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CARNSORE: Hypothetical reactor accident study

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CARNSORE: HYPOTHETICAL REACTOR ACCIDENT STUDY

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Abstract. Two types of design-basis accident and a series of hypothetical core-melt accidents to a 600 MWe reactor are described and their consequences assessed. The PLUCON 2 model was used to calculate the consequences which are presented in terms of individual and collective doses, as well as early and late health consequences.

The site proposed for the nuclear power station is Carnsore Point, County Wexford, south-east Ireland. The release fractions for the accidents described are those given in WASH-1400. The analyses are based on the resident population as given in the 1979 census and on 20 years of data from the meteorological station at Rosslare Harbour, 8.5 km north of the site.

The consequences of one of the hypothetical core-melt accidents are described in detail in a meteorological parametric study. Likewise the consequences of the worst conceivable combination of situations are described.

Finally, the release fraction in one accident is varied and the consequences of a proposed, more probable "Class 9 accident" are presented.

Contract report commissioned by the Irish Electricity Supply Board.

June 1984
Risø National Laboratory, DK 4000 Roskilde, Denmark

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1. INTRODUCTION, SUMMARY, AND CONCLUSIONS

Introduction

This report (Risø-R-427) was commissioned by the Irish Electricity Supply Board (ESB) in 1979. It was originally intended for submission to a tribunal of inquiry into a proposed nuclear power station at Carnsore Point, County Wexford, Irish Republic, and was prepared by Risø National Laboratory under contract with ESB. Similar work is described in the reports: Risø-R-356 (1977) "Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-melt Accidents at the Barsebäck Reactor", and Risø-R-462 (1982), "Radioactive Contamination of Danish Territory after Core-melt Accidents at the Barsebäck Power Plant".

The present report describes the calculations of doses from design-basis accidents and hypothetical core-melt accidents to a 600 MWe reactor plant and gives an assessment of the expected consequences.

It was agreed that the analysis should follow the accident descriptions, sequences and probabilities found in the American Nuclear Regulatory Commission's WASH-1400 study, published in 1975: "Reactor Safety Study, An Assessment of Accident Risk in U.S. Commercial Nuclear Power Plants" (NUREG-75/014).

For all accidents the consequences are described under the assumption that the most common weather conditions prevail. In one case parametric studies were made on the effect of different weather conditions, and the worst conceivable conditions were used in the analysis of the consequences.

Maximum individual as well as population doses are calculated for a variety of compass directions. Acute and long-term health and genetic consequences are described.

Summary

Chapter 2 gives the distribution of the resident population in the vicinity of Carnsore Point based on the 1979 census. This is detailed in a polar grid system having sixteen angular sectors. Only six of the sectors are inhabited as the remaining ten cover the surrounding sea.

Chapter 3 describes the effects of meteorological conditions on atmospheric dispersion patterns resulting from accidents. The applicability of the Gaussian dispersion model to the present study is discussed. Twenty years of data from the meteorological station at Rosslare Harbour, 8.5 km north of Carnsore Point, were analysed in order to define statistics for wind speed and direction, stability conditions, and rain. Use of the Rosslare data in the accident study is validated. The meteorological conditions chosen for the consequence calculations are specified. Finally, the ranges of meteorological parameters applied in the parametric study are given.

Chapter 4 outlines the choice of reactor physics input data for the selected WASH-1400 accident sequences. Reactor core inventory at the release times, release fractions for isotope groups, and detailed accident descriptions and related probabilities are discussed. Recent findings concerning accident analyses and probabilities are commented upon and a release fraction parameter range is proposed for further analysis.

Chapter 5 gives a detailed description of PLUCON 2, the Gaussian dispersion and dose model used. Also described are the assumptions underlying isotopic decay, shielding factors, and the health physics data necessary to calculate individual and collective doses to the whole body or specific organs. Bone-marrow doses are preferred in consequence descriptions throughout the report. The limitations of the model are further discussed as well as the choice of reduction factors for shielding and sheltering indoors.

Chapter 6 describes in detail the design-basis accidents for the two reactor types PWR and BWR. Although the consequences are found to be of minor importance they are included in the report as their probability of occurrence is relatively high compared with the hypothetical core-melt accidents.

Chapter 7 analyzes in detail the consequences of ten hypothetical core-melt accidents. Individual plume centre-line bone-marrow doses are described for all accidents. Doses to specific organs, the dose distribution for different isotope groups, and collective doses are also given to some extent. Finally, early and late somatic effects as well as genetic effects are discussed.

Chapter 8 is a parametric study showing the dose variation that would result from altering such parameters as weather stability category, wind speed, deposition velocities, and rainfall rate. These parameters are varied for one accident release category, PWR 2. The worst conceivable situations are further described. Moreover, consideration is given to the variation in consequences when varying the release fraction in one accident. Finally, the consequences of a proposed "Class 9 accident" are discussed.

Conclusion

No health consequences are to be expected from the two design-basis accidents.

For all ten hypothetical release categories no early fatalities are to be expected assuming that supportive hospital treatment is available. Assuming minimal treatment for the individuals exposed, the highest figure for early fatality is 0.4 in the PWR 3 case, which means a 67% probability that no cases would occur, 27% that one, 5% that two, and 1% that three cases would occur. If evacuation is successfully completed then the probability that no early fatalities would occur increases to 100%.

Assuming a cancer mortality risk of 125 per 10^4 Sv, the greatest number of excess cancer fatalities is found in the case of a cold PWR 1A release if this should take place in the most heavily populated direction. This figure was calculated to be 100, corresponding to 4.5 excess cases per 1000 persons over a 30-year period. The corresponding "natural" death rate from cancer for the area under consideration is, however, between 51 and 78.6 (59 for the Irish Republic as a whole). The probability for this release is found to be far below 1.6×10^{-8} per reactor year (or less than once per 60,000,000 reactor years).

In the parameter study of the PWR 2 release category, the worst situation occurs in very heavy rain if the release takes place in the most heavily populated direction (probability less than 8×10^{-10} per reactor year, or less than once per 1,250,000,000 reactor years). About ten early fatalities can be expected after minimal hospital treatment and about four cases after supportive treatment. The number of latent cancer fatalities totalling 50.6 is, however, smaller than it is in the most probable atmospheric situation without rain where it is 56 cases. An evacuation scheme reduces population exposure significantly. The 56 latent cancer fatalities calculated for the PWR 2 release are then reduced to 41.

In a proposed "Class 9 accident", bone-marrow doses are found to be of the order of 0.1 Sv (10 rem) inside a distance of 2 km downwind of the site.

2. POPULATION DISTRIBUTION

2.1. Data

Population density in the vicinity of Carnsore Point is low. Most of the inhabitants are scattered among small towns, villages and farms. Wexford is the only population centre within 30 km of the site. This town is about 20 km from Carnsore Point and has a population of about 14000. (See Fig. 2.1).

The data describing the geographical distribution of the population in the area are based on the 1979 census (Central Statistics Office, Dublin). This gives data for the population inside administrative areas such as district electoral divisions, towns, etc.

In order to adapt the population data for input to the Risø computer programs, the area out tc 30 km from Carnsore point was divided into squares of various sizes based on the National Grid (see Fig. A 1 in Appendix 1) and the population in each square was determined from the census.

The size of the squares depends on their distance from Carnsore Point. This is because the dose consequence model used in the study shows that doses decrease rapidly (exponentially) with distance (see Chapter 5). The population density within each square is assumed to be uniform.

The square sizes choser are shown in Fig. 2.2.

