1 m layer of the plume subjected to depletion.

In columns 11 and 13 of Table 3-5 the calculated concentrations are given of In and ZnS.CdS respectively, at the sampling point at 1 m above ground level as a fraction of the concentration at 1 m with no removal. In columns 12 and 14 the calculated total mass is given of In and ZnS.CdS respectively, in the plume as a fraction of the total mass with no removal. The calculated ratios of ZnS.CdS to In concentration at 1 m appear in column 15 and the measured ratios of ZnS.CdS to In in column 16.

When one evaluates the results from deposition studies, the order of magnitude uncertainty in deposition velocity values should be kept in mind (Sehmel, 1980). An acceptable correspondence between calculated and experimental results was obtained under most conditions. The standard deviation for the In/ZnS.CdS ratios was found to be in the range of 50-60 % (Section 3.1.6). The three runs yielding the poorest results are 1976-I, L-1 and L-2. This can partly be explained
by referring to Figs. 3-11(b) and 3-11(i), which indicate the presence of relatively densely forested areas immediately in front of the sampling point. The depletion is extremely dependent on particle size, as is shown by the dramatic change in ZnS-CdS concentration over forested areas, and the magnitude can be expected to be very sensitive to the choice of individual parameters, such as tree density, which determine the scavenging area. The values of the parameters chosen for the model result in excessive depletion for this particular condition.

The uncertainty in the experimental values is illustrated by the cases where samples were taken in succession under more or less the same meteorological conditions and over the same terrain. The experimental ratio for sample 1976-J in Table 3-5 is the average of two values, viz. 21.3 and 19.9 %, and for sample 1976-I three values, viz. 38.8, 60.6 and 42.4 %. Note also the large differences between samples G-1 and G-2, and K-1 and K-2; both these sets of samples were taken under very similar meteorological conditions and over the same terrain.

To show the importance, when simulating deposition over a certain area, of incorporating all terrain types and scavenging to higher levels above the surface, where applicable, runs 1976-I, L-1, L-2 and K-3 were recalculated by not including the trees and simulating the terrain as "grass" only, using $z_0$ values as originally estimated for each terrain type. The ZnS-CdS to In ratios show dramatic increases to 92, 73, 85 and 72 % respectively, which are in excess of the experimental values.

Predicted results were found to be quite sensitive to the
values of the relevant input parameters. Thus, when sample G-2 was recalculated, but changing \( z_0 \) from 0.4 to 0.1 m, \( \bar{u} \) from 5.5 to 2.8 m s\(^{-1}\), \( \delta \theta/\delta z \) from 9.6 to 15.3 K(100 m\(^{-1}\)) and also, in the process, increasing the depletion rate by about 65%, the ZnS.CdS/In ratio at \( z = 1 \) m at the sampling point decreased from 0.40 to 0.022. When only \( \delta \theta/\delta z \) was changed to 15.3 K(100 m\(^{-1}\)), keeping the other variables the same, the ratio decreased to 0.37. When only the depletion rate was increased five-fold, the ratio decreased to 0.16. The relatively large number of uncertainties in the input values, such as variations in wind speed and \( \delta \theta/\delta z \) with distance from the release point and with time (long sampling times), and variations in depletion rate, may cause relatively large errors in the predictions.

The choice of tracers to be used in experimental work is a difficult one. Particulate tracers have a narrow size range suitable for this type of work, viz. approximately 0.05 to 5 \( \mu m \) diameter, for runs of distances of about 5 km and more. Particles outside this range may be markedly reduced by coagulation (Sheih, 1977) and gravitational settling for the smaller and the larger size ranges respectively. Naturally, suitable gases may also be used as tracers.

The layer thickness (\( \Delta z \)) of 1 m may be too large for calculations under stable atmospheric conditions and over flat terrain. Such conditions result in a sharp increase in concentration with height near the surface. But flat terrain was chiefly encountered only in the vicinity of the bay where atmospheric conditions were seldom more than "slightly" stable. On the other hand, where the plume traversed grassy terrain, the vegetation height varied from 0.3 to 1 m, causing the scavenging
surface to extend high into the first horizontal layer.

There are various shortcomings in using a dual-tracer technique for the evaluation of plume depletion with a surface-depletion model. Some important points are:

(i) Small differences in the ground-level concentration found for the respective tracers may be difficult to interpret in terms of plume depletion of the one relative to the other, due to the errors of a statistical and analytical nature in sampling and analyses.

(ii) Large differences in particle size may result in significant gravitational settling of part of the plume consisting of the larger particles under conditions of high stability and low wind speeds.

(iii) It is difficult to take into account effects such as chemical/physical changes during airborne transport of the tracer particles/molecules.

(iv) It is also difficult to take into account preferential depletion of a part of the plume due to the width of the size distribution of particulate tracers (Alps and Kühn, 1979) except if mono-disperse aerosols are used.

Particular concerns as regards the model simulation are:

(i) The complex variation of $\bar{u}$ and $K_z$ with height may reduce the accuracy in concentration and dispersion estimates in the vertical (Markee, 1967b).
(ii) A major problem is the estimation of the deposition rate of particles/gas molecules moving through forests. Individual trees can usually be ignored, while clumps of trees are treated by multiplying $v_d$ by a realistic value of $A$, taking tree height into account. The difficulty arises when trees are closely packed, as in forests. The vertical temperature (Fritschen and Edmonds, 1974) and wind profiles become distorted and wind speeds near the ground are difficult to calculate. It was found by Raynor (1967) that with a forest in the plume path, particles tended to penetrate the forest at tree trunk height or rise above the canopy, following the wind pattern (mentioned elsewhere).

The program discussed here gives only the percentages of the total plume material left over after specified distances of travel, and also the percentages of material left at certain relevant heights, but not surface contamination; to obtain the latter the lateral "spread-out" of the plume will have to be considered. As a first approximation one can determine surface contamination in the following two steps: (i) Determine the deposition rate expressed as the number of particles.s$^{-1}$m$^{-2}$ or kg.s$^{-1}$m$^{-2}$ (average ground-level air concentration $\bar{\chi}$ of the unmodified plume - i.e. the concentration at which lateral diffusion is ignored - multiplied by $v_d$ or $v_d\times A$) at specified distances of plume travel, and multiply this by the time taken by the plume to move over this surface to obtain "surface contamination" (in kg.m$^{-2}$ or number of particles.m$^{-2}$) by the unmodified plume ($W'$); (ii) calculate "real" ground level air-concentration values ($\bar{\chi}$) at the specified distances by including $\sigma_y$ in the Gaussian
diffusion equation. The ratio \( \frac{X}{X'} \) multiplied by \( W' \) gives the required surface-contamination value (kg.m\(^{-2}\) or number of particles.m\(^{-2}\)).

3.2.4 Conclusions

A comparison of the results of total tracer left in the plume with the fraction left at a height of 1 m above ground level, especially in a stable atmosphere, shows the inaccuracy in directly correlating concentration reduction at the surface with total plume depletion as is done by the source-depletion approach. Another important deduction is that more accurate estimates of the effect of dry deposition on air concentration near the surface can be obtained if surface-type changes are considered, and not only an "average" surface assumed.

Due regard should be taken of the possible sources of error when the model discussed here is used for the evaluation of surface contamination by, and plume depletion of, airborne contaminants in an area of concern, such as the vicinity of a nuclear reactor. This program can be adapted to do the calculations, and by an iterative process the deposition rates can be adjusted over the different types of terrain to get a meaningful correlation between calculated and experimental concentration ratios.

The A-values used in the deposition term for plume movement over surfaces covered with trees are based on estimates of the total surface area of the obstacles, i.e. total surface area per tree (regarding a tree as a cylindrical object with its whole outside surface effective in scavenging) multiplied by the number of trees, per unit surface area. From the results above it can be seen that the values of A are extremely
critical, and accurate values will be difficult to estimate for certain types of terrain, but they can be obtained iteratively.

A number of sampler arcs can be set up at various distances from the source (preferentially at the boundaries of terrain type changes) when using a dual-tracer technique to evaluate the deposition model. More meaningful results may be obtained when samplers are installed at more than one height and when the two tracers used have a larger difference in deposition velocities (one tracer could be non-depositing).

A set of tables and graphs can be constructed which gives plume depletion and surface contamination in the relevant sectors surrounding the source, classified according to the various meteorological conditions. On the other hand, once meaningful depletion rates for the various aerosols/gases of interest have been established by this approach, they can be used in a dispersion computer program incorporating a similar surface-depletion model for real-time analyses.

Various refinements can be made to the program described above, such as enabling the adjustment of the diffusivity profile with distance from the source, and with time.
PART 4

ATMOSPHERIC STUDIES IN THE KOEBERG-CAPE TOWN AREA

4.1 INTRODUCTION

Atmospheric studies were carried out by the Isotopes and Radiation Division of the Atomic Energy Board at Duynefontein, where the Koeberg Power Station is situated, under contract to the Electricity Supply Commission. The purpose was to determine safe radioactive releases to the atmosphere during normal operation of the nuclear reactors, and to determine the fate of accidental releases to the atmosphere.

A number of reports (Langenberg, 1970, 1972; Halliday and Venter, 1971; Basson and van As, 1976) on atmospheric movement in this area have been published by the Isotopes and Radiation Division in cooperation with the Chemical Engineering Department of the University of Natal and the Air Pollution Research Group of the CSIR. In the present study this work was expanded by using tracer experiments, (i) to investigate the role of complex and changing wind-field patterns in long-range (50 km) trajectories of released effluent, (ii) to measure dispersion under various meteorological conditions, and (iii) to formulate suitable mathematical and other methods for estimating the trajectory and dispersion during an accidental release to the atmosphere.

An important part of the study presented here is the tracer dispersion experiments conducted under various weather conditions and wind fields (viz. main gradient winds, land and sea breezes and conditions with fluctuating wind fields), and the comparison with simulated runs by means of a mathematical model.
The estimation of pollution levels during accidental releases by means of simple tables and graphs has disadvantages, and will be difficult to cope with under the following conditions:

(i) releases of effluent occurring for extended periods (e.g. up to 20 h or more), under changing weather conditions and wind directions, and transported over long distances;

(ii) meteorological and other relevant conditions (such as lapse rate, surface roughness, etc.) changing with distance such as where the plume moves for some distance over-land and then over the sea. Especially important here is the depth of the land and sea breezes and the change in depth when moving away from the coastline;

(iii) certain complex meteorological situations, such as wind directional shear, fumigation in the internal boundary layer, varying mixing depth, etc.;

(iv) cases where certain parameters, such as release rate, change with time.

As all the complicating factors may come into play, some model or approach has to be used that will incorporate these factors, and be able to sum the concentration values obtained over time periods of a few hours or even days. As such an approach may require time- and distance-dependent data on wind speed and direction, surface roughness, temperatures, etc., there is a need for computer calculations.

The effect of changes in effluent trajectories with
distance from the source may not be important enough to be included in estimates of monthly, seasonal or yearly dosage in the environment during normal reactor operation, and models based on straight-line trajectories may be usefully employed (van der Hoven, 1967).

A relatively simple numerical model for the estimation of plume trajectory and dispersion during short-term releases was adapted for use in this area. (See Appendix E.) Dispersion experiments were performed by releasing a tracer material continuously for a few hours at a time and collecting samples for air concentration measurements at distances between 1 and 30 km from the release point.

4.1.1 Meteorological Conditions

For a significant portion of the year, a stable stratification is experienced in the lower few hundred metres of the atmosphere along the west coast of South Africa from the Cape Peninsula northwards, due to the cold Benguela Current. The data from radiosonde soundings in Cape Town, conducted two to three times daily over a four-year period, have shown an annual surface inversion frequency at 01h30 of 50-60 % and at 13h30 of less than 5 % (Tyson et al, 1976). The average annual early-morning depth is 600-700 m and average annual strength of the order of 5°C, while the winter depth is 500-600 m and winter strength 6-7°C. During nights with low wind speeds and little insulation from clouds, the strength of this surface inversion may in places be enhanced by katabatic air movement. The land-breeze/gravity-wind layer was found to be of the order of 50 m deep at Koeberg, with a temperature increase from the surface to its apex of the order of 10°C.
Marked variability of wind and weather is common in this area, due partly to the interaction between the prevailing warm southeaster winds and cool westerlies. Superimposed on these systems and their interactions is the land-breeze sea-breeze cycle, where the latter winds may blow more or less at right angles to the gradient winds in the area under consideration. Due, inter alia, to the blocking effect of Table Mountain and the other mountain ranges in this area, as well as the localised effects of the land and sea breezes, a large degree of channelling and deflecting of winds occurs, with the effect that large deviations in wind directions expected from the prevalent synoptic systems can be observed. Thus, with the approach of a low-pressure system from the west, the wind directions at masts in the southern part of the region may be S to SE, while they may be N to NW in the north. If these gradient winds have low velocities, the western coastline may experience the sea breeze from the SW. These conditions may persist for periods of several hours. This is one type of situation which may be difficult to handle analytically during short-term releases from Koeberg. Other complex wind-field situations occur, such as when the SW sea breeze and NW or SE gradient winds more or less balance out, resulting in an observed wind at Koeberg blowing from the NW or SE for a certain period and suddenly switching to SW, and vice versa. The other complex situation is the land breeze (to be discussed later).

The dominant meso-meteorological factors influencing the study of atmospheric dispersion around Koeberg arise from the abovementioned weather conditions. However, wind-flow characteristics in the immediate vicinity of the reactor site can be quite different from those more than 10 km away because, inter alia,
(a) the influence of sea and land breezes normally diminishes with distance from the coastline. The land breeze/gravity wind originates partly in the topographically higher regions to the E and NE of Koeberg (a few tens of kilometres away) and flows in a W to SW direction, thus influencing the area immediately to the SW and E-NE of Koeberg, but not normally Cape Town and its suburbs directly; and

(b) the Blouberg Ridge, less than 10 km away to the S to SE of Koeberg (see Fig. 4-1), represents a dividing line between the typical Cape Flats climate and that of the southern west coast (Langenberg, 1970). While the vicinity of Cape Town is subject to the influence of high mountains and two sea currents with differing temperatures, the situation is less complex at Koeberg. Furthermore, this ridge creates a wind shelter in strong winds, particularly those from the south.

The land breeze/gravity wind requires special attention. Its temperature increment may be of the order of 1-10°C per 30 m at Koeberg and it may penetrate only a few kilometres to the SW over the sea. A major problem in estimating the trajectory of pollutants from Koeberg is that the breeze depth may vary from < 10 to 150 m, and, especially when it is shallow, directional wind shear in the lower few tens of metres may be very marked. Another important phenomenon observed during the tracer studies is the movement of aerosols from Koeberg for some distance out over the sea under the influence of the land breeze, after which they may be returned to the land, resulting in relatively high
Fig. 4.1.
Koeberg-Cape Town area: general lay-out.
concentrations at ground level.

4.1.2 Complicating Phenomena in the Study

Certain phenomena which influence this study in general, and aspects of the numerical modelling of dispersion in particular, are discussed below.

4.1.2.1 Fumigation

Fumigation occurs when an inversion layer (which may contain high concentrations of airborne effluent) is "broken up" from ground level due to heating of the surface and the subsequent convection of air. This can result in increased ground-level concentrations of the effluent trapped between the ground and the remainder (elevated portion) of the inversion layer.

This phenomenon is of particular importance in the land-sea interface with on-shore or off-shore air flow. With air flow over a region where the surface boundary conditions change, the effect at the boundary is propagated upward, causing a change in the air mass to a certain depth. This change in the boundary conditions may be a change in surface roughness and/or temperature. This internal boundary layer (IBL) at coastal sites requires investigation (as yet not undertaken) because of its influence on dispersion, and the need for measuring important weather variables at relevant heights above the surface. Such a study will be especially important with regard to on-shore air movement, and will involve distances of some several hundred metres or even several kilometres from the coastline. After this distance, more or less complete adjustment to the new surface takes place. Two situations of primary importance in on-shore flows are (i) where the sea is colder than the land (daytime), causing an elevated inversion (and fumigation below) where the cold air moves over the hot air, starting at the coastline and increasing in depth inland to some
maximum height, and (ii) where the sea is warmer than the land (nighttime), causing an unstable layer above the ground-based inversion. In both situations air moves from a smooth to a rough surface.

This phenomenon (IBL) and resultant ground concentrations can be treated mathematically (Bierly and Hewson, 1962; Wang, 1977; Misra, 1980), and the distance from the coastline vs. height of fumigation can be calculated by means of relatively simple numerical relationships such as those proposed by Elliott (1958), Peterson (1969), Peters (1975) and van der Hoven (1967), and which were tested by van der Hoven (1967) and Collins (1971). Two mutually similar relationships tested and giving good results are those by SethuRaman (1976) and Raynor et al (1975), and are of the form

$$Z_H = \frac{u*} {\frac{\sigma}{\Delta T/\Delta z}}$$

where $Z_H$ is the height (m) of the internal boundary layer, $F$ is the fetch (m) over the down-wind surface, $\theta_1$ is the potential air temperature (K) over the source area, $\theta_2$ is the potential temperature over the down-wind surface, and $\Delta T/\Delta z$ is the lapse rate over the source region (°C.m$^{-1}$).

The presence of the internal boundary layer necessitates a meteorological mast with at least two measuring levels inside this layer, and either two levels above the layer, or a secondary measuring point over the source area (over the sea in the case of Koeberg).

As part of a study of the possible effects of the IBL in the Koeberg area, one should investigate the position of the reactor containment buildings relative
to this layer, and whether or not the point(s) of release will always be outside the layer (keeping in mind the close proximity of the buildings to the coastline).

It was decided not to treat fumigation in long-distance plume simulation in any special way, but to consider only the changes in wind direction and lapse rate which are encountered near the surface. Two reasons for this simplified approach are

(i) the inaccuracy in assessing the precise position of the plume relative to the coastline at any time, but especially during low wind-speed situations when wind directions are not well defined; and

(ii) an insufficiency of relevant weather data from other parts of the region (depth of the inversion layer, wind directions at higher levels, etc.).

4.1.2.2 Mixing depth

The consideration of this phenomenon is important in the Koeberg area due to a frequent elevated inversion with the base lower than 100 m above the ground.

In order to incorporate this effect in the dispersion model, Turner's (1967) argument is followed. At a height \(2.15 \sigma_z\) above the plume centreline, the concentration is one-tenth of that at the centreline at the same distance. When the situation exists where \(1/10\) of the centreline concentration is experienced at the inversion base (say this height is \(L\)) this inversion can be assumed to affect the vertical concentration distribution. If \(x_L\) is taken as the distance where
\[ \sigma_z = \frac{L}{2,15} \text{ (or 0,47 L)} \], assume that at \( 2x_L \) the plume has become uniformly distributed in the mixing layer. For distances greater than \( 2x_L \), the concentration in the mixing layer can be calculated from the following (Turner, 1967):

\[ X(x,y,z) = \frac{Q}{\sqrt{2\pi\sigma_y \bar{U}}} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right). \]

If the low elevated inversion occurs frequently enough, its effect should be incorporated in the estimation of yearly average dilution factors (Draxler, 1980).

4.1.2.3 Incorporation of stability in the dispersion model

In this study only lapse rate and wind speed (and not \( \sigma_0 \)) will be used to determine stability type, as no method was available to measure \( \sigma_0 \) at the time of the dispersion experiments. Eventually the two approaches will be compared at the Koeberg site where an instrument for the determination of \( \sigma_0 \) was installed during 1979.

The area under study is relatively large (500 - 1 000 km\(^2\)), with the sea influencing the land mass from two sides and thus increasing the complexity of the wind-field and stability patterns to be taken into account for simulation purposes. The effect of the wind field on plume trajectory is treated by the incorporation of an interpolation scheme (Wendell, 1972) in the dispersion model (the same scheme as used in Section 3.1.3.1), using wind data from all working meteorological masts. A similar interpolation scheme was incorporated to take lapse rate from all the masts into account. Due to the significant differences in the lapse rate which may be
experienced when a plume moves over the coastline, the simple interpolation scheme was modified to use temperature data from certain specific masts only. For this purpose provision is made in the program to divide the area on the Koeberg-Cape Town grid system into specified regions (these regions can be entered into the program).

In the simulation runs presented here four regions or sectors were specified, viz. the sea along the west coast, the coastal area in the west and the land mass to the east divided into a southern and a northern part - see Fig. 4-1. Where the plume moves in one region only, temperature data from that region alone will be used for interpolation purposes; when the plume starts in a region (say A) and moves over an adjacent one (B) then temperature data from masts in both regions A and B are to be used (see Appendix E).

For the purpose of stability-classification determinations in an area with high-velocity winds for a significant part of the year, the effect of wind speed was included. Two approaches considered were classification by means of the Richardson number and by stability length. The Richardson number unmodified has the disadvantage that wind velocity at two heights must be known. (To have two wind recorders per mast is one disadvantage; another may be the relative errors in readings at low wind speeds; note here that relatively rugged anemometers will be necessary for the high wind speeds often encountered in the SW Cape.) A simplified form in which the Richardson number can be used, is to have a "stability indicator" of the form (Bultynck et al., 1970)

$$S = \frac{\delta \theta}{\delta z} \bar{u}^2 (z_1)$$
where $z_t$ is any specific reference height at which wind speed $\bar{u}$ will always be measured; or another similar form is the bulk Richardson number, which also requires wind speed at one height only.

