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The Risø model for calculation the consequences of the release of radioactive material to the atmosphere

Thykier-Nielsen, Søren

Publication date:
1980

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Thykier-Nielsen, S. (1980). The Risø model for calculation the consequences of the release of radioactive material to the atmosphere. (Risø-M; No. 2214).

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Risø National Laboratory

Risø-M-2214

July 1980

THE RISØ MODEL FOR CALCULATING THE CONSEQUENCES OF THE
RELEASE OF RADIOACTIVE MATERIAL TO THE ATMOSPHERE

S. Thykier-Nielsen

ISBN 87-550-0707-4

ISSN 0418-6435

Risø repro 1980

CONTENTS	Page
1. INTRODUCTION	5
2. DISPERSION MODEL	6
2.1. General description	6
2.2. The dispersion formula	8
2.3. Average concentrations in the plume	11
2.4. Effective dispersion height	13
2.5. The apparent source strength	13
2.6. Deposition	15
2.6.1. Deposition in general	15
2.6.2. Deposition of daughter products	19
3. CALCULATION OF DOSES	23
3.1. Doses to individuals	23
3.1.1. Inhalation doses	23
3.1.2. External gamma doses from the plume ..	24
3.1.3. External gamma doses from deposited radioactive material	25
3.2. Isodose curves	27
3.3. Collective doses	29
3.4. Calculation of mean values for a given spectrum of meteorological situations	30
4. DATA AND CALCULATION PROCEDURES FOR SPECIAL SITUATIONS	33
4.1. Dispersion parameters	33
4.1.1. Correction for initial dispersion	36
4.1.2. Surface roughness	37
4.2. Effective dispersion height	39
4.3. Daughter products	40
4.4. Depositability	41
4.5. Data for calculation of external gamma doses.	41
4.5.1. Gamma energy groups	41
4.5.2. Photon yields of the isotopes distributed in energy groups	42

	Page
4.5.3. Energy absorption coefficients, linear attenuation coefficients and dose build-up factors for the energy groups	44
4.6. Weathering	44
4.7. Shielding factors, etc.	45
4.8. Dose factors for inhaled isotopes	46
4.9. Calculation of average values of doses and concentrations of material	48
4.9.1. Area	49
4.9.2. Atmospheric stability	49
4.9.3. Wind speed	50
4.9.4. Mixing height	51
4.9.5. Precipitation frequency	51
4.9.6. Wind direction	53
4.9.7. Adjacent sectors	53
4.10. Population data	53
4.11. Consequences of doses	56
5. CONCLUSION.....	59
REFERENCES	60
APPENDIX, PLUCON2 - a short description	63

1. INTRODUCTION

When making a safety evaluation of a nuclear plant it is necessary to estimate the consequences of a release of radioactive material from the plant; therefore Risø continuously develops calculation models and the associated computer programs for this purpose.

The present report gives a brief description of the most important features of the calculation model currently used at Risø for calculating radiation doses and contamination levels resulting from a release of radioactivity to the atmosphere. In addition, a survey is given of the data generally used in the model.

The calculation model is implemented as a computer program, PLUCON2, written in Burroughs ALGOL for a B6700 computer.

2. DISPERSION MODEL

2.1. General description

In a continuous release of material from a source (e.g., a chimney stack) to the atmosphere, the material will be carried with the wind and spread like a smoke plume. The transport and mixing of the material will be determined by the state of the atmosphere along the direction of diffusion, by the topography of the area, and by the properties of the materials released. The most important atmospheric parameters are wind direction, wind speed and the vertical temperature gradient because these determine the transport direction, the dilution at the moment of release and the turbulent mixing.

The so-called Gaussian dispersion model (Fig. 1) has been chosen to describe the dispersion of the plume in the atmosphere.

To day, this model is the most used method for practical calculations of plumes from single sources [1, 2, 4 and 17].

This is both because the model, in its simplest form, only requires meteorological measurements at one point and because the distribution parameters ascribed to the model incorporate a lot of empirical knowledge of the behaviour of the plume, such that the theoretical weaknesses of the model are often compensated for. Moreover, it is relatively easy to calculate radiation doses on the basis of the diffusion formulas that can be set up on the basis of this model.

Under ideal conditions (horizontal and homogeneous terrain, steady wind, stability conditions which are neither extremely stable nor unstable, etc.) the model can forecast concentrations to within a factor of 2-3 up to about 10 km from the source [18].

Under other conditions, the use of the Gaussian model is based on extrapolations that seek to include the knowledge available on diffusion in the atmosphere.

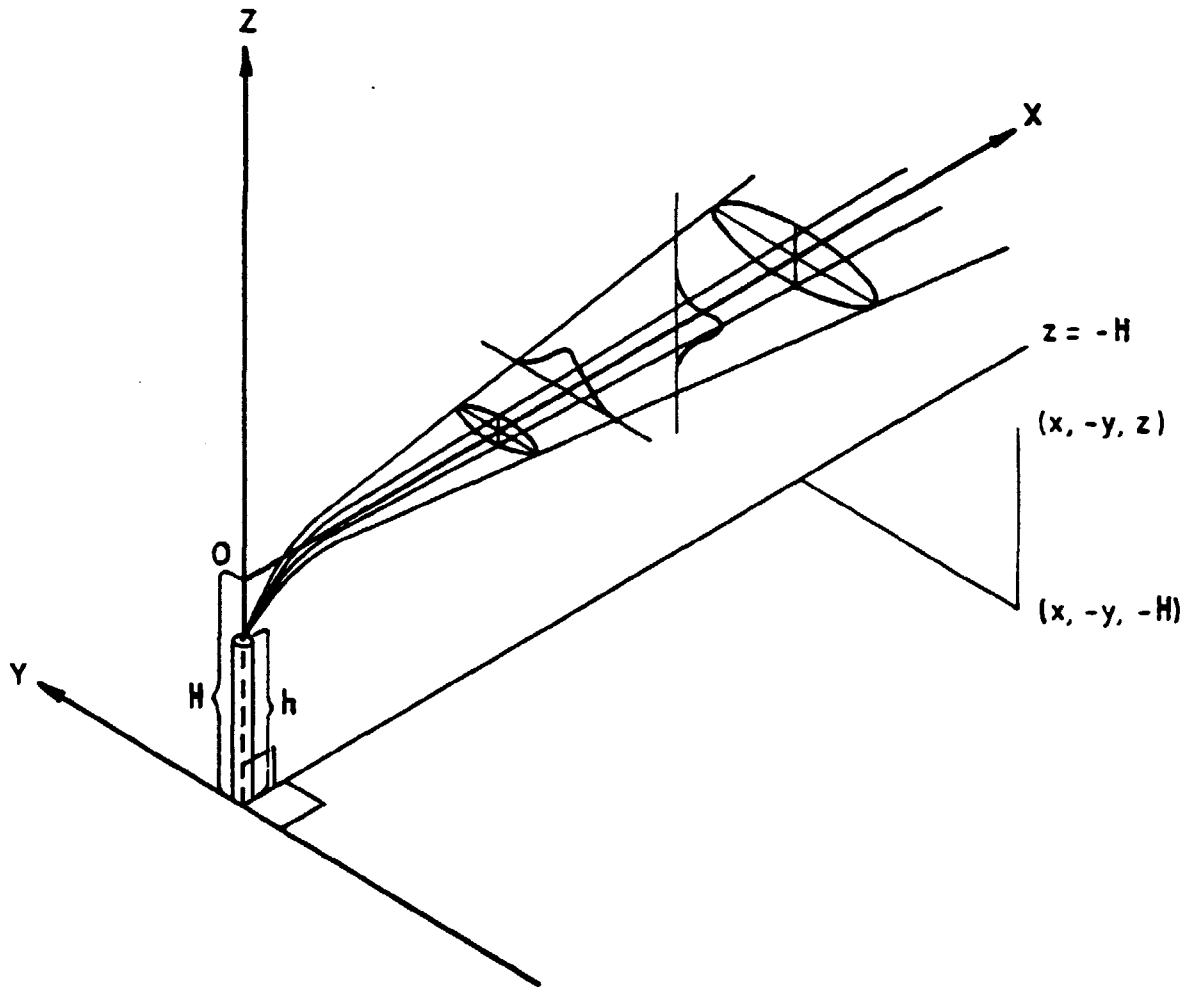


Fig. 1. The plume from a chimney stack described by the Gaussian diffusion model. The stack height is h and the effective stack height is H .

Normally, the model works reasonably well up to 20-30 km from the source. At greater distances it will normally overestimate the concentrations. For the long-term mean values, measurements [19] show that the overestimation increases with distance from the source and that at a distance of 50 km it can be up to a factor of 10.

Use of the Gaussian dispersion model at distances of more than 50 km from the source cannot be recommended in general.

2.2. The dispersion formula

According to the Gaussian dispersion model, the material is assumed to have a normal (Gaussian) distribution in the plane perpendicular to the wind direction. If it is further assumed that the surface of the earth is totally reflecting, then the dispersion formula in a rectangular coordinate system with the origin at the source point (point of release) and the x-axis in the wind direction will be:

$$X(x,y,z,s,u) = Q(x,t) \cdot Sg(x,y,z,s,u) \quad (1)$$

as

$$Sg(x,y,z,s,u) = \frac{1}{2 \cdot \pi \cdot u \cdot \sigma_y(x,s) \cdot \sigma_z(x,s)} \cdot \quad (2)$$

$$\exp\left(-\frac{y^2}{2 \cdot \sigma_y(x,s)^2}\right) + \left[\exp\left(-\frac{z^2}{2 \cdot \sigma_z(x,s)^2}\right) + \exp\left(-\frac{(z+2 \cdot H)^2}{2 \cdot \sigma_z(x,s)^2}\right) \right]$$

where

$X(x,y,z,s,u)$	= concentration (C_i/m^3) at a point with the coordinates (x,y,z)
$S_g(x,y,z,s,u)$	= relative concentration (sec/m^3)
(x,y,z)	= coordinates of the detector point (m)
s	= category of atmospheric stability
u	= wind speed (m/sec)
$\sigma_y(x,s)$	= horizontal dispersion parameter (m)
$\sigma_z(x,s)$	= vertical dispersion parameter (m)
$Q(x,t)$	= apparent source strength (C_i/sec) at the time t
H	= effective stack height (m)

Formula (2) assumes that the diffusion in the wind direction (the x-direction) can be neglected. This assumption applies when the release spans a period of time that is equal to or greater than the transport time ($\frac{x}{u}$) from the source to the detector point in question [2 and 4].

Formula (2) cannot be used in cases where the dispersion conditions are markedly affected by a mixing layer where there is turbulent diffusion and which upwards limits the atmospheric layer in which the released material is assumed dispersed. The existence of such a mixing layer will imply that the vertical material distribution changes, with increasing distance from the source point, from a Gaussian to a homogeneous distribution. If the mixing layer is assumed to be totally reflecting, then the relative concentration distribution, according to Turner [2], can be calculated as described in the following.