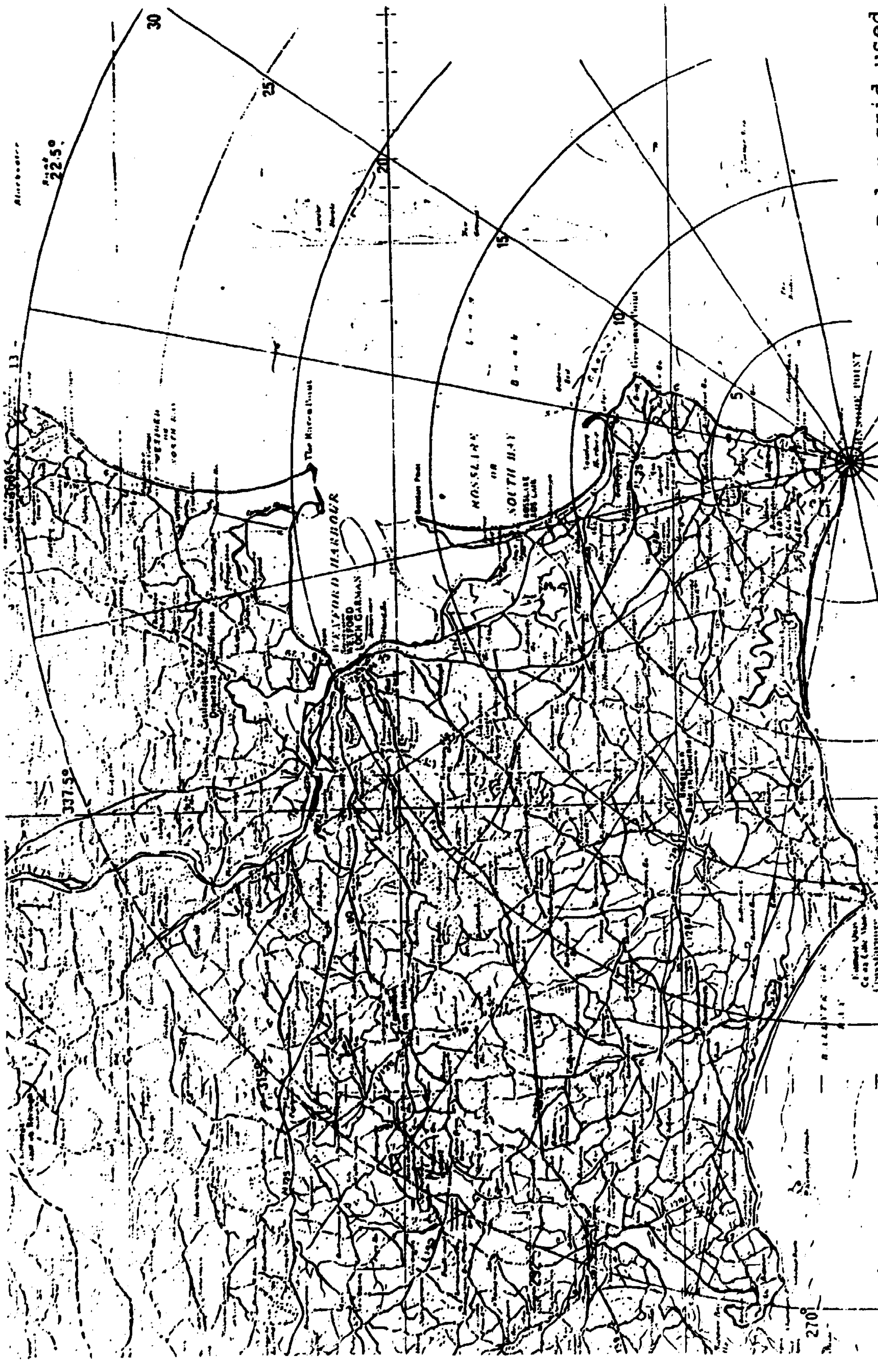


Fig. 2.1. Polar grid used for describing the population distribution and collective doses.

Distance from Carnsore	Square size
50 km - 100 km	10 × 10 km
20 km - 50 km	5 × 5 km
5 km - 20 km	1 × 1 km
0 km - 5 km	0.5 × 0.5 km
The coordinates for Carnsore Point in the National Grid are: x = 311.94 km y = 103.81 km	

Fig. 2.2. Square sizes used in the description of the population distribution in the vicinity of Carnsore Point.

The population data for the squares in the grid were provided by the ESB and are shown on Figs. A2-A4.

2.2. Population distribution in the Carnsore area

The distribution of the resident population in the vicinity of Carnsore Point was calculated using the above-mentioned data and a polar grid. The population data for the meshes in the polar grid and the accumulated population data for selected sectors are shown in Figs. 2.3-2.8.

Figures 2.3, 2.5 and 2.7 show that for distances of less than 2 km and between 5 km and 12.5 km from Carnsore Point the most populated sector lies in the 360° direction. For distances of between 2 km and 5 km and of between 12.5 km and 25 km, the most populated sector lies in the 337.5° direction. In the sector segment between 25 km and 30 km, most population is found in the 315° direction.

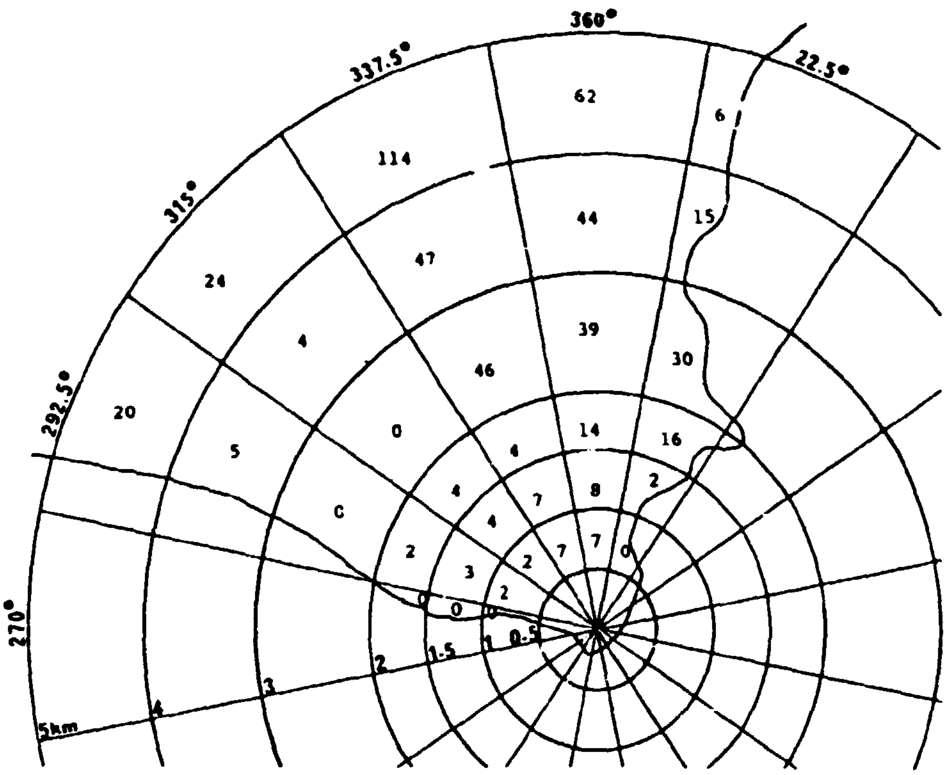


Fig. 2.3. Resident population (1979) 0.5 to 5 km from Carnsore Point.

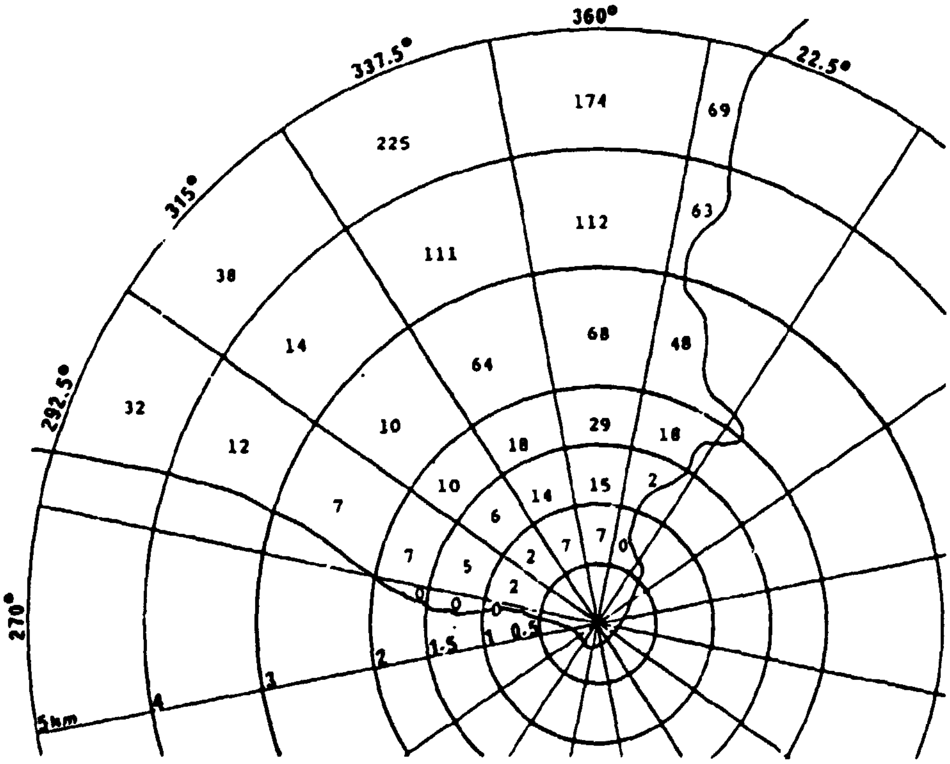


Fig. 2.4. Accumulations of the resident population (1979) 0.5 to 5 km from Carnsore Point.