Stability length was used indirectly as a stability indicator. To simplify the approach, an average roughness length of 0.1 m was taken for the whole area. A reference table was developed by calculating the mass diffusivity ($K_z$) values in a wind speed of 3 m.s$^{-1}$ at a height of 45 m for $\frac{\Delta T}{\Delta z} = -5, -2.5, -1, +1,$ and $+4$ $K(100 \text{ m})^{-1}$, giving the limits for the stability categories. The stability classification scheme given in Table 4-1 was then constructed by similar calculations of $K_z$ values at other wind speeds and lapse rates. The set of relationships by Briggs (1974) was used for the calculation of dispersion coefficients. The combination of Table 4-1 with Briggs' relationships is termed "Subroutine 4". The use of lapse rate alone in the determination of stability class, and using Briggs' relationships for calculating the $\sigma$'s ("Subroutine 1" - Section 3.1.3.2) is also incorporated in the model.

A number of dispersion runs with samplers at a short distance from the release point were performed for the determination of dispersion coefficients specifically for the Koeberg-Cape Town area. Unfortunately, sampling was of too long a duration (1-11 h) in winds which were, most of the time, continuously changing direction, and poor estimates of the $\sigma$'s were obtained.

The important and complex, very stable situation normally occurs during land-breeze/gravity-wind conditions, which will initially be treated with the same classification scheme used for the other weather types, but some adaptation could be necessary, as has been pointed out by
Table 4-1. Stability-classification scheme for "Subroutine 4"

<table>
<thead>
<tr>
<th>$\delta \theta / \delta z \ (K(100 \ m)^{-1})$</th>
<th>$\bar{u} \leq 1 \ (m.s^{-1})$</th>
<th>$1 &lt; \bar{u} \leq 2$</th>
<th>$2 &lt; \bar{u} \leq 3$</th>
<th>$3 &lt; \bar{u} \leq 4$</th>
<th>$4 &lt; \bar{u} \leq 5$</th>
<th>$5 &lt; \bar{u} \leq 6$</th>
<th>$6 &lt; \bar{u} \leq 8$</th>
<th>$8 &lt; \bar{u} \leq 10$</th>
<th>$10 &lt; \bar{u} \leq 12$</th>
<th>$\bar{u} &gt; 12$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -15</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>-8 to -15</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>-5 to -8</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>-2.5 to -5</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>-1 to -2.5</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>+1 to -1</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>+4 to +1</td>
<td>F</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>+8 to +4</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>+15 to +8</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>&gt; +15</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>E</td>
<td>E</td>
<td>D</td>
</tr>
</tbody>
</table>
other workers. It has been found, for example, that with plume meandering in stable conditions, although $\sigma_z$ may be very small, the corresponding $\sigma_y$ values may be near those for unstable conditions.

4.1.2.4 Transport over water

Plume movement over the sea may occur under the following three weather conditions:

SE winds: these may not be very important as pollutants moving out over the sea seem to have a small chance of moving back to the land, and there is no large population centre near the coastline within 50 km north of the site.

NE winds: these can be divided into two categories: berg winds (warm winds originating in a high-pressure region at higher altitudes in the interior) and the land breeze/gravity wind. Berg winds do not seem to be important as they will transport pollutants from Koeberg directly to the sea, apparently not returning to the coastline. The land breeze is important. The effect of Coriolis forces in changing the wind direction should be investigated.

Turbulence of air moving over water may differ significantly from that moving over land, as mentioned earlier. A complicating factor is the change in surface roughness with changes in wind speed and turbulence, causing changes in turbulence. This change in surface roughness with wind speed can be treated mathematically. Kitaigorodskii (1970) derived a set of expressions in which surface roughness is dependent on the frequency spectrum of the waves and the root-mean-square wave height. Other variables come into consideration in
evaluating this set of expressions, such as friction velocity, which on its own is dependent on surface roughness.

The water-vapour flux may also have a marked effect on turbulence (Gifford, 1976). This vapour flux may also be taken into consideration mathematically (Monin, 1970; Thompson, 1972; Warner, 1973). From these equations (where water-vapour flux is taken into consideration) the Richardson number or stability length can be modified, depending on the atmospheric conditions.

To include mathematical expressions for the two above-mentioned phenomena in dispersion calculations would complicate matters considerably. Two values only for the roughness length may suffice. For winds below 6-7 m.s\(^{-1}\), the sea surface is regarded as aerodynamically smooth (Sutton, 1953) and the roughness length \(z_o\) can be taken as 0.001 m (Mulholland, 1977). For stronger winds an appropriate value for \(z_o\) is 0.006 m (Sutton, 1953). These results for the higher wind speeds were taken from work by Munk (1947), and by Rossby and Montgomery (1935). The roughness length with high wind speeds may not be important in this area, as the only condition where over-water transport may be important is in a low wind speed land breeze or gravity wind.

The stability classification scheme given in Table 4-1, based on a \(z_o\) of 0.1 m, was used here for transport over water.

Another factor complicating air movement over a coastline are the shifts in trajectory which may occur. 

".... tra=
jectories starting from various points along the coast-
line are very complex, with numerous reversals, loops
and directional shifts" (van der Hoven, 1967). This
phenomenon has also been observed in the Koeborg area.

4.1.2.5 Entrainment of the plume in building wakes

Buildings and other large obstacles near the release point
strongly influence the dispersion of pollutants down-wind.
This effect is important for distances of the order of
a few hundred metres down-wind, and especially under
conditions of directional wind shear. For effluents
released in one particular case from a short stack,
the plume could be regarded as having been released from
an elevated source whenever the vertical exit velocity
of the plume was at least five times the horizontal
wind speed at release height (Johnson et al., 1975).
In other circumstances, effluent may be downwashed into
the building wake.

Studies by Meroney and Symes (1971) and Meroney and Yang
(1970) indicate that building wakes persist much further
downstream in neutral and stable conditions than was
calculated by the much-quoted equation

\[ \frac{X}{Q} = \left[ \left( \pi \sigma_y \sigma_z + CA \bar{u} \right) \right]^{-1} \]

where \( Q \) is the source strength, \( A \) the area of the building
cross section normal to wind flow, and \( C \) a form factor
dependent on building shape, with a value between one
half and two. It is important in this respect to know
when (at which wind speed, buoyancy of plume, etc.) a plume
will become entrained to ground level in the building
wake.

Studies on wake dispersion have been done by a number of
workers, such as Halitsky (1977), who modelled turbulence along a longitudinal axis downwind of a reactor containment structure; the parameters required to quantify the model for a specific site are the size and shape of an equivalent flat plate to replace the buildings in the complex, and are to some extent arrived at by trial and error. Clarke and Macdonald (1978) proposed the use of a "virtual source" model, where the point source is assumed to be at such a distance upwind of the buildings so that the plume released from this virtual source has the cross-sectional dimensions of the buildings by the time it has travelled from the virtual source to the buildings.

As so much depends on the layout and shapes of the buildings and on the wind speeds and stabilities involved, this portion of the study can only be conducted after the buildings have been completed. Measurements could be obtained by means of tracer studies (Raynor et al., 1979).

4.1.2.6 Topography

Although the area around Koeberg is fairly flat, with the nearest mountains about 10 km away, the shoreline is characterised by a number of low (20-30 m) dunes. Because of the elevated release, these may not be important except under very stable conditions and during effluent entrainment in building wakes. (The effect of the dunes could also be studied after the reactor buildings have been erected.) The mountains which may have an effect on pollutant trajectories are Dassenberg (approximately 20 km NNE from the site) and a number of mountains to the SE (10 to 30 km away) with large relatively flat areas between them. See Fig. 4-1 for the general topographical characteristics of the area. These mountains may lead to certain errors in plume-tra=
jectory calculations. Another important mountain is Table Mountain which may cause significant changes in concentration patterns over Cape Town itself and the Southern Suburbs (Dutkiewicz and Fuggle, 1977). The latter area was not included in this study. Work has been done previously by, inter alia, Dutkiewicz and Fuggle (1977). Sampling points for the atmospheric tracer dispersion experiments to the S-SE-E are located on an arc approximately 25-30 km from Koeberg. These positions were chosen as they were on the outskirts of urban areas to the north of Cape Town, Bellville and Durbanville, and to the south of the important mountain obstacles (except for samplers in the vicinity of Table Mountain). The concentration of a tracer released at Koeberg under the influence of the N-NW winds is measured after it has encountered the mountain obstacles but before it moves over built-up areas. As the terrain continues to be flat and devoid of complicating factors, extrapolations of concentrations at the sampling arc under consideration to longer distances may be made reasonably safely (Dutkiewicz and Keen, 1978).

4.1.2.7 City heat-island effect

Studies of the effect of the city heat-island on turbulence will not be considered at this stage. Such an effect will be localised in the city itself and may enhance dispersion (Hirt and Shaw, 1973; Tyson et al., 1972; Gifford, 1972).

4.1.2.8 Deposition

Dry deposition can be treated by means of the surface-depletion approach, utilising K-theory (see Section 3.2). A dual-tracer deposition study (as given in Section 3.2) will not be attempted due to the more simple surface
types (very few forests) and the higher priority allotted to plume trajectory studies.

In wet-deposition determinations it may be sufficient to consider only below-cloud scavenging. One reason is the difficulty in assessing the effects of rain-out (in-cloud scavenging). What has been suggested (Haeggblom et al, 1969) is to assume the washout coefficient to be constant in the vertical through the whole plume, and that the plume is affected uniformly so that the density distribution remains Gaussian. This approach can give rise to relatively large errors. It has been found experimentally that less contamination is washed out at low levels than higher up (Kortzeborn and Abraham, 1970). This is due to the fact that raindrops decrease in size as they fall, thus reducing their collision efficiencies. Furthermore, a fraction of the raindrops evaporates completely before reaching the ground, transporting particles from a higher to a lower level, thus increasing the particle concentration near the ground relative to that higher up. Also, convection and updraughts, especially during thunderstorms, will transport pollutants into the clouds, increasing the effects of in-cloud scavenging. Due to the difficulty of studying and predicting the effects of precipitation scavenging during short-term effluent releases, partly because of the long distances involved and the very localised "patches" of rain experienced during a typical rainy day in this region, it may be sufficient to use published wash-out coefficients for both accidental and seasonal/yearly wet deposition calculations.

4.2 EXPERIMENTAL PROGRAM

4.2.1 Measurement of Wind-Field and Other Weather Variables

A system of meteorological masts was erected over the area
shown in Fig. 4-1 during 1977/78. Ten of the masts directly communicate the data collected (wind direction at 10 m, wind speed at 10 and 2 m and temperature at 2 m and the temperature difference between 10 and 2 m) to a central station at Koeberg where the data were recorded. Data were collected continuously, averaged over selected periods and transmitted in turn from each of the ten satellite stations to the central station. See Appendix A.

Three other instrumented weather masts were used:

(i) a 45 m mast at Koeberg with a wind-speed and direction recorder at its top, recording at the central station,

(ii) a 2 m mast near the central station with a mechanical type Lambrecht wind-speed and direction recorder, and

(iii) a 10 m mast at Stikland (mast 12) with a mechanical Lambrecht wind recorder.

Although there was no permanent temperature sensor on the 45 m mast, a temporary sensor was used during tracer experiments in 1978.

During the two monthly periods of conducting tracer experimental runs during 1978, an Aerovironment monostatic acoustic radar system set up at the "main station" hut at Koeberg was used to determine vertical turbulence activity up to a height of 1 000 m. This apparatus has been found to give good results in the determination of turbulence fluctuations caused by inversion layers, wind shear, etc. (von Gogh and Zib, 1978; Jensen and Petersen, 1979; Beran and Hall, 1974).
A Vaisala radiosonde system was on loan from Armscor for the tracking of weather balloons. Unfortunately, very little data was gathered by this due to technical failures. A theodolite/pilot balloon system was used for the determination of the vertical wind profile during tracer runs. All balloons were released from the Duynefontein site.

During the winter of 1977 a series of trajectory measurements with constant volume balloons (tetroons) was conducted from Duynefontein under various atmospheric conditions. Tetroons were tracked with theodolites as well as by means of a transponder/passive tracker system. The results of these flights are not discussed in this work.

4.2.2 Tracer Experiments

4.2.2.1 Tracer generator and sampling system

All tracer work was done with the indium aerosol (Norden and van As, 1979) reported on earlier. Air samplers, each consisting of a metal case with an air pump driven with an electric motor, an air-flow meter and filter-holder, were used to collect samples on membrane filters with 0.8 μm pore diameter mounted on the filter-holder, about 1 m above ground level.

4.2.2.2 Tracer dispersion runs

Air sampler locations

Tracer experiments were planned to be utilised simultaneously for long-range trajectory and dispersion coefficient determinations. All air samplers were deployed to span an arc covering about 90° - 100°. The samplers at the longer distances were installed in
more or less fixed positions at farmhouses and at weather masts (see Fig. 4-1). Those taking samples at shorter distances for the dispersion coefficient determinations (a total of 10) were moved, during an experiment, to cover an arc of about 90° with the centre of this arc more or less coincident with the plume axis. Positions are shown in Fig. 4-2. The samplers on this arc were not all at the same distance from the release point (for practical reasons samplers were deployed along navigable roads), and could not be activated and deactivated simultaneously. It took approximately 5 min from activation (or deactivation) of the first sampler to the last one on the arc.

Tracer experimental procedure

During an experimental run (which lasted for 5-10 h each) filters on the samplers close in were normally changed twice, but usually only one set of filters was used on the further ones. Results from near and far samplers would be classified respectively under "short-distance" and "long-distance" samples. The relatively long sampling times during tracer runs are expected to smooth out the effects of local peak concentrations on measured data. Peak-to-mean concentration ratios of the order of 1.5 can be expected for sampling times of 1.5 to 5 h (Singer et al, 1963). The release rate of the indium tracer was kept constant at about 15 g.h\(^{-1}\). During the experiment a number of 100 g pilot balloons were released from the central station to determine wind speeds and directions up to altitudes of 1 000 - 2 000 m. The number of balloons released varied from 0 to 3, depending on the atmospheric conditions. Balloon tracking was initially done with two theodolites; once the ascent speed of 50 m.min\(^{-1}\) was established, only one theodolite was used.
Fig. 4-2.
Air sampler positions in the immediate vicinity of Koeberg.
4.3 EXPERIMENTAL RESULTS 1977/78/80

It was initially planned to conduct a number of tracer runs in all the important weather types and thus in all the seasons, with special emphasis on stable winter-time conditions. During 1977 a series of nine runs was conducted during July/August under conditions of (i) stable land breezes, (ii) sea breezes, (iii) southerly and northwesterly winds and (iv) under conditions with fluctuating wind directions. The latter conditions were the most frequent. In 1978 six runs were performed during April/May, mainly in south-southeasterly winds, which occur frequently in this area during the summertime. As these conditions do not differ much from those in summer, and as dispersion during these conditions can be predicted with a fair amount of accuracy, it was decided not to repeat the work in the summer. During July/August 1978 seven tracer runs were performed, mostly under the complex ground-level inversion conditions, and also during the northwesterlies. The latter winds are mostly winter-time phenomena, occurring with the approach of low-pressure synoptic systems. Only two tracer runs were conducted during the winter of 1980, and they will not be discussed in detail.

The results of the tracer runs (not all are presented here) were categorised according to the wind directions observed at Koeberg and the nearest weather masts, viz. the S-SE, the NW, the SW, the land breeze and fluctuating wind fields. Note that there may be some overlap, with, for example, a tracer run starting off in one wind regime and ending in another; the categorisation will be according to the predominant direction observed at Koeberg. Only where significant changes in the wind field occurred, will such a run be classified under "fluctuating wind fields". The sea breeze was normally
experienced as SW at Koeberg, but a number of runs performed under such conditions were classified under "fluctuating wind fields" because of the continuous wind-field changes often experienced in sea-breeze conditions. The "land breeze" includes katabatic air movement.

Model simulations and comparison with experimental results

A comparison between experimental and calculated concentrations obtained for tracer experiments and the simulations will be given in this section. As mentioned earlier, average wind and temperature data from all working weather masts during each half-hour of a run were used in the simulations. Unfortunately, reliable temperature-difference values were obtained only from a few masts during a run, and the suspect data were eliminated with care. Average values for lapse rate and wind speed during a run are given in the text.

The figures accompanying the description of the tracer experiments indicate the prevailing wind-field patterns during an experiment, as well as the observed and calculated tracer concentrations. Concentrations are calculated using the dispersion model described earlier (Sections 3.1.3, 4.1.2.2 and 4.1.2.3), employing "Subroutines" 1 and 4 for the determination of dispersion coefficients. This dispersion model was the one used in the Richards Bay study, but with the few adaptations mentioned earlier in this chapter, to incorporate changes in stability with distance from the source, and to take mixing depth into account.

Note that there are a few occasions presented in the figures where a certain sampler was not activated during the experimental run, but were calculated concentration values are given. Furthermore, a symbol (©) is placed
in the position of a concentration value (experimental or calculated) if that value is zero or on or below the \( 0.1 \times 10^{-8} \text{ kg.m}^{-3} \) level (which is more or less the experimental limit of detection); where all three concentration values (experimental and calculated) are below \( 0.1 \times 10^{-8} \), a single \( \wedge \) symbol is used at this sampler position.

4.3.1 Tracer Experiments in S-SE Winds

4.3.1.1 Run H - 23/08/77 (tracer release period 10h19 - 17h18)

A SE wind was experienced at all the mast positions until about 13h30 - 14h00 when a S-SW wind (sea breeze) was recorded at mast 4, followed by 3 and 5. From about 15h00 to 17h30 the SW was also dominant at masts 11 and 1 (the latter only briefly). By 18h00 all positions again recorded a S-SE. See Fig. 4-3. This is a typical example of a weak SE with a weak sea breeze during the afternoon, penetrating only a few kilometres inland.

Air samples were collected at samplers 5, 11, 12 and 13 continuously from about 11h00 to 1700. Wind speed 2 - 5 m.s\(^{-1}\); lapse rate -1 to -4 K(100 m\(^{-1}\)).

The model predicted the presence of tracer material at sampling points 5 and 12, and tracer was measured at points 5 and 13. See Fig. 4-4. The correlation between experimental and calculated results is good for position 5 which is the position nearest to the average plume axis, while the correlation is poor for the two further points, indicating a misprediction of plume trajectory of a few degrees.

4.3.1.2 Run BA - 21/4/78 (tracer release period 13h47 - 17h23)

During the entire period all the masts indicated SE winds, except mast 9 where a SW wind was prevalent. See
Fig. 4-5.

Two sets of samples were taken at short distance (Figs. 4-6(b) and (c)) for the periods 14h00 - 15h30 (period 1) (wind speed 7 - 11 m.s\(^{-1}\) and lapse rate -11 to -14 \(K(100 \text{ m})^{-1}\)) and 16h00 - 17h15 (period 2) (wind speed 9 - 14 m.s\(^{-1}\) and lapse rate -10 to -12 \(K(100 \text{ m})^{-1}\)). One set of samples was taken at long-distance samplers (Fig. 4-6 (a)), for the period 13h30 - 16h30 (wind speed 7 - 10 m.s\(^{-1}\) and lapse rate -11 to -14 \(K(100 \text{ m})^{-1}\)).

The acoustic radar trace showed the presence of thermals (convection due to a heated surface) from the ground up to at least 700 m.

Air samples were collected at sampler points 11, 12 and 25 (long distance) and points 101, 102, 103, 104, 105, 106, 107 and 110 (short distance). Good correspondence was obtained between predicted and observed concentration results on or near the plume axis (Fig. 4-6). Again, a misprediction of the plume trajectory by a few degrees (it must be kept in mind that wind directions are input in the model with precision to the nearest 5°) caused a certain discrepancy in observed to predicted concentration ratios.

4.3.1.3 Run BD - 1 to 2/5/78 (tracer release period 21h36 - 02h50)

As in run BA all the masts recorded S-SE winds for the whole period (Fig. 4-7). A pilot balloon (tracked 02h45 - 03h12) showed a SE wind (4-7 m.s\(^{-1}\)) from ground level to 700 m, then changed through E to NE up to 1 200 m (2-7 m.s\(^{-1}\)), and again through E to ESE (5-8 m.s\(^{-1}\)) to 1 400 m.

Two sets of samples were taken at short distance,
21h45 - 23h25 ($\bar{u} - 6$ to $7 \text{ m.s}^{-1}$, $\delta \theta/\delta z - +3$ to $+4 \text{ K}(100 \text{ m})^{-1}$), and 00h50 - 02h30 ($\bar{u} - 6$ to $9 \text{ m.s}^{-1}$, $\delta \theta/\delta z - +3 \text{ K}(100 \text{ m})^{-1}$); and one set at long distance, 22h45 - 03h30 ($\bar{u} - 5$ to $7 \text{ m.s}^{-1}$, $\delta \theta/\delta z - +3$ to $+5 \text{ K}(100 \text{ m})^{-1}$). The acoustic radar trace showed what seemed to be a stable layer from the ground to 200-300 m in the vertical.

Air samples were collected at samplers 11, 12 and 25 (long distance) and 102, 103, 104, 105, 106, 107 and 110 (short distance). The correspondence between predicted and experimental concentration values at both short and long distance is weak, mainly because of a difference of about 20° between the respective axes of the predicted and real plumes. The axis values correspond well (Fig. 4-8). The error in predicted trajectory is most probably due to katabatic wind-flow near ground level even in the 5-10 m.s$^{-1}$ wind velocities. This is an important night-time condition which is most marked during cold nights with low wind speeds; at the 10 or 45 m direction measuring height the gradient wind (SE or NW) may be recorded while the NNE-NE gravity wind may be experienced in the lower few metres only. This phenomenon can cause a "shift" of tracer trajectory near ground level in a more westerly direction.