The material distribution under the mixing layer is first affected from the distance x_L , where the concentration at the lower boundary of the mixing layer is equal to one tenth of the concentration in the centreline of the plume. From the distance x_L a gradual transition from a Gaussian to a homogeneous distribution takes place in the vertical plane. The material distribution can, for $x_L < x$, be calculated by "folding" the actual source with respect both to the ground and to the lower boundary of the mixing layer. In other words, there is a superposition of a number of imaginary sources (in principle in-

finitely many), which are identical with the actual one, but are located at different distances below the ground, respectively, above the lower boundary of the mixing layer. From a distance x_C ($x_L < x_C$) the vertical material distribution can, to a good approximation, be considered to be homogeneous.

x_L is calculated from the relation:

$$\sigma_z(x_L) = \frac{L-H}{\sqrt{2 \cdot \ln(10)}} = 0.466 \cdot (L-H) \quad [m]$$

where

L = the mixing height (height of the air layer in which the released material is dispersed) [m]

H = the effective dispersion height [m]

x_C is calculated from:

$$\sigma_z(x_C) = \sigma_{zL} = \sqrt{\frac{2}{\pi}} \cdot L = 0.798 \cdot L$$

Then one finds the following expressions for the relative concentration are found:

a. $0 < x < x_L$

$$Sg(x, y, z, s, u) = \frac{\exp\left(-\frac{y^2}{2 \cdot \sigma_y(x, s)^2}\right)}{2 \cdot \pi \cdot \sigma_y(x, s) \cdot \sigma_z(x, s) \cdot u} \cdot \quad (3)$$

$$\left[\exp\left(-\frac{z^2}{2 \cdot \sigma_z(x, s)^2}\right) + \exp\left(-\frac{(z+2 \cdot H)^2}{2 \cdot \sigma_z(x, s)^2}\right) \right]$$

b. $x_L \leq x \leq x_C$

$$Sg_{B1}(x, y, z, s, u) = \frac{\exp\left(-\frac{y^2}{2 \cdot \sigma_y(x, s)^2}\right)}{2 \cdot \pi \cdot \sigma_y(x, s) \cdot \sigma_z(x, s) \cdot u} \cdot$$

$$\left\{ \exp\left(-\frac{z^2}{2 \cdot \sigma_z(x, s)^2}\right) + \exp\left(-\frac{(z+2 \cdot H)^2}{2 \cdot \sigma_z(x, s)^2}\right) + \right. \quad (4)$$

$$\sum_{i=1}^4 \left[\exp\left(-\frac{1}{2} \cdot \left(\frac{2 \cdot i \cdot L - 2 \cdot H - z}{\sigma_z(x, s)}\right)^2\right) + \exp\left(-\frac{1}{2} \cdot \left(\frac{2 \cdot i \cdot L - z}{\sigma_z(x, s)}\right)^2\right) \right.$$

$$\left. + \exp\left(-\frac{1}{2} \cdot \left(\frac{2 \cdot i \cdot L + z}{\sigma_z(x, s)}\right)^2\right) + \exp\left(-\frac{1}{2} \cdot \left(\frac{2 \cdot i \cdot L + 2 \cdot H + z}{\sigma_z(x, s)}\right)^2\right) \right] \left. \right\}$$

c. $x_C \leq x$

$$Sg_{B2}(x, y, z, s, u) = \frac{\exp\left(-\frac{y^2}{2 \cdot \sigma_y(x, s)^2}\right)}{\pi \cdot \sigma_y(x, s) \cdot \sigma_{zL} \cdot u} \quad (5)$$

The formulas given under b and c only apply for $-H < z < H$.

2.3. Average concentrations in the plume

At a given distance, x , from the release point, the average concentration, $Sgm(x, z, s, u, \alpha)$ for a (narrow) sector is [4]:

$$Sgm(x, z, s, u, \alpha) = \sqrt{\frac{\pi}{2}} \cdot \frac{\sigma_y(x, s)}{2 \cdot x \cdot \operatorname{tg}(\alpha)} \cdot$$

$$\left[\operatorname{erf}\left(\frac{x \cdot \operatorname{tg}(\alpha)}{\sqrt{2} \cdot \sigma_y(x, s)}\right) - \operatorname{erf}\left(-\frac{x \cdot \operatorname{tg}(\alpha)}{\sqrt{2} \cdot \sigma_y(x, s)}\right) \right] \cdot Sg(x, 0, z, s, u)$$

Where

$$\text{erf}(t) = \int_0^t \frac{2}{\sqrt{\pi}} \cdot e^{-v^2} dv, \text{ the error function}$$

α = the half sector-angle for the sector in question
 $2x \cdot \text{tg}\alpha$ = the sector width.

Formula (6) is a approximation for sectors with a width of 30° or less.

Another from a meteorological viewpoint principally different way to calculate the average concentration in a given sector is to use the crosswind-integrated concentration:

$$\begin{aligned} \text{Sg}_t(x, z, s, u) &= \int_{-\infty}^{+\infty} \text{Sg}(x, y, z, s, u) dy \\ &= \sqrt{2\pi} \cdot \sigma_y(x, s) \cdot \text{Sg}(x, 0, z, s, u) \end{aligned}$$

The average concentration, $\text{Sgm}_t(x, z, s, u, \alpha)$, at a given distance, x , will then be for a sector of width 2α be:

$$\begin{aligned} \text{Sgm}_t(x, z, s, u, \alpha) &= \frac{\sqrt{2 \cdot \pi} \cdot \sigma_y(x, s)}{\frac{\alpha}{180} \cdot 2 \cdot \pi \cdot x} \cdot \text{Sg}(x, 0, z, s, u) \\ &= \sqrt{\frac{2}{\pi}} \cdot \frac{90 \cdot \sigma_y(x, s)}{\alpha \cdot x} \cdot \text{Sg}(x, 0, z, s, u) \end{aligned} \tag{7}$$

It can be shown that

$$\text{Sgm}(x, z, s, u, \alpha) < \text{Sgm}_t(x, z, s, u, \alpha) \text{ for all } \alpha > 0.$$

For given x -values, the difference between Sgm and Sgm_t will be smaller the smaller σ_y is in relation to the half sector-width, i.e.,

$$\frac{\sigma_y(x, s)}{x \cdot \text{tg}\alpha} \rightarrow 0 \Rightarrow \frac{\text{Sgm}(x, z, s, u, \alpha)}{\text{Sgm}_t(x, z, s, u, \alpha)} \rightarrow 1.$$

2.4. Effective dispersion height

When the release point is in an open country, the height at which the dispersion of the released material starts (the effective dispersion height) is generally greater than the actual height above ground of the release point. This difference is mainly a result of the turbulence around the point of discharge, and of the speed of the discharged material in an upwards direction. Moreover, the temperature of the discharged material is of importance, because the plume (or cloud) will ascend to a height that depends partly on the relationship between the heat released by the cloud and the heat it absorbs from the surrounding air, and partly on the atmospheric stability and wind speed. If the plume (or cloud) contains radioactive material, then heat will continuously be produced in the plume (cloud). This self-heating might be so great that the plume continues to rise for a very long period of time, which means that the effective stack height increases at the same time as the plume (cloud) moves in the wind direction. In the dispersion formulas, the effective stack height H (a constant) must then be replaced by the function $H(x)$, which is a function of the distance in the wind direction, x . This problem is dealt with in greater detail in section 4.2 and in [12] and [3].

2.5. The apparent source strength

The apparent source strength, $Q(x,t)$, is equal to the release rate for the material corrected for changes on the stretch between source point and detector point (as a result of fallout, radioactive decay, etc.).

If a radioactive isotope is released with a constant speed, c [Ci/sec], the apparent source strength will be:

$$Q(x,t) = \epsilon \cdot e^{-\lambda \cdot \frac{x}{u}} \text{ [Ci/sek] for } tf_1 + \frac{x}{u} \leq t \leq tf_2 + \frac{x}{u} \quad (8)$$

$$= 0 \text{ for } t < tf_1 + \frac{x}{u} \vee tf_2 + \frac{x}{u} < t$$

where

tf_1 = time of start of release

tf_2 = time of end of release

λ = the decay constant.

The decay of the isotopes during transport in the wind direction away from the release point implies the creation of daughter products. Considering the situation where an isotope, the parent, and its radioactive daughter product are both released from the source with the constant speeds ϵ_p [Ci/sec] and ϵ_d [Ci/sec], respectively, the apparent source strengths will be:

for the parent

$$Q_p(x,t) = \epsilon_p \cdot e^{-\lambda_p \frac{x}{u}} \text{ [Ci/sec]}$$

for the daughter product

$$Q_d(x,t) = \epsilon_d \cdot e^{-\lambda_d \frac{x}{u}} + \frac{\epsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p} \cdot \left(e^{-\lambda_p \frac{x}{u}} - e^{-\lambda_d \frac{x}{u}} \right) \text{ [Ci/sec]}$$

where

λ_p = the decay constant for the parent [sec^{-1}]

λ_d = the decay constant for the daughter product [sec^{-1}]

It should be noted that ϵ_d may be equal to 0 (i.e., no separate release of the daughter product).

When calculating doses the time-integrated source term is used:

$$I(x, te_1, te_2) = \int_{te_1}^{te_2} Q(x, \tau) d\tau$$

When the release rate is constant we find:

$$I(x, t_{e1}, t_{e2}) =$$

$$(\min(t_{e2}, t_{f2} + \frac{x}{u}) - \max(t_{e1}, t_{f1} + \frac{x}{u})) \cdot Q(x, t) \quad (9)$$

for $t_{e1} \leq t_{f2} + \frac{x}{u} \wedge t_{f1} + \frac{x}{u} \leq t_{e2}$, and

$$= 0 \text{ for } t_{f2} + \frac{x}{u} < t_{e1} \vee t_{e2} < t_{f1} + \frac{x}{u}$$

2.6. Deposition

2.6.1. Deposition in general

A part of the material in the plume may fall to the ground during transport in the wind direction. The deposition mechanisms are quite complicated, and therefore only the methods for calculating dry deposition and washout that are connected to the Gaussian model are given here. For further reference, see [6,7 and 11].

When considering dry deposition the so-called velocity of deposition, v_g , is used; it is defined as:

$$v_g = \frac{\text{the change in ground surface concentration per sec}}{\text{concentration of material above the ground}}$$

The amount of material that is deposited per unit time per unit of area of the ground is calculated as:

$$w_D(x, y, s, u) = v_g \cdot \chi'(x, y, -H, s, u) \quad [\text{Ci/m}^2/\text{sek}] \quad (10)$$

where

$$v_g = \text{velocity of deposition [m/sec]}$$

$$\chi'(x, y, -H, s, u) = Q_D(x, t, s) \cdot Sg(x, y, -H, s, u)$$

$$= \text{Concentration of material above the ground [Ci/m}^3\text{] corrected for deposition.}$$

$Q_D(x,t,s)$ = the apparent source strength [Ci/sec]
corrected for deposition.

Assuming that deposition takes place along the whole stretch from source point to detector point, $Q_D(x,t,s)$ is calculated as:

$$Q_D(x,t,s) = Q_0 \cdot \exp\left(-\lambda \cdot \frac{x}{u} - \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp\left(-\frac{1}{2} \cdot \left(\frac{H}{\sigma_z}\right)^2\right)}{\sigma_z(x,s)} dx\right)$$

(11)

where Q_0 is the apparent source strength at the release point. Washout is described by the so-called washout coefficient, l_g , that is defined as:

$$l_g = \frac{\text{washed-out amount of activity/total amount of activity}}{\text{duration of precipitation}}$$

= relative change of amount of activity in the plume per unit time.

The amount of material that is deposited per unit area of the ground per unit time is calculated as:

$$W_N(x,y,s,u) = \frac{Q_N(x,t,s) \cdot l_g}{\sqrt{2} \cdot \pi \cdot u \cdot \sigma_y(x,s)} \cdot \exp\left(-\frac{y^2}{2 \cdot \sigma_y(x,s)^2}\right) \text{ [Ci/m}^2 \text{ sec]}$$

(12)

where

l_g = washout coefficient [sec^{-1}]
 $Q_N(x,t,s)$ = $Q_0(t) \cdot e^{-(l_g + \lambda) \cdot \frac{x}{u}}$ [Ci/sec]
 = apparent source strength corrected for washout
 $Q_0(t)$ = apparent source strength [Ci/sec] at the release point.