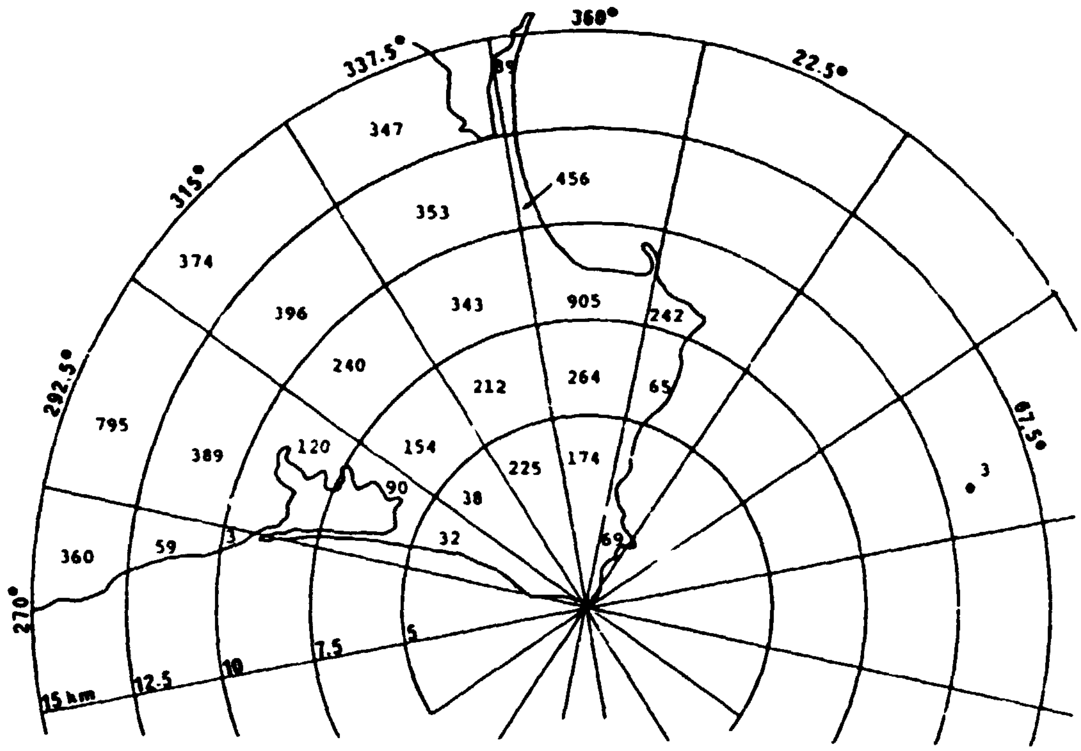


Fig. 2.5. Resident population (1979) 5 to 15 km from Carnsore Point.

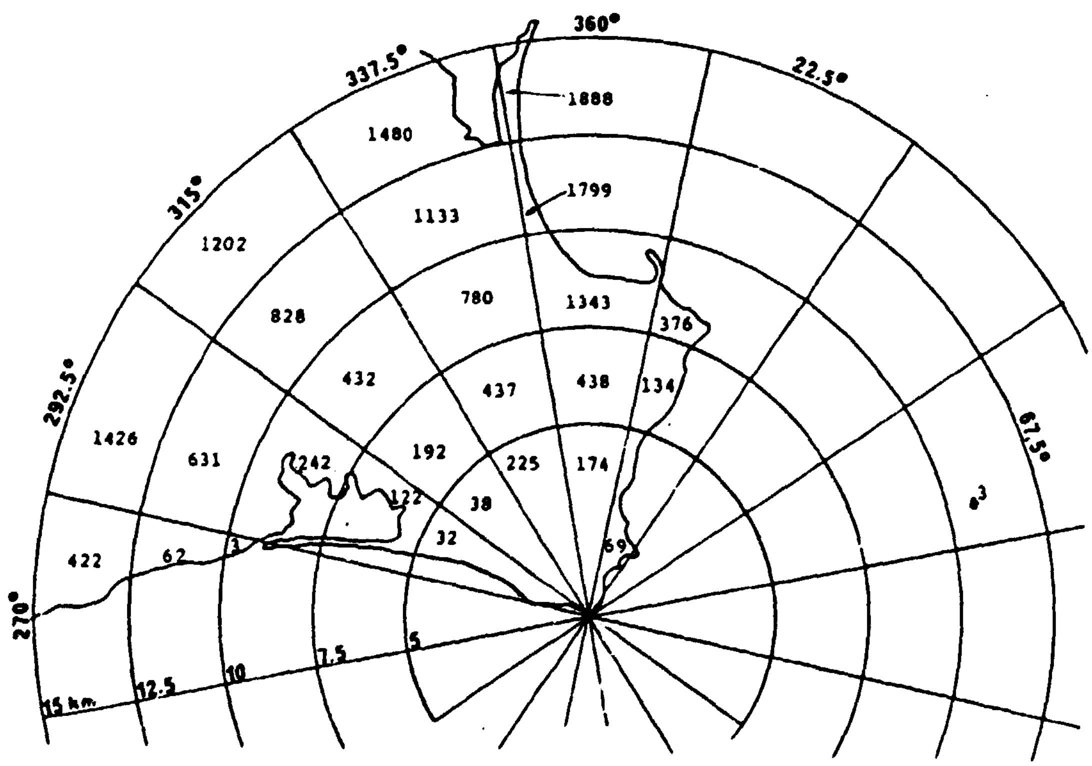


Fig. 2.6. Accumulations of the resident population (1979) 5 to 15 km from Carnsore Point.

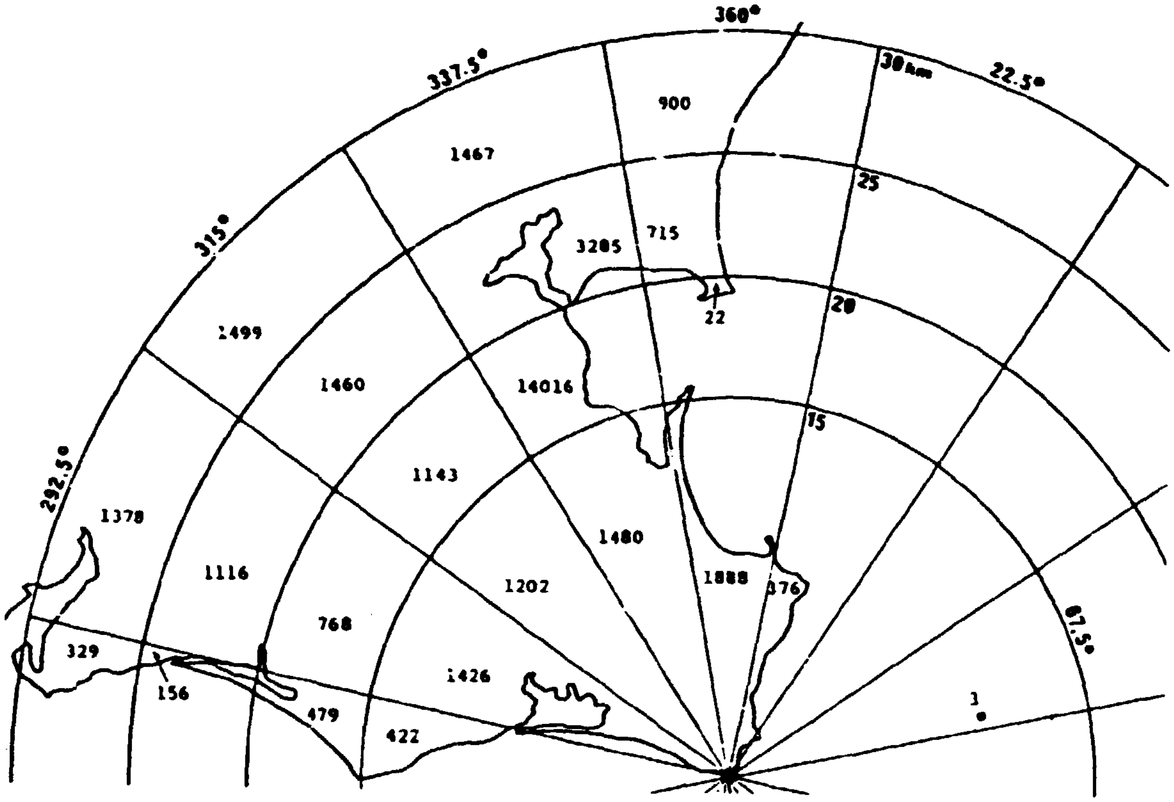


Fig. 2.7. Resident population (1979) 15 to 30 km from Carnsore Point.