4.3.1.4 Run BE - 4/5/78 (tracer release period 02h52 - 05h23)

A S or SE wind was experienced at all the masts. See Fig. 4-9.

Only one set of samples was taken at short distance, 03h00 - 04h30 ($\bar{u} - 7$ to $10 \text{ m.s}^{-1}$, $\delta \theta/\delta z - +1$ to $+2 \text{ K}(100 \text{ m})^{-1}$). A weak acoustic radar trace indicated the stable layer approximately 200 m deep.
Air samples were collected at samplers 103, 104, 105, 106, 107, 110 and 111. Like run BD, this is also a night-time run, and again poor correspondence between predicted and experimental concentration values is obtained with higher tracer values sampled by the westernmost samplers. See Fig. 4-10.

4.3.1.5 General conclusions on tracer experiments in S-SE gradient winds

With a relatively strong SE wind ($\geq 5$ m.s$^{-1}$) at Koeberg the wind direction at all the other masts tends to be S-SE, and the direction of movement and tracer air concentrations downwind can be readily estimated. In weaker SE winds the sea breeze results in a SW surface wind over Koeberg (run H). During the night the prediction of plume direction may be in error by $20^\circ$ or more due to a shallow land-breeze/gravity-wind layer.

4.3.2 Tracer Experiments in N-NW Winds

4.3.2.1 Run CA - 15/7/78 (tracer release period 14h30 - 23h20)

The wind direction at all the masts was NW (W to NW to NNW) until about 17h30; then the direction at masts 3, 4 and 6 gradually changed to NNE. By about 19h30 seven of the ten masts experienced the NE gravity wind/land breeze; mast 7 NNW, 9 SW to WNW and 10 fluctuating drastically NE, E, SE, SW. A pilot balloon released at 17h00 indicated a NNW wind up to 350 m (then lost). See Figs. 4-11 (a), (b) and (c).

Two sets of samples were taken at the short-distance sampling points, 14h50 - 16h15 ($\bar{u}$ - 4 to 10 m.s$^{-1}$, $\delta \theta/\delta z$ -1 to -6 K(100 m)$^{-1}$), and 16h50 - 18h30 ($\bar{u}$ - 4
Fig. 4-3(a).
Wind field during tracer run H (10h00 - 13h30).

Fig. 4-3(b).
Wind field during tracer run H (13h30 - 18h00).
Tracer concentration results, run H: 11h00 - 17h00 (23/8/77).

Fig. 4.4.
Fig. 4-5
Wind field during tracer run BA (13h30 - 17h30)

Fig. 4-6(a)
Tracer concentration results, run BA, long distance: 13h30 - 16h30 (21/4/78).
Fig. 4-6(b). Tracer concentration results, run BA, short distance, period 1: 14h00 - 15h30 (21/4/78).

Fig. 4-6(c). Tracer concentration results, run BA, short distance, period 2: 16h00 - 17h15 (21/4/78).
Fig. 4-7. Wind field during tracer run BD (21h30 - 04h00).

Fig. 4-8(a). Tracer concentration results, run BD, long distance: 22h45 - 03h30 (1 to 2/5/78).
Tracer concentration results, run BD, short distance, period 1: 21h45-23h25 (1/5/78).

Tracer release rate normalised to 1 kg s⁻¹. Units of concentration in kg m⁻³ x 10⁻⁸.

- Experimental values
- Subroutine 1
- Subroutine 4

- Samplers activated during run
- Samplers activated with zero tracer sampled

Tracer concentration results, run BD, short distance, period 2: 00h30-02h30 (2/5/78).

Tracer release rate normalised to 1 kg s⁻¹. Units of concentration in kg m⁻³ x 10⁻⁸.

- Experimental values
- Subroutine 1
- Subroutine 4

- Samplers activated during run
- Samplers activated with zero tracer sampled
Fig. 4-9.
Wind field during tracer run BE (02h30 – 05h30).
Fig. 4-10. Tracer concentration results, run BE: 03h00 - 04h30 (4/5/78).
to 6 m.s\(^{-1}\), \(\delta \theta/\delta z - -3\) to +3 K(100 m\(^{-1}\)); and one at long distance with starting times 16h30 - 19h00 (samplers 9 and 20 the last to be started and stopped) and end times 23h00 - 01h00 (\(\bar{u} - 1\) to 6 m.s\(^{-1}\), \(\delta \theta/\delta z - -3\) to +4,5 K(100 m\(^{-1}\)). The acoustic radar trace was illegible.

Air samples were collected at samplers 22, 23, 26, 27, 3, 9 and 20 (long distance) and 122, 124, 125, 126, 127 and 4 (short distance). The results from the long-distance samplers (Fig. 4-12(a)) show a marked difference between predicted and observed values to the east of the area, while for those to the southwest (samplers 9 and 20) the correspondence is good. The latter two samples were obtained during land-breeze/gravity-wind conditions, and these results were later repeated (runs CD and CE discussed below) in similar atmospheric conditions. The bad correspondence at samplers to the east could be due to topographical channeling effects and/or wind shear. The latter factor most probably played the dominant role as this discrepancy in experimental to predicted ratios was already visible at a short distance from the release point (Fig. 4-12(c)).

4.3.2.2 Run CF - 4/8/78 (tracer release period 10h16 - 18h02)

The wind direction was predominantly NW at most of the masts during the entire period; the exceptions were masts 2 and 6 where it fluctuated around SW, NE and SE until about 14h00 (Figs. 4-13(a) and (b)). Two pilot balloons released at 11h40 and 16h30 showed a NW (3-9 m.s\(^{-1}\)) direction up to a height of 2 000 m.

Two sets of samples were taken at long-distance samplers, from 11h30 to 15h30 (\(\bar{u} - 3\) to 6 m.s\(^{-1}\), \(\delta \theta/\delta z - -1\) to -9...
K(100 m)$^{-1}$), and from 15h30 to 18h30 ($\bar{u} - 2$ to $6$ m.s$^{-1}$, $\delta\theta/\delta z - -7$ to $+3$ K(100 m)$^{-1}$). The acoustic radar recorder indicated thermals from the ground for most of the time.

Air samples were collected at sampling positions 3, 4, 9, 10, 20, 22, 23, 26, 27 and 28. Good correspondence between experimental and predicted results was obtained during the second period; the single high experimental value at sampler 22, and zero at 23, indicates a misprediction between the real and estimated plume trajectories of about $10^\circ$. The simulation results compare poorly with the experimental results in the first set of samples taken; this may be due partly to the obstructive effect of the Tierberg mountains. The two tracer values observed at samplers 4 and 20 cannot be explained as the wind direction was fairly constant from the NW up to 2 000 m above ground (it could be due to sample contamination). See Fig. 4-14. Although strict precautions are taken to prevent sample contamination, the latter is not excluded and is a possible explanation.

4.3.2.3 General conclusions on tracer runs in NW winds

As in the case of S-SE winds, plume trajectory can be fairly easily determined in the higher wind speeds, except during the night when wind-shear effects may cause significant differences between predicted and observed concentration values.

4.3.3 Tracer Experiments in SW Winds

4.3.3.1 Run BF - 9/5/78 (tracer release period 17h35 - 21h30)

At the masts in the Koeberg area (1, 2, 3, 11) the wind
winds, except mast 9 where a SW wind was prevalent. See

Fig. 4-11(a).
Wind field during tracer run CA (14h30 – 17h30).

Fig. 4-11(b).
Wind field during tracer run CA (17h30 – 19h00).

Fig. 4-11(c).
Wind field during tracer run CA (19h00 – 01h30).
Fig. 4-12(a).
Tracer concentration results, run CA, long distance: 16h30 – 01h00.
(15 to 16/7/78).

Fig. 4-12(b).
Tracer concentration results, run CA, short distance, period 1:
14h30 – 16h15 (15/7/78).
Fig. 4-12(c).
Tracer concentration results, run CA, short distance, period 2:
16h50 - 18h30 (15/7/78).

Fig. 4-13(a).
Wind field during tracer run CF (10h00 - 14h00).

Fig. 4-13(b).
Wind field during tracer run CF (14h00 - 19h00).
Fig. 4-14(a).
Tracer concentration results, run CF, period 1: 11h30 - 15h30 (4/8/78).

Fig. 4-14(b).
Tracer concentration results, run CF, period 2: 15h30 - 18h30 (4/8/78).
was SW until about 19h00 and N-NW at the other masts. Later a very shallow land-breeze layer was experienced at masts 4 and 11 (only about 10 m deep and thus not seen in the figure where the direction is recorded at 45 m, with an inversion strength of > 20 K(100 m)\(^{-1}\) in this lower 10 m; \(\bar{u} = 1 \text{ m.s}^{-1}\)). The wind direction at masts 1 and 2 fluctuated between NW and SW. (See Figs. 4-15 (a) and (b)). Three pilot balloons were released during this time; the first at 16h40 experienced a W-SW wind (~ 1 m.s\(^{-1}\)) to a height of 200 m, then S (2-3 m.s\(^{-1}\)) up to 650 m, and S-SW (3-5 m.s\(^{-1}\)) up to 1400 m. The second balloon was released at 17h55: 0 to 350 m - SW (1-2 m.s\(^{-1}\)), 350 to 900 m - SE (2-3 m.s\(^{-1}\)); and the 3rd at 20h55: 0 to 400 m - SW (1-3 m.s\(^{-1}\)), 400 to 800 m - SE (2-4 m.s\(^{-1}\)). The last balloon, ascending at 50 m.min\(^{-1}\), did not register the shallow gravity wind/land breeze.

One set of samples was taken at short-distance samplers, from 17h40 to 19h20 (\(\bar{u} = 1.5\) to 3 m.s\(^{-1}\), \(\delta \theta / \delta z = -2\) to -4 K(100 m)\(^{-1}\)); and one at long distance, from 18h30 to 21h30 (\(\bar{u} = 1.5\) to 3 m.s\(^{-1}\), \(\delta \theta / \delta z = -4\) to +10 K(100 m)\(^{-1}\)). The acoustic sounder recorder indicated very little turbulence above about 50 m until 20h00 from when at 100 m it started recording either wind shear, which is unlikely from the pilot balloon results, or an inversion layer above the ground-based one.

This run was performed in a SW wind which was fairly localised to the Koeberg area, with a shallow land-breeze/gravity-wind layer developing which did not affect the 45 m wind recorder at Koeberg. The tracer run results are interesting in that nothing was detected in a 90° sector covering N to E from the release point at short distance although the wind direction at both 2 and 45 m was initially (during the sampling time of the
short distance samplers) SW, the former (2 m recorder) turning gradually through SE to NE. It is assumed that the gravity wind/land breeze initially did not pass over the dune with the wind recorders but did affect the samplers which were positioned at a lower level, transporting tracer material away from these samplers. Samplers were running (at long distance) at sampler positions 14, 16, 13, 24, 25 and 4, of which only 13 and 14 intercepted tracer. (See Fig. 4-16.) The results at short distance are not presented in a figure. No sampler at long distance had significant tracer concentration passing it in the simulated run, the predicted plume passing somewhere between samplers 13 and 14, and 14 and 16 most of the time.

4.3.3.2 Run CB - 18/7/78 (tracer release period 14h45 - 17h54)

The wind direction was more or less SW at masts 1, 2, 3, 4, 6, 9 and 11, and NW at 7, 8 and 10 until about 16h30; it became SE at 10, NW and later NE at 11, fluctuating NW, NE at mast 4, and the other masts showing more or less the same directions than earlier. (Fig. 4-17.) Only two sets of samples were taken at short-distance samplers, from 15h30 to 16h35 ($\bar{u}$ - 3 to 5 m.s$^{-1}$, $\delta\theta/\delta z = +1$ to $+2.5 \text{ K(100 m)}^{-1}$), and from 17h05 to 17h50 ($\bar{u}$ - 1.5 to 3 m.s$^{-1}$, $\delta\theta/\delta z = +2 \text{ K(100 m)}^{-1}$). The acoustic sounder trace was illegible.

Samplers 111, 112, 113, 115, 116, 117, 118 and 119 were activated. The tracer concentration results of both sets of samples show a marked shift in predicted to actual trajectory, of the order of 30°. (See Fig. 4-18.) Both sets of samples were taken during stable...
atmospheric conditions with significant directional wind shear, and again, as mentioned above, during such conditions wind shear and topographical channeling effects may cause a shift in plume trajectory as well as a "fanning out" of the plume (note the position of the Blouberg Ridge). The increasingly SW direction of the wind from the measuring height at 45 m down to ground level caused the marked widening of the plume in a NE direction.

4.3.3.3 General conclusions on tracer runs in SW winds

The driving force for a SW wind at Koeberg may be either sea-breeze conditions or the presence of a low-pressure system (a coastal low or post-frontal low-pressure system). Only two runs in SW winds are reported here, but actually this wind direction was an important component of most of the runs in fluctuating wind fields (Section 4.3.5). An important phenomenon during sea-breeze conditions is the high variability in wind direction in a short span of time. A second phenomenon is the fact that the wind at a certain mast may change from the sea breeze to the gradient wind and back again in a short period of time; thus the direction sensor may record a SW wind (sea breeze) for, say, half an hour, and then suddenly change to a NW (if this is the gradient wind direction), with an accompanying increase in wind speed, and after some time in this direction, suddenly change back to SW, etc. As in the SE and NW gradient winds, wind shear and topographical channeling effects may play a role in significantly altering plume trajectory during stable atmospheric conditions. As the sea-breeze layer may be very shallow (of the order of a few tens of metres) during the day, directional wind shear
plays a most important role in markedly widening the plume. The following table of winds measured at three heights on the 76 m Koeberg mast, taken on 2/8/80, illustrates the point:

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Wind Direction at 10 m (u)</th>
<th>Wind Direction at 46 m (u)</th>
<th>Wind Direction at 76 m (u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10h00</td>
<td>135° (1.6 m.s⁻¹)</td>
<td>112° (3.5 m.s⁻¹)</td>
<td>123° (3.7 m.s⁻¹)</td>
</tr>
<tr>
<td>11h00</td>
<td>214° (1.9)</td>
<td>169° (1.8)</td>
<td>166° (2.7)</td>
</tr>
<tr>
<td>12h00</td>
<td>224° (3.4)</td>
<td>189° (4.0)</td>
<td>182° (4.3)</td>
</tr>
<tr>
<td>13h00</td>
<td>169° (3.4)</td>
<td>142° (6.4)</td>
<td>144° (5.9)</td>
</tr>
<tr>
<td>14h00</td>
<td>148° (4.9)</td>
<td>136° (6.9)</td>
<td>146° (7.3)</td>
</tr>
</tbody>
</table>

4.3.4 Tracer Experiments in the Land Breeze/Katabatic Wind

4.3.4.1 Run CC - 19/07/78 (tracer release period 00h15 - 08h25)

The wind direction was initially (first half-hour) NE (due to the land breeze/gravity wind) at most of the masts. Then it changed to NE or SE or SW (see Figs. 4-19(a), (b), (c) and (d)), with some fluctuation. By 08h30 none of the masts experienced the land breeze any longer. The direction at mast 11 (Koeberg) changed from NE to E to SE (the latter direction since about 06h00). The land-breeze/gravity-wind layer at Koeberg was 5-30 m deep for the largest part of the time. Two balloons were tracked; the first released at 04h40 indicated a SE (2-5 m.s⁻¹) from 0 to 400 m, 400 to 700 m - SW (2-3 m.s⁻¹), and 700 to 1 000 m - WNW to NW (1-3 m.s⁻¹); and the second balloon at 06h45: 0 to 600 m - SE to SSE (3-4 m.s⁻¹), 600 to 1 900 m - SSW to W (2-4 m.s⁻¹), and 1 900 to 3 600 m - WNW (2-4 m.s⁻¹).
Fig. 4-15(a).
Wind field during tracer run BF (17h30 – 19h00).

Fig. 4-15(b).
Wind field during tracer run BF (19h00 – 22h00).

Fig. 4-16.
Tracer concentration results, run BF, long distance: 18h30 – 21h30 (9/5/78).
Fig. 4-17.
Wind field during tracer run CB (14h30 - 16h30)
Fig. 4-18(a).
Tracer concentration results, run CB, period 1: 15h30 – 16h35 (18/7/78).

Fig. 4-18(b).
Tracer concentration results, run CB, period 2: 17h05 – 17h50 (18/7/78).
One set of samples was taken at long-distance samplers, 02h00 - 08h00 (samplers to the south of Koeberg), and 05h30 - 09h30 (the two samplers to the north) \((\bar{u} - 1 \text{ to } 3 \text{ m.s}^{-1}, \bar{\theta}/\bar{z} - +12 \text{ to } +15 \text{ K(100 m)}^{-1})\). The acoustic sounder trace was illegible. Two balloons with radio-sondes were released at 04h40 and 06h45; the first indicated a stable layer from the ground to 200 m (temperature difference of 9°C), then a more or less neutral atmosphere to 450 m, a stable layer to 900 m, and then again more or less neutral to 6 000 m; the second radiosonde: stable to 250 m (10°C change), isothermal to 500 m, stable to 650 m, and then neutral to slightly stable to 6 000 m.

Samplers were activated at positions 11, 12, 10, 4, 40, 3, 41, 9 and 20. Relatively high tracer concentration values were obtained experimentally by samplers to the north and south of Koeberg along the coastline, while the simulated run showed zero at all the samplers. The nearest that the simulated plume trajectory approached land was about 3 km to the west of sampler 11. The experimentally obtained concentration results are not presented in a figure, and the values obtained were as follows \((\text{in } (\text{kg x }10^{-8})\text{m}^{3}, \text{release rate normalised to } 1 \text{ kg.s}^{-1})\): sampler 11 - 19,3; 12 - 2,2; 4 - 1,21; 3 - 27,0; 40 - 2,32; 10 - 4,44; 41 - 8,36; 9 - 1,99; 20 - 3,89. These results are hard to explain; a NE land breeze coupled with a SE gradient wind should move the tracer out over the sea if only surface winds were considered. One possibility is that tracer returned to land in the land-breeze return flow, although such flow was not detected by the weather balloons.

A tracer run performed during July 1980, under very similar weather conditions and in a similar wind field, and only
with samplers to the south of Koeberg activated, gave similar high concentration values at samplers 20 and 9. The land-breeze layer thickness at Koeberg was of the order of 2 - 20 m.

4.3.4.2 Run CD - 28/07/78 (tracer release period 02h37 - 07h33)

For the whole period the wind direction was NNE to NE most of the time at all the masts except masts 5 (N), 7 (NNW), and 8 (N). The direction at masts 2, 8 and 10 fluctuated between NNW and NE (Fig. 4-20). Two pilot balloons were tracked; the first released 03h00: 0 to 50 m - NNE (5 m.s\(^{-1}\)), 50 to 1 300 m - NW (4 - 7 m.s\(^{-1}\)); and the second released at 06h00: 0 to 50 m - NNE (5 m.s\(^{-1}\)), 50 to 100 m - N (7 m.s\(^{-1}\)), 100 to 700 m - NW (5 - 8 m.s\(^{-1}\)).

One set of long-distance samples was taken, 03h00 - 08h30 (\(\bar{u} = 2\) to 5 m.s\(^{-1}\), \(\delta T/\delta z = +2\) to +8 K(100 m\(^{-1}\)). The acoustic radar trace was illegible.

Samplers were activated at positions 4, 3, 10, 28, 22, 23, 26, 27, 41, 9 and 20. A good correspondence was obtained between observed and calculated concentrations at sampler 20. (See Fig. 4-21.) The temperature sensors on mast 5 (Robben Island) were out of order; and to see what would have been the effect if this position read a neutral lapse rate for over-water plume travel, a value for \(\delta T/\delta z = 0\) was entered in a second simulation run. The results did not differ much; the concentration values for samplers 20 and 10 changed from 55.7 x 10\(^{-8}\) kg.m\(^{-3}\) to 55.2 x 10\(^{-8}\) and from 0.17 x 10\(^{-8}\) to 0.44 x 10\(^{-8}\) respectively. The amount of tracer sampled at position 27 is only a factor 2 higher than the detection limit and may thus be due to contamination, but it may also be due to wind shear: tracer dispersing out of the layer experiencing a
N-NE wind into the NW gradient wind (which was experienced below 50 - 100 m above the surface at the coastline), may be moved by the NW wind to ground level.

4.3.4.3 Run CE - 29/07/78 (tracer release period 01h44 - 08h00)

This was a run in atmospheric conditions similar to those for run CD, with the land breeze only more weakly developed and not extending so far over the sea. Until about 03h00 the 45 m wind recorder at mast 11 (Koeberg) indicated NW-NNW winds, while the 2 m Lambrecht recorder showed a NE for the whole period until near the end of the tracer release time. As can be seen from Figs. 4-22 (a) - (c) the wind directions at all the masts were between NE and NNW most of the time. The important similarity with run CD is the N-NE winds at the release point, the N over the sea (Robben Island) and the NW in the vicinity of Cape Town (mast 7). Two pilot balloons were tracked; the first released 06h00: 0 to 50 m - NNE (5 m.s\(^{-1}\)), 50 to 100 m - ~ N (4 m.s\(^{-1}\)), 100 to 550 m - NNW (4-5 m.s\(^{-1}\)); and the second at 08h30: 0 to 50 m - NNE (6 m.s\(^{-1}\)), 50 to 100 m - ~ N (8 m.s\(^{-1}\)), 100 to 150 m - NNW (7 m.s\(^{-1}\)), 150 to 1 200 m - NW (5-10 m.s\(^{-1}\)).