When dealing with average concentrations at given distances (see section 2.3) the factor

$$\exp\left(-\frac{y^2}{2 \cdot \sigma_y(x,s)^2}\right),$$

in formula (12) is replaced either by

$$\sqrt{\frac{\pi}{2}} \cdot \frac{\sigma_y(x,s)}{2 \cdot x \cdot \operatorname{tg}(\alpha)} \cdot \left(\operatorname{erf}\left(\frac{x \cdot \operatorname{tg}(\alpha)}{\sqrt{2} \cdot \sigma_y(x,s)}\right) - \operatorname{erf}\left(-\frac{x \cdot \operatorname{tg}(\alpha)}{\sqrt{2} \cdot \sigma_y(x,s)}\right) \right)$$

or by

$$\sqrt{\frac{\pi}{2}} \cdot \frac{90 \cdot \sigma_y(x,s)}{\alpha \cdot x}$$

The concentration of material in the plume, corrected for washout, will be:

$$\chi_N(x,y,z,s,u) = Q_N(x,t,s) \cdot S_g(x,y,z,s,u).$$

During precipitation both dry and wet deposition (washout) may occur simultaneously. Assuming that the two mechanisms of deposition can affect the material in the plume independently of each other, then $Q_{DN}(x,t,s)$, the source term corrected for deposition, can be calculated:

$$Q_{DN}(x,t,s) = Q_0(t) \cdot \exp\left(-(\lambda+1_g) \cdot \frac{x}{u} - \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \frac{\exp\left(-\frac{1}{2} \cdot \left(\frac{H}{\sigma_z}\right)^2\right)}{\sigma_z(x,s)} dx\right)$$

(13)

The amount of material that is deposited per time unit per area unit of ground will be:

$$\begin{aligned}
 W_{DN}(s,y,s,u) &= v_g \cdot Q_{DN}(x,t,s) \cdot Sg(x,y,-H,s,u) \\
 &+ \frac{Q_{DN}(x,t,s) \cdot l_g}{\sqrt{2} \cdot \pi \cdot u \cdot \sigma_y(x,s)} \cdot \exp\left(-\frac{y^2}{2 \cdot \sigma_y(x,s)^2}\right) \text{ [Ci/m}^2\text{/sec]}
 \end{aligned}
 \tag{14}$$

Provided that the amount of material deposited is not removed from the site of deposition by other means than radioactive decay, then it applies, both to dry deposition and to washout, that the total amount deposited, at a given time, t , will be:

$$\begin{aligned}
 w(x,y,s,u,t,td_1,td_2) &= \int_{td_1}^t w(x,y,s,u) dt \\
 &= 0 \quad \text{for } t \leq td_1 \\
 &= w(x,y,s,u) \cdot \frac{1}{\lambda} \cdot \left(1 - e^{-\lambda \cdot (t - td_1)}\right) \quad \text{for } td_1 < t \leq td_2 \\
 &= w(x,y,s,u) \cdot \frac{1}{\lambda} \cdot \left(1 - e^{-\lambda \cdot (td_2 - td_1)}\right) \cdot e^{-\lambda \cdot (t - td_2)} \quad \text{for } td_2 < t
 \end{aligned}
 \tag{15}$$

where

td_1 = start time of deposition
 td_2 = end time of deposition.

It is assumed that the dispersion conditions and the deposition parameters (v_g and l_g) do not alter in the period of time under consideration.

If there is a mixing layer above the release point, this will affect the dispersion conditions, and hence perhaps the deposition too. In this case formulas (10)-(15) are not necessarily applicable.

2.6.2. Deposition of daughter products

In general the source terms for airborne radioactive isotopes should be calculated as solutions to coupled differential equations of the type:

$$\frac{dQ_i(t)}{dt} = -\lambda_i Q_i(t) + \lambda_i \cdot \sum_{j=1}^{i-1} Q_j(t) \cdot f_{ji} - G_i(t) \cdot Q_i(t) \quad (16)$$

where

- t = transportation time ($= \frac{x}{u}$)
- $Q_i(t)$ = amount of isotope no. i. at time t (= source term).
- f_{ji} = branching ratio fraction of decays of isotope no. i leading to the formation of isotope no. j.
- λ_i = decay constant for isotope no. i.
- $G_i(t)$ = depletion function for isotope no. i.
- i = isotope no. The first isotope in a decay chain has no. 1, the next no. 2 and so on.

When only wet deposition is considered the function

$$G_i(t) = l_g$$

For a single isotope (no radioactive daughter products) equation (16) becomes

$$\begin{aligned} \frac{dQ_1(t)}{dt} &= \lambda_1 \cdot Q_1(t) - l_g \cdot Q_1(t) \\ \Rightarrow Q_1(t) &= Q_1^0 \exp(-(\lambda_1 + l_g) \cdot t) \end{aligned}$$

where

$$Q_1^0 = Q_1(t = 0).$$

Let us now consider the situation mentioned in 2.5 where an isotope, the parent, and its radioactive daughter product are both released from the source with constant rate ϵ_p [Ci/sec], respectively, ϵ_d [Ci/sec]. When calculating the source strength of the daughter product, corrected for deposition, and the amount of the daughter product on the ground, it must be taken into account whether the mother product is deposited on the ground or not.

The source strength of the daughter product corrected for deposition is calculated from (16). There are two cases:

a. No deposition of the mother product.

$$Q_d^*(x,s) = \epsilon_d \cdot \exp(-\lambda_d \cdot \frac{x}{u}) \cdot g(x,s) + \quad (17)$$

$$\frac{\epsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p + \ell} \cdot (\exp(-\lambda_p \cdot \frac{x}{u}) - \exp(-\lambda_d \cdot \frac{x}{u})) \cdot g(x,s)$$

b. Deposition of the parent.

$$Q_d^*(x,s) = (\epsilon_d \cdot \exp(-\lambda_d \cdot \frac{x}{u}) + \frac{\epsilon_p \cdot \lambda_d}{\lambda_d - \lambda_p} (\exp(-\lambda_p \cdot \frac{x}{u}) - \exp(-\lambda_d \cdot \frac{x}{u}))) \cdot g(x,s) \quad (18)$$

where

$$l = l_t = \left(+ \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp\left(-\frac{1}{2} \cdot \left(\frac{H}{\sigma_z(x,s)}\right)^2\right)}{\sigma_z(x,s)} dx \right) \cdot \frac{u}{x}$$

for dry deposition

$$= l_g$$

for wet deposition (washout)

$$= l_g + \frac{u}{x} \cdot \int_0^x \frac{v_g}{u} \sqrt{\frac{2}{\pi}} \cdot \frac{\exp\left(-\frac{1}{2} \left(\frac{H}{\sigma_z(x,s)}\right)^2\right)}{\sigma_z(x,s)} dx$$

for simultaneous dry and wet deposition

$$g(x,s) = \exp\left(- \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp\left(-\frac{1}{2} \left(\frac{H}{\sigma_z(x,s)}\right)^2\right)}{\sigma_z(x,s)} dx\right)$$

for dry deposition

$$= \exp\left(-l_g \cdot \frac{x}{u}\right)$$

for wet deposition

$$= \exp\left(-\left(l_g \cdot \frac{x}{u} + \int_0^x \frac{v_g}{u} \cdot \sqrt{\frac{2}{\pi}} \cdot \frac{\exp\left(-\frac{1}{2} \left(\frac{H}{\sigma_z(x,s)}\right)^2\right)}{\sigma_z(x,s)} dx\right)\right)$$

for simultaneous dry and wet deposition.

Other symbols are the same as given earlier.

It is assumed that the same deposition parameters can be used for both parent and daughter product.

To facilitate the solution of the differential equations (16), used when deriving the expression for the source strength of the daughter product in the case of dry deposition, the function $g(x,s)$ is approximated by the expression $\exp(-1_t \cdot \frac{x}{u})$. This approximation is only used when calculating the amount of daughter product created by the decay of the parent during transport from the source to the detector point. It gives rise to a slight overestimation of both the source term $Q_d^*(x,s)$ and the amount of the daughter product deposited on the ground.

The amount of material that is deposited per area unit of ground per time unit is found by replacing Q_D , Q_N or Q_{DN} in formulas (10), (12) and (14) by the relevant expression for Q_d^* .

The total deposited amount of the daughter product at a given position up to a given time, t , will be:

$$W_d(x,y,s,u,t) = \int_{td_1}^t w_d(x,y,s,u) dt \quad (19)$$

If the parent is not deposited, the expression for W_d will be the same as for W , i.e., the expression indicated under formula (15). The following expressions thus apply only in cases where both parent and daughter product are deposited:

$$\begin{aligned} W_d(x,y,s,u,t,td_1,td_2) &= 0 \quad \text{for } t \leq td_1 \\ &= w_d(x,y,s,u) \cdot \frac{1}{\lambda_d} (1 - \exp(-\lambda_d \cdot (t - td_1))) \\ &+ w_p(x,y,s,u) \cdot \left(\frac{1}{\lambda_p} + \frac{1}{\lambda_d - \lambda_p} \cdot (\exp(-\lambda_d \cdot (t - td_1))) \right. \\ &\quad \left. - \frac{\lambda_d}{\lambda_p} \cdot \exp(-\lambda_p \cdot (t - td_1)) \right) \quad \text{for } td_1 < t \leq td_2 \\ &= w_d(x,y,s,u) \cdot \frac{1}{\lambda_d} (1 - \exp(-\lambda_d \cdot (td_2 - td_1))) \cdot \exp(-\lambda_d \cdot (t - td_2)) \\ &+ w_p(x,y,s,u) \cdot \frac{1}{\lambda_d - \lambda_p} \cdot \left(\frac{\lambda_d}{\lambda_p} \cdot (1 - \exp(-\lambda_p \cdot (td_2 - td_1))) \cdot \exp(-\lambda_p \cdot (t - td_2)) \right. \\ &\quad \left. - (1 - \exp(-\lambda_d \cdot (td_2 - td_1))) \cdot \exp(\lambda_d \cdot (t - td_2)) \right) \quad \text{for } td_2 < t \end{aligned} \quad (20)$$

3. CALCULATION OF DOSES

3.1. Doses to individuals

3.1.1. Inhalation doses

A person who at a given time is at a given point, P(x,y,z) will inhale radioactive material at a rate equal to the product of the inhalation rate and the concentration of radioactive material at P.

The resulting dose (in rem or sievert) to an organ (lung, thyroid, etc.) is calculated as:

$$D_I(x,y,z,s,u) = \zeta\beta \cdot S(x,y,z,s,u) \cdot \sum_{i=1}^{n_{iso}} \delta_{k,i}(d) \cdot I_i(x,te_1,te_2) \quad (21)$$

where

- β = inhalation rate [m³/sec]
- $S(x,y,z,s,u)$ = relative concentration [sec/m³]
- s = stability-category
- u = wind speed [m/sec]
- $\delta_{k,i}(d)$ = dose to organ k per inhaled unit of radioactivity of isotope i, integrated from the time when the plume has passed point P to d days after this time [rem/Ci]
- $I_i(x,te_1,te_2)$ = integrated source term [Ci]
- te_1 = start of exposure [sec]
- te_2 = end of exposure [sec]
- n_{iso} = total number of isotopes in the plume.
- ζ = reduction factor for filtration (gl)

3.1.2. External gamma doses from the plume

The external gamma radiation dose to a person at a given point $P(x_d, y_d, z_d)$ is found by integrating the radiation from the plume. If the plume contains n_{iso} isotopes whose photon energies are distributed over n_e energy groups, the gamma dose (in rem) at point P is found to be:

$$D_G(x_d, y_d, z_d, s, u) = \frac{K}{4\pi} \cdot \eta \cdot \prod_{k=1}^{n_e} E_k^Y \cdot \sigma_k^Y \cdot \prod_{i=1}^{n_{iso}} f_{k,i} \cdot$$

$$\int_{\max(0, u \cdot (te_1 - tf_2))}^{u \cdot (te_2 - tf_1)} \frac{I_1(x, te_1, te_2)}{2 \cdot \pi \cdot \sigma_y(x, s) \cdot \sigma_z(x, s) \cdot u} \cdot$$

$$\left(\int_{-H}^{\infty} \left(\exp\left(-\frac{z^2}{2 \cdot \sigma_z(x, s)^2}\right) + \exp\left(-\frac{(z+2 \cdot H)^2}{2 \cdot \sigma_z(x, s)^2}\right) \right) \cdot \right.$$

$$\left. \left[\int_{-\infty}^{+\infty} \frac{B(\mu_k \cdot r) \cdot e^{-\mu_k \cdot r}}{r^2} \cdot \exp\left(-\frac{y^2}{2 \cdot \sigma_y(x, s)^2}\right) dy \right] dz \right] dx$$

(22)

where

- r^2 = $(x-x_d)^2 + (y-y_d)^2 + (z-z_d)^2$ [m²]
- s = stability category
- tf_1 = start of release [sec]
- tf_2 = end of release [sec]
- te_1 = start of exposure [sec]
- te_2 = end of exposure [sec]
- K = conversion factor, the dose rate/(absorbed energy per gram per Ci) [(rem/sec)/(MeV/g)/Ci]
- n_e = number of energy groups
- E_k^Y = mean photon energy in the k'th energy group [MeV]

$\sigma_k^Y = \sigma^Y(E_k^Y)$	= energy absorption coefficient for air, in the k'th energy group [m^2/g]
$f_{k,i}$	= photon yield for isotope i, in the k'th energy group
$\mu_k = \mu(E_k)$	= linear attenuation coefficient for air, in the k'th energy group [m^{-1}]
$B(\mu_k \cdot r)$	= $1 + K_E(E_k^Y) \cdot \mu_k \cdot r$, build-up factor for the k'th energy group
$I_i(x, te_1, te_2)$	= integrated source term for isotope i [Ci]
η	= shielding factor for buildings, etc.