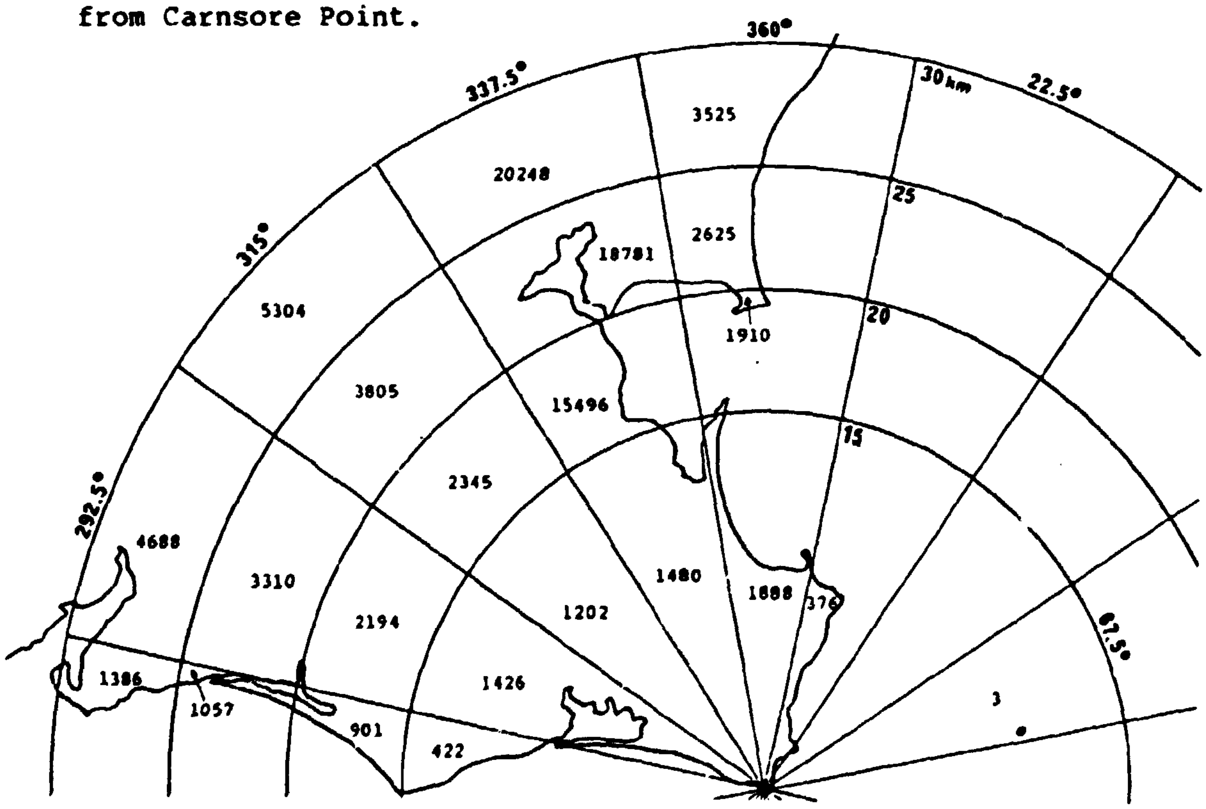


Fig. 2.8. Accumulations of the resident population (1979) 15 to 30 km from Carnsore Point.

As 50% of the total population residing at a distance of less than 30 km from Carnsore Point are found in the area lying at a distance of between 12.5 km and 25 km in the 337.5° direction which includes Wexford, this sector will receive the greatest collective doses. However, the greatest individual doses will probably be found in the 360° direction that has the highest population density close to Carnsore Point.

REFERENCE

CPI (February 1980). Census of Population of Ireland, Vol. 1, Population of District Electoral Divisions, Towns and Larger Units of Area, Central Statistics Office (Dublin).

3. METEOROLOGY

3.1. Introduction

The materials released to the atmosphere following an accident in a nuclear power plant are to a large extent gases, droplets, and small particles, and these may be carried far away by the wind in the same way as is the exhaust from a smoke stack. The simplest picture of the atmospheric transport mechanism is that of a horizontal plume, made up of the released airborne material, and lined up in the direction of the wind. The vertical and horizontal dimensions of this plume will increase with increasing distance from the source because of the turbulent mixing.

In the plume the concentration of the effluent will be determined mainly by the release rate, distance from source, wind speed, turbulence, and the removal by dry and wet deposition.

The calculation of concentrations of radioactive material following a nuclear accident at Carnsore Point are based on this simple plume picture, namely the so-called Gaussian plume model; consequently knowledge of the climatology in the area that could be affected is essential.

The Gaussian plume model is discussed in the following together with the influence of the state of the atmosphere on its parameters.

3.2. The Gaussian Plume Model

Only in exceptional circumstances is the smoke issuing from a stack shaped as a smooth, horizontal cone with a straight axis. The exact deviation of the shape from this "ideal" is difficult to determine, but fortunately it seems that in many cases (see, e.g., Gi, 68) the shape of the plume becomes quite regular if averaged over a few minutes. This smooth average plume is really what the Gaussian plume model is able to describe. (See Fig. 5.2)

In its simplest form, the model is a statement about the concentration X as function of the coordinates x, y, and z in a coordinate system with the origin in the source, which is considered to be a point source, the x-axis in the mean wind direction, and the z-axis vertical:

$$X(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right) . \qquad (1)$$

Here Q is the source strength in, for example, Ci s^{-1}, u the wind speed, and σ_y and σ_z the distances in the lateral and vertical directions from the axis at which, for a particular x, the concentrations fall to $1/\sqrt{e} \sim 0.6$ of that at the axis. The two so-called dispersion parameters, σ_y and σ_z, are only functions of x for given atmospheric conditions.

The only atmospheric quantities entering directly into (1) are wind speed and wind direction, which define the coordinate system.

Time does not appear explicitly in the Gaussian plume picture, and one can imagine that (1) describes a tube, extending from the source to infinity, through which material is pushed at speed u. Since the amount crossing a vertical cross section per unit time is proportional to u, and as the amount that has to be transported away per unit time is constant, the concentration must be inversely proportional to u.

As a rule the Gaussian plume model is not used in the form (1), because the presence of the ground, or equivalently the effect of the finite height H of the release point, must be taken into account. It is generally assumed that the dispersed material is reflected at the ground so that the effect of the release height is accounted for by introducing an imaginary additional source in the mirror image with respect to the ground. Instead of (1) the concentration becomes

$$X(x,y,z) = \frac{Q}{2\pi u\sigma_y\sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left\{\exp\left(-\frac{z^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+2H)^2}{2\sigma_z^2}\right)\right\} \quad (2)$$

The technical details of the application of the Gaussian plume model in the Risø Model are given in Th 80.

The following two subsections discuss the applicability of the model and the influence of the state of the atmosphere on its parameters.

3.2.1. General applicability of the model

So far only one condition for the validity of the Gaussian model has been mentioned, namely that the rough outlines of the instantaneous plume must be smoothed over a period of time to make it conform to the shape of a Gaussian plume. However, by this stage a number of assumptions have been made for the application of the model to the case of the dispersion of airborne material from a source of pollution.

Firstly, the atmospheric turbulence must be homogeneous and statistically stationary. This implies - in non-technical terms - that statistically there is no beginning and no end, in space or in time, of the turbulent wind field. Of course, the atmosphere is not that ideal and consequently this assumption can at best be only approximately true. The diurnal variation of the atmospheric parameters, for example, will totally invalidate stationarity over periods of more than a few hours. Further, the sudden changes due to sunrise and sunset may cause the atmosphere to respond in such a way that the stationarity assumption will not be even approximately true, however brief the period of time. Terrain features such as hills, valleys, trees, buildings, and even changes in the horizontal directions of crops, on the other hand, can bring into doubt the assumption of homogeneity in the horizontal directions. Most important, the very presence of the ground seems to violate even the idea of homogeneity in the vertical direction. Because the wind speed is zero at the ground there must be a wind shear that will only gradually disappear with distance from the ground. Therefore the Gaussian plume model should not be expected to be of much use, if the source is too close to the ground. However, because the parameters used in the model are fitted to experimental data from releases close to the ground, the model usually performs reasonably well in such situations.

Formulas (1) and (2) indicate that the pollutants are transported in the wind direction by the mean wind and diffuse vertically and laterally because of turbulent motion. The effect of turbulence on longitudinal transport is entirely ignored. A sufficient condition for this to be a good approximation is that the root mean square wind speed σ_u is small compared to u. Usually this is not the case when u is small (say less than 0.5 ms^{-1}); under such circumstances there is so little transport away from the source that no plume is formed at all. If u has a finite magnitude when σ_u/u is not small compared to unity, the longitudinal turbulent transport may be neglected and the plume picture restored, provided the distance x from the source is large compared to the horizontal spatial scale of the turbulence.

As already mentioned, time does not enter explicitly into the Gaussian plume formula but it may enter indirectly, through σ_y and σ_z. Time can also be considered as entering through the source strength Q and the wind speed u. This is conceptionally a contradiction to the assumption about stationarity, at least as far as u is concerned, but a possible way to deal with time-varying wet deposition on the ground, resulting from a time-varying precipitation rate, is to ascribe the corresponding dilution of the plume to a time of variation in Q. Real time variation in Q, corresponding to the fact that a physical source must at least have a time of start and a time of stop, can be thought of as follows. A certain amount of effluent, truncated at both front and rear ends, but shaped according to the "Gaussian cone", travels down this cone at the speed u. In this way it exposes different places downstream from the source at different times. The time variation of σ_y and σ_z results from the wavering of the plume under the influence of eddies larger than the transversal plume dimensions. A discussion of the growth of these two parameters with time is given later.

The Gaussian plume formula applies to a point source. If the source has a finite spatial extent, the resulting plume can be thought of as a sum of several point sources, but usually it is easier and sufficiently accurate to substitute the real situation by one in which there is one point source upstream with respect to the real source containing the whole source strength. The distance upstream is determined by the transversal dimensions of the real source. Having "travelled" from the fictitious point of release to the real source, σ_y and σ_z should be approximately equal to the transversal dimensions of the source.