One set of long-distance samples was taken, sampling period 02h30 - 09h00 (\(\bar{u} - 1\) to 3 m.s\(^{-1}\), \(\delta \theta/\delta z - +1\) to +12 K(100 m\(^{-1}\)). The acoustic sounder trace was illegible.

Samplers 4, 10, 3, 22, 27, '41, 9 and 20 were activated during the run. (See Fig. 4-23.) Again good correspondence was obtained between the calculated and observed concentration values for the furthest sampler (20), and again tracer was experimentally sampled at a sampler in the eastern part of the region (sampler 22) indicating possible movement of tracer in the NW wind above the land-
breeze layer. The same explanation may hold for the experimentally obtained tracer concentration (with zero predicted) at samplers 3 and 9. The relatively high concentration values predicted at sampler 4 (with zero obtained experimentally) is due partly to the fact that the simulated plume trajectory is based on wind measurements at 45 m on mast 11, while the "real" plume was largely influenced by the NE land breeze experienced at a lower level.

4.3.4.4 Run CG - 06/08/78 (tracer release period 01h35 - 06h10)

The land-breeze/gravity-wind layer was well developed and deeper than during the previous three runs (about 150 m; one of the deepest observed during the three winter seasons). Most of the masts registered the land breeze (NE); masts 6, 8 and 10 fluctuated between NW and NE. The significant difference between the wind fields experienced during this run and runs CD and CE is that the direction over the sea (Robben Island) was NE in this case (compared to the dominant N during the others). (See Fig. 4-24.) One pilot balloon was tracked (04h00): 0 to 100 m - NE (4-5 m.s\(^{-1}\)), 100 to 200 m - NNE to N (3 m.s\(^{-1}\)), 200 to 350 m - NNW (2-4 m.s\(^{-1}\)), 350 to 850 m - NW to NNW (2-3 m.s\(^{-1}\)), 850 to 1 050 m - N to NNE to N (3-5 m.s\(^{-1}\)), 1 050 to 1 150 m - NNW (5-8 m.s\(^{-1}\)).

One set of samples at long-distance samplers was taken - samplers 3, 4, 9, 20, 27 and 41 - during the period 02h30 to 06h30 (\(\bar{u} - 1\) to 2.5 m.s\(^{-1}\), \(\delta\theta/\delta z\) as measured between 2 and 42 m at Koeberg at 03h00: 14 K(100 m)\(^{-1}\)).

The trace of the acoustic sounder indicated a surface-based stable layer at least 100 m deep.

The concentration results obtained from the run are not
presented in a figure as the values obtained are all below the detection limit in both the simulation and actual runs. Only one sample (from sampler 9) had a very low quantity of In tracer, just above detection limit: \( \bar{\chi} = 0.36 \times 10^{-8} \text{ kg.m}^{-3} \) (at a release rate of 1 kg.s\(^{-1}\)). The tracer presumably moved out over the sea for the whole run, not to return to land (in significant quantities) during the run. Although the land breeze/gravity wind could be reinforced by the berg wind, the low surface temperatures experienced during the run (2-5°C) indicate that this was probably not the case.

4.3.4.5 **General conclusions on tracer runs in the land breeze**

(1) The land breeze/gravity wind will take airborne pollutants from a source on Duynefontein out over the sea. If the gradient wind is SE such pollutants may be moved in a general NW direction when leaving the influence of the land wind, and continue out over the sea. If the gradient wind is a NW the pollutants may be returned to the land in a SE direction; but if the land breeze extends far enough over the sea (the criterion may be that Robben Island also experiences a NE) the NW will not return the pollutants concerned directly to the coastline.

(2) The plume trajectory experienced in a situation such as explained in remark (1) in a NW gradient wind can be simulated relatively accurately by the model used here (runs CD and CE). Possibly because of the blocking effect of Table Mountain, there may be a more general movement of air in a SE direction past this mountain and over Cape Town and Paarden Island where mast 7 is the only
indicator of the NW wind. Thus sampler 9 (at mast 7) registered much higher concentrations experimentally than when simulated. This factor (higher concentrations observed than predicted) may be enhanced by plume material diffusing out of the lower layers of the atmosphere into the NW gradient wind, thus "fanning out" the plume.

(3) Wind shear plays an important role in the land breeze, especially in a very shallow land breeze such as during run BF when this wind was not even experienced on the higher ground at Koeberg. The low tracer concentrations sampled at certain inland samplers when the main recorded trajectory is out over the sea (as in runs CD and CE) is also a case in point. The tracer concentration values obtained experimentally during run CC may be largely due to wind direction changes at higher levels over the sea. The results obtained during this run are difficult to explain.

4.3.5 Tracer Experiments in Fluctuating Wind Fields

4.3.5.1 Run B - 30/07/77 (tracer release period 13h03 - 16h39)

The run started off with a NE to E wind at masts 3 and 11, a SE at masts 1, 2 and 5 and a SW at 4. The sea breeze was experienced at all the masts (except 2 and 5) by 15h00, and from then until 17h00 the wind directions fluctuated between E-SE and SW. Fig. 4-25 gives the wind field, with the directions of the wind at each mast as it was experienced there most of the time.

One set of samples was taken at long-distance samplers, 14h00 - 16h30 ($\bar{u}$ - 1,5 to 2,5 m.s$^{-1}$, $\partial \theta / \partial z$ -1 to -8
Wind field during tracer run CC (00h00 - 05h30).

Fig. 4-19(a).

Wind field during tracer run CC (00h30 - 05h30).

Fig. 4-19(b).

Wind field during tracer run CC (05h30 - 08h00).

Fig. 4-19(c).

Wind field during tracer run CC (08h00 - 10h30).

Fig. 4-19(d).
Fig. 4-20.
Wind field during tracer run CD (02h30 - 08h30).
Fig. 4-21.
Tracer concentration results, run CD: 03h00 – 08h30 (28/7/78).
Fig. 4-22(a). Wind field during tracer run CE (01h30 - 03h00).

Fig. 4-22(b). Wind field during tracer run CE (03h00 - 09h00).

Fig. 4-22(c). Wind field during tracer run CE (09h00 - 10h00).
Fig. 4-23.
Tracer concentration results, run CE: 02h30 – 09h00 (28/7/78).
Fig. 4-16.
Tracer concentration results, run BF, long distance: 18h30 - 21h30
(9/3/78)

Fig. 4-24.
Wind field during tracer run CG (01h30 - 07h30).

K(100 m)$^{-1}$.

Samplers 10, 11, 12, 4, 18, 19 and 3 were used during the run. The correspondence between predicted and observed concentrations at samplers to the north of Koeberg is good (unfortunately a wider sector was not covered by samplers), and poor to the south, which cannot be explained because in the run the plume never seemed to move in a southerly direction (by observing surface wind-directions). Fig. 4-26.

4.3.5.2 Run C - 31/07/77 (tracer release period 13h15 - 21h03)

Initially the wind field was more or less the same as during the beginning of run B. From about 14h30 until 15h00 either a SW or SE wind was experienced at all the masts, except 5 with a NE or SE. From 15h00 to 15h30 the masts on the coastline (11, 3 and 4) experienced a SW wind and the others SE. From 16h00 to 18h30 all the masts experienced a SW, except 5 (SE or NE, the latter most of the time). From this time to the end of the run the wind directions changed to SE - ESE, and to ENE at masts 1 and 2. (See Figs. 4-27 (a), (b) and (c).)

Two sets of samples at long-distance samplers were taken, 14h00 - 19h00 ($\bar{u} - 1$ to 4 m.s$^{-1}$, $\delta \theta/\delta z - 6$ to $+8$ K(100 m)$^{-1}$; the positive lapse rates during early evening), and 19h00 - 21h30 ($\bar{u} - 1$ to 5 m.s$^{-1}$, $\delta \theta/\delta z - 2$ to $+14$ K(100 m)$^{-1}$).

Tracer air concentration was sampled at samplers 11, 12, 5, 13, 14, 15, 6 and 16. With most of the samples fair correspondence was obtained between calculated and observed values. (See Figs. 4-28 (a) and (b).) This is a typical example of sea-breeze conditions along the West Coast.
4.3.5.3 Run D - 02/08/77 (tracer release period 10h27 - 15h15)

For the first two hours of the run the wind directions at the masts were N-NE (masts 11, 1, 2 and 4), SE (3 and 5) and W (9) most or part of the time, changing all the time. From about 13h00 to the end of the run the directions were either SW or NW, fluctuating NW-SW at some of the masts (3 and 4 - on the coast). (See Figs. 4-29 (a) and (b).)

Two sets of samples were taken at long-distance samplers, 11h00 - 14h30 (\( \bar{u} \) - 4 to 8 m.s\(^{-1}\), \( \delta \theta/\delta z = -3 \) to -10 K(100 m)\(^{-1}\)), and 14h30 - 18h00 (\( \bar{u} \) - 5 to 10 m.s\(^{-1}\), \( \delta \theta/\delta z = -1 \) to -7 K(100 m)\(^{-1}\)).

Air samples were collected at positions 4, 19, 18, 14, 15, 16, 17, 6, 3, 7, 9 and 20. Good results were obtained especially with Subroutine 4 in the simulation. (See Figs. 4-30 (a) and (b).)

4.3.5.4 Run E - 04/08/77 (tracer release period 10h22 - 17h46)

From early morning to about 10h30 all the masts recorded NE-E wind directions. The directions changed through SE and SW, and by 12h00 all were fluctuating SE-SW-NW without any visible tendency, remaining like that until the end of the run. A weather balloon with radiosonde released at 14h10 indicated a SW wind from ground level to 2 000 m. The wind field during the run is given in Figs. 4-31 (a) to (d). Fig. 4-31 (c) and Fig. 4-31 (d) show how the wind-field patterns alternated during the same period.

Two sets of samples at long distance were taken during the
periods 11h00 to 16h00 ($\bar{u}$ - 0.5 to 5 m.s$^{-1}$, $\delta \theta/\delta z$ = -2 to -10 K(100 m)$^{-1}$), and 14h00 - 18h30 ($\bar{u}$ - 0.5 to 5 m.s$^{-1}$, $\delta \theta/\delta z$ = -11 to +6 K(100 m)$^{-1}$; the positive lapse rates during the evening). The radiosonde released at 14h10 indicated a near neutral atmosphere in the lower 1 400 m, with an inversion "lid" above this region (temperature increase with height of inversion layer 7°C in 350 m).

Samplers 4, 18, 19, 3, 7, 9 and 20 were activated during period 1, and 12, 5, 13, 6, 14, 15, 16, 17, 18 and 19 during period 2. A fairly good correspondence between calculated and observed air concentration values was obtained, with most calculated values within a factor 10 of the corresponding observed values (8 out of 12, excluding those where both were "zero"). (See Figs. 4-32 (a) and (b).)

An explanation for the fact that positions 3 and 9 (period 1) gave zero concentrations in the simulation could be because the wind field in the simulation suddenly changed at 11h00, switching the plume trajectory rapidly from an over-water to an over-land one, passing these samplers more rapidly than the "real" plume did, without affecting them significantly.

4.3.5.5 General conclusions on tracer runs in fluctuating wind fields

The most important characteristics of wind fields under these conditions are wind directions varying over 90° to 360° sectors in short time periods, as well as generally low wind speeds. An important component of such winds is the sea breeze (SW) which at times may penetrate only a few kilometres over the land and sea, influencing only those masts near the west coast. The sea breeze occurs during periods with weak pressure gradients which may
Fig. 4-25. Wind field during tracer run B (13h00 - 17h00).

Fig. 4-26. Tracer concentration results, run B. 14h00 - 16h30 (30/7/77).
Fig. 4-27(a).
Wind field during tracer run C (13h00 – 15h30).

Fig. 4-27(b).
Wind field during tracer run C (15h30 – 16h30).

Fig. 4-27(c).
Wind field during tracer run C (18h30 – 21h30).
Fig. 4-28(a).
Tracer concentration results, run C, period 1: 14h00 - 19h00 (31/7/77).

Fig. 4-28(b).
Tracer concentration results, run C, period 2: 19h00 - 21h30 (31/7/77).
Fig. 4-29(a).
Wind field during tracer run D (10h00 - 12h30).

Fig. 4-29(b).
Wind field during tracer run D (12h30 - 16h30).
Fig. 4-30(a).
Tracer concentration results, run D, period 1: 11h00 - 14h30 (2/8/77).

Fig. 4-30(b).
Tracer concentration results, run D, period 2: 14h30 - 18h00 (2/8/77).
Fig. 4-31(a).
Wind field during tracer run E (10h00 - 10h30).

Fig. 4-31(b).
Wind field during tracer run E (10h30 - 11h30).
Fig. 4-20.
Wind field during tracer run CD (02h30 - 09h30).
Tracer release rate normalised to 1 kg. s\(^{-1}\)
Units of concentration in kg. m\(^{-3}\) x 10\(^{-6}\)

- **Experimental values**
- **Subroutine 1**
- **Subroutine 4**
- • Samplers activated during run
- ◦ Samplers activated with zero tracer sampled

Fig. 4.32(a).
Tracer concentration results, run E, period 1: 1100 - 1600 (4/8/77).
TRACER RELEASE RATE NORMALISED TO 1 kg. s⁻¹
UNITS OF CONCENTRATION IN kg. m⁻³ × 10⁻⁸

1 EXPERIMENTAL VALUES

SUBROUTINE 1
SUBROUTINE 4

SAMPLERS ACTIVATED DURING RUN
SAMPLERS ACTIVATED WITH ZERO TRACER SAMPLED

Fig. 4-32(b).
Tracer concentration results, run 2, period 2: 14h00 – 18h30 (4/8/77).
just balance out the effects of the land-sea temperature differences, causing sudden changes from SW to SE and back to SW, or SW to NW. See also the discussion in Section 4.3.3. Complex and fluctuating wind fields are also caused by the presence of coastal low-pressure systems. The observed wind-field patterns and the results of the tracer runs show the importance of having a model utilising computational means to take continuous trajectory changes with time and distance into account when calculating concentration levels during a short-period radioactive release. Fairly good correspondence between predicted and observed ground-level concentrations can be obtained when using the model described here, partly due to the large sectors covered by a plume under such conditions, and the accompanying easing out of peak concentrations.

4.4 DISCUSSION OF AND CONCLUSIONS FROM THE KOEBERG ATMOSPHERIC STUDY RESULTS

4.4.1 Choice of a Turbulence Classification Scheme

Table 4-2 gives the averages of the calculated to experimental ratios for the short-distance runs, obtained with the two subroutines, as well as the ratios of the integral \( \frac{1}{B_0} \int X dy \) for the calculated and experimental results. (Results from runs BB and BC, although not discussed earlier, are also presented.) This integral is obtained by normalising all concentration values as if the samplers were on an arc, all at the same distance from the release point; a summation is made of all the concentrations (on the arc) multiplied by the distances between the samplers. The Briggs' relationships for the determination of the dispersion coefficients, and the turbulence classification scheme based on lapse rate alone, as used in this study, adequately describe turbulence diffusion in the area under study (see Table 4-2). Superimposing the effect
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of wind speed (Subroutine 4 results) in most cases improved the results or gave the same concentration values, or, at worst, gave the more conservative (overestimated) air concentrations.

Figs. 4-33 to 4-37 show comparisons of the predicted and measured concentration values from all the tracer runs, at long- and short-distance samplers. (Note that, (i) the results from run CC and run BF, short-distance samples, are not given in the figures, and (ii) concentration values smaller than 0.01 ng.m\(^{-3}\) is indicated as 0.01 on the appropriate axis.) The following points are clearly apparent from these results:

- The correlation between predicted and measured values obtained during positive lapse-rate conditions in S-SE winds (Fig. 4-34) and land-breeze conditions (Fig. 4-36) is generally poorer than that obtained during negative lapse rates (Fig. 4-33).

- During fluctuating wind fields (Fig. 4-37) an unusually large number of calculated values showed predicted concentrations ≤ 0.01 ng.m\(^{-3}\) while the corresponding measured values were larger than this. Furthermore, the coordinate points in Fig. 4-37 show a steeper gradient than expected. These results can be explained by the broadening of the plume due to directional wind shear and the large random wind-direction fluctuations not adequately considered by the model. The determination of \(\sigma_y\) is difficult under these directional wind shear conditions. A solution is to obtain \(\sigma_y\) from the simultaneous readings at more than one level on the weather mast by means of e.g. a sigma computer.

- In Fig. 4-35 (NW winds) about half of the points to be
Fig. 4-33. Comparison of predicted and measured mean concentrations for tracer runs in S-SE winds — negative lapse rate.

Fig. 4-34. Comparison of predicted and measured mean concentrations for tracer runs in S-SE winds — positive lapse rate.

Fig. 4-35. Comparison of predicted and measured mean concentrations for tracer runs in NW winds.

Fig. 4-36. Comparison of predicted and measured mean concentrations for tracer runs in the land breeze/gravity wind.

Fig. 4-37. Comparison of predicted and measured mean concentrations for tracer runs in the sea breeze/fluctuating wind fields/SW winds.
found on the graph axes are from runs in a positive lapse rate, while only a third of all samples taken are from runs in such (stable) atmospheric conditions.

The large fluctuations in wind direction that occur, as well as other factors which broaden the plume, require the use of $\sigma_\theta$ as a diffusion parameter. The use of lapse rate in light wind-speed conditions should be considered, as proposed by Raynor et al (1979). One possible scheme to be proposed here, based on arguments given above, is to use $\sigma_\theta$ for the determination of $\sigma_y$ and a derivative of the Richardson number or Monin-Obukhov stability length for $\sigma_z$.

From the short-distance tracer concentration results it appears that instead of using half-hourly averaged wind data, averages over shorter time periods will give better results at points near the source in continuously fluctuating wind fields.

From our present knowledge it seems imperative to use the lower two measuring levels (10 and 46 m) on the Koeberg mast for lapse rate determinations, due to the shallowness of the IBL at the mast (~10% of the time of the order of 50 m). More work should be done in studying the IBL experimentally.

4.4.2 Plume Trajectory Uncertainty and Need for a Model

Due to the large changes in wind direction which may occur in time and distance from the source, as discussed above, there seems to be a need for a model capable of taking trajectory into account and requiring a suitable computer on account of the magnitude of the fluctuations in wind direction over the long periods involved. The
model used for simulation of the tracer runs described in this study seems to be able to describe most of the wind-field types studied. The model broke down mainly in stable land-breeze conditions with significant directional wind shear near the surface.

Only when the land-breeze layer is sufficiently thick and extending relatively far out to sea, and on condition that the bulk of the effluent stays entrained in this layer, can a reliable estimation be made of plume trajectory (over a few tens of kilometres of the trajectory in any case). The problem is that the depth of the land breeze is mostly of the order of metres or tens of metres only, while the release point can vary from ground level to about 70 m. The possibility of airborne effluent entrainment in the wake of the building(s) is a further complicating factor. This situation (a shallow land-breeze layer) may be complicated by a change in layer depth with time (see discussion on run CC) and with distance. The possible trajectory of a plume released into a land-breeze layer is illustrated in runs CD, CE and CG; depending on the depth of this layer and the strength of the wind, tracer/airborne effluent may be transported for tens of kilometres or only a few kilometres out over the sea before the gradient wind (normally SE or NW) may transport the airborne matter further in the new direction. Coriolis forces may also play a role in trajectory changes, especially with low wind speeds.

Wind-shear effects may set in at very short distances from the release point. An important situation, mentioned earlier, is where a very shallow (a few metres) land breeze exists, which may not be experienced at the measuring points. This phenomenon cannot be easily
handled by a numerical model. There may thus be a need for a lower level wind recorder or other means, such as a fog or smoke generator, to observe the existence of such winds when needed. A smoke generator may be of considerable assistance in defining the plume trajectory for short distances from the source under conditions with wind shear near the surface, and to investigate the effects of the buildings on the site on plume behaviour.

With regard to wind shear at higher levels more experimental work should be done in the Koeberg-Cape Town area by means of devices such as tethered balloons.

For the reasons discussed above, a model for use with short-term releases should make provision for changing diffusion parameters at various distances from the release point, and also be able to take into account stable layers aloft. Such layers are experienced to within 50 - 100 m from the surface at the coastline for more than 10% of the year.

There are relatively sophisticated trajectory models which take into account, for example, topography, the synoptic pressure gradient and surface temperature differences, and which can be utilised to determine wind patterns in the vertical. The increase in predictive accuracy to be expected with such a model is currently being investigated. A major disadvantage in using this class of models is that they are costly in computer time and memory, and that currently existing programs cannot be used on a real-time basis. It is furthermore doubtful if these models will be able to handle adequately complex situations with a very shallow land breeze.
4.4.3 The Study of Macro Weather Systems and Optimum Mast Positions

Other workers, such as Draxler (1979a), have proposed the use of a set of more than one weather mast to determine plume trajectories on a meso scale. Draxler suggested a network of such stations with a spacing of 25 km to be necessary to handle complex flow features. Raynor et al (1979) proposed the use of at least two secondary masts at a suitable distance from the coastline, where measurements representative of conditions in the unmodified air can be determined on either side of the coastal internal boundary layer.

An investigation is currently being carried out on optimum positions for satellite meteorological masts in the area. The data from various combinations of masts in the present meteorological system are used in simulations of plume behaviour during tracer runs performed, and compared with actual tracer results. In this way, it may be possible to select two or three positions for secondary masts.