The creation of radioactive daughter products (see 2.5) and deposition (see 2.6) can be taken into account in the integrated source term.

The model for external gamma doses only takes the possible existence of a mixing layer into account to a limited extent: the vertical dispersion parameter, σ_z , is calculated as described in section 2.2, i.e., its maximum value will be $\sigma_{zL} = 0.798 \cdot L$, where L is the mixing height. The concentration function, on the other hand, is not "folded" as given in formula (4). This approximative method does not increase the uncertainty with more than a few per cent.

The integration over three dimensions, given in formula (22), is carried out by means of Gauss-Christoffel quadrature with weight points calculated according to a method described by Walter Gautchi [21] and [22].

3.1.3. External gamma doses from deposited radioactive material

The external gamma dose from radioactive material deposited on the ground to a person who is at a given point P is found by integrating the dose contributions from the ground. It is assumed in the calculation that the ground can be considered as an infinite, flat source, where the radioactive material is deposited with a uniform density, corresponding to the density on the ground directly under point P. The dose is by convention

calculated at points that lie 1 m above the ground.

$$D_S(x,y,s,u) = 0.2304 \cdot \eta \cdot \eta_g \cdot T \cdot \sum_{k=1}^{n_e} E_k^\gamma \cdot \mu_{en}(E_k^\gamma) \cdot I_k^*(\mu_k \cdot l)$$

$$\sum_{i=1}^{n_{iso}} f_{k,i} \cdot \int_{te_1}^{te_2} w_{e_1}(t, td_1) \cdot W_i(x,y,s,u,t,td_1,td_2) dt$$

(23)

where

- $D_S(s,y,s,u)$ = external gamma dose 1 m above the ground from radioactive material deposited on the ground [rem]
- $\mu_{en}(E_k^\gamma)$ = linear energy absorption coefficient for air for photon energy E_k^γ [m^{-1}]
- $\mu(E_k^\gamma)$ = linear attenuation coefficient for air for the photon energy E_k^γ [m^{-1}]
- k = energy group number ($1 \leq k \leq 8$)
- i = isotope number
- n_{iso} = number of isotopes
- n_e = number of energy groups
- E_k^γ = mean photon energy for energy group no. k
- $f_{k,i}$ = photon yield for isotope i in the k 'th energy group

$$I_k^*(\tau) = \int_{\tau}^{\infty} \frac{B_k(\rho) \cdot e^{-\rho}}{\rho} d\rho$$

- $B_k(\rho)$ = $1 + K_E(E_k^\gamma) \cdot \rho$, build-up factor for the k 'th energy group.

$W(x,y,s,u,t,td_1,td_2)$	= concentration of isotope i [Ci/m^2] on the ground vertically beneath the detector point at time t , when the deposition takes place in the time span from td_1 to td_2 (see otherwise section 2.6).
$we_i(t,td_1)$	= correction factor for weathering of isotope i , at time t , when deposition starts at time td_1 (see 4.6)
te_1	= start of exposure [sec]
te_2	= end of exposure ended [sec]
td_1	= start of deposition started [sec]
td_2	= and of deposition [sec]
η	= shielding factor for buildings, etc.
η_g	= shielding factor for surface roughness
T	= correction factor for backscatter.

3.2. Isodose curves

The coordinates for the isodose curve for a given dose level, D_i , are found from:

$$D(x_i, y_i) = D_i \tag{24}$$

where

$D(x,y)$ = dose to an individual at the point (x,y) .

The Gaussian model implies that the curve is always symmetrical around the axis of the plume, where the dose/concentration is greatest. In most cases equation (24) cannot be solved explicitly, so that in practice a numerical method of solution must be used.

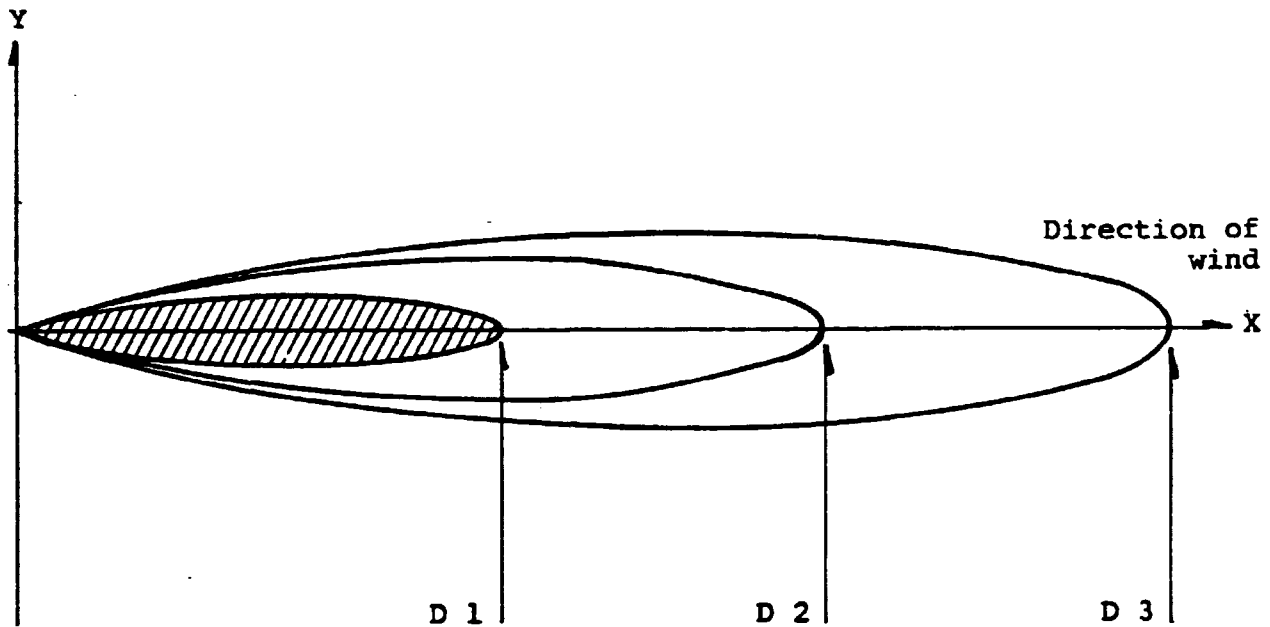


Fig. 2

Fig. 2. Isodose curves for the Gaussian plume model.
The dose is greater than D_1 inside the hatched area.

The assumption of a Gaussian dispersion model implies that the doses inside an area limited by the isodose curve are greater than or equal to the dose for which the isodose curve is calculated. The area of this space (hatched in fig. 2) is calculated from:

$$A_{D_1} = 2 \cdot \int_{x_{D_1 \text{ min}}}^{x_{D_1 \text{ max}}} Y_{D_1}(x) dx$$

where

A_{D_1} = part of the area where the dose $\geq D_1$.

$Y_{D_1}(x)$ = positive value of y , which is the solution to the equation:

$$D(x, y_{D_1}(x)) = D_1$$

It applies that $|y_1| < |y_2| \Rightarrow D(x_0, y_1) > D(x_0, y_2)$

$x_{D_1 \text{ min}}$ = the smallest abscissa where the dose is equal to D_1 , i.e., $D(x_{D_1 \text{ min}}, 0) = D_1$

$x_{D_1 \text{ max}}$ = the largest abscissa where the dose is equal to D_1 , i.e., $D(x_{D_1 \text{ max}}, 0) = D_1$

$$x_{D_1 \text{ min}} < x_{D_1 \text{ max}}$$

3.3. Collective doses

The collective dose to a given group of individuals is defined as the sum of the doses to the individuals of the group.

If there are n individuals in the group, then:

$$DB_n = \sum_{i=1}^n D_i$$

where

DB_n = collective dose for n individuals [man rem]

D_i = dose to individual i [rem]

The collective dose within an area with a given population density, is calculated analogously:

$$DB_A = \int_A D(x, y) \cdot B(x, y) \cdot da$$

where

- DB_A = the collective dose for area A [man rem]
 $D(x,y)$ = dose to an individual at point (x,y) within
A [rem]
 $B(x,y)$ = the population density in an infinitesimal
area at the point (x,y) [persons/m²]

3.4. Calculation of mean values for a given spectrum of meteorological situations

When calculating the mean values of doses and concentrations of material, the area around the release point is divided up into a number of sectors of suitable width.

For each of these sectors we find:

- a) The probability that the wind is blowing from the release point and out into the sector.
- b) The distribution of the atmospheric stability (e.g., Pasquill's categories A-G)
- c) For each stability category: the distribution of the wind speed on a number of wind-speed intervals as well as the mean wind speed within the intervals.
- d) The distribution of the precipitation rate within the stability categories.

When calculating, for example, the annual mean doses it is assumed that all wind directions within the individual sector are equally probable, so that the dose/concentration at a given distance is constant over the whole width of the sector. When dealing with mean values of doses/concentrations for short-term releases, it is assumed that the wind direction is identical with the central axis of the sector. Possible contributions from sectors adjacent to the sector in question are included in calculating the dose. However, for the sake of clarity, these contributions to the doses/concentrations are not included in the formulas given below.

On the basis given above, the following formula can be set up for calculating the average dose/concentration at a given point in a given sector:

$$\bar{D}_i(x,y) = p'_i \cdot \sum_{j=0}^{n_s} \sum_{k=1}^{n_h} P^{*j,k|i} \cdot \left(\sum_{m=1}^{n_\lambda} P^*_{m|i,j,k} \cdot D(x,y,j,lg_m, \langle u \rangle_{i,j,k}) \right) \quad (25)$$

where

- p'_i = probability that the wind blows from the release point and into sector i .
- $P^{*j,k|i}$ = probability that the stability is category j at the same time as the wind speed is in group k - all provided, that the wind direction is in sector i .
- $P^*_{m|i,j,k}$ = probability that the precipitation intensity is in class m , provided that the wind is in sector i , the stability is category j , and the wind speed in group k .
- $D(x,y,j,lg_m, \langle u \rangle_{i,j,k})$ = dose/concentration at point $P(x,y)$ when the stability category is j , the wet deposition parameter has value lg_m corresponding to precipitation rate in class m , and the wind speed is $\langle u \rangle_{i,j,k}$.
- $\langle u \rangle_{i,j,k}$ = mean wind speed in group k , when the stability is of class j and the wind direction is in sector i .
- n_g = number of categories of stability
- n_h = number of wind speed groups
- n_λ = number of classes of precipitation intensity.