3.2.2. The influence of averaging time on time-mean concentrations

One of the characteristics of the Gaussian dispersion model with dispersion parameters σ_y and σ_z given as increasing functions of the distance x from the source, is that the plume concentration will decrease with x. Very often the Gaussian plume is thought of as a cigar-shaped cloud which is constant with time. In general this picture is incorrect because - as easily appears from looking at the exhaust from a real stack - the plume will waver in time in both vertical and lateral directions with respect to the mean wind direction. However, for practical computations this steady Gaussian plume model will generally give satisfactorily accurate results, provided that σ_y and σ_z are averaged over the specified time of interest. A short qualitative discussion of plume kinematics is needed to explain why this is so.

Consider a plume as being composed of a series of puffs as indicated in Fig. 3.1, where such a series is shown in an instantaneous or "frozen" picture. (In order to illustrate the general idea better, only a fraction of the total number of puffs is shown). Each puff is transported away from the source by the wind, and simultaneously it grows due to the action of turbulent eddies with linear dimensions less than or equal to its size. The technical term for this growth process is relative diffusion, and the growth rate is determined mainly by eddies of a size comparable to the puff itself. Statistically the average puff size will be a function only of x for a given atmospheric situation. The average instantaneous plume can thus be characterised by the lateral and vertical root-mean-square widths σ_{Oy} (x) and σ_{Oz} (x) as functions of x.

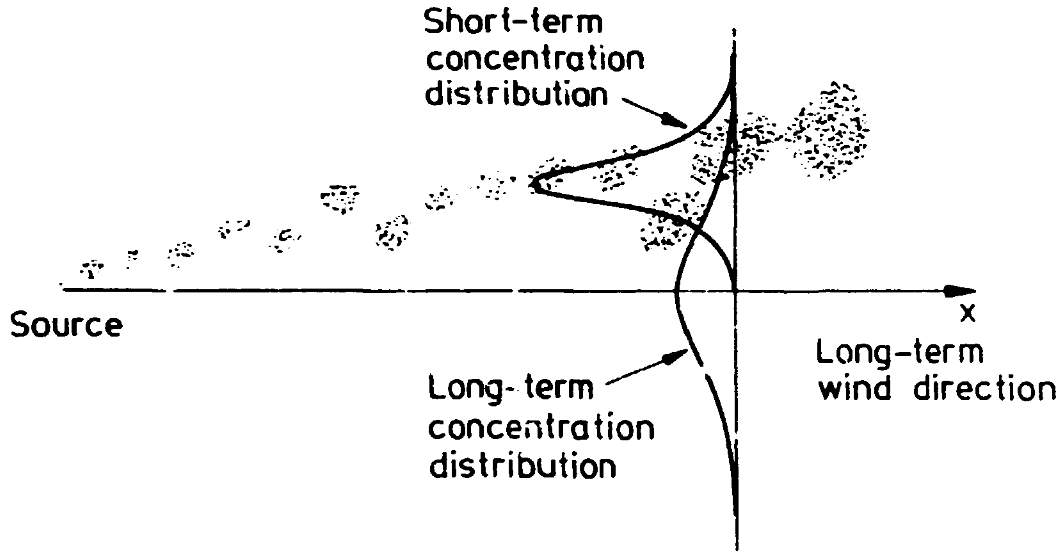


Fig. 3.1. Series of puffs.

As a puff moves with the wind, larger and larger eddies will take part in and be responsible for its growth. The eddies larger than the puff, on the other hand, will make it move around in a random fashion and give rise to the aforementioned wavering of the plume. At a particular distance x downstream from the source, and along an axis determined by the long-term wind direction, the puffs will pass a plane perpendicular to this direction with a randomly varying distance of their centres from the axis. For short-term averaging the root-mean-square width will be smaller than the corresponding long-term averaged root-mean-square width. This is indicated in Fig. 3.1 which shows the short- and long-term distributions of the puff distances from the axis. The long-term distribution has its maximum at the axis and is broader than the short-term distribution, the maximum of which is generally off the axis. The root-mean-square widths of these distributions of distances from the axis are functions of both distance x and averaging time T. They are directly related to the concentration distributions, for which the total-root-mean-square widths are found by adding the root-mean-square distance and the root-mean-square puff size "by the squares" in both vertical and lateral directions. Expressed formally, the mathematical relations are

$$\sigma_y^2\ (x,T) = \sigma_{oy}^2\ (x) + \sigma_{1y}^2\ (x,T) \tag{3}$$

and

$$\sigma_z^2\ (x,T) = \sigma_{oz}^2\ (x) + \sigma_{1z}^2\ (x,T)\ , \tag{4}$$

where σ_{1y} (x,T) and σ_{1z} (x,T) are the root-mean-square horizontal and vertical distances from the axis at the distance x for the averaging time T.

A case in which the relative diffusion may be neglected is discussed later, but in general both this and the "random walk" contributions (σ_{1y} and σ_{1z}) must be considered. The relative importance of the two terms will change with x for a fixed T. The relative diffusion will become more and more important with increasing distance, because the puffs will grow and comprise larger and larger eddies in their growth, until in the last somewhat speculative stage all turbulence on all scales is involved in the relative diffusion. For distances shorter than several tens of the linear scale of the turbulence, dimensional arguments together with order-of-magnitude evaluations show that relative diffusion is unimportant if the averaging time is large compared with the Eulerian time scale. Under such circumstances several formulas have been suggested to relate root-mean-square width at one averaging time to that at another. The one chosen here is that used by Thykier-Nielsen (1980), namely

$$\sigma_y\ (x,T) = \sigma_y\ (x,T = T_o) \times \left(\frac{T}{T_o}\right)^{1/3} \qquad (5)$$

and

$$\sigma_z\ (x,T) = \sigma_z\ (x,T = T_o) \times \left(\frac{T}{T_o}\right)^{1/3} \qquad (6)$$

where T is measured in seconds and T_o is equal to 1800 seconds.

2.2.3. Atmospheric parameters

Before plume formulas (1) or (2) can be used in a computer model, the wind direction and actual magnitudes of Q, u, σ_y, σ_z and H must be determined. The only parameters determined directly are the wind speed and direction. As mentioned before, the source strength Q used in (1) or (2) need not be the actual amount of material pouring out of the source during one unit of time. A factor to reduce Q is introduced to account for losses due to deposition and radioactive decay. Atmospheric stability will influence both diffusion parameters σ_y and σ_z, as well as the effective height of release H. This section discusses the following meteorological parameters relevant to dispersion in the atmosphere: precipitation, atmospheric stability, wind direction, wind speed, and mixing height.

Precipitation and deposition - Whether or not there is precipitation is of great importance for the rate of removal of pollutants from the plume. When there is no precipitation the plume is diluted only because of deposition on the ground; this process is called dry deposition. In this case the lower boundary of the plume is affected directly. When there is precipitation the interior of the plume will be diluted directly.

Dry deposition is usually described quantitatively by means of a so-called deposition velocity v_g (m/s) defined as the downward turbulent flux divided by the concentration, both measured at the same reference height, usually about 1 m above the ground.

The magnitude of v_g is a direct measure of the efficiency of the dry deposition. It depends largely on wind speed and turbulence intensity, but also of great importance are the physical, chemical, photochemical, and biochemical processes taking place at the surface when material is deposited. To a large extent these depend on the form of the pollutant, i.e. whether it is a gas or an aerosol, and in the latter case, what the particle sizes are. Because deposition velocities depend strongly on the type of material to be deposited, the composition of the plume changes downstream in the sense that the ratios between the concentrations of the different constituents change with distance from the source.

There is wet removal of effluents when there is precipitation. It is important to distinguish between below-cloud scavenging, or wash-out, and in-cloud scavenging, or rain-out. For wash-out a removal rate or wash-out coefficient l_g (s^{-1}) is usually introduced. This is defined as the rate of change of the concentration divided by the concentration, and it is proportional to the precipitation rate; for gases it is a function of how close the concentration in the water drops is to the equilibrium concentration, and for aerosols a function of the aerosol and drop sizes, the latter in the form of a collection efficiency. Plume composition changes downstream when there is wash-out too.

Rain-out is a term covering processes whereby material is removed from the plume to the droplets or condensation nuclei of clouds and where deposition can take place later elsewhere with the rain from the cloud. Rain-out can lead to completely unpredictable deposition patterns. On the one hand this can give a significant reduction of concentration in the plume but, on the other, there may be increased contamination of areas at larger distances from the source.

A quantitative description of this phenomenon would require as a minimum a good model for cloud dynamics, including condensation processes, in particular the effect of condensation nuclei.

However, neglect of this phenomenon will cause the predicted doses to be overestimated in cases where rain-out would have taken place.