A correlation between surface wind fields and synoptic data supplied by the Weather Bureau should furnish additional information on plume trajectories to be expected during specific synoptic conditions, thus decreasing the reliance on satellite masts and giving information on expected plume movement at least a few hours in advance. A comparison of synoptic data with surface wind-field data obtained from the present system of meteorological masts is being done at present.
CONCLUSION

A relatively unsophisticated Gaussian dispersion model, based on the so-called segmented-plume approach, for determining air concentrations of airborne effluent at ground level down-wind from a source, was developed and tested with experimental data. Plume trajectory was incorporated with the assistance of an interpolation scheme which calculated the resultant wind for all plume segments from a number of weather masts. A simple turbulence typing scheme, using lapse rate only or lapse rate and wind speed, was used in the atmospheric study in the Koeberg area. The model, utilising three approaches for the determination of dispersion coefficients (two simple schemes and one based on stability length theory), was first applied using experimental data from tracer work done in the Richards Bay area. Plume trajectories were generally less complex than in the Koeberg area, and good results were obtained, especially under less stable atmospheric conditions. Although stability length theory improved the results obtained during stable atmospheric conditions over distances less than approximately 5 km, the results over longer distances under these conditions, and results over all distances under neutral to unstable conditions, were not significantly improved relative to results from the simpler approaches. The model was adapted for the Koeberg study, and was found to give good results at distances up to 30 km in all those atmospheric conditions prevailing most of the time. In certain more complex wind fields encountered in the Koeberg area, such as with sea or land breezes experienced on the coast, and with rapidly changing wind patterns, when wind data at a number of points in the area were taken into consideration, the results showed larger deviations from the measured ones but were of acceptable accuracy. In certain very
complex atmospheric conditions, e.g. with very shallow (2-50 m deep) katabatic air-flow layers and thus marked directional wind shear near the surface, no meaningful simulation of plume transport could be done. In a shallow sea breeze the plume may be markedly broadened by wind shear, resulting in tracer being spread over a bigger area than that predicted by the model. However, during land breeze conditions there were occasions when tracer was detected in directions not expected from the available wind data. Under these conditions, and with the available data, even more sophisticated models cannot be expected to give good results. Fortunately, these complex atmospheric conditions only prevail very infrequently (probably < 10% of the time) and can be characterised. Only in very stable katabatic flow at Richards Bay, and only at distances shorter than 5 km from the source (with a 25 m release height), did stability length theory produce significantly better dispersion results than the simpler ways by which to determine the dispersion coefficients. The former approach was not utilised in the dispersion model used for the Koeberg study due to the fact that in very stable conditions, releases on the coastline would normally be taken out to sea within about 100 m from the source.

The Koeberg-Cape Town area was generally a more complex region for such a study than that at Richards Bay, mainly because of the longer distances involved in the former case and the much more complex weather systems, wind fields and topography encountered. It is of special significance that the effects of directional wind-shear near the surface were found to be not nearly as severe in the Richards Bay area as in the Cape.

In strong gradient winds (SE and NW directions) topography,
i.e. elements such as mountains and dunes, did not seem to play a marked role in changing plume trajectories from Koeberg. In lighter winds directional wind shear, very often encountered from the early evening to the morning, and sometimes even in the middle of the day, had a marked effect in distributing airborne tracer to positions far from the expected plume path. For this reason the dispersion model was not complicated by incorporating topography.

The dual-tracer experimental technique to be used with the surface-depletion deposition model developed here showed promise, and was initially intended for use in the Koeberg study. This model was found to give reasonably good results in the Richards Bay area when using published deposition velocity values over areas with little or no vegetation and over areas with grass and low shrubbery only. With the numerical simulation of plume depletion over bushy and forested areas too high depletion rates were obtained. If the computer program were modified to adjust the deposition velocity values by iteration, and with a suitable dual-tracer experimental program to supply input values for the model, a method could be devised to characterise the scavenging potential of specific surface types. The respective deposition velocities of the two tracers should be sufficiently different to provide concentration ratios far from unity, as measured near ground level. This dual-tracer technique was not applied in the Koeberg study for the following reason: The expected large variations in the ground level concentration ratios of the two tracers, as was found in the Richards Bay study, will necessitate the taking of large numbers of samples under a variety of atmospheric conditions and in a number of relevant sectors, requiring an excessive effort. Also, a lack of resources and manpower and the
higher priority given to the plume trajectory and dispersion investigation forced the decision to postpone the experimental work on deposition.

For the experimental work, a tracer-generating apparatus was developed by which a very fine indium aerosol (count-median diameter 0,02 μm, mass-median diameter 0,07 μm) can be released by evaporating an alcoholic solution of indium chloride at 1 000°C. Also developed was an analytical procedure by which small indium concentrations (< 0,1 ng) in air-filter samples could be determined quantitatively by means of neutron activation and solvent extraction. Good results were obtained with these techniques, and they were used throughout the experimental program. There are several advantages, such as cost and ease of tracer release, in using inert gas tracers, and such techniques may be considered for use in future atmospheric studies. The advantages of particulate tracers lie in the easier sampling of large air volumes for extended time periods and in the fact that certain phenomena such as dry deposition cannot be imitated by an inert gas.

The tracer experimental work was a valuable tool in the atmospheric studies performed, as regards the verification of turbulence typing schemes and numerical dispersion and deposition models. It was also found to be most useful in the investigation of certain complex phenomena such as wind shear. While specific turbulence typing schemes are often used without prior verification for certain regions, the role of topographical and wind shear effects in a complex region (from a meteorological/topographical point of view) such as the Cape Town area, requires information on plume trajectories, which can only be obtained by means of tracer experiments.

This work has progressed to the point where little additional information would be obtained by extending the experimental tracer work. Rather more effort
should be put into the measurements of vertical wind and temperature profiles, especially in situations of complex atmospheric conditions. This part of the study commenced during the winter of 1980 when two or three tethered balloons fitted with instruments for measuring such profiles, anchored by 500 m long cables to motor vehicles on land and sea, were used to do simultaneous measurements at a number of points in the area of interest. At the same time weather balloons with radiosondes for measuring winds, temperatures, air pressures and humidity were released from a point at Koeberg to gather additional information to a height of a few kilometres. Data obtained can be used either qualitatively or quantitatively in a numerical model for simulating air movement in three dimensions.

From the present study it would seem that at least two or three weather masts in addition to the one at Koeberg will be necessary to define plume trajectories in wind fields of "intermediate" complexity. Part of the ongoing study will be directed towards determining optimal positions for other masts, as well as establishing correlations which may exist between the macro weather systems (from data supplied by the Weather Bureau) and surface wind fields, thus enabling a worker to predict, at least partly, relevant wind fields - and thus plume trajectories - from macro weather data. The present system of masts is continuously gathering data for this purpose.
APPENDIX A

TELEMETRY SYSTEM FOR METEOROLOGICAL DATA GATHERING
(J. Starkey, 1978)

A1 INTRODUCTION

This telemetry system was originally developed and built for the Department of Chemical Engineering, University of Natal by the then Instrumentation Division of the Atomic Energy Board.

The system consists of three units, viz. (i) central data gathering and control unit (known as the Transmitter Station); (ii) 10 Satellite Stations each equipped with wind-speed, wind-direction and temperature-measuring devices; (iii) automatic switching unit which is used to change filters remotely on the aspirators at each satellite station.

A2 TRANSMITTER STATION

The Transmitter Station is the heart of the telemetry system which has been designed to gather meteorological data. Included in the system are 10 Satellite Stations which are deployed in the area to be investigated, and which gather weather data at their respective sites. This data is redisplayed on numerical readouts and recorded on magnetic tape.

By broadcasting 10 characteristic tone signals, the Transmitter Station is able to interrogate each Satellite Station individually, and it does so in a scanning mode. Every 15 s, a tone code is generated with a duration of
one second, and the corresponding Satellite Station responds by sending back its data to the Transmitter Station. All the Satellite Stations are interrogated in this way, and it thus takes 150 s to make one scan of all 10 stations. Two extra "time slots" are included in the scanning sequence, bringing up the overall cycle time to 180 s.

Radio transmission is carried out over commercial 5W VHF transceivers, and data is encoded in the form of frequency-modulated FSK signals. Five data quantities are recorded at each Satellite Station, and these are displayed on individual readouts at the Transmitter Station. Information is displayed as it is received from a station, and it remains on the display unit until replaced by new information from the following station.

A tape recorder forms a permanent record of the received data, together with timing information. By means of a suitable interface this recorded data can be replayed directly into the "event counter" of a computer for processing. Recently (1978) a printer was built by the then Instrumentation Division to print the incoming data directly on strip chart. This printer is programmed to either give the data out directly, or, if so preferred by the operator, to print out data averaged over 2, 5, 10 or 20 cycles.

During one of the extra "time slots", one of four selectable auxiliary tone signals can be transmitted, thus enabling certain switching functions to be performed at the Satellite Stations.

A3 SATELLITE STATIONS

Each Satellite Station gathers temperature and wind infor-
information at its specific location, and transmits the data via a radio telemetry link to the central unit. By strategically placing the various stations in a given area, it is possible to obtain weather data over the entire area. Data from any specific stations are updated every three minutes. The latest data received from each station are displayed at the Transmitter Station as they are received. The instruments at each Satellite Station comprise two anemometers, two temperature sensors, and a wind direction vane, all mounted on a steel mast. A temperature sensor and an anemometer are mounted at 10 m and at 2 m respectively and wind direction at 10 m only. Temperature data are displayed as the "lower" temperature and the "differential" temperature between the two sensors. Due to the long distances over which Satellite Stations were deployed, a repeater link had to be installed at a strategic position to relay data between the main station and the various Satellite Stations.

A4  AUTOMATIC SWITCHING UNIT

In atmospheric dispersion tests, tracer materials introduced into the atmosphere are collected on filters, and subsequently detected by particle counting, neutron activation, or some such technique. During such tests the filters are mounted on portable aspirators which are deployed at selected sites within the area to be investigated. To obtain data about the time of arrival of the collected material, it is necessary to change the filters periodically. This operation is often inconvenient owing to the considerable distance which may separate the various aspirators, and in some cases, their relative inaccessibility.

The function of the Remote Filter-Changing Units is to
effectively change the filters at several remote sites by means of the telemetry system. Clearly an aspirator can only be operated via the telemetry system if it is situated at one of the Satellite Stations.

The units allow one to select one of four filters initially mounted on each aspirator. The selection is made by means of a rotary switch on the telemetry central station. Depending on the switch position, the station periodically transmits one of four tone signals, and on receipt of such a tone, the Remote Filter-Changing Unit opens a solenoid-activated valve, thus drawing air through the chosen filter.

Logic circuits within each unit prevent more than one valve from being open at any time. The aspirator pump motor is arranged to run if and only if any one valve is open.

A5 PRINCIPLE OF OPERATION

A5.1 Transmitter Station

Broadly speaking the function of the Transmitter Station can be divided into two parts:

(a) timing and sequencing circuits which control the overall operation of the telemetry system;

(b) decoding and display circuits which interpret the data received from the Satellite Stations.

A5.1.1 Timing and sequencing circuits

The output of a 1 MHz crystal oscillator is divided in frequency to 1 Hz, and then fed to a modulo-15 four-bit
binary counter termed the time counter. By decoding the count of 14 in this counter, a one-second pulse is derived at the end of each 15-second period, and this signal is used to key the transceiver to the transmit mode. A further four-bit binary counter, the station counter, is clocked at the end of each 15-second period. This counter is designed to be modulo-12, and its 12 states correspond to the 12 "time slots" in the scanning sequence.

The tone generator consists of a number of Microfork ceramic tuning-fork resonators which can be switched into an oscillator circuit by means of miniature reed relays. Decoding circuits select the appropriate tone resonator depending on the state of the station counter. Consequently, the oscillator frequency corresponds with the current state of the station counter. Owing to the high Q-factor of the resonators, the oscillator circuit takes a considerable time to stabilise when a new resonator is selected. For this reason the tone to interrogate a station is actually broadcast during the final second of the period assigned to the previous station. Thus the tone for station one is broadcast when the station counter is in state 0, and so on.

The state of the station counter is displayed as a decimal number with the data, thus enabling one to identify data with its station of origin. By the time a Satellite Station responds to its tone signal and starts to transmit data, the station counter at the Transmitter Station will have advanced to correspond with that station.

Overall time information is maintained by effectively counting the number of three-minute scan cycles in a three-digit BCD counter called the period counter. Ultimately, the stored data are replayed from the tape...
record into the event counter of a computer. This latter device can conveniently accumulate counts of up to 256. Since there are more than 256 three-minute intervals in a day, the signal from the station counter which clocks the period counter, is first divided by two in frequency. Thus this latter counter increments only every second scanning cycle, and its output at any time corresponds to the number of completed six-minute intervals since the start of the record. This output is also displayed with the telemetry data. A pre-settable initial value is read into the period counter at the start of any record.

A5.1.2 Decoding and display circuits

The output signal from the transceiver at the Transmitter Station is fed to an FSK demodulator which regenerates the various pulse trains of data from the Satellite Station. Five such strings of pulses are produced by each station when it is interrogated, and the number of pulses in each string corresponds to the quantity of data encoded.

To display the various data quantities, the incoming pulse strings are fed into successive display counters whose output constitutes the numerical display. Special "allotting" circuits direct the various pulse strings to the appropriate display counters. Provision is made to clear each display counter shortly before data is fed into it.

To initiate a recording sequence, it is only necessary to turn the instrument on, set up the day and period numbers on the thumbwheel switches, and press the start button. The cycle switch must be in the up position. Only after the second scan of the 10 stations will reliable data be received from them. During the eleventh
time slot an auxiliary tone code may be transmitted, and the frequency of this tone can be selected from one of four values by means of the auxiliary tone rotary switch on the front panel.

A5.2 Satellite Stations

A5.2.1 Radio link and data coding

Each Satellite Station houses a VHF radio transceiver which is normally in the receive mode. The transceiver output, taken from the extension speaker socket, is fed to a narrow-band piezo-electric filter, which transmits only the tone frequency corresponding to its own station. When such a tone is sensed, a "transmit cycle" is initiated. This lasts for about 10 s and is controlled by a local timing circuit within the Satellite Station. During the transmit cycle, the transceiver is switched to the transmit code, and the five data quantities pertaining to the Station are transmitted sequentially via the repeater station to the central unit.

The ten-second transmission period is divided into five time slots - one for each data quantity (temperature, wind speed, etc.). The circuit for each data quantity incorporates a latch which is set at the start of its respective time slot by the control circuit. The instrument circuit itself resets the latch after a period proportional to the data quantity to be coded. A "modulator" circuit receives the five latch signals sequentially and "OR's" them together, after which the composite signal is gated with a 100 Hz clock signal. Thus five pulse trains are generated, the lengths of which correspond to the five data quantities to be coded. Gaps between the various pulse bursts serve to identify the different quantities.
A further circuit converts the 100 Hz pulses to a frequency-shift-keyed signal, the frequencies 1 kHz and 1.2 kHz corresponding to logical 0 and 1 respectively.

A5.2.2 Wind-speed recording

Wind speed is measured with Weather Measure W103-3L sensitive anemometers. These instruments give a pulse for each revolution of the cup head. During the three-minute interval between successive transmit cycles, these pulses are accumulated in an up-down counter. To read out the average wind speed in the appropriate time slot of a transmit cycle, the counter is counted down to zero using a 100 Hz clock signal. As soon as zero is reached the circuit latch is reset and the next averaging operation begins.

To allow for a wide range of wind speeds a "scaling counter" is included which enables one to divide the incoming signal frequency by 1, 2, 4, 8 or 16. Thus the full scale range of the coded signal can be altered by the above factors. Such a scale change is performed by altering a jumper connection on the circuit board.

In the absence of wind, zero pulses would accumulate in the up-down counter. This would confuse the data-coding system, and consequently a special circuit is provided which extends the "on" period of the latch by 40 ms. The result is the effective adding of four pulses to each pulse train generated.

A5.2.3 Temperature recording

Air temperature is measured by platinum resistance sensors mounted within suitable aspirators. The sensing elements are coupled in bridge-type circuits, and miniature
reed relays select the respective inputs for the two temperature readings. The millivolt input signals are amplified by a differential-input operational amplifier.

This amplified signal is compared with the output of a digital-to-analogue converter, and the latter is driven from a counter. As soon as the circuit latch is set, the counter is counted up from zero using a 100 Hz clock signal. A ramp signal is thus produced, and when the digital-to-analogue converter output reaches the input signal level, the latch is reset and the counter returned to zero. Hence the time for which the latch is set is proportional to the input signal.

As in the case of the anemometer circuits, a special delay is generated which effectively adds four pulses to the output signal.

A5.2.4 Wind-direction recording

The wind-direction encoder consists of a direction-sensitive vane, the shaft of which carries seven optically coded discs. Combined light sources and detectors at the rim of each disc detect clear and opaque sectors of the disc, and thereby generate a Gray-type code of the shaft position. Logic circuits convert the position information to a binary number, and this is sampled and accumulated at intervals of 2.56 s. Sixty-four such samples are accumulated during each three-minute period, and by effectively dividing the total count by 64, an averaged value is obtained.

Normally, one or more complete rotations of the vane would confuse the simple procedure outlined above. Consequently, special circuits are provided which
effectively extend the direction scale over four complete revolutions, and thereby allow for a limited number of "north-point crossings".

A5.3 Automatic Switching Unit

Under normal operation, the telemetry system transmits a "filter tone" for a period of one second at intervals of three minutes. Thus after changing the filter select switch, it will be necessary to wait for a period of up to three minutes before the newly selected filter becomes active.

The speaker output signal, from the radio transceiver at the Satellite telemetry station, is fed to four narrowband piezo-electric "tone filters" which respond to the four filter tones. Detectors at the output of the tone filter generate logic signals when the various tones are received.

These logic signals are fed to a multiple latch which has four outputs so connected that if any one is set, the remaining three are reset. The latch outputs control the solenoid valves which regulate the air flow through the filter elements. When one of the latch inputs is activated, the corresponding output is automatically set, and thus all remaining outputs are reset. Thus as soon as any filter tone is received, the appropriate valve will open, and any other valve which was open, will close.

A timer is included in the device which is triggered or retriggered whenever a tone is sensed by one of the detectors. It has a period of approximately four minutes, and thus remains set when a filter is selected. However, if filter tone signals cease, then the timer will even=
tually reset, and in so doing it automatically resets all four latch outputs.

Power is fed to the pump motor in each aspirator via a relay in the Remote Filter-Changing Unit. The relay coil is energised by a diode network which OR's together the voltages on the solenoid valves. Thus the motor runs whenever any one of the valves is open. Indicating lights show which valve, if any, is open.

Provision is made to operate the system manually if desired. A single six-position rotary switch on each unit controls the device as follows:

<table>
<thead>
<tr>
<th>Switch position</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>System disabled. All valves closed.</td>
</tr>
<tr>
<td>REM</td>
<td>System operates via telemetry</td>
</tr>
<tr>
<td>1</td>
<td>Valve 1 open</td>
</tr>
<tr>
<td>2</td>
<td>Valve 2 open</td>
</tr>
<tr>
<td>3</td>
<td>Valve 3 open</td>
</tr>
<tr>
<td>4</td>
<td>Valve 4 open</td>
</tr>
</tbody>
</table>

A5.4 **Repeater Link** (only used in Koeberg studies)

A repeater with a 20 W output receives data on 59.9 MHz and transmits on 54.5 MHz. A UHF transceiver at the Transmitter Station transmits at 462.7 MHz; the transmission is received by a UHF receiver at the repeater, which is coupled to a VHF transmitter transmitting on 54.5 MHz. The transceivers at the Satellite Stations receive this signal and then transmit the coded data on 59.9 MHz which are received by the VHF transceiver at the repeater. The signal is then transmitted by the UHF transmitter at the repeater and received at the Transmitter Station on 452.7 MHz.
NOTES ON THE FLOW-DIAGRAM OF THE DISPERSION COMPUTER PROGRAM (Computer program devised by G.W.J. van der Berg)

1. Various control values are read: (a) the number of half-hours the simulation is to run; (b) the number of intervals each sub-plume will be divided into for concentration calculation; (c) the number of the subroutine to be used to calculate \( \sigma_y \) and \( \sigma_z \); (d) the number of masts used from which wind-direction and wind-speed data are obtained (NREF); (e) the number of points for which concentrations must be calculated; and (f) the size in minutes for the duration of each sub-plume.

2. The flow-diagram box is a non-standard symbol for a loop; in this case Do .... NP = 1, MAXP; in FORTRAN the assertion NP \( \leq \) MAXP is a test for the end of the loop. If it is true the bottom exit is taken.

3. The decision to read data is arrived at by means of the following argument:

A value, NPM, is calculated by

\[ NPM = \text{MOD}(\text{NP}-1, \text{KINT}) \]  

where the MOD function is defined as the remainder after division of NP-1 by KINT,

NP as in the flow-diagram,

KINT = the number of sub-plumes in a plume.

If NPM = 0, the 'T' exit of the decision box is taken and data is read.

If NPM \( \neq \) 0, a sub-plume is being generated and
The reason for this decision is that some masts frequently become inoperative for a time, with loss of data. The easiest way to overcome the problem is to interpolate from the masts that gave correct data. The interpolation scheme used is that discussed in Section 3.1.3.1 in the text.