The mean value of the collective dose in a given area in a given sector will be:

$$\overline{DB}_i(A) = p_i' \cdot \sum_{j=0}^{n_s} \cdot \sum_{k=1}^{n_h} P''_{j,k|i} \cdot \sum_{m=0}^{n_\lambda} P_m^*|i,j,k \cdot \int_A D(x,y,j,lg_m, \langle u \rangle_{i,j,k}) \cdot B(x,y) d\omega \quad (26)$$

where

A = area in which the collective dose is to be calculated

B(x,y)dω = number of individuals in the infinitesimal area dω around point (x,y) within A.

Analogously, the total collective dose for an annulus around the release point will be:

$$\overline{DBT}(x_1, x_2) = \sum_{i=1}^n P_i' \cdot \sum_{j=0}^{n_s} \sum_{k=1}^{n_h} P''_{j,k|i} \cdot \sum_{m=0}^n P_m^*|i,j,k \cdot \int_{A_c(x_1, x_2)} D(x,y,j,lg_m, \langle u \rangle_{i,j,k}) \cdot B(x,y) d\omega \quad (27)$$

$$\sum_{m=0}^n P_m^*|i,j,k \cdot \int_{A_c(x_1, x_2)} D(x,y,j,lg_m, \langle u \rangle_{i,j,k})$$

$$\cdot B(x,y) d\omega$$

where

n = number of sectors

A_c(x₁, x₂) = area of the annulus limited by the radii x₁ and x₂ where x₁ < x₂.

4. DATA AND CALCULATION PROCEDURES FOR SPECIAL SITUATIONS

4.1. Dispersion parameters

The stability of the atmosphere is normally classified in the six Pasquill categories A-F [2,5]. For the stability categories, Turner's [2] ten-minute average values for the dispersion parameters ($\sigma_y(x,s)$ and $\sigma_z(x,s)$) are used. The dispersion parameters as a function of distance from the release point are shown in figs. 3 and 4.

These dispersion parameters can be used when the release lasts up to half an hour (1800 sec). If the release lasts longer (several hours), a correction is made for fluctuations of the wind direction.

As in WASH 1400 [3], this correction is made using a horizontal distribution parameter, $\sigma'_y(x,y)$, that is calculated as:

$$\sigma'_y(x,s) = \sigma_y(x,s) \cdot \left(\frac{t}{1800}\right)^{1/3}$$

where

- $\sigma'_y(x,s)$ = corrected horizontal dispersion parameter
- $\sigma_y(x,s)$ = horizontal dispersion parameter, 10-minute average value
- t = duration of release (sec).

In the case of a relatively long release duration and/or large fluctuations in wind direction, it can be necessary to use averages for sectors according to the methods given in 2.3.

The above considerations assume no alteration in atmospheric stability during the release. If the atmospheric stability and wind speed do vary during the release, then it is necessary to average over the stabilities and wind speeds that occur, as is described in section 3.4.

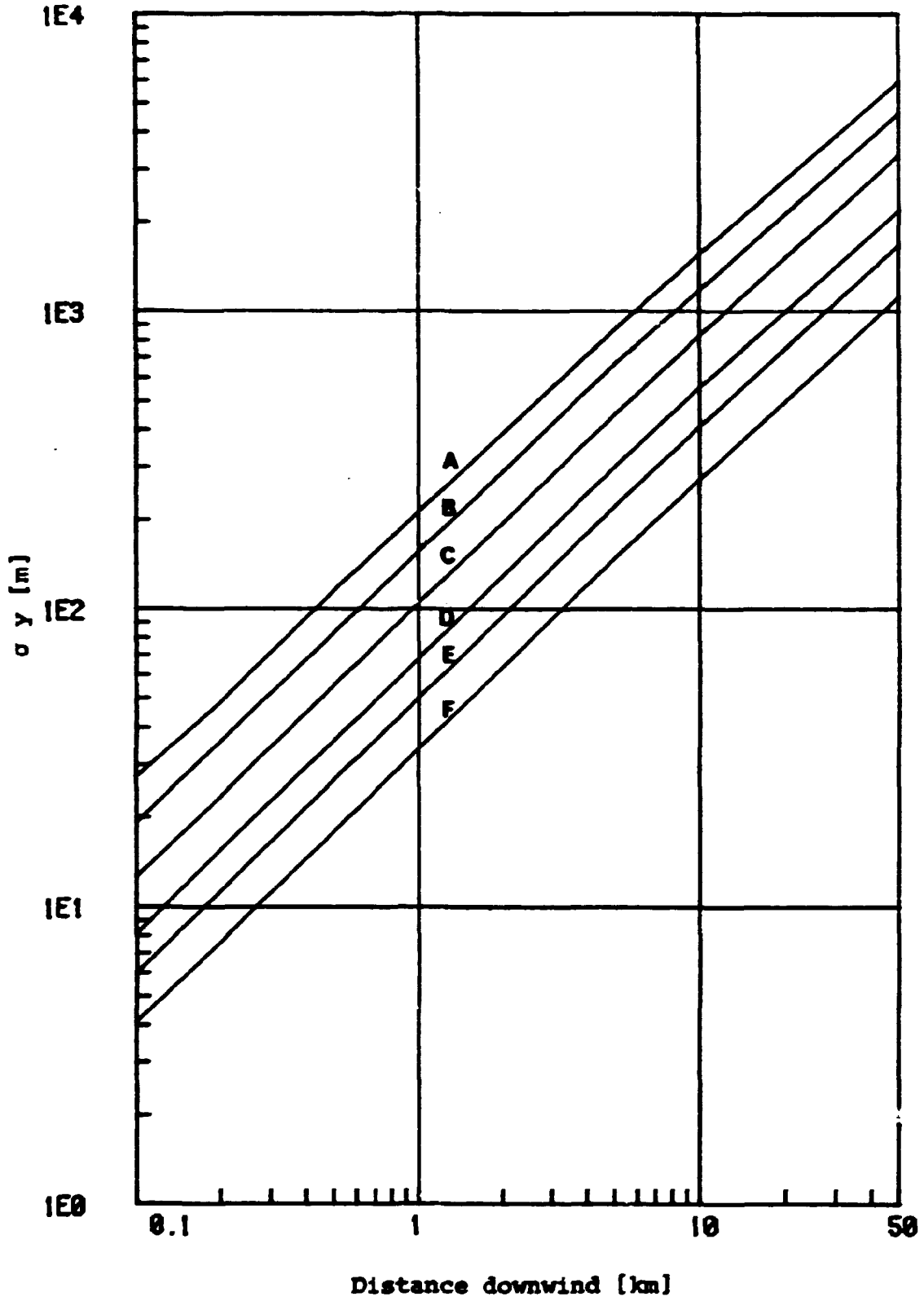


Fig. 3. Horizontal dispersion parameter (σ_y) as a function of distance in the wind direction.

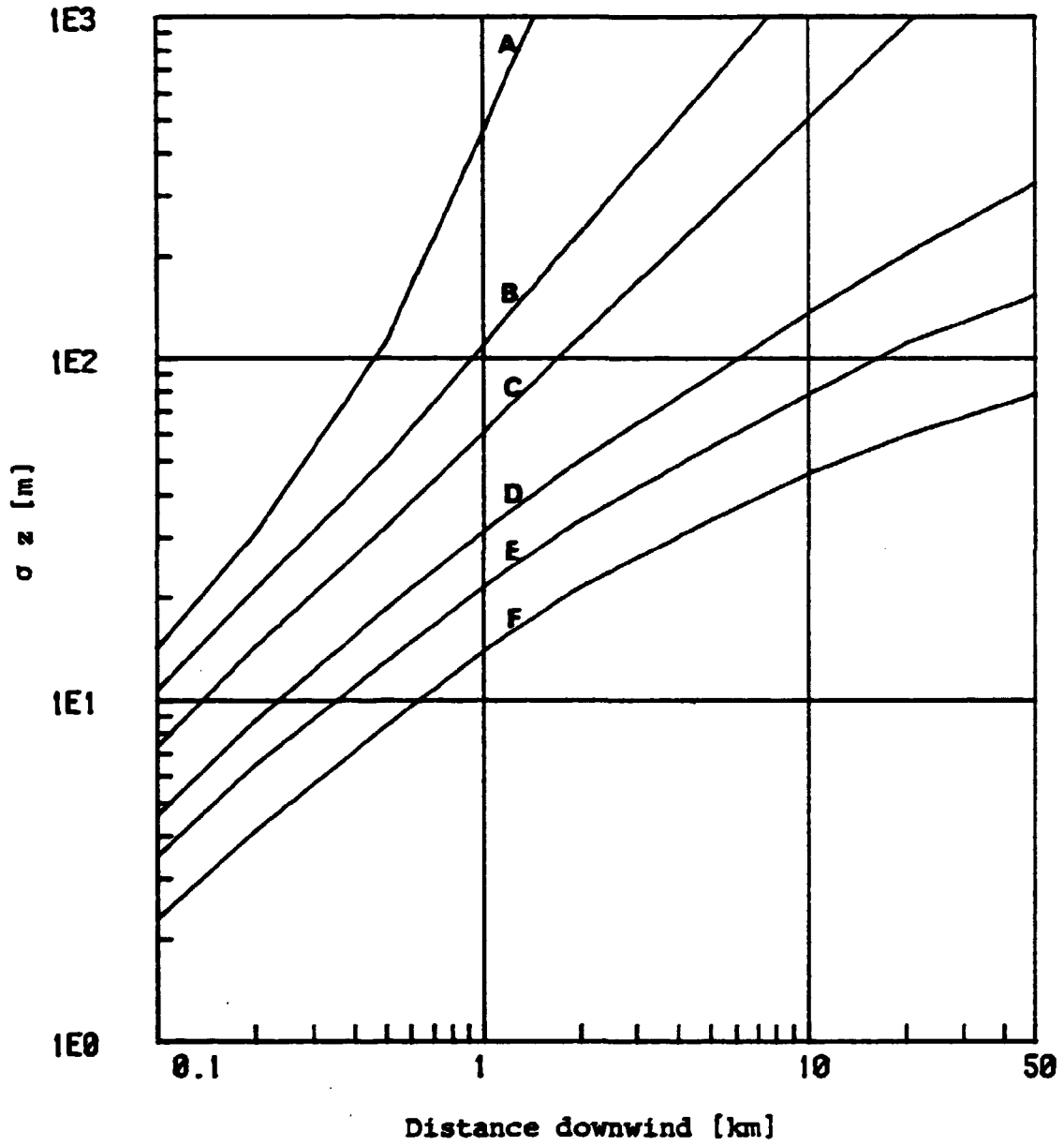


Fig. 4. Vertical dispersion parameter (σ_z) as a function of distance in the wind direction.

4.1.1. Correction for initial dispersion

If the material is released from a short stack, the presence of buildings or the like near the stack will often considerably increase the initial dispersion.

In the Risø model the aerodynamic dispersion around a building can be accounted for by assuming that the dispersion takes place as if the release occurred from a virtual point source located some distance upwind of the building.

The location of the virtual point source is selected so that the plume dimensions are similar to those of the building at the virtual distance x_v , as shown in fig. 5.