In the Gaussian model, dry deposition and wash-out are accounted for by source depletion. For dry deposition this means that Q is reduced with a distance-dependent factor, as though the plume was diluted with the same fraction through the entire cross section at that distance. This does not correspond to the actual situation because the effect of dry deposition must be greater on the concentration close to the ground than on that further away. However, the deposition is usually so small that the approximation is considered to be quite accurate. For washout, source depletion means that Q is reduced by both a space -u and a time-dependent factor, where the latter reflects the variation in precipitation intensity. This way of modelling the wet scavenging is in principle completely correct if the horizontal dimensions of the part of the plume considered are smaller than those of the rain belt.

It should be borne in mind that when there is rain wash-out it is in general more efficient in diluting the plume than dry deposition. Measuring the efficiency of wash-out in terms of a deposition velocity, v_g will be about $\sigma_z l_q$ which typically is 0.03 m/s, but this can be as large as of the order of 1 m/s, whereas v_g for dry deposition is typically about 0.01 m/s or less.

Atmospheric stability - The stability of the atmosphere is an important concept for describing its dispersion conditions. Stability can be illustrated by the following example: If a small parcel of air is moved upward (or downward), it will expand (or be compressed) because the pressure in the atmosphere decreases with height. As the volume of the parcel changes, so does its temperature, a decrease in temperature corresponding to expansion and vice versa. This type of thermodynamic process without heat transfer is called an adiabatic expansion (or compression), and the change in temperature which occurs can be computed if the variation of pressure with height is specified. In the lower atmosphere the temperature change with height for an adiabatic expansion is -1oC per 100 m altitude increase.

If the surrounding atmosphere has a temperature distribution that decreases with height at the same rate, the air parcels will be in equilibrium with each other. In this case the condition of the atmosphere is said to be neutral. Under situations of neutral stability, atmospheric turbulence occurs only as a result of friction with the surface of the earth.

If the temperature in the atmosphere falls more than 1°C for a height increase of 100 m, a parcel which moves upward will arrive at surroundings that are relatively colder. As the warmer parcel is lighter it will have a positive buoyancy and the upward movement will continue. If, on the other hand, the parcel moves downwards it will arrive at surroundings that are relatively warmer, and movement will therefore continue downward. Under such unstable conditions where each movement in the vertical direction is increased, a stronger turbulence results than in a neutral situation. If such conditions prevail, the atmosphere is said to be unstable.

If the temperature in the atmosphere falls less than 1°C for a height increase of 100 m, or if the temperature rises with increasing height, it can be seen by arguments analogous to those above that turbulent motions will be counteracted. In such situations where buoyancy forces act to oppose vertical motions, the condition of the atmosphere is said to be stable. In a stable atmosphere, the turbulence level is less than in the neutral atmosphere, and when there is strong stability, turbulence motions can be nearly eliminated.

The Rosslare Harbour measurements show that unstable, neutral, and stable atmospheric conditions occur for approximately 7, 81, and 12% of the time, respectively.

Stability conditions in the atmosphere have much influence on its dispersive ability. This fact can be appreciated by watching the visible behaviour of smoke in the atmosphere. It is well known that the smoke trail from a tall stack takes a variety of forms according to the weather conditions and the time of day. Neutral conditions are characterized by moderate wind speed and a thoroughly cloudy sky or high wind speed with or without clouds. Under neutral conditions smoke shows a fairly straight, well-defined trail which increases in width and height as the distance from the source increases. Unstable conditions are usually characterized by light winds together with sufficient sunshine to warm the ground surface. Smoke behaves in a very irregular fashion and the strongly disturbed air over the heated surface leads to a rapid spread in the vertical and to an erratic variation in the direction of travel of successive sections of the smoke plume; it rapidly reaches a stage where it is no longer visible. Stable situations occur more frequently at night when the wind is generally light and the sky sufficiently clear to result in an appreciable cooling of the ground. Vertical and horizontal spread is considerably reduced and the smoke moves downwind in compact visible form for appreciable distances, often not showing a straight trail but something more like a meandering river.

The three categories described above constitute the simplest classification of diffusive conditions. In the literature the following terminology is often used:

Atmospheric conditions	Plume behaviour
unstable	looping
neutral	coning
stable	fanning

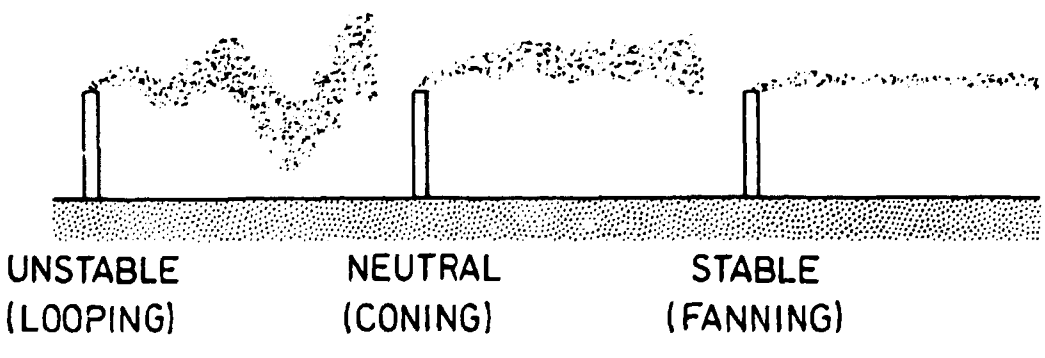


Fig. 3.2. The three characteristic plume forms.

Many years of measurement of wind speed, wind direction, and horizontal and vertical fluctuations of wind direction, all at the effective stack height, yield the best set of singlepoint meteorological measurements for estimating climatological statistics for the atmospheric dispersion ability relating to the stack considered. Measurements of wind direction fluctuations are rather intricate turbulence measurements and have rarely, if ever, been obtained on a climatological basis.

In practical diffusion calculations, the meteorological specifications will often have to be in terms of the routine data available on mean wind speed and direction, and cloud cover or vertical temperature gradient.

Mean wind direction is an important parameter in defining the direction in which the plume is transported. The applicability of the Gaussian plume model requires a steady mean wind direction. A shift in the mean wind direction during a continuous release will result in a larger area being passed by various sections of the plume whereby the actual doses will be appreciably smaller than calculated.

Wind speed is directly important in determining the initial dilution because the initial volume of air containing the amount of material emitted in a given time must be proportional to the wind speed. However, the wind speed also has an additional controlling influence on diffusion through its effect on turbulent mixing in the atmosphere. Turbulent mixing is also strongly influenced by the state of the sky through its control of the thermal stratification of the atmosphere.

Mixing height - Just as the vertical growth of a plume is limited by the presence of the ground, so can growth be limited from above; for example, when the layer in which the plume is transported is of neutral stratification and has a stable layer aloft. The layer of the lower atmosphere in which free vertical plume rise and growth is possible is called the mixing layer. Its thickness is called the mixing height. The effect of a limited mixing height on vertical dispersion can be accounted for in the same way as the effect of the ground, i.e. by using an imaginary additional source in the mirror image with respect to the top of the mixing layer. Often a simpler approach is used where a uniform distribution of material in the vertical is assumed from a distance which is twice the distance where the mixing height equals the effective stack height plus twice the vertical dispersion parameter. In the intermediate area between this distance and that where the plume hits the top of the mixing layer, the concentrations may be obtained by interpolation.

Section 3.3.2 discusses the use of these parameters in climatological estimates of diffusion.

3.2.4. Application of the Gaussian model to Carnsore Point

In view of the preceding discussion, the Gaussian plume model might seem rather restricted in its applicability to real situations. Despite this, use of the model is almost the only available method for calculating the atmospheric dispersion of material emitted from single sources. This is because the model and the parameters ascribed to it incorporate much empirical knowledge of the behaviour of plumes, so that its weaknesses are often compensated for.

The diffusion conditions most closely resembling the idealised assumptions behind the model are characterised by a diffusion over a horizontal homogeneous terrain to a distance of several km from the source. This presumes source heights of less than 100 - 200 m, stability conditions that are neither extremely stable nor unstable, a moderate wind, and measurements with averaging times from 10 to 60 min. Experiments to verify the model carried out under such conditions have shown that it should be able to forecast concentrations to within a factor of 2-3. Use of the Gaussian model in cases where these conditions are not fulfilled is based on extrapolations that attempt to include knowledge about diffusion in the atmosphere. Furthermore, in real situations the occurrence of instationary and inhomogencous conditions will generally tend to lead to concentrations lower than those predicted by the model.

With regard to Carnsore Point and the prevailing meteorological, climatological, and ortographical conditions there, use of the Gaussian plume model is well justified. Because there are no terrain obstructions in the field of interest; moreover the influence of the coastal situation is minimal for the most frequent weather conditions (neutral stability, wind speed 6 m/s).

3.3. Meteorological statistics

3.3.1. Rosslare meteorological data

General description of site and measurements - The Carnsore Point site is located in south-east Ireland on the shores of the Irish Sea and the Atlantic Ocean. The climate is characterised by mild, moist winters and cool, cloudy summers with some rainfall, and it is moderated by the warm maritime air associated with the Gulf Stream. The prevailing winds are westerly to south-westerly and the average humidity is high, about 85%. The normal temperature range is 6-20°C with rainfall averaging about 1000 mm per annum. Meteorological data are available from the nearby meteorological station at Rosslare Harbour, 8.5 km north of the Carnsore Point site.