5. The increment from $\theta_s(I)$ to $\theta_e(I)$ is determined with $\text{AINCR}(I) = (\theta_s(I) - \theta_e(I))/\text{TLINT}$, where \text{TLINT} is the floating-point equivalent of \text{KINT}, defined in note 3.

6. $x$ and $y$ are arrays that contain the $(x,y)$ coordinates respectively of the start and end of each sub-plume. When the first sub-plume is generated the situation is that of Fig. B-1. With the interpolated values of $\theta$ and $R$, $x_f$ and $y_f$ are calculated:

$$x_f = R \sin \theta$$
$$y_f = R \cos \theta.$$

These points denote the $(x,y)$ coordinates at the end of the sub-plume interval. The $x$ and $y$ increments are given by

$$\text{XI} = (X(1) - x_f)/\text{TINT}$$
$$\text{YI} = (Y(1) - y_f)/\text{TINT},$$

where $\text{TINT}$ is the number of intervals into which a sub-plume must be divided (see note 1(b)).

7. Fig. B-2 shows exaggeratedly what the situation might be at the end of sub-plume 1. $R_1$, $\theta_1$ is
DEVELOPMENT OF THE SUB-PLUMES
the direction in which the new sub-plume \( R_1 \) will move. A particle at point \( (x(2), y(2)) \) will move in the direction of \( R_2 \) at an angle of \( \theta \), determined by means of the interpolation of the wind field at \( (x(2), y(2)) \). The whole sub-plume \( R \) will thus move towards \( R' \), as sub-plume \( R_1 \) is formed. The dotted lines show how sub-plume \( R \) changes as sub-plume \( R_1 \) is formed.

The concentration at a point in the "shadow" (see note 8) of both sub-plumes will be calculated at 10 (or another suitable number - note 1(b) - input) consecutive positions during the movement of \( R \) to \( R' \).

8. A point is defined to be in the "shadow of a plume" (i.e. a concentration calculation due to the effect of the plume on this point has to be made) if a line from that point can be drawn perpendicularly onto the plume. Thus, in Fig. B-3, point \( P \) is in the shadow of the plume, while point \( p' \) is not. The distance, \( D \), is given by

\[
D = \frac{(x_m - x_p)^2 + (y_m - y_p)^2 - (x_L - x_p)^2 - (y_L - y_p)^2 + (x_m - x_L)^2 + (y_m - y_L)^2}{\sqrt{(x_m - x_L)^2 + (y_m - y_L)^2}}.
\]

If \( D > 0 \) and \( D < \) the length of the plume, that point is considered to be in the shadow of the plume.

The distance, \( Y \), of the point from the plume is given by

\[
Y = \sqrt{(x_m - x_p)^2 + (y_m - y_p)^2 - D^2}.
\]

Using \( D \) and \( Y \), as well as \( \sigma_y \) on \( \sigma_z \) and the interpolated wind speed, the concentration for the point can be calculated as discussed in Section 3.1.3.
9. DT/DZ is the lapse rate in °C/100 m, T0 is the temperature at ground level and TZ21 is the temperature difference between the sensors at 2 heights (Z₁ and Z₂).

The flow-diagram is given in Figs. B-4(a) and (b).
CO-ORDS OF POUTS
FOR CONCENTRATION CALCULATION

INITIAL WIND DIRECTION
\( \theta_{0} \) = W N W

DETERMINE INCREMENTS FROM & III TO f^lll. 1 = HREF

INTERPOLATE FOR I

Fig. B-4(a).
Flow-diagram of dispersion program.

Fig. B-4(b).
Flow-diagram of dispersion program — continued.
A SUBROUTINE FOR THE NUMERICAL SOLUTION OF THE GENERAL LINEAR PARABOLIC EQUATION IN ONE SPACE DIMENSION IF THE COEFFICIENTS ARE NOT TIME-DEPENDENT (J.D. Neethling)

The following problem is to be solved: \( y = y(x,t) \) is sought such that

\[ \frac{\partial y}{\partial t} = A(x) \frac{\partial^2 y}{\partial x^2} + B(x) \frac{\partial y}{\partial x} + C(x)y + f(x,t) \]  

(1a)

with \( x \in (a,b) \), \( 0 < t \leq t_f \) subject to the boundary values

\[ py(a,t) + ay_x(a,t) = \phi_a(t) \]  

(1b)

\[ qy(b,t) + By_x(b,t) = \phi_b(t) \]  

with \( t > 0; \alpha, \beta \) either 0 or 1 and initial values

\[ y(x,0) = g(x) \]  

(1c)

In order to apply Douglas' method, the equation is brought to another form by means of the transformation

\[ y(x,t) = A(x)X(x)V(x,t) \]

with \( X \) chosen to eliminate the first space derivative. This is achieved by putting \( X(x) = \exp\left\{-\int_a^x \frac{B(\tau)}{2A(\tau)} d\tau\right\} \) provided the integral exists. Equation 1 then becomes

\[ L(V) = \frac{\partial V}{\partial t} = \frac{\partial^2 (AV)}{\partial x^2} + \hat{C}.V + \hat{f}(x,t) \]  

(2a)

with \( \hat{C} = C - \frac{B^2}{4A} + \frac{BA'-AB'}{2A} + A'' \)

\[ \hat{f} = \frac{f(x,t)}{A(x)} \exp\left\{\int_a^x \frac{B}{2A} d\tau\right\} \cdot \]
Boundary values are
\[ \alpha V_x(a,t) + pV(a,t) = \phi_a(t) \quad \text{(2b)} \]
\[ \beta V_x(b,t) + qV(b,t) = \phi_b(t) \]

Initial values are
\[ V(x,0) = \hat{g}(x) \quad \text{(2c)} \]

with
\[ \hat{p} = \alpha \left[ \frac{2A'(a)-B(a)}{2A(a)} \right] + p \]
\[ \hat{q} = \beta \left[ \frac{2A'(b)-B(b)}{2A(b)} \right] + q \]
\[ \phi_a(t) = \frac{\phi_a(t)}{A(a)} \quad \phi_b(t) = \frac{\phi_b(t)}{A(b)} \exp\left[ \int_a^b \frac{B}{2A} \, d\tau \right] \]
and
\[ \hat{g}(x) = \frac{g(x)}{A(x)} \exp\left[ \int_a^x \frac{B}{2A} \, d\tau \right] . \]

We discretise the variables:
\[ x^0 = a, \quad x_{m+1} = x_m + h, \quad x_N = b, \quad t_{m+1} = t_m + k \]

and write
\[ V(x_m, t_n) = V^n_m \]

The t derivative is approximated with a Taylor series
\[ V^{n+1}_m = \exp(k \frac{\partial}{\partial t}) V^n_m \]

written in the form
\[ \exp(-\frac{1}{2}k\frac{\partial}{\partial t}) V^{n+1}_m = \exp(\frac{1}{2}k\frac{\partial}{\partial t}) V^n_m . \]

By (2a) we thus have
\[ \exp(-\frac{1}{2}kL) V^{n+1} = \exp(\frac{1}{2}kL) V^n \]
which on truncation yields:

\[- \frac{1}{2} k f_{n}^{m+1} + (1 - \frac{1}{2} k C_m) v_{m}^{n+1} - \frac{1}{2} k \frac{\partial^2}{\partial x^2} (AV)^{n+1}_m\]

\[= \frac{1}{2} k f_{n}^{m} + (1 + \frac{1}{2} k C_m) v_{m}^{n} + \frac{1}{2} k \frac{\partial^2}{\partial x^2} (AV)^{n}_m . \]

We now use the approximation

\[
\frac{\partial^2}{\partial x^2} \approx \frac{1}{h^{2} r} \frac{\delta_{x}^{2}}{1 + \frac{1}{12} \delta_{x}^{2}} \quad \text{and put } r = \frac{k}{h^{2}} .
\]

Pre-multiplying (3) on both sides with \(1 + \frac{1}{12} \delta_{x}^{2}\) gives:

\[
(1 + \frac{1}{12} \delta_{x}^{2}) \left[ (1 - \frac{1}{2} k C_m) v_{m}^{n+1} - \frac{1}{2} k f_{m}^{n+1} \right] - \frac{1}{2} r \delta_{x}^{2} (AV)^{n+1}_m
\]

\[= (1 + \frac{1}{12} \delta_{x}^{2}) \left[ (1 + \frac{1}{2} k C_m) v_{m}^{n} + \frac{1}{2} k f_{m}^{n} \right] + \frac{1}{2} r \delta_{x}^{2} (AV)^{n}_m .
\]

which yields the difference formula:

\[X_{i} v_{i-1}^{j+1} + Y_{i} v_{i}^{j+1} + Z_{i} v_{i+1}^{j+1} = R_{i}^{j} . \quad \text{(4)}
\]

with

\[X_{i} = \frac{1}{12} (1 - \frac{1}{2} k C_{i-1}) - \frac{r}{2} a_{i-1} = Z_{i-2}
\]

\[Y_{i} = \frac{5}{6} (1 - \frac{1}{2} k C_{i}) + r a_{i}
\]

\[R_{i}^{j} = (\frac{1}{6} - X_{i}) v_{i-1}^{j} + (\frac{1}{3} - Y_{i}) v_{i}^{j} + (\frac{1}{6} - Z_{i}) v_{i+1}^{j}
\]

\[+ \frac{k}{24} (\hat{r}_{n}^{m-1} - \hat{r}_{n+1}^{m-1} + 10 (\hat{r}_{n}^{m} - \hat{r}_{n+1}^{m}) + \hat{r}_{n}^{m+1} - \hat{r}_{n+1}^{m+1} ) .
\]

This tridiagonal system of equations is solved using the Thomas algorithm.

To deal numerically with the boundary conditions to the
same order of accuracy as the discretisation used above, use is made of a Taylor expansion which is given here for \( x = a \) (we set \( f = 0 \) for simplicity):

\[
y_1 = y_0 - h(y_x)_0 + \frac{1}{2}h^2(y_{xx})_0 - \frac{1}{6}h^3(y_{xxx})_0 + O(h^4). \tag{5}
\]

Whilst \( (y_x)_0 = y_x(a, t) \) may be found from (1b), \( y_{xx} \) and \( y_{xxx} \) must be eliminated using (1a).

We differentiate (1a) and let \( x = a \),

\[
\frac{3}{\partial t}(y_x) = \frac{3}{\partial x}(y_t) = Ay_{xxx} + (A' + B)y_{xx} + (B' + C)y_x + C'y, \tag{6}
\]

from which \( \frac{3}{\partial t}(y_x) \) is eliminated by using (1b):

\[
\frac{3}{\partial t}(y_x) = \frac{1}{a} \left[ \phi_a'(t) - py_t \right] \quad \text{at } x = a.
\]

\( y_{xx} \) is eliminated from (5) by use of (1a). Carrying through the algebraic manipulations, one obtains the equation \((a = 1)\):

\[
y_{t+1,0} = \frac{1}{\{pA_0h + [(A_0 + B_0)h - 3A_0]\}h^2} \left( y_o y_{t+1}^0 + Z_o y_1^{t+1} \right)
+ A_0 h^3 \phi_a^{t+1} + \xi o \phi_a^{t+1} \tag{7}
\]

with

\[
\xi_o = \left[ (A_o B_1 - B_o A_1 + A_o C_o - B_o^2)h^2 + 3A_o B_0 h - 6A_o^2 \right] h
\]

\[
y_o = p \xi_o - \left[ (A_o C_1 - A_0 C_o - B_0 C_0)h^3 + 3A_o C_0 h^2 - 6A_0^2 \right]
\]

\[
Z_o = -6A_o^2.
\]

Writing \( \Gamma_o = pA_o h + [(A_0' + B_0)h - 3A_0] \), \( \tau = \frac{k}{h^2} \)
discretisation of (7) with respect to $t$ yields:

$$y_{o}^{\ell+1} - y_{o}^{\ell} = \frac{\theta}{\Gamma_{o}} \{ y_{o}y_{1}^{\ell+1} + z_{o}y_{1}^{\ell+1} + A_{o}h^{3} \phi_{a}^{\ell+1} + \xi_{o}\phi_{a}^{\ell+1} \}$$

$$+ \frac{(1-\theta)}{\Gamma_{o}} \{ y_{o}y_{1}^{\ell} + z_{o}y_{1}^{\ell} + A_{o}h^{3} \phi_{a}^{\ell} + \xi_{o}\phi_{a}^{\ell} \}.$$ 

The equation for $y_{o}^{\ell+1}, y_{1}^{\ell+1}$ becomes $y_{o}y_{1}^{\ell+1} + z_{o}y_{1}^{\ell+1} = \hat{R}_{o}^{\ell} \quad (8)$

with

$$\hat{y}_{o} = \Gamma_{o} - \theta r y_{o} \quad \hat{z}_{o} = \theta r z_{o}$$

$$\hat{R}_{o} = \Gamma_{o}v_{o}^{\ell} + \theta r \left[ A_{o}h^{3} \phi_{a}^{\ell+1} + \xi_{o}\phi_{a}^{\ell+1} \right]$$

$$+ (1-\theta) \left[ y_{o}y_{1}^{\ell} + z_{o}y_{1}^{\ell} + A_{o}h^{3} \phi_{a}^{\ell} + \xi_{o}\phi_{a}^{\ell} \right].$$

Of course, for the solution of the tridiagonal system, (8) has to be reformulated in terms of $\gamma$ in the obvious way. The numerical value of $\theta$ lies between 0 and 1 and may often be taken as half, although there are sophisticated ways of adjusting $\theta$ during a computation. The equivalent equation at $x = b$ reads ($\theta = 1$):

$$\hat{X}_{N}y_{N}^{\ell+1} + \hat{Y}_{N}y_{N}^{\ell+1} = \hat{R}_{N}^{\ell} \quad (9)$$

with

$$\hat{x}_{N} = - \theta r x_{N} \quad \hat{y}_{N} = \Gamma_{N} - \theta r y_{N}$$

$$\hat{R}_{N} = \Gamma_{N}y_{N}^{\ell} + \theta r \left[ -A_{N}h^{3} \phi_{b}^{\ell+1} + \xi_{N}\phi_{b}^{\ell+1} \right]$$

$$\xi_{N} = \left[ (A_{N}B_{N}^{1} - B_{N}A_{N}^{1} + A_{N}C_{N} - B_{N}^{2})h^{2} - 3A_{o}B_{o}h - 6A_{o}^{2} \right] h$$

$$X_{N} = - 6A_{N}^{2}$$

$$Y_{N} = p \xi_{N} - \left[ (A_{N}C_{N}^{1} - A_{N}C_{N} + B_{N}C_{N})h^{2} + 3A_{N}C_{N}h^{2} - 6A_{N}^{2} \right]$$
\[ \Gamma_N = -\{ pA_N h + \left[ (A'_N + B_N) h + 3A_N \right] \} . \]

With \( \alpha \) and/or \( \beta \) equal to zero the relevant boundary equation, of course, falls away.
APPENDIX D

DUAL-TRACER DEPOSITION PROGRAM: DESCRIPTION OF SUBROUTINES AND FUNCTIONS

D1 MAIN

Controlling procedures are carried out by means of this subroutine. See Fig. D-1. Fig. D-2 gives a simple flow-diagram of the program.

ZH - first height from z = 0 m where concentration is calculated; taken as 1.1 m above "ground level"; this is the lower reflection height.

DT - time step length (= DELTAX/UZS, or Δx the step length in metres divided by the wind speed).

DZ - spacing (in metres) between the horizontal levels. This is calculated by using the input values of ZT and B: \[ \frac{ZT - A}{B} \] (see Section D2 Input), where A = 1,1. Note the optimum relationship between DZ and DT (Section 3.2.2.3).

TT - total time plume has "travelled" at any stage.

NEWC - this gives true or false if there is a change of the terrain type over which the plume is "moving".

TETA - \( \theta \). See subroutine DOUG.

SOM - the summation \( \bar{u} \Delta z_i \sum_i^N x_i \) (n being the number of levels in the vertical in which concentration is calculated; thus this gives the "total amount" of tracer in a segment of the plume.

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Fig. D-1. Subroutine and function stacking diagram for deposition and plume-depletion program
INPUT DATA: DISTANCE OF PLUME TRAVEL, TERRAIN AND METEOROLOGICAL VARIABLES AND VALUES OF PARAMETERS FOR THE CALCULATION OF PLUME DEPLETION

CALCULATE STABILITY LENGTH L AND \( k_2 \) VALUES

CALCULATE AIR CONCENTRATION AT THE HEIGHTS NEEDED AFTER 1st TIME STEP

CALCULATE PLUME DEPLETION RATE FOR TRACER OVER PRESENT TERRAIN

CALCULATE PLUME DIFFUSION AND DEPLETION (AND NEW CONCENTRATION PROFILE) FOR 1 TIME STEP FOR THE ONE TRACER

HAS A TIME STEP BEEN REACHED WHERE CONCENTRATION PROFILE IS TO BE OUTPUT?

OUTPUT CONCENTRATION PROFILE

HAS THIS TIME STEP BROUGHT PLUME TO A NEW TERRAIN TYPE OR HAS THIS TRACER COVERED THE TOTAL DISTANCE?

HAVE ALL 3 TRACERS COVERED THE TOTAL DISTANCE?

STOP

Fig. D-2.
Flow-diagram of deposition program.
from ground level to the upper horizontal reflection layer.

**SKAT (1) and SKAT (2)** - the first two values for $a$ (or $\frac{1}{L}$) for the iteration procedure.

**ZAI (1)** - the lowest horizontal layer.

The rest of the symbols are explained in the other subroutines.

Note that statements 1910 to 1980 are a set of calculations for the refinement of TETA as used in DOUG.

### D2 INPUT

**Card 1**: This card contains the title (OPSK), which can be up to 80 characters long.

**Card 2**: Col 1-10 - NAFSTD - total distance of plume travel in seconds (integer).

**Card 3**: Col 1-10 - NTAL - number of types of terrain to be encountered by the plume (integer).

**Card 4**: Col 1-10 - NNTAL - total number of time steps to be calculated by the program (integer).

**Card 5**: Col 1-10 - ZT - number of horizontal levels (including lowest one at 1.1 m) for which the concentrations have to be calculated.

Col 11-20 - B value to be used in the calculation of DZ.

**Card 6**: Col 1-10 - UZS - wind speed at tracer release
height, in m·s⁻¹.

Col 11-20 - ZNS - height of tracer release (metres above ground level plus 1,1).

Card 7 : Col 1-10 - INTAL - number of horizontal levels at which \( K_z \) values as calculated by the program have to be output (integer).

Col 11-20, 21-30, etc. - specific levels (in metres above ground) at which \( K_z \) has to be output (maximum = 100).

Card 8 : Col 1-10 - Z1 - lower height (in metres above ground level) at which temperature is measured.

Col 11-20 - Z2 - higher height at which the temperature is measured.

Col 21-30 - TZ21 - temperature difference \( T(Z_2) - T(Z_1) \), in °C.

Card 9 : Col 1-10 - TO - absolute temperature (K) at ground level.

Card 10: Col 1-10 - Z0 - general roughness length \( z_0 \) in metres.

Card 11: Col 1-10 - DELTAX - distance step length (\( \Delta x \)) in metres.

Card 12: Col 1-10 - NANTAL - number of times concentration profiles have to be output (integer).

Card 13: Col 1-10 - NAF(1),

Col 11-20 - NAF(2), etc. - distances of plume
travel (in seconds) at which terrain type changes (integer).

Card 14: Col 1-10 - NUITV(1),

Col 11-20 - NUITV(2), etc. - distances of plume travel (in seconds) at which program output is required (integer).

Card 15: Col 1-10 - ITIPE(1),

Col 11-20 - ITIPE(2), etc.; a total number of NTAL (card 3) - types of terrain in sequence to be encountered by plume (integer).

ITIPE = 1: terrain is "flat",
2: terrain is "grassy", and
3: terrain is "trees, etc."

Card 16: Col 1-10 - ZP(1),

Col 11-20 - ZP(2), etc. - heights above ground level (in metres) up to where deposition has to be calculated, in sequence for each terrain type encountered. Note that ground level is 1.1 m; thus, if only deposition at ground level, the ZP value to be input is 1 m (if ΔZ is 1 m) above 1.1 (actually if 2.0 m - the minimum quantity - is input as ZP, deposition in the lower 1 m layer will occur).

Card 17: Col 1-10 - Z0I(1),

Col 11-20 - Z0I(2), etc. - roughness length values (in metres) in sequence for each terrain type; for the calculation of deposition rates.
Card 18: Col 1-10 - AA(1),

Col 11-20 - AA(2), etc. - the A-values (see Section 3.2.2.2) for each terrain type.

D3  TOETS 1

Summation of concentrations in the vertical:

SUM (the same as "SOM" - Section D1) - \( \bar{u}_i \Delta \Sigma X_i \).

D4  SUB2N

Determination of deposition rates of the tracers.

VDI(I) - deposition velocity \( (\text{m.s}^{-1}) \).

UASTER - friction velocity \( u_* \) \( (\text{m.s}^{-1}) \) as determined for each terrain type encountered.

VDI(JTIPE) - deposition velocity for In tracer.

VDI(IJTIPE) - deposition velocity for ZnS.CdS tracer.

RZ1 - deposition rate for In tracer.

RZ2 - deposition rate for ZnS.CdS tracer.

D5  APN

Determination of diffusivity profile.

AFN - diffusivity \( K_z \).

ANUUT - \( \alpha \) (or \( \frac{1}{L} \)), where \( L \) is the Monin-Obukhov stability length.
ZN - height at which $K_z$ is calculated.