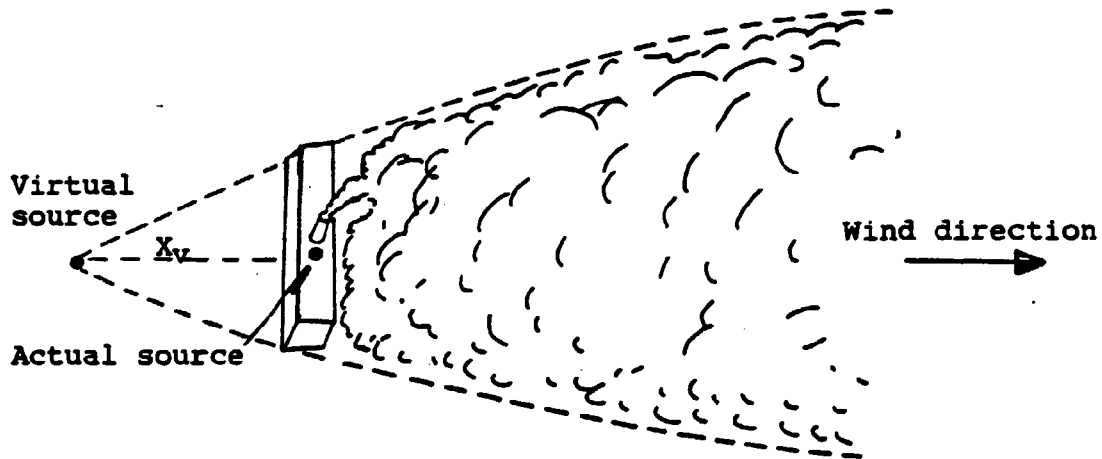


Fig. 5. Determination of virtual source.

Note that, normally, there will be two "virtual point sources" - one for the horizontal and one for the vertical distribution.

The upwind distances for the virtual point sources are found from equations (28) and (29):

$$\sigma_y(x_{v_y}(s), s) = \sigma_{y_0} \quad (28)$$

$$\sigma_z(x_{v_z}(s), s) = \sigma_{z_0} \quad (29)$$

where

- σ_{y_0} = initial value of σ_y
 σ_{z_0} = initial value of σ_z
 $x_{v_y}(s)$ = distance in the wind direction at the virtual source point for σ_y
 $x_{v_z}(s)$ = distance in the wind direction at the virtual source point for σ_z .

The dispersion parameters, $\sigma'_y(x)$ and $\sigma'_z(x)$, in the distance x from the actual source point, are found from:

$$\sigma'_y(x,s) = \sigma_y(x+x_{v_y}(s),s)$$

$$\sigma'_z(x,s) = \sigma_z(x+x_{v_z}(s),s)$$

In the case of dry deposition of the released material, the amount of material deposited is calculated as if deposition (and thus the release) had started at the virtual source point. In other words, it is assumed that deposition is augmented by the increased turbulence around the building.

4.1.2. Surface roughness

The vertical distribution parameter depends on the surface roughness. If use is made of a starting-point of σ_z -values corresponding to a roughness length of 10 cm, e.g., the Pasquill-Turner values in figs. 3 and 4, these may be corrected by Hosker's method [23] so that they correspond to a different roughness length. The method is:

$$\sigma_z(x,s,R_1) = \sigma_z(x,s,R_0) \cdot F_{R_0}(x,R_1)$$

where

- $\sigma_z(x,s,R)$ = vertical distribution parameter at distance x from the source point when the category of stability is s and the roughness is R .
 R_0 = "basic value" for the roughness length.
 $F_{R_0}(x,R)$ = correction factor for σ_z when the roughness

length is R , and the basic value is R_0 .
 $F_{R_0}(x, R_0) \equiv 1$.

If Hosker's method is used $R_0 = 10$ cm, and one finds:

$$F_{10}(x, R) = \begin{cases} \frac{\ln(c_1(R)) \cdot x^{\frac{d_1(R)}{d_2(R)}}}{1 + c_2(R) \cdot x} & \text{for } R < 10 \text{ cm} \\ 1 & \text{for } R = 10 \text{ cm} \\ \ln(c_1(R)) \cdot x^{\frac{d_1(R)}{d_2(R)}} \cdot \left(1 + \frac{1}{c_2(R) \cdot x}\right) & \text{for } R > 10 \text{ cm} \end{cases}$$

x is given in meters.

The values for the parameter set $c_1(R)$, $d_1(R)$, $c_2(R)$ and $d_2(R)$ are given in table 1. Note that these parameters are assumed to be independent of the atmospheric stability.

Roughness length	c_1	d_1	c_2	d_2
1 cm	1.56	0.048	6.25×10^{-4}	0.45
4 cm	2.02	0.027	7.76×10^{-4}	0.37
10 cm	e	0	0	0
40 cm	5.16	-0.098	18.6	-0.225
100 cm	7.37	-0.0957	4.29×10^3	-0.60
400 cm	11.7	-0.128	4.59×10^4	-0.78

Table 1. Parameters for roughness formula (from [23]).

4.2. Effective dispersion height

The effective dispersion height is assumed to be constant and thus independent of the distance from the release point. Thermal plume rise is calculated using Brigg's formula [3,12]. Decay heat and the latent heat of the accompanying steam are disregarded. In cases of unstable or neutral atmosphere, the effective dispersion height, H, is determined by:

$$H = h + (36 \cdot p)^{1/3} \cdot u^{-1} \cdot x^{2/3} \quad (30)$$

where

h = the physical stack height [m]

p = the release rate of the heat content of the plume
(less the latent heat) [MW]

x = the distance from the release point [m]

u = wind speed [m/s]

The plume rise is assumed to end at a distance from the release point that is numerically equal to $177 \cdot p^{2/5}$ (km). Inserting this value in (30) gives the final height of the plume as:

$$H = h + 104 \cdot p^{3/5} \cdot u^{-1} \quad (31)$$

If the atmosphere is stable then H is determined by:

$$H = h + \frac{215 \cdot p^{1/3}}{u \cdot \rho}$$

where the stability parameter ρ is given by:

$$\rho = \frac{g}{T} \cdot \frac{\partial \theta}{\partial z} \quad (s^{-2})$$

Here, $\frac{\partial \theta}{\partial z}$ is the potential temperature gradient for the atmosphere, g is the acceleration due to gravity, and T the temperature of the atmosphere ($^{\circ}K$).

4.3. Daughter products

In the calculation of external gamma doses from airborne as well as from deposited radioactive material, the following simplified decay chains are used:

mother product daughter product

Kr 85m	→	Kr 85
Kr 88	→	Rb 88
Kr 89	→	Rb 89
Sr 90	→	Y 90
Sr 91	→	Y 91
Zr 95	→	Nb 95
Zr 97	→	Nb 97
Mo 99	→	Tc 99m
Ru 105	→	Rh 105
Ru 106	→	Rh 106
Te 129m	→	Te 129
Te 131m	→	Te 131
Te 132	→	I 132
Sb 127	→	Te 127
Sb 129	→	Te 129m
I 131	→	Xe 131m
I 133	→	Xe 133
I 135	→	Xe 135
Xe 133m	→	Xe 133
Xe 135m	→	Xe 135
Xe 137	→	Cs 137
Xe 138	→	Cs 138
Ba 140	→	La 140
Ce 143	→	Pr 143
Ce 144	→	Pr 144
Nd 147	→	Pm 147
Np 239	→	Pu 239

4.4. Depositability

Argon-41 and all the krypton and xenon isotopes are reckoned to be non-depositable. The other isotopes under consideration are reckoned to be depositable.

4.5. Data for calculation of external gamma doses

4.5.1. Gamma energy groups

Division into energy groups as shown in table 2 is most appropriate when calculating external gamma doses [11].

Group No.	Energy range (MeV)	Average energy (MeV)
1	0-0.080	0.04
2	0.081-0.150	0.12
3	0.151-0.250	0.20
4	0.251-0.510	0.38
5	0.511-0.850	0.68
6	0.851-1.330	1.09
7	1.331-2.030	1.68
8	2.031-3.000	2.53

Table 2. Groups for photon energies.

4.5.2. Photon yields of the isotopes distributed in energy groups

Table 3. Photon yield of the isotopes in energy groups

Isotope	Energy group No.							
	1	2	3	4	5	6	7	8
Ar 41						0.99		
Kr 83m	0.08							
Kr 85m			0.76	0.14				
Kr 87				0.50	0.09	0.01	0.05	0.13
Kr 88	0.02		0.29	0.02	0.13	0.05	0.19	0.55
Kr 89		1.00	0.25	0.24	0.39	0.25	0.42	0.09
Rb 86						0.09		
Rb 88						0.14	0.21	0.02
Rb 89				0.01	0.10	1.10	0.05	0.26
Sr 91				0.01	0.96	0.37		
Zr 95					0.98			
Zr 97				0.09	0.01	0.04	0.03	
Nb 95					0.99			
Nb 97					1.96			
Mo 99	0.01	0.05	0.06	0.01	0.17			
Tc 99m		0.89						
Ru 103				0.90	0.06			
Ru 105		0.06		0.45	0.62	0.05		
Rh 105				0.25				
Rh 106			0.28	0.57	2.11	0.67	0.28	1.00
Sb 127				0.43	0.63			
Sb 129			0.03	0.08	0.83	0.47	0.07	
Te 127m								
Te 127								
Te 129m					0.03			
Te 129	0.16			0.09				
Te 131m	0.05	0.33	0.18	0.25	0.83	0.61	0.05	
Te 131		0.68		0.23	0.06	0.12		
Te 132	0.14	0.04	0.88					
I 131	0.03			0.87	0.09			
I 132				0.06	2.37	0.28	0.13	

Table 3 - continued

Isotope	Energy group No.							
	1	2	3	4	5	6	7	8
I 133				0.02	0.88	0.10		
I 134		0.04	0.02	0.14	1.44	1.08	0.15	
I 135			0.02	0.07	0.14	0.65	0.32	
Xe 131m			1.96					
Xe 133m			0.10					
Xe 133		0.37						
Xe 135m					0.81			
Xe 135			0.90		0.03			
Xe 137				0.33				
Xe 138			0.09	0.60		0.01	0.36	0.04
Cs 134				0.01	2.16	0.03	0.03	
Cs 136	0.13	0.06	0.26	0.60	1.00	1.00		
Cs 137					0.85			
Cs 138		0.02	0.02	0.35	0.11	0.36	0.77	0.23
Ba 140	0.15		0.06	0.09	0.24			
La 140				0.70	0.28	0.15	0.95	0.03
Ce 141		0.48						
Ce 143	0.12		0.02	0.49	0.11	0.01		
Ce 144	0.02	0.11						
Pr 144					0.01			
Nd 147		0.28		0.03	0.13			
Pm 149				0.03				
Np 239		0.23	0.14	0.18				
Pu 238								
Pu 239								
Pu 240								
Pu 241								
Am 241	0.35							
Cm 242								
Cm 244								

Source: Refs. 25, 26 and 27.

Note: Photon yields of less than 1% (0.01) are not included in the table nor in the calculations of external gamma radiation doses.

4.5.3. Energy absorption coefficients, linear attenuation coefficients and dose build-up factors for the energy groups

Table 4. Data for energy groups

Energy group No.	Energy absorption coefficient, $(\frac{\mu_{en}}{\rho})$ (cm ² g ⁻¹)	Linear attenuation coefficient μ (m ⁻¹)	Dose build-up factor coefficient, K_E
1	6.10 E-2	2.78 E-2	2.52
2	2.30 E-2	1.82 E-2	5.13
3	2.65 E-2	1.58 E-2	3.60
4	2.97 E-2	1.26 E-2	2.28
5	2.94 E-2	9.83 E-3	1.59
6	2.72 E-2	7.89 E-3	1.24
7	2.48 E-2	6.28 E-3	0.96
8	2.18 E-2	5.07 E-3	0.80

Source: Refs. 25 and 28.

Note: The build-up factor is defined as $B_E(r) \equiv 1 + K_E \cdot \mu \cdot r$, where

$$K_E \equiv \frac{\mu - \mu_{en}}{\mu_{en}}$$

4.6. Weathering

Radioactive material that is deposited on the ground (e.g., in agriculturally cultivated areas) will sink into the soil with time and thus the dose rate above ground is reduced. This phenomenon, which is called weathering in WASH-1400 [3], is included in our calculations in the same way as it is in WASH-1400. In the time integration of the dose rate, we take into account the fact that this is reduced more rapidly than by radioactive decay alone.