The Rosslare Meteorological Station is situated 26 m above mean sea level (MSL) on the bank rising from the harbour. The dataset used in the analysis covers the period 1959-1978 and is available on magnetic tapes. A description of the total synoptic weather dataset from Rosslare Harbour is given elsewhere. The following data were used in this study:

- Wind direction in tens of degrees from the north
- Wind speed in knots
  (both averaged over a 10-min period prior to time of observation)
- Present weather
- Past weather
- Total amount of cloud in octas
- Height of lowest significant cloud base in hundreds of feet (ceiling)

- Amount of precipitation, in millimetres and tenths, which fell in the 60-min period ending exactly on the hour
- Rain gauge adjustment in hundredths of a millimetre
- Duration, in tenths of an hour, of precipitation which fell at a rate of not less than 0.1 mm per hour during the 60 min period ending exactly on the hour.

Applicability of the Rosslare Harbour data to conditions pertaining to the Carnsore Point site - Because of the very short distance between Rosslare Harbour and Carnsore Point the weather will in general be the same in both places. However, measurements of wind speed and direction at low heights are strongly influenced by the character of the surrounding terrain. Wind measurements at Rosslare Harbour are made at 10 m height over a terrain which rises to 26 m above MSL at a distance of 100 m from the shore line. Hence winds from the sector west over north to southeast will have experienced the rise in elevation of the terrain before meeting the measuring instruments at the meteorological station. Because wind speeds over an escarpment are usually higher than over the surrounding terrain, wind speeds measured at Rosslare Harbour in the W-N-E-SE sector may be expected, on average, to be higher than those that could be measured at the Carnsore site.

On the other hand, the winds in the most important direction in this study, i.e. 156° (sector 6), cfr. Fig. 3.5, towards Wexford, will have passed almost 3 km of land before meeting the Rosslare instrument whereas a wind coming from the sea would meet an instrument at the site directly. Hence the wind speed in sector 6 will, on average, be higher at the site compared with that at Rosslare Harbour.

The wind direction distribution might be somewhat disturbed by the banks at Rosslare Harbour. However, the measured distribution appears as should be expected and is in accordance with measurements from other Irish meteorological stations (W.H. Wann, 1973).

Meteorological conditions at Rosslare Harbour are thus, in general, concluded to be representative of those pertaining to the site. The wind speed is probably underestimated in the direction towards Wexford, but this only introduces a conservatism into the calculated dose-probability relations.

A statistical analysis (Supplement 8) shows that the wind speed data from Rosslare Harbour have a distribution in accordance with expectation, hence indicating that the data are without flaws. (Supplements 1-8 are available on request from Risø Library, see reference list).

3.3.2. Weather categories

In the previous discussion of the state of the atmosphere and its dispersive ability, three basic states were identified: unstable, neutral and stable. Obviously the atmosphere does not limit itself to three well-separated and easily identifiable states; on the contrary, there is a wide spectrum of states. This circumstance, together with the need for a method to identify distinguishable dispersive states of the atmosphere by means of routine meteorological measurements, led F. Pasquill (1961) to propose a classification system. This system, which has been widely used ever since, assigns the following stability classes to the atmosphere:

No.	Letter	State	Simple state
1	A	extremely unstable	
2	B	moderately unstable	unstable
3	C	slightly unstable	
4	D	neutral	neutral
5	E	slightly stable	
6	F	moderately stable	stable
7	G	extremely stable	

In the meteorological statistics given in Supplements 1-5 the stability classes were determined by means of the wind speed, and a net radiation index by the following procedure (Turner, 1964):

I) If the total cloud cover is 10/10 and the ceiling is less than 7000 feet, use net radiation index equal to 0 (whether day or night).

II) For night time (between sunset and sunrise):

a) If total cloud cover $\leq$ 4/10, use net radiation index equal to -2.

b) If total cloud cover $\geq$ 4/10, use net radiation index equal to -1.

III) For day time:

a) Determine the insolation class number as a function of solar altitude from Fig. 3.3.

b) If total cloud cover $\leq$ 5/10, use the net radiation index in Fig. 3.4 corresponding to the insolation class number.

c) If cloud cover $\geq$ 5/10, modify the insolation class number by following these six steps:

1) Ceiling < 7000 ft, subtract 2.

2) Ceiling $\geq$ 7000 ft but < 16,000 ft, subtract 1.

3) Total cloud cover equal 10/10, subtract 1. (This will apply only to ceilings $\geq$ 7000 ft since cases with 10/10 coverage below 7000 ft are considered in item I above).

4) If insolation class number has not been modified by steps (1), (2), or (3) above, assume modified class number equal to insolation class number.

5) If modified insolation class number is less than 1, let it equal 1.

6) Use the net radiation index in Fig. 3.4 corresponding to the modified insolation class number.

When applying this procedure 3 octas were taken as equivalent to a cloud cover of 4/10. The solar altitude needed for Fig. 3.3 was calculated for the geographical position of Rosslare Harbour for each hour around the year using the expression (Seller, 1965)

$$\cos(90-a) = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\tau \qquad (7)$$

where a is the solar altitude, ϕ latitude, δ solar declination, and τ the hour angle ($\tau = 0^o$ at noon). Thus for any particular set of measurements the corresponding insolation class number could be determined from Eq. (7) in combination with Fig. 3.3 (Turner, 1964).

Solar altitude (a)	Insolation	Insolation class number
$60^o < a$	strong	4
$35^o < a < 60^o$	moderate	3
$15^o < a < 35^o$	slight	2
$a < 15^o$	weak	1

Fig. 3.3. Insolation as a function of solar altitude.

For "a" less than or equal to zero, night-time conditions were assumed. The stability class was finally obtained from Fig. 3.4 as a function of wind speed and net radiation index which, for day time, is equivalent to the above insolation class number modified according to point III above.

Wind speed m/s	Net radiation index						
	4	3	2	1	0	-1	-2
< 2	1	1	2	3	4	6	7
2-3	1	2	3	4	4	5	6
3-5	2	2	3	4	4	4	5
5-6	3	3	4	4	4	4	5
6 <	3	4	4	4	4	4	4

Fig. 3.4. Stability class as a function of net radiation and wind speed.

3.3.3. Results of the statistical analysis

The results of the statistical analysis are found in Supplements 1 to 7.

The probabilities (relative frequency of occurrence) of the wind being in a certain sector together with a certain stability, rainfall, and wind speed are listed in Supplements 1-5. Definitions of the wind direction sectors and the wind speed groups are given in Figs. 3.5 and 3.6. Each page in Supplements 1-5 gives a wind sector, the number of observations in the sector, and the corresponding percentage. The distribution of the observations in the sector in the seven stability categories also appears. The observations in the categories are further distributed into the five wind speed intervals. The probabilities given are conditional; hence the probability of there being a wind direction in sector X and a wind speed in group Y, under atmospheric conditions described by a stability category Z and rain in interval Q, is

$$P = P_X \times P_Y \times P_Z \times P_Q \qquad (8)$$

where P_X is the probability for wind sector X, P_Z the probability for stability category Z, P_Y the probability for wind speed group Y, and P_Q the probability for rain interval Q. As an example, Supplement 5 gives the probability for wind in sector 6, stability D, wind speed greater than 6 m/s (group 5) and rain between 5-10 mm/hr: $P_X = 13.4\%$, $P_Z = 100\%$, $P_Y = 87.5\%$, $P_Q = 0.1\%$.

$$P = 0.134 \times 1 \times 0.875 \times 0.001 = 0.0001 = \underline{0.01\%}$$

i.e., in one year (= 8766 hours) this situation will occur on average for approximately one hour.

$$0.0001 \frac{\text{occurrence}}{\text{hour}} \times 8766 \frac{\text{hour}}{\text{year}} \approx 1 \frac{\text{occurrence}}{\text{year}}$$

A condensate of the statistics in Supplements 1-5 appears in Figs. 3.7 to 3.13.