$F$ - 

$F(ZN)$ - the tracer air concentration at height ZN.

AWDE

Determination of the stability length through iteration.

PK - Von Karman constant $k$.

$DTHEDZ$ - lapse rate $\delta\theta/\delta z$.

$DELTAT$ - temperature difference at two heights.

$BAI$ - values for $a$ (or $\frac{1}{L}$) obtained during iteration.

$OL$ - stability length $L$.

$ALPHA$ - $a$ (or $\frac{1}{L}$).

$USTER$ - general friction velocity ($u_*$) for whole terrain; for the calculation of $K_z$ values.

TOETS

Subroutine for the determination of friction velocity and vertical heat flux.

$PHIT$ - $\phi_T$

$BFN, CFF, PH1, PH2, BEL, DBF, DCF, DPH1$ and $DPH2$

All these subroutines and functions are used in DOUG, and explained in Section D11.
D10  OUTPUT

Most of the input values are output, as well as certain important parameters calculated such as

\[ u^* \] ("USTER"),
\[ L \] ("L"), and
\[ K_z \] values at the heights specified on input card 7 ("EZ WAARDES").

The vertical concentration profiles for the tracer types are output at each of the distances specified in sequence; first for each of the distances (in chronological sequence) where no deposition occurred, then for the In tracer, and then the ZnS.CdS. RZ and CFF give the depletion rate in the horizontal layers where deposition occurred. "SOM VAN PRODUKTE" gives the "SOM" - values (explained in Section D1).

At each output distance two tables of figures are given. The first one gives the concentration values at every eighth interval in the vertical, starting at 1,1 m, while the second table gives the concentrations at each interval (with 1,1 m also as the first height) for the lower 20 layers only.

D11  DOUG

Determination of dispersion and deposition (see Section 3.2.2.3 and Appendix C).

Note: \( f(x,t) \) assumed 0 in current version. Calling statement:

\[
\text{CALL DOUG}(A,B,N,T,IAL,IBE,P,Q,DX,DT,AFN,BFN,CFF,PH1,PH2,F,DAF,DBF,DCF,DPH1,DPH2,BEL,TETA,U,V)
\]

with the following parameter meanings:
A, B  Start point a and end point b of the interval for x

N  number of subdivisions of [ab] (see DX)

T  current value of t

IAL  α in Eq. 1b; integer which is either 0 or 1 (see Appendix C)

IBE  β in (1b); values as for IAL

P, Q  p, q in Eq. 1b

DX  x increment DX = (B-A)/N

DT  t increment

AFN .... BEL, function subprograms to be declared external in calling program (see Eq. 1):

AFN(X) Returns with A(X) for given X

BFN(X) B(X)

CFF(X) C(X)

PH1(T) \( \dot{\phi}_a (t) \); T = t

PH2(T) \( \dot{\phi}_b (t) \)

F(X)  g(x); x = X

DAF(X) A'(x); x = X

DBF  B'(x); x = X
DCF $C'(x)$

DPH1 $\tilde{f}_a'(t); t = T$

DPH2 $\tilde{f}_b'(t)$

BEL(Y) $BEL = \exp\left\{ -\int_0^y \frac{B(t)}{2A(t)} \, dt \right\} ; y = Y$

TETA $\theta$ of Eq. 8, Appendix C

U output vector containing current values of solution of (1) in positions 1, ..., N+1; dimensioned N+1 in calling program

V vector to be dimensioned N+1 in calling program; on exit contains $V(x_i), i = 1, ..., N, N+1$ of equation (2a); must not be destroyed in calling program

TRIDAG This subroutine is not included in the main listing, but a separate listing is added. Its function is explained in the listing, viz. to get the solution of a system of linear equations $Ax = b$ where $A$ has a tridiagonal structure.
Fortran program listing of deposition model
DATUM VOLTOOI: 5 AUGUSTUS
PLUIM:
E
G
R
P
S
E
S
E
I
S
E
O
G
B
R
U
I
K:

FUNKSIES:

AFN: BEREKEN DIE E7 WAARDE VIR N GEHEE HOOGTE EN ALPHA.
CF: STOOR DIE KORREKTE ONTWIKKINGSFAKTOR AAN DOUG.
SFN, PH, PHZ, BEL: GEBRUIK EERSTE DJUG.

OPSTEL VAN DATA:

* - ALLE VERANDERLIKES WAT SO GEMERK IS, MOET HEELE REGS IN DIE VELD
GESKRYF WORD EN KRY GEEN DESIMALE PUNT NIE.

** - ANDERE GETALLE KAN ENIGE PLEK IN DIE GESPECIFISEERDE VELD STAAN EN
MEET •* DESIMALE PUNT BEVAT.

** - ALLE VERANDERLIKES WAT SO GEMERK IS, MOET HEELE REGS IN DIE VELD
GESKRYF WORD EN KRY GEEN DESIMALE PUNT NIE.


** - ALLE VERANDERLIKES WAT SO GEMERK IS, MOET HEELE REGS IN DIE VELD
GESKRYF WORD EN KRY GEEN DESIMALE PUNT NIE.
C KAART VO 5
READ(5,3000)
300 FORMAT (2F10.0)
WRITE(6,939)
939 FORMAT (/' HOGTE TOT WAAR BEREKENINGS GEDDE WORD',F10.1//' WAAR
C KAART NO 9
READ(6,4001) UJS, ZNS
400 FORMAT (2F10.0)
WRITE(6,985) UJS, ZNS
985 FORMAT (/' SNEELDET ON HOGTE VAN VLILATINGSPOINT ',F10.1/
C KAART NO 7
READ(6,3000) TOTAL, VARETTY, INTAL
300 FORMAT (4F10.0)
WRITE(6,811)
811 FORMAT (/[1.7F10.0],[8F10.0])
C KAART NO 6
WRITE(6,902)
902 FORMAT ([1.8F10.0])
C KAART NO 8
WRITE(6,802)
802 FORMAT (/[1.7F10.0])
C KAART NO 10
READ(6,8012)
8012 FORMAT (/[1.7F10.0])
C KAART NO 11
READ(6,9881)
9881 FORMAT ([1.7F10.0])
C KAART NO 9
READ(6,988)
988 FORMAT ([1.7F10.0])
C KAART NO 12
READ(6,136)
136 FORMAT (8I5)
C KAART NO 13
READ(6,135)
135 FORMAT (8I5)
C KAART NO 10
READ(6,1012)
1012 FORMAT (8I5)
C KAART NO 11
READ(6,1011)
1011 FORMAT (8I5)
C KAART NO 12
READ(6,1010)
1010 FORMAT (8I5)
C KAART NO 19
READ(6,1009)
1009 FORMAT (8I5)
C KAART NO 18
READ(6,1008)
1008 FORMAT (8I5)
C KAART NO 17
READ(6,1007)
1007 FORMAT (8I5)
C KAART NO 16
READ(6,1006)
1006 FORMAT (8I5)
C KAART NO 15
READ(6,1005)
1005 FORMAT (8I5)
C KAART NO 14
READ(6,1004)
1004 FORMAT (8I5)
30 CALL ADE(Omega,AUK,SKAT)
777 CONTINUE
WRITE(6,1003)
1003 FORMAT (8I5)
DO 777 JJ=1,INTAL
777 CONTINUE
WRITE(6,1002)
1002 FORMAT (8I5)
DO 10 JJ=1,3
10 CONTINUE
DO 50 I=1,NTAL
50 CONTINUE
CALL DGEA(TT,IV,IT,I,W,P,DT,AFN,DPH,TFF,DPHI,FPH,FPHI,FPH2,FPH3)
DO 100 K=1,5
100 CONTINUE
IF(HOU.LE.0.)GOTO 67
IF(U(J).LE.0.)TETA=0.5
LT=0.1T
AL=#L(101.1(1)/ALO11(1),U(J),J=1,20)
GOTO 39
TETA=0.5
NEW=.FALSE.
TIT=TT
DT=0.1J/J,J=1,NANTAL
DO 666 JJJ=1,NANTAL
IPI=0.1T(U(J,J,J)+U(I,J)+U(J,J)+U(J,J,J)+U(I,J,J,J)+U(J,J,J,J))
SEKONDES = 0.
10 CONTINUE
WRITE(6,9999)TITYP
9999 FORMAT(/,1X,' TITYP TERREIN ',A110)
RZ1=V0(1)/DT
RZ2=V0(1)/DT
RTYPE=TTYD
TTYD=AAA
WRITE(6,9999)RTYP
9999 FORMAT(/,1X,' A SE WAARDE ',A110)
WRITE(6,9999)RZ2
9994 FORMAT(/,1X,' RZ VIR ZNCS ',A110)
FUNCTION AFN(N)
COMMON /ABVELD/ANUL,UK
IF (ANUL.GT.0.) GO TO 20
ANUL=UK*Z/SQRT(1.1+6.*ANUL)
GOTO 40
20 IF (ZN.LE.1./ANUL) GO TO 30
ANUL=UK*Z/6.
GOTO 40
30 ANUL=UK*Z/1.1+5.*Z*ANUL
RETURN
END
SUBROUTINE TOETSIF(ZAI,UI,UIJ)
COMMON /PARRA/ANUL,RZ1,RTYP,RTYP,RTYP,RTYP,RTYP,RTYP,RTYP
DIMENSION V0(1)
UASTER = 0.1*Z*ANUL/(1./ALO11(1))
WRITE(6,9999)UASTER
9999 FORMAT(/,1X,' UASTER ',A110)
RETURN
END
FUNCTION BF(N)
COMMON /VELD,ZNUIT,UK
IF (ZNUIUT.GT.0.) GO TO 20
HAKIES=SORT([1.-6.*ZNUIUT])
BFNUK=HAKIES*[8.*ZNUIUT/HAKIES]
GO TO 40
20 IF (ZNUIUT.LT.1./ANUUI) GO TO 30
BFNUK=6.*
GO TO 40
30 HAKIES=[5.1.*ZNUIUT]
BFNUK=HAKIES*ZNUIUT/HAKIES)/UK
40 RETURN
END

FUNCTION CFF(U)
COMMON /PARR/ANUUI,RZ1,RZ2,IFLAG,NEWC,ZP(100),IJ
IF (IFLAG.GT.100) GO TO 10
IF (IFLAG.LT.100) GO TO 10
10 CFF=ANUI
GO TO 40
20 CFF=RZ1
GO TO 40
30 CFF=RZ2
40 RETURN
END

FUNCTION PH1(U)
PH1=0.
RETURN
END

FUNCTION PH2(U)
PH2=0.
RETURN
END

FUNCTION F(ZN)
COMMON /GVELO/ZNS,DT,IN
COMMON /YELD/UZS,Z0I,ZI,Z2,ZA,TO
ZN*ASS(IN}
E*AFNJZN)*DT
EZ1=4*E .
EO * 2. * UZS * SQRT(3.14159265 * E )
A1=ZN-ZNS
A=-A1*A1/EZ1
IF (A.GT.50.) A=50.
E1=EXP(A)
AI-A2*A2/EZ1
IF (A.GT.50.) A=50.
E2=EXP(A)
RETURN
END

FUNCTION BEL(ZN)
COMMON /BELINT/H
A=AFNJZN)
8=AFNJH)
BEL=SORTIB/A)
RETURN
END

SUBROUTINE AWDECA,UK,BEGINA
DIMENSION BEGINAI(),BA(),FUNKSI(2)
COMMON /VEL01/0ELTAT,UZ,Z0,ZI,Z2,ZA,TO
DATA G/9.8/,PK/0.4/,TAU/0.01/
8A(1)*BEGIN*m
3A(2)<BEGINA(2)
BEREKEN KONSTANTE OEEL IN DIE VERGELYKING OM ALPHA TE BEPAAL
DTHEOZ*DELTAT/(Z2-Z1) + 0.01
COMST*1.5665*ZA*DTHEDZ/T0
CONST*CONST/(UZ*UZ*PK*PK)
BEREKEN FUNKSI5 VIR 3FI0E ALPHA-WAARDES
10 CALL T0ETS(Z0,ZI,Z2fZA,BA,CONST,FUNKSI,P)
BEREKEN NUWE WAAROS VIR ALPHA VO=LSN ITERASIE FORMULE
BA(3)*8A(3)+8A(2) >*FUNKSI(l)/(FUNKSII21-FUNKSICI)
T0ETS OF OU EN NUWE ALPHA MIN GENDEG VERSKIL
IF (BAS(BA(3)-BA(2)).IE.0.005) GO TO 15
IF (BA(3)-.GT.0.AND.BA(2)+.LT.0.) BA(1)=BA(2)
IF (BA(3)+.LT.0.AND.BA(2)+.GT.0.) BA(1)=BA(2)
GO TO 10
A BA(3) IS WAARDE VAN ALPHA. BEREKEN KORREKTE USTER
15 CALL TOETS(Z0,ZI,Z2,ZA,BA,CONST,FUNKSI,P)
SUBROUTINE TOETS(Z0, Z1, Z2, ZA, BA, CONST, FUNKS, P)

SUBROETINE BEREKEN FUNKSIE EN SY AFGELEIDE SE WAARDES

DIMENSION BA(1), FUNKS(11)

DO 50 I = 1, 2
   AZ = BA(I)*ZA
   SV = 1. + 5.*AZ
   IF (AZ <= 0) GO TO 15
   IF (BA(I)GE.0.) GO TO 20
   SW = SQRT(1.-16.*AZ)
   PHIT = SV
   GO TO 35
   15 IF (ZA.LT.0.) GO TO 15
   IF (ZA.GT.1./2.*AZ) GO TO 30
   ZA = 0.

IF (BA(I).LT.0.) GO TO 20
IF (ZA.GT.1./2.*AZ) GO TO 30
ZAL(T). = 1. / AZ

20 IF (ZA.LE.0.) GO TO 15
   SW = SQRT(1.-16.*AZ)
   PHIT = SV
   GO TO 35

25 IF (ZA.GT.1./2.*AZ) GO TO 30
   0 = ZA <= 1./AZ
   IF (ZA.LT.0.) GO TO 20
   SW = 2.*ATAN(SWA) - 2.*ATAN(SWO) - ALOG((SVA+1.)/(SVA-1.))/720.1
   IF (SVA+1.) GO TO 35
   30 IF (ZA.GT.1./2.*AZ) GO TO 30
   SW = 2.*ATAN(SWA) - 2.*ATAN(SWO) - ALOG((SVA+1.)/(SVA-1.))/720.1
   IF (SVA+1.) GO TO 35
   PHIT = SV
   35 CONTINUE
   RETURN
END

FUNCTION DBF(I)

COMMON/ABVELD/ALFA, UK
ZL = ZA
DB = 0.
IF (ALFA.LT.0.) GO TO 1
IF (ZL.LT.10.) RETURN
DB = (1.-10.)/UK*ALFA/(1.-16.*ZL)**3
RETURN
1 DOB = (16.)*UK*ZL*ALFA/(1.-16.*ZL)**1.5
RETURN
END

FUNCTION DCF(X)

RETURN
END

FUNCTION DPH1(T)

RETURN
END

FUNCTION DPH2(T)

RETURN
END

FUNCTION DBF(Z)

RETURN
END
SUBROUTINE QUASIS(A,B,N,F,ICL,ICL1,IUB,IB,D,H,DT,AFN,CFN,PH1,PH2,F)

COMMON /PARRANUL,RZ1,RZ2,FLAG,NEWC,IZ(I100),I1

DO 10 R1=1,1001,ICL1
    IFICL1.RZ1(R1).GT.DT.GOTO 10
    IFICL1.RZ1(R1).EQ.DT.R1=(1001)*AFN(R1),CFN(R1)

    IFINW.EQ.10GOTO 10
    IFINW.EQ.11GOTO 10

10 N1=N1+1

RR=DT*DX/DX
ONX=1./6.
ETF=2./3.

PM1=0.*FLOAT(I1)*AFN(I1)/AFN(A)
PH2=PH1/AFN(A)
CPH=CFN(A)/AFN(A)

IFIP1.GT.DT.IAND.INOT.NEWC)GOTO 1

IFINW.EQ.7GOTO 10
IFIP1.GT.DT.GOTO 1

10 CONTINUE

RETURN
END
SUBROUTINE TRIDIAG(A,N,AL,B,N,BL,C,N,CL)

DIMENSION AL(1),BL(1),CL(1)

A(1) = CL(1) + AL(1) + BL(1)

DO 10 I = 2,N

A(I) = CL(I-1) + AL(I) + BL(I-1)

10 CONTINUE

WHERE MAXN IS THE LENGTH OF THE MAIN DIAGONAL.

DESCRIPTION OF PARAMETERS

N - ORDER OF THE MAIN DIAGONAL.

DATA AL, BL, CL, A(1:N-1), C(1:N-1), B(1:N-1) / O(N) / 0.

USAGE

CALL TRIDIAG(A,B,C,N)

PURPOSE

TO COMPUTE THE SOLUTION OF A NON SYST OF LINEAR EQUATIONS
APPENDIX E

MODIFICATIONS TO THE BASIC DISPERSION COMPUTER PROGRAM
TO INCORPORATE PLUME MOVEMENT OVER COMPLEX TERRAIN

(Computer program devised by G.W.J. van der Berg)

E1 MODIFICATIONS TO THE PROGRAM

E1.1 The grid can be sub-divided into sectors (max. = 10), by specifying their boundaries with the (x,y) co-ordinates of segments that make up the boundaries. A maximum of 20 segment co-ordinates can be given. To determine into which sector a given point (x,y) falls, the data below have to be given by the user. See Fig. E-1. Here the grid is sub-divided into 3 sectors, A, B and C, by 9 segments (numbered 1 to 9). The x-axis is taken as "segment 0". After numbering the grid similarly to the figure, the data are generated, using the following procedure:

(a) Make up a list of 4 arrays, XST, YST, XEN, YEN, containing the x-start, y-start, x-end and y-end co-ordinates respectively of each segment. In the example there will be 9 * 4 = 36 entries. Segment 0 is not entered here. This data must be given in the same order as the numbering of the segments (which is arbitrary).

(b) Set up an array, ISEGm which contains segment numbers defining the sectors. For this specification only segment numbers that lie "below" points in a sector must be given (compare accomp=
anying table with Fig. E-1). In the example, ISEGM will contain the following:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ISEGM(I)</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>1</td>
<td>.7</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

The double lines in the table indicate the start and end of each sector definition. In practice the sectors will be numbered, and they must be entered in numerically increasing order into the array. Also, each sub-group must be entered in ascending order. In the array each segment must be entered once and only once. This places a constraint on the initial choice of the shape of the sectors. For instance, if segment no. 5 was chosen as the dotted line in Fig. E-1, segment 0 would appear twice in the array. Point P would be wrongly interpreted as lying in sector A. Although this was never a problem in this program, the portion marked xx' could also be defined as a segment for sector B. This was not tried, but it should not cause problems.

(c) Next, an array (IPOINT) must be given that contains pointers to the start of each segment definition in ISEGM. If there are n segments there must be (n + 1) pointers. Pointer (n + 1) must point to the last entry (+1) in ISEGM. In this example IPOINT will have the following entries:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td>IPOINTER(I)</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>7</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>
This description is summarised under the heading "CARD 2" and "CARD 3" in the main program listing.

Note that no segment may be parallel to the y-axis.

For each sub-plume the program keeps track of sectors through which it moved, and also of the current sector it occupies. Only temperature data from masts in this list are used for the interpolation of data for the sub-plume. If the sub-plume moves off the grid boundaries, only the last entry in this list is used.

To do this, a matrix ISEC (200,10), i.e. a maximum of 200 sub-plumes and 10 sectors, and an array LAST (200) is used. LAST contains pointers to the last entry in ISEC for each sub-plume. This array initially contains zeroes. The first four entries of ISEC and LAST might be the following (x denotes undefined locations):

<table>
<thead>
<tr>
<th>ISEC</th>
<th>1 2 3 4 5_ _10</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1 4 3 2 x_ _x</td>
</tr>
<tr>
<td>J</td>
<td>1 3 x x x_ _x</td>
</tr>
<tr>
<td>3</td>
<td>1 x x x x_ _x</td>
</tr>
<tr>
<td>4</td>
<td>x x x x x_ _x</td>
</tr>
</tbody>
</table>

From this example it is clear that the release point is in sector 1, because it is the first entry for sub-plumes 1, 2 and 3. Also, it is very early in the simulation run because sub-plume four has not yet formed.
If sub-plume 1 moves off the grid boundaries, the value of LAST(I), say J, is looked up. The value of ISEC(I,J) is then written into ISEC(I,1) and LAST(I) is changed to 1. In this way only the last sector, i.e. the sector from which the sub-plume left the grid boundaries, is used for future interpolations, until the sub-plume returns to the grid.

E1.3 The values of Z1 and Z2 (note 9 of the first program - Appendix B) are no longer read in, because of varying values for each mast. Instead ΔT/ΔZ is calculated by hand, and with the absolute temperature, T₀, is read in with the wind speed/direction data from each mast each half-hour. These data are then also interpolated, like the speed/direction data, for each sub-plume.

Note that when no ΔT data is available at a certain mast, the T₀ value should also not be read in, otherwise a value of 0 for ΔT/ΔZ is used in the interpolation; wind speed and direction for this mast could still be input.

E1.4 Provision is also made to read in, with the wind speed/direction data, the inversion lid height, as discussed in the text. If this is not relevant it must be given as zero.

E2 NOTES ON THE FLOW-DIAGRAM OF THE MODIFIED PROGRAM

To prevent confusion, the notes from the old flow-diagram (Appendix B) were not included in the modified flow-diagram (Fig. E-2). However, they still apply.