The dose rate up to the time t after deposition is normally

calculated, as it is in WASH-1400, from:

$$D_{g_i}(t) = D_{g_i}(0) \cdot \left(0.63 \cdot \exp(-1.13t) + 0.37 \cdot \exp(-0.0075t) \right) \cdot \exp(-\lambda_i t)$$

where

$D_{g_i}(t)$ dose rate in air, 1 m above an infinite surface source of isotope i , at time t

λ_i decay constant for isotope i

t time [y].

The formula has been derived experimentally for Cs 137, but it is used in PLUCON2 and in WASH-1400 for all isotopes deposited, see ref. 32.

Recent experiments at Risø indicate that for build-up areas (asphalt roads) a weathering factor of $0.6 \cdot \exp(-9.5 \cdot t) + 0.4 \cdot \exp(-0.0075 \cdot t)$ may be more appropriate. Both formulas can be used in PLUCON2.

4.7. Shielding factors, etc.

Typical values for shielding factors are:

a. External gamma dose from plume.

For people inside wooden buildings: $\eta = 0.9$

For people out of doors 11% of the time and inside buildings partly constructed of wood for the remainder of the time [3]:

$\eta = 0.75$

For people inside brick buildings: $\eta = 0.6$

For people out of doors for 11% of the time and inside buildings built mostly of brick or the like for the remainder of the time: $\eta = 0.66$.

b. External gamma dose from deposited activity:

For people inside wooden buildings: $\eta = 0.4$

For people out of doors for 11% of the time and inside buildings made partly of wood for the remainder of the time: (as in the USA [3]): $\eta = 0.33$

For people inside brick buildings: $\eta = 0.2$

For people out of doors 11% of the time, and inside buildings made mostly of brick or the like for the remainder of the time: $\eta = 0.26$.

The calculation of doses from deposited activity furthermore includes the following factors:

Shielding factor for the surface roughness of the earth: $\eta_g = 0.7$

Correction factor for backscatter: $T = 1.14$ (for all isotopes).

All the above factors are taken from WASH-1400, appendix VI [3].

4.8. Dose factors for inhaled isotopes

Dose factors giving the relationship between the amount of a given isotope that is inhaled and the resulting dose to a given organ, integrated from the time when the plume has passed to a given number of days after this time, are taken from WASH-1400, appendix VI, table D-2 [3]. For whole-body doses data from refs. 29, 30 and 31 are used. The data are given in table 4.

The dose factors for children under five years of age are assumed to be three times as large as the corresponding dose factors for adults.

Table 4. Committed effective dose equivalent for whole-body doses

Isotope	H ₅₀ [rem/Ci]	Isotope	H ₅₀ [rem/Ci]	Isotope	H ₅₀ [rem/Ci]
H 3	62	Rh 106	0	Ba 140	3500
Rb 86	6300	Sb 127	2700	La 140	0
Rb 88	78	Sb 129	590	Ce 141	0
Rb 89	36	Te 127m	9300	Ce 143	0
Sr 89	6200	Fe 127	230	Ce 144	0
Sr 90	2.3 E5	Te 129m	9300	Pr 143	0
Sr 91	930	Te 129	93	Pr 144	0
Y 90	0	Te 131m	3100	Nd 147	0
Y 91	0	Te 131	370	Pm 147	0
Zr 95	19000	Te 132	9300	Pm 149	0
Zr 97	2600	I 131	31000	Np 239	0
Nb 95	0	I 132	310	Pu 238	0
Nb 97	0	I 133	6200	Pu 239	0
Mo 99	1900	I 134	93	Pu 240	0
Te 99m	14	I 135	930	Pu 241	0
Ru 103	3000	Cs 134	46000	Am 241	0
Ru 105	410	Cs 136	9300	Cm 242	0
Ru 106	56000	Cs 137	31000	Cm 244	0
Rh 105	440	Cs 138	93		

Solubility class D is used for all isotopes.

Source: refs. 29, 30 and 31.

The following specific organs can be considered:

- Bone marrow
- Lungs
- Gastrointestinal tract
- Bones
- Thyroid gland (thyreoidea)
- Gonads
- Breast

When calculating stochastic effects of doses the weighting fac-

tors of ICRP are used, these are given in table 5.

Table 5. Weighting factors of ICRP

Tissue (organ)	Weighting factor (w_T)
Whole body	1
Gonads	0.25
Breast	0.15
Red marrow	0.12
Lungs	0.12
Thyroid	0.03
Bone (Endosteum)	0.03
Remainder (each of 5 organs)	0.06

Inhalation rates used are given in the following table.

Table 6. The inhalation rates (l/min) for different ages and levels of activity (based, in part, on WASH-1400 [3])

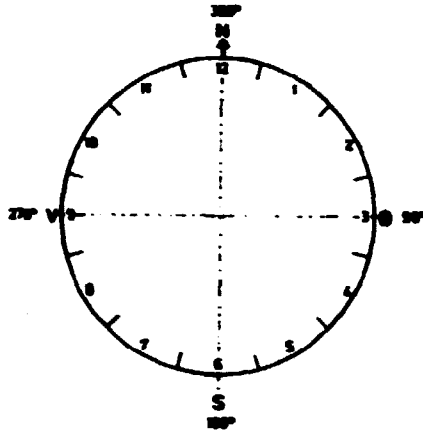
Level of activity	Age			
	1 year	5 years	10 years	Adults (15 years <)
Very active	3.57	8.82	13.7	21.0
Normally active (8 hours/day)	2.71	6.70	10.4	16.0
Average over 24 hr	2.35	5.80	8.97	13.8

4.9. Calculation of average values of doses and concentrations of material

Calculations of average values of doses, concentrations and collective doses are normally based on the following assumptions:

4.9.1. Area

The area around the release point is divided up into 12 sectors of 30° width:



Sector No. 1 comprises the interval from 15° to 45°, sector No. 2 from 45° to 75°, etc., and sector No. 12 comprises the interval from 345° to 15°.

4.9.2. Atmospheric stability

The stability is divided into six classes according to Pasquill:

Stability class	Pasquill category	Description
0	A	Very unstable
1	B	Unstable
2	C	Slightly unstable
3	D	Neutral
4	E	Moderately stable
5	F	Stable

Pasquill's category G (extremely stable) is omitted because the determination of dispersion parameters for this is very uncertain [3,5]. In addition, category G is relatively rare, and the dispersion conditions under this category are more similar to

conditions under category A (very unstable) than to those under category F. All in all, the omission of category G does not give rise to any important error.

4.9.3. Wind speed

The wind speed is divided up into five groups [16]:

Group	0	1	2	3	4
Wind speed [m/s]	$u < 1$	$1 \leq u < 3$	$3 \leq u < 6$	$6 \leq u < 10$	$10 \leq u$

Throughout the dispersion formulas the reciprocal wind speed, which is included as a factor, is used in the calculations.

$\frac{1}{\langle \frac{1}{u} \rangle}$ = the reciprocal value of the average value of the reciprocal wind speed in the individual speed groups.

The average value of the reciprocal wind speed cannot be given for speed group 0, where in principle it can be infinitely great, and group 0 is therefore omitted in the calculation of mean values of doses, etc. In Risø's meteorological statistics [16] the probability of wind speeds in group 0 is less than 1.1%, which implies that the discrepancy resulting from the omission of this group in calculating doses, etc., is very small (less than 1%).

In the calculations the wind speed at the level of the actual plume height is used, that is the wind speed data from the meteorological statistics is, if necessary, corrected according to the velocity profile at the site in question.

The probabilities p'_i and $p^n_{j,k|i}$ (formulas 25, 26, 27) are estimated on the basis of data from Risø [16]. The Gaussian dispersion model described earlier is used with Pasquill stability

classification and ten-minute mean values for the dispersion parameters σ_y and σ_z .

4.9.4. Mixing height

The mixing heights given in table 5 for the individual stability categories is used.

Pasquill category	A	B	C	D	E	F
Mixing height [m]	1500	1500	1000	500	200	200

Table 7. Typical mixing heights for Pasquill stability categories.

These values are recommended for use in the Federal Republic of Germany [13], and they are quoted in a report, presented to the German Ministry of the Interior. This report gives a survey of the general distribution conditions relating to distribution from nuclear plants [14].

In calculating the plume lift as a result of initial heat, it is assumed - in agreement with WASH-1400 - that the mixing layer is not penetrated by the plume.

4.9.5. Precipitation frequency

Only few data are available on the distribution of the frequency of precipitation. Those most easily available are contained in an investigation of the precipitation at Risø in the year 1966 [15]. In this investigation the precipitation frequency is given under two categories of stability: unstable (~ Pasquill A+B+C+D+ E(partly)) and stable (~ Pasquill F+ E(partly)). Based on these data, the following distribution of precipitation frequency can be set up on Pasquill's stability categories:

Stability (Pasquill category)	A	B	C	D	E	F
Precipitation frequency (% of hours with given stability)	21.4	21.4	21.4	21.4	15.9	10.5

Table 8. Precipitation frequency as a function of atmospheric stability (Pasquill categories) [15].

The precipitation frequency is assumed to be independent of wind direction and wind speed. The intensity of precipitation is assumed to be constant, when precipitation occurs, and moreover it is assumed to be independent of atmospheric stability.

In calculating the mean values of doses and concentrations (formulas (25), (26) and (27)), the following data and parameter values are used:

$$n_{\lambda} = 1$$

number of precipitation intensity classes minus 1.

The two classes are:

class No. 1: precipitation

class No. 0: dry weather.

$$P_{1|i,j,k}^* = P_{1|j}^*$$

precipitation frequency for stability j (table 8). Index i indicates the sector (wind direction). k refers to wind speed group.

$$P_{0|i,j,k}^* = P_{0|j}^* = 1 - P_{1|j}^*$$

frequency of dry weather for stability j.

$$l_{g_1} = l_g (> 0)$$

mean value of wet deposition parameters for all situations with precipitation.

$$l_{g_0} = 0$$

wet deposition parameter for dry weather.

4.9.6. Wind direction

The assumptions related to the variation of wind direction in time and space are:

- a) No turning of the wind direction between the release point and the point at which the dose is calculated.
- b) Short-term release: when the wind blows in a given sector, the mean direction always coincides with the mid axis of the sector.
- c) Annual mean values: the crosswind-integrated dose/concentration values are used. This means that the wind direction is assumed to swing backwards and forwards so that the material is uniformly distributed across the individual sectors. Considering a given sector, the dose will therefore only vary with distance from the release point. On the other hand, the dose at a given distance will normally differ from sector to sector.

4.9.7. Adjacent sectors

The dose contribution from adjacent sectors is included in the dose in the individual sectors.

4.10. Population data

Population distribution is described by population densities for meshes in a rectangular grid covering the area under consideration.

For Denmark a grid with mesh size of 1 × 1 km is used. The grid is based on the UTM grid (Universal Transverse Mercator grid [20]). Denmark lies in two different north/south-going UTM zones

(zones 32 and 33 [20]). For practical reasons, it was decided to use the coordinate system of the one zone for the whole country. The coordinate system for zone 32 was chosen. Jutland, Funen and West Zealand lie in this zone. The grid is shown in fig. 6.

At present population distribution data based on a forecast for 1985 are used. The forecast was prepared at Risø in collaboration with relevant public authorities - planning authorities, statistical offices, etc. - and it comprises the resident population. This forecast uses a mesh size of 2×2 km in describing the population distribution.

A new forecast for the geographical distribution of the resident population in Denmark in the year 1992 has been made. The mesh size in the description of the population distribution is here 1×1 km.

In the near zone, i.e., the area within about 5 km of the release point there is generally need of a more detailed description of the population-distribution. The description of this distribution is made either using a polar grid or using a rectangular grid with a mesh size of, for example, 0.5×0.5 km.