(1) In addition to the variables read in by the "old"
Fig. E-2(a).  Flow-diagram of modified dispersion program — part 1.

Fig. E-2(b).  Flow-diagram of modified dispersion program — part 2.
program (Appendix B), the following were added:

(g) The number of sectors the grid is divided into;

(h) The number of segments used to divide the grid.

This is fully discussed under Section E1.1 above.

(2) This is discussed in Section E1.1.

(3) See Section E1.4.

(4) See Section E1.2.

E3 NOTES ON THE LISTING OF THE PROGRAM

No listing is included with Appendix B, as the program discussed here is basically the same, but more comprehensive.

The accompanying listing was compiled by the FORTRAN H-compiler to simplify the addition of changes to the program if desired. The original program was compiled by the G-compiler.

E3.1 MAIN

The functions of this subroutine are explained in the listing, viz. handling of the input and output data, calculating plume movement on the grid system, interpolating the relevant weather variables and calculating air concentrations, etc.
E3.2 SECTOR, XFORM

These are sufficiently well explained in the listing.

E3.3 SIGMA, AFN, EWRDEB, ALPHAW, ATOETS

The seven alternative "subroutines" which can be used for the determination of the dispersion coefficients are partly discussed in the main text.

Sub. 1: This is not discussed in the text, and is of the form \( \sigma_i = ax^b \) with \( x \) the distance from the release point and \( a \) and \( b \) parameters dependent on stability (Venter, 1978).

Sub. 2: This is discussed in Section 1.2.1.1, and is based on work by Venter et al (1973).

Sub. 3: \( \sigma_z \) is determined by means of the Monin-Obukhov stability length. Subroutine AFN in the listing has the same function as AFN in the deposition program (Appendix D), viz. to calculate diffusivity; subroutine EWRDEB determines \( K_z \) at height \( z = 10 \) m; ALPHAW has the same function as AWDE (Appendix D), viz. to calculate \( L \) by means of an iterative procedure; and ATOETS the same as TOETS in Appendix D for the determination of \( u_* \) and the vertical heat flux. \( \sigma_y \) is determined, using the scheme by Briggs (1974), which is also used in Sub. 6.

To avoid confusion this method is given the number "Subroutine 2" in the main text.

Sub. 4: Dispersion coefficients are determined by means
of the relationships by Smith (1973).

This is "Subroutine 3" in the text.

Sub. 5: The coefficients are determined by means of the Sutton parameters.

Sub. 6: Briggs' classification scheme (Briggs, 1974) is used, referred to as "Subroutine 1" in the text.

Sub. 7: This is "Subroutine 4" in the main text; see discussion in Section 4.1.2.3.
Fortran program listing of dispersion model
CARD 1:
  COLUMNS 1-5: NO. OF PLUMES
  COLUMNS 6-10: NO. OF INTERVALS
  COLUMNS 11-15: NO. OF SUBROUTINE TO DETERMINE SIGMA Y AND
  SIGMA Z. LEGAL VALUES ARE 1 TO 7
  COLUMNS 16-20: NO. OF REFERENCE POINTS
  COLUMNS 21-25: LENGTH OF INTERVAL IN MINUTES INTO WHICH
  30-MIN-INTERVAL MUST BE DIVIDED
  COLUMNS 31-35: NO. OF SECTORS INTO WHICH GRID IS
  DIVIDED.
  COLUMNS 36-40: NO. OF DIVIDING SEGMENTS
  FOR EACH

CARD 2:
  COLUMNS 1-5: START X-COORDINATE FOR SEGMENT(I)
  SAME Y-COORDINATES
  BASED ON THOSE COLUMNS 31-35.
  COLUMNS 6-10: SAME Y-COORDINATE
  COLUMNS 11-15: END X-COORDINATE FOR SEGMENT(I)
  COLUMNS 16-20: SAME Y-COORDINATE
  REPEAT FOR EACH SEGMENT

CARD 3:
  COLUMNS 1-5: POINTER TO START OF SECTOR DEFINITION 1
  COLUMNS 6-10: POINTER TO START OF SECTOR DEFINITION 2
  ETC. FOR ALL SECTORS.
  IF THERE ARE N SECTORS, THERE MUST BE N+1 POINTERS.
  POINTER N+1
  MUST POINT TO THE END+1 OF SECTOR N. AFTER THE POINTERS, GIVE THE
  SECTOR DEFINITIONS, STARTING ON A NEW CARD.

CARD 4:
  COLUMNS 1-5: X-COORDINATE OF REFERENCE POINT
  COLUMNS 6-10: Y-COORDINATE OF REFERENCE POINT
  COLUMNS 11-15: X-COORDINATE OF RELEASE POINT
  COLUMNS 16-20: Y-COORDINATE OF RELEASE POINT
  COLUMNS 11-15: RELEASE HEIGHT
  COLUMNS 6-10: X-COORDINATE OF FIRST POINT WHERE CONCENTRA-
  TION MUST BE CALCULATED
  COLUMNS 6-10: Y-COORDINATE OF ABOVE MENTIONED POINT
  COLUMNS 11-15: X-COORDINATE OF SECOND POINT DO. AS ABOVE
  COLUMNS 16-20: Y-COORDINATE OF SECOND POINT
  AFT.
  ALL CO-ORDINATES ARE GIVEN, GIVE 20-VALUE CARDS IF SUBROUTINE
  3 IS
  NOT USED.

CARD 5:
  COLUMNS 1-5: WIND DIRECTION OF FIRST REFERENCE POINT
  COLUMNS 6-10: WIND DIRECTION OF SECOND REFERENCE POINT ETC.
  COLUMNS 1-5: HOUR
  COLUMNS 6-10: MINUTES
  TIME AT WHICH MEASUREMENTS

CARD 9:
  COLUMNS 1-5: WIND SPEED OF FIRST REFERENCE POINT
  COLUMNS 10-14: DEVIATION(DELTA) FOR FIRST REFERENCE POINT
  COLUMNS 16-20: TO OF FIRST REFERENCE POINT
  COLUMNS 16-20: WIND SPEED OF SECOND REFERENCE POINT
  ETC. UNTIL CARD IS FULL, OR ALL REFERENCE POINTS SPECIFIED.
  WHEN ALL SPEEDS ARE GIVEN, PUNCH ON A NEW CARD,
  COLUMNS 1-5: THE INVERSION LID HEIGHT, IF THIS HEIGHT IS NOT
  RELEVANT, GIVE IT AS ZERO.

REMARKS
  REPEAT CARDS 8 & 9 FOR EACH NEW READING
  PUNCH VALUES ON CARDS 1, 3 AND 8 AS FAR RIGHT AS POSSIBLE IN GIVEN
  COLUMNS WITHOUT A DECIMAL POINT
  PUNCH VALUES ON ALL OTHER CARDS WITH A DECIMAL POINT, ANYWHERE
  WITHIN THE GIVEN COLUMNS
  IF SOME DATA ARE NOT AVAILABLE FOR CARD 9, LEAVE THOSE COLUMNS
  BLANK.
READ(5,74) (XYGRID(I),I=1,NPOINT)
C FORMALCALC EG. 3 READ (2,60) (XYGRID(I),I=1,NPOINT)
C READ START WIND DIRECTION
CARD 8 READ(5,74) T(HETAI),I=1,NREF
CALL XFORM(THETAI,NREF)
C DO CALCULATIONS ONCE FOR EACH PLUME
GO TO 72 NP=1,NXP
C IF NP=0) GO TO 23
7 T(HETAI)=T(HETAI)
NORTHPOINT=1,NREF
C IF (NP,NREF=0) GO TO 23
CARD 9 READ(5,731) NUUR,MINUTE
C ADJUT TIME TO PROGRAM CONVENTION
TMINUTE=MINUTE-30
GO TO 9
8 MINUTE+MINUTE=30
IF NUUR=NUUR-1 I=01 NUUR=NUUR+24
C READ REF. POINT WIND SPEED, WIND DIRECTION (DEG)
CARD 9 READ(5,74) RRIGE,YTHETAI,DLTA(M1,T0M1)
10 FORMAT(6F7.2)
READ(5,74) AL
IF AL .EQ. 0.2 GO TO 11
AL=AL/2.506628
11 WRITE(6,79) NUUR,MINUTE
WRITE(6,76) STREEP,I=1,21
WRITE(6,75)XSTREEP,I=1,21
CALL XFORM(THETAI, NREF)
C CHECK FOR REF. POINTS WITH NO DATA
GO TO 10
J=0
GO TO 10
J=I+1
IF IS I=NREF
C CHECK WIND SPEED
GO TO 10
J=I+1
I=I+1
IF I =NREF
GO TO 10
12 T(HETAI)=INTERRT(R)
DO 15 I=1,NREF
CHECK WIND SPEED
IF CSF(R) .EQ. 0.2 GO TO 12
JP=JR+1
IRDATA=IRDATA+1
GO TO 15
12 IRDATA=IRDATA+1
13 IF T(HETAI) .EQ. 0.2 GO TO 14
JP=JP+1
IRDATA=IRDATA+1
GO TO 15
14 IRDATA=IRDATA+1
CONTINUE
C CHECK IF SOME SPEED/DIRECTION DATA MISSING
C SOME'SPEED/DIRECTION DATA MISSING. INTERPOLATE FOR IT
DO 17 I=1,NREF
SUM=O.
SUM=O.
YSUM=O.
KSUM=O.
KSUM=INTERR(R)
XX=REFX(R)
YY=REFX(R)
DO 16 J=1,JR
L=IRDAT(A)
S=CSF(L)-0.2
SUM=SUM+S
SUM=SUM+S
YSUM=YSUM+S
KSUM=KSUM+S
16 YSUM=YSUM+S
KSUM=KSUM+S
17 T(HETAI)=RT(SUM/SUM)
C CHECK IF SOME TEMP, DATA MISSING
C SOME TEMPERATURE DATA MISSING. INTERPOLATE FOR IT
DO 17 I=1,NREF
SUM=O.
SUM=O.
YSUM=O.
KSUM=O.
KSUM=INTERR(T)
XX=REFX(T)
YY=REFX(T)
DO 16 J=1,JR
L=IRDAT(A)
S=CSF(L)-0.2
SUM=SUM+S
SUM=SUM+S
YSUM=YSUM+S
KSUM=KSUM+S
16 YSUM=YSUM+S
KSUM=KSUM+S
17 T(HETAI)=RT(SUM/SUM)
C BIBLIOGRAPHY

* not studied in the original
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21 DO 25 I=1,NREF
   22 THEN(I)=SIN(I)**2 + (YY-YYREF(I))**2
   23 SUM.SUM*ADD
   24 XSUM.XSUM*ADD*SINTHETA(I)
   25 YSUM.YSUM*ADD*COSTHETA(I)
   26 YSM+YSUM*ADD*COSTHETA(I)
   27 XSM+XSM*SINTHETA(I)
   28 XSM+XSM*ADD
   29 XSM+SINTHETA(I)
   30 XSM+XSM*ADD*SINTHETA(I)
   31 XSM+XSM*ADD
   32 XSM+XSM*ADD*COSTHETA(I)
   33 XSM+XSM*ADD
   34 XSM+SINTHETA(I)
   35 XSM+XSM*ADD
   36 XSM+XSM*ADD*COSTHETA(I)
   37 XSM+XSM*ADD
   38 XSM+SINTHETA(I)
   39 XSM+XSM*ADD
   40 XSM+SINTHETA(I)
   41 XSM+XSM*ADD
   42 XSM+XSM*ADD
   43 XSM+XSM*ADD
   44 XSM+XSM*ADD
   45 XSM+XSM*ADD
   46 XSM+SINTHETA(I)
   47 XSM+XSM*ADD
   48 XSM+SINTHETA(I)
   49 XSM+XSM*ADD
   50 XSM+SINTHETA(I)
   51 XSM+XSM*ADD
   52 XSM+SINTHETA(I)
   53 XSM+XSM*ADD
   54 XSM+SINTHETA(I)
   55 XSM+XSM*ADD
   56 XSM+SINTHETA(I)
   57 XSM+XSM*ADD
   58 XSM+SINTHETA(I)
   59 XSM+XSM*ADD
   60 XSM+SINTHETA(I)
   61 XSM+XSM*ADD
   62 XSM+SINTHETA(I)
   63 XSM+XSM*ADD
   64 XSM+SINTHETA(I)
   65 XSM+XSM*ADD
   66 XSM+SINTHETA(I)
   67 XSM+XSM*ADD
   68 XSM+SINTHETA(I)
   69 XSM+XSM*ADD
   70 XSM+SINTHETA(I)
   71 XSM+XSM*ADD
   72 XSM+SINTHETA(I)
   73 XSM+XSM*ADD
   74 XSM+SINTHETA(I)
   75 XSM+XSM*ADD
   76 XSM+SINTHETA(I)
   77 XSM+XSM*ADD
   78 XSM+SINTHETA(I)
   79 XSM+XSM*ADD
   80 XSM+SINTHETA(I)
   81 XSM+XSM*ADD
   82 XSM+SINTHETA(I)
   83 XSM+XSM*ADD
   84 XSM+SINTHETA(I)
   85 XSM+XSM*ADD
   86 XSM+SINTHETA(I)
   87 XSM+XSM*ADD
   88 XSM+SINTHETA(I)
   89 XSM+XSM*ADD
   90 XSM+SINTHETA(I)
   91 XSM+XSM*ADD
   92 XSM+SINTHETA(I)
   93 XSM+XSM*ADD
   94 XSM+SINTHETA(I)
   95 XSM+XSM*ADD
   96 XSM+SINTHETA(I)
   97 XSM+XSM*ADD
   98 XSM+SINTHETA(I)
   99 XSM+XSM*ADD
   100 XSM+SINTHETA(I)
   101 XSM+XSM*ADD
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   189 XSM+XSM*ADD
   190 XSM+SINTHET
DO 33 K = 1, I
   L = K (1, I)
   CONTINUE
   IF (L .EQ. IS) GO TO 35
   ELSE
      UPDATE *LAST* POINT & ENTER NEW SECTOR
   END IF
   UNDER = 0.0 . 0 . 0
   UND E R = Y R E F ( K 1 ) = 2 . 8 5 3 0 5 3 1
   IF (U N D ER .LT. 0.0) GO TO 3 7
   D O 3 5 I = 1,7
      X S U M = X S U M + R H O I A D * ( S I N T H E T A ( K ) )
      Y S U M = Y S U M + R H O I A D * ( C O S T H E T A ( K ) )
   C A L C U L A T E W I N D S P E E D
   C A L C U L A T E W I N D D I R E C T I O N ( R A D I A N S )
   S T O P
   C A L C U L A T E N E C T A N GE N T E N C T I ( K )
DIST=DIST*335.0

IF (ISQY+ISQZ+ISQ) .GT. 0.0 .OR. SIGY .LT. 0.0 .OR. SIGZ .LT. 0.0 GO TO 55

IF (SIGY*SIGZ) .GT. 0.0 .OR. SIGY .LT. 0.0 .OR. SIGZ .LT. 0.0 STOP

WRITE(6,75)ISTR,IST28)

IFICALC .NF.. 31 GO TO 69

IF CILFAG.EQ.1

62 IF (ALPHA-EQ.1.

63 IF (ALPHA .EQ. 1.0/ALPHA) GO TO 66

64 IF (SIGY*SIGZ) .GT. 0.0 .OR. SIGY .LT. 0.0 .OR. SIGZ .LT. 0.0 STOP

WRITE(6,75)ISTR,IST28)

IFICALC .NF.. 31 GO TO 69

IF CILFAG.EQ.1

62 IF (ALPHA-EQ.1.

63 IF (ALPHA .EQ. 1.0/ALPHA) GO TO 66

64 IF (SIGY*SIGZ) .GT. 0.0 .OR. SIGY .LT. 0.0 .OR. SIGZ .LT. 0.0 STOP

WRITE(6,75)ISTR,IST28)

IFICALC .NF.. 31 GO TO 69

IF CILFAG.EQ.1

62 IF (ALPHA-EQ.1.

63 IF (ALPHA .EQ. 1.0/ALPHA) GO TO 66

64 IF (SIGY*SIGZ) .GT. 0.0 .OR. SIGY .LT. 0.0 .OR. SIGZ .LT. 0.0 STOP

WRITE(6,75)ISTR,IST28)

IFICALC .NF.. 31 GO TO 69

IF CILFAG.EQ.1

62 IF (ALPHA-EQ.1.

63 IF (ALPHA .EQ. 1.0/ALPHA) GO TO 66

64 IF (SIGY*SIGZ) .GT. 0.0 .OR. SIGY .LT. 0.0 .OR. SIGZ .LT. 0.0 STOP

WRITE(6,75)ISTR,IST28)

IFICALC .NF.. 31 GO TO 69

IF CILFAG.EQ.1

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WRITE(6,75)ISTR,IST28)

IFICALC .NF.. 31 GO TO 69

IF CILFAG.EQ.1

62 IF (ALPHA-EQ.1.

63 IF (ALPHA .EQ. 1.0/ALPHA) GO TO 66

64 IF (SIGY*SIGZ) .GT. 0.0 .OR. SIGY .LT. 0.0 .OR. SIGZ .LT. 0.0 STOP

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LEVEL 21.8 (JUN 74)

SUBROUTINE TO CONVERT REAL CO-ORD. SYSTEM TO
INPUT IN DEGREES, OUTPUT IN RADIANS.
DIMENSION THETA(1)

IF (THETA .LT. 0.0) GO TO 2
THETA = THETA + 360.0

2 CONTINUE
RETURN
END

LEVEL 21.8 (JUN 74)

AFNI'UK*ZN/(1.*ZN*ANUUT)
AFN«UK*ZN/6.

VF3R
XFOR
XFOR003C
XFOR0040
XFOR0050
XFOR0060
XFOR0070
XFOR0080

iodine effluents from air to grass. Mawson, C.A. (ed.)
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**NOTE**

1. All memory locations above 1F000 are reserved for operational purposes.
2. Data storage is limited to 512 bytes, with 128 bytes allocated to each function block.
<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>g</strong></td>
<td>gravitational acceleration</td>
<td>m.s(^{-2})</td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>vertical heat flux</td>
<td>W.m(^{-2})</td>
</tr>
<tr>
<td><strong>k</strong></td>
<td>von Karman constant (0,40)</td>
<td>m(^{2}).s(^{-1})</td>
</tr>
<tr>
<td><strong>K(_z)</strong></td>
<td>Monin-Obukhov stability length</td>
<td>m</td>
</tr>
<tr>
<td><strong>L</strong></td>
<td>tracer or effluent release rate</td>
<td>kg.s(^{-1}) or number of particles.s(^{-1})</td>
</tr>
<tr>
<td><strong>Q</strong></td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>absolute temperature</td>
<td>K</td>
</tr>
<tr>
<td><strong>T(_0)</strong></td>
<td>absolute temperature at ground level</td>
<td>K</td>
</tr>
<tr>
<td><strong>u(z)</strong></td>
<td>wind speed at height z</td>
<td>m.s(^{-1})</td>
</tr>
<tr>
<td><strong>u(_f)</strong></td>
<td>friction velocity (\sqrt{\frac{T(_0)}{\rho_0}})</td>
<td>m.s(^{-1})</td>
</tr>
<tr>
<td><strong>v(_d)</strong></td>
<td>deposition velocity</td>
<td>m.s(^{-1})</td>
</tr>
<tr>
<td><strong>x</strong></td>
<td>horizontal distance to release point</td>
<td>m</td>
</tr>
<tr>
<td><strong>y</strong></td>
<td>perpendicular (horizontal) distance from plume axis</td>
<td>m</td>
</tr>
<tr>
<td><strong>z</strong></td>
<td>height above ground level</td>
<td>m</td>
</tr>
<tr>
<td><strong>z(_0)</strong></td>
<td>roughness length</td>
<td>m</td>
</tr>
<tr>
<td><strong>z(_1)</strong></td>
<td>measurement height for lower temperature</td>
<td>m</td>
</tr>
<tr>
<td><strong>z(_2)</strong></td>
<td>measurement height for upper temperature</td>
<td>m</td>
</tr>
<tr>
<td><strong>z(_s)</strong> (or h)</td>
<td>tracer release height</td>
<td>m</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>$\theta$</td>
<td>potential temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\frac{\partial \theta}{\partial z}$ or $\frac{\partial \theta}{\partial z}$</td>
<td>potential temperature gradient</td>
<td>K m$^{-1}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>air density</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\rho_o$</td>
<td>air density at ground level</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\sigma_x$, $\sigma_z$</td>
<td>respectively the horizontal and vertical dispersion coefficients</td>
<td>m</td>
</tr>
<tr>
<td>$\tau_o$</td>
<td>shear stress at ground level</td>
<td>N m$^{-2}$</td>
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<tr>
<td>$\delta_H$</td>
<td>$\frac{kz}{u_*} \frac{\partial u}{\partial z}$ dimensionless wind shear</td>
<td></td>
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<tr>
<td>$\tilde{\theta}_H$</td>
<td>$\frac{z}{u_*} \frac{\partial \theta}{\partial z}$ dimensionless temperature gradient</td>
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<tr>
<td>$\chi$</td>
<td>air concentration</td>
<td>kg m$^{-3}$ or number of particles m$^{-3}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>deposition rate</td>
<td>mass in kg or number of particles deposited m$^{-2}$ s$^{-1}$</td>
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</tbody>
</table>
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