In the near zone the geographical distribution of persons is made in the following categories:

a. Resident population:

Comprises: permanent habitations, old people's homes, hospitals, etc.

b. Seasonal population:

Comprises: weekend cottages, holiday camps, camping sites, hotels, etc.

c. Daily varying population:

Comprises: industrial concerns, schools, bathing beaches, restaurants, cinemas, etc.

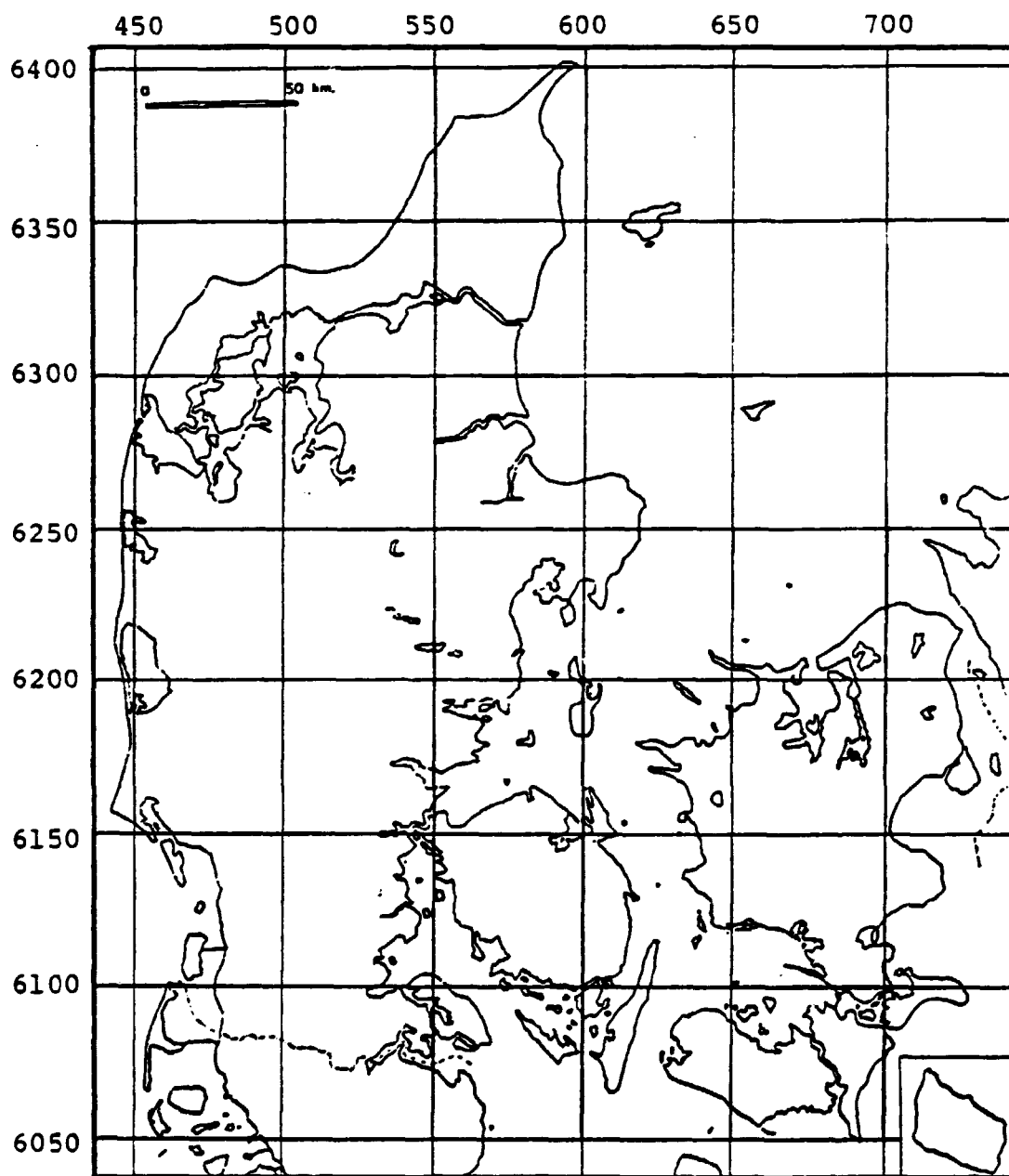


Fig. 6. Grid used for the description of the population distribution in Denmark. The grid is based on the UTM-grid (Universal Transverse Mercator-grid). Unit for coordinates: km.

For the seasonal population it is assumed that residence in the area amounts on average to $1\frac{1}{2}$ months/year.

For industrial concerns, etc., a working period of 8 hours/day is assumed.

The distribution of the population with regard to age and sex is also investigated inside the near zone.

4.11. Consequences of doses

The consequences of a given dose expressed by the expected number of injuries arising from the circumstance that a number of persons were exposed to this dose, can be calculated from:

$$C_i(B_D, D) = Ps_i(D) \cdot B_D$$

where

$C_i(B_D, D)$ = expected number of injuries of type i , as a result of B_D persons receiving a dose of magnitude D .

$Ps_i(D)$ = probability of injury of type i as a result of one individual receiving a dose D .

Considering a given area A with population density $B(x, y)$, the total number of injuries of a given type in the area will be

$$C_{iA} = \int_A Ps_i(D(x, y)) \cdot B(x, y) da$$

where

C_{iA} = total number of injuries (i.e., persons sustaining injuries of type i inside the area A .

$D(x, y)$ = the dose at point (x, y) , $(x, y) \in A$.

The relation between consequence and dose can be of different kinds. In the present version of the Risø model a choice can be made between four different relations:

1. Step function

$$P_s(D) = \begin{array}{ll} 0 & \text{for } D < D_1 \\ P_1 & \text{for } D_1 \leq D < D_2 \\ P_2 & \text{for } D_2 \leq D < D_3 \\ \vdots & \\ P^{n-1} & \text{for } D_{n-1} \leq D < D_n \\ 1 & \text{for } D_n \leq D \end{array}$$

where

$$\begin{array}{ll} 1 \leq n \leq 20 & \\ 1 \leq i \leq n & \text{for all } i \\ 0 < p_i \leq 1 & \text{for all } i \\ p_{i-1} < p_i & \text{for all } i > 1 \\ D_{i-1} < D_i & \text{for all } i > 1 \end{array}$$

2. Trapez function

$$P_s(D) = \begin{array}{ll} 0 & \text{for } D < D_1 \\ \frac{D - D_1}{D_2 - D_1} & \text{for } D_1 \leq D < D_2 \\ 1 & \text{for } D_2 \leq D \end{array}$$

where

$$D_1 < D_2$$

3. Integrated Gaussian distribution

$$\begin{aligned}
 & 0 && \text{for } D \leq 0 \\
 P_s(D) = & \frac{1}{\sigma_D \cdot \sqrt{2\pi}} \cdot \int_{-\infty}^D \exp\left(-\frac{(u-\mu_D)^2}{2 \cdot \sigma_D^2}\right) du && \text{for } D > 0
 \end{aligned}$$

4. Double Gaussian distribution

$$\begin{aligned}
 & 0 && \text{for } D \leq 0 \\
 P_s(D) = & \frac{1}{\sigma_{D_1} \cdot \sqrt{2\pi}} \int_{-\infty}^D \exp\left(-\frac{1}{2} \left(\frac{u-\mu_{D_1}}{\sigma_{D_1}}\right)^2\right) du && \text{for } 0 < D \leq D_m \\
 & \frac{1}{\sigma_{D_2} \cdot \sqrt{2\pi}} \int_{-\infty}^D \exp\left(-\frac{1}{2} \left(\frac{u-\mu_{D_2}}{\sigma_{D_2}}\right)^2\right) du && \text{for } D_m < D
 \end{aligned}$$

where it applies that

$$\frac{1}{\sigma_{D_1}} \int_{-\infty}^{D_n} \exp\left(-\frac{1}{2} \left(\frac{u-\mu_{D_1}}{\sigma_{D_1}}\right)^2\right) du = \frac{1}{\sigma_{D_2}} \int_{-\infty}^{D_n} \exp\left(-\frac{1}{2} \left(\frac{u-\mu_{D_2}}{\sigma_{D_2}}\right)^2\right) du$$

i.e., $P_s(D)$ is continuous for $D > 0$.

For all four types of relation it applies that a lower boundary can be set up for doses that result in consequences, so that

$$D < D_{\min} \Rightarrow P_s(D) = 0$$

5. CONCLUSION

The main features of the present version of the Risø model for calculating the consequences of the release of radioactive material to the atmosphere have been described. The model is continuously changed to reflect the present state of art and to satisfy the demands of the users of the model.

In Denmark the model has been used in all nuclear safety studies since 1976. However, the model is very flexible and can also be used for studies of airborne releases of non-radioactive material.

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APPENDIX

PLUCON2 - a short description

Risø's computer program, PLUCON2, for calculating doses to individuals and collective doses is based on the models and calculation methods described in the present report. The program is written in ALGOL for Risø's Burrough's B6700 computer.

PLUCON2, which is based on the Gaussian plume model, can be used for calculations in the area from 0.1 to 50 km from a given release point.

The following can be calculated:

- a) Concentrations of airborne material.
Concentrations of radioactive material deposited on the ground.
Doses to individuals and concentrations of isotopes:
External gamma doses from airborne radioactive materials.
Internal doses from the inhalation of radioactive materials.
External gamma doses from radioactive material deposited on the ground.
- b) Doses to individuals and collective doses for specific meteorological situations.
- c) Probability distribution of doses to individuals for a given probability distribution of the meteorological parameters.
- d) Isodose curves: coordinates, area and number of persons receiving doses in given intervals.
- e) Consequences of doses:
For given dose-consequence relations the number of injuries (i.e., the number of persons that, for example, will suffer from cancer) can be calculated for a given release.

The calculations can be made for both normal operational releases and for accidental releases.

Both old and new units can be used (i.e. Curie and Rem or Bequerel and Sievert).

Correction factors for shielding, decontamination, run-off and plouging can be used. It is possible to divide the area around the release point into meshes where different correction factors can be used (see fig. 7).

To a limited extent results from PLUCON2 has been compared to results from dose calculation programs used in the other Nordic countries - Finland, Norway and Sweden [17] and [24]. The comparison only comprised doses to individuals in specific meteorological situations. Based on the results of the calculations, it can be concluded that there are no significant differences between outcome of the different dose calculation programs used in the Nordic countries.

<p>Title and author(s)</p> <p>THE RISØ MODEL FOR CALCULATING THE CONSEQUENCES OF THE RELEASE OF RADIOACTIVE MATERIAL TO THE ATMOSPHERE</p> <p>by S. Thykier-Nielsen</p>	<p>Date July 1980</p> <p>Department or group Health Physics</p> <p>Group's own registration number(s)</p>
<p>pages + tables + illustrations</p>	
<p>Abstract</p> <p>A brief description is given of the model used at Risø for calculating the consequences of releases of radioactive material to the atmosphere. The model is based on the Gaussian plume model, and it provides possibilities for calculation of: doses to individuals, collective doses, contamination of the ground, probability distribution of doses, and the consequences of doses for give dose-risk relationships. The model is implemented as a computer program PLUCON2, written in ALGOL for the Burroughs B6700 computer at Risø. A short description of PLUCON2 is given.</p> <p>INIS Descriptors: COMPUTER CALCYLATIONS; DOSE RATES; EARTH ATMOSPHERE; FISSION PRODUCTS; GASEOUS WASTERS; GAUSS FUNCTION; NUCLEAR POWER PLANTS; P CODES; PLUMES; RADIATION DOSES; RADIONUCLIDE MIGRATION; SPATIAL DISTRUBUTION.</p> <p>UDC (621.311.2 : 621.039) : (551.510.721 : 614.73) : (681.3.06 : 519.283)</p> <p>Available on request from Rise Library, Rise National Laboratory (Rise Bibliotek), Forsøgsanlæg Rise), DK-4000 Roskilde, Denmark Telephone: (03) 37 12 12, ext. 2262. Telex: 43116</p>	<p>Copies to</p>