No.	Degrees
1	355 - 24
2	25 - 54
3	55 - 84
4	85 - 114
5	115 - 144
6	145 - 174
7	175 - 204
8	205 - 234
9	235 - 264
10	265 - 294
11	295 - 324
12	325 - 354

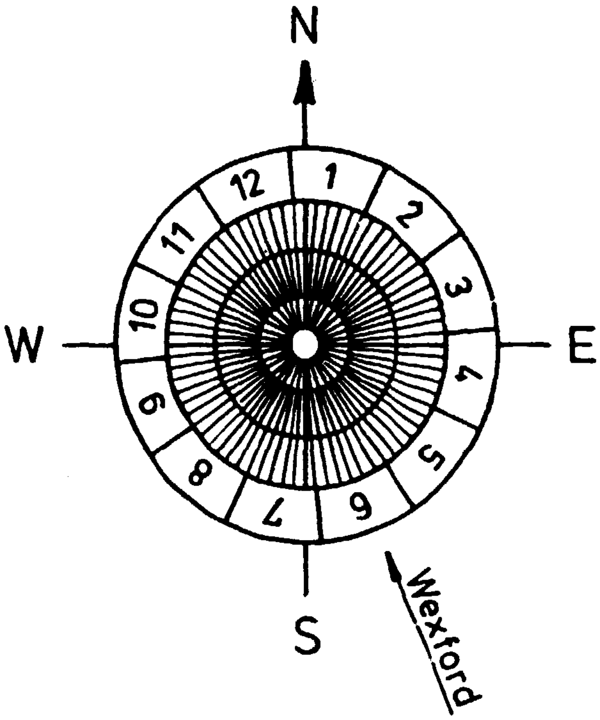


Fig. 3.5. Definition of wind- direction sectors. The meteorological convention is such that a wind in, say, sector 6 comes from a direction in the interval 145 - 174 degrees. Note that different convention is used in Chapters 2,5,6,7 and 8.

Group	1	2	3	4	5
Wind speed u[m/s]	< 2	2-3	3-5	5-6	> 6

Fig. 3.6. Wind speed groups.

The figures show that in dry weather, unstable (A + B + C), neutral (D), and stable (E + F + G) conditions prevail 7, 79, and 14% of the time, respectively. In rainy weather, on the other hand, only neutral conditions are of any significance. In the Wexford sector the same picture appears, the values being: unstable 10%, neutral 84%, and stable 6%. The percentage of unstable versus stable situations is reversed, however. Because of this and because D is so dominant, it could be argued that the distribution in dry weather

unstable 10%
neutral 80%
stable 10%

would represent a reasonable choice, irrespective of wind direction. Such a rounding - off would also agree with the general uncertainty in the classification scheme.

Supplements 6 and 7 give the results of an analysis of rain intensities - rainfall amounts and their accumulations - over specific periods.

Supplement 6 gives the number of occurrences of a given intensity in mm/h over time intervals of 6, 12 and upto 60 min. As an example, an intensity of 5 mm/h was observed 106 times, corresponding to 0.05% of the time or approximately 5 hours a year. Of the 106 incidents, 38 took place over a 6-min period corresponding to an intensity of 0.08 mm/min and a total amount of 0.5 mm.

It follows from Supplement 6 that rain occurs for 11.7% of the total time, and 58% of the rain-filled hours show an intensity of less than 1 mm/h, 97% an intensity less than 5 mm/h, and 99.7% an intensity less than 10 mm/h.

The rain categories in Supplements 2-4 are chosen in accordance with these probabilities; hence the category with light rain (0.1 - 1 mm/h) covers 60% of all rainfall situations, and that with moderate-to-strong rain (1-5 mm/h) covers the remaining 40%.

It should be noted that the Gaussian dispersion model operates with a constant intensity of rain from the time of release. Hence for the computation of the statistics of rain occurring together with specific weather types as given in Supplements 2-4, it is rather the statistics of total amount of rainfall over the period considered that have to be considered.

Stability \ Sector		ALL	1	2	3	4	5	6	7	8	9	10	11	12
ALL	%		5.5	6.8	5.8	3.5	5.1	6.6	12.4	21.2	11.3	7.8	6.5	7.5
	u		5.9	7.7	6.2	5.5	6.6	6.5	6.7	6.4	4.8	4.4	5.1	5.8
A	%	0.3	0.4	0.6	2.0	1.3	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.2
	u		0.9	1.2	1.3	1.4	1.4	1.5	1.3	1.4	1.2	1.3	1.2	1.1
B	%	1.9	2.8	4.5	7.1	5.0	2.4	3.0	1.0	0.6	0.4	0.8	1.0	1.6
	u		1.5	3.1	2.8	2.7	3.1	3.4	3.4	3.4	2.7	2.6	2.5	2.5
C	%	4.6	9.2	5.7	7.6	7.2	4.2	4.3	2.6	2.8	3.6	5.0	5.8	5.3
	u		1.0	3.5	2.4	2.2	2.6	3.1	3.1	3.3	2.6	2.6	2.5	2.7
D	%	81.2	73.8	85.1	78.6	79.2	87.2	87.3	89.3	86.0	71.7	69.2	75.2	81.9
	u		7.5	8.5	7.1	6.3	7.2	7.0	7.2	6.0	5.5	5.1	5.9	6.4
E	%	8.0	4.6	2.9	3.0	4.9	4.6	3.5	4.7	7.6	17.9	16.0	10.8	7.9
	u		3.9	4.1	3.9	4.0	3.8	3.8	3.6	3.6	3.7	3.6	3.8	4.1
F	%	3.0	5.4	0.9	1.0	1.7	1.1	1.4	1.9	2.5	5.2	6.7	5.2	2.3
	u		0.5	1.8	1.7	1.7	1.7	1.8	1.8	1.9	2.0	1.9	1.8	1.7
G	%	1.0	3.8	0.4	0.5	0.8	0.4	0.4	0.5	0.6	1.2	2.2	2.1	0.8
	u		0.2	1.1	1.1	1.0	1.2	1.2	1.2	1.3	1.3	1.3	1.2	1.1

Fig. 3.7. All data. Probability 100% No. of observations 189922

Stability \ Sector		ALL	1	2	3	4	5	6	7	8	9	10	11	12
ALL	%		5.7	7.2	6.0	3.4	4.6	5.8	10.9	21.1	12.0	8.4	7.0	8.0
	u		5.7	7.6	5.9	5.2	6.1	5.9	6.2	6.1	4.7	4.4	5.1	5.7
A	%	0.3	0.5	0.6	2.2	1.5	0.3	0.1	0.0	0.0	0.0	0.0	0.1	0.2
	u		0.9	1.2	1.3	1.4	1.4	1.5	1.3	1.4	1.2	1.3	1.2	1.1
B	%	2.1	3.1	4.9	7.9	5.7	3.0	3.9	1.3	0.7	0.4	0.8	1.0	1.7
	u		1.5	3.1	2.8	2.7	3.1	3.4	3.4	3.5	2.6	2.6	2.5	2.5
C	%	5.1	9.9	6.1	8.4	8.1	5.2	5.5	3.3	3.1	3.8	5.2	6.0	5.7
	u		1.1	3.5	2.4	2.2	2.7	3.1	3.1	3.3	2.7	2.6	2.6	2.7
D	%	78.9	71.6	84.0	76.4	76.3	84.2	83.9	86.4	84.2	70.0	67.6	74.0	80.7
	u		7.4	8.4	7.0	6.0	6.7	6.4	6.7	6.7	5.[illegible]	5.1	5.9	6.4
E	%	9.0	5.1	3.1	3.4	5.6	5.6	4.4	5.9	8.5	19.2	16.9	11.4	8.5
	u		3.9	4.1	3.9	4.0	3.8	3.8	3.6	3.6	3.7	3.6	3.8	4.2
F	%	3.4	5.8	1.0	1.1	2.0	1.3	1.7	2.4	2.8	5.4	7.1	5.4	2.4
	u		0.6	1.8	1.7	1.7	1.7	1.8	1.8	1.9	2.0	1.9	1.8	1.7
G	%	1.2	4.2	0.4	0.6	0.9	0.5	0.5	0.7	0.6	1.3	2.4	2.2	0.9
	u		0.2	1.1	1.1	1.0	1.2	1.2	1.2	1.3	1.3	1.3	1.2	1.1

Fig. 3.8. No precipitation. Probability = 87.3% No. of observations 165807

Stability \ Sector		ALL	1	2	3	4	5	6	7	8	9	10	11	12
ALL	%		4.5	4.2	4.7	3.3	7.5	10.6	21.2	23.8	8.0	4.7	3.2	4.2
	u		7.4	10.1	8.0	7.1	8.4	8.3	8.2	7.7	5.7	5.0	6.0	6.8
A	%	0.0	0	0.1	0	0.2	0.1	0	0	0	0	0	0	0.1
	u		0	1.5	0	2.6	1.5	0	0	0	0	0	0	1.0
B	%	0.2	0.3	0.1	0	0.5	0.1	0	0.1	0.0	0.5	0.4	0.2	0.6
	u		1.5	3.6	0	2.6	1.0	0	3.3	2.6	3.7	3.8	2.6	3.0
C	%	1.1	3.5	0.8	1.1	1.8	0.5	0.4	0.4	0.7	1.9	3.4	2.7	0.8
	u		0.5	1.6	1.7	1.2	1.3	2.4	2.6	2.4	2.1	1.9	2.4	1.7
D	%	96.8	92.9	98.3	98.4	96.8	98.3	98.5	98.6	97.2	92.4	91.3	94.2	96.7
	u		7.9	10.3	8.1	7.2	8.6	8.4	8.3	7.9	5.9	5.3	6.2	6.9
E	%	1.2	0.4	0.1	0	0.4	0.9	0.5	0.7	1.5	3.3	3.7	1.3	1.2
	u		3.6	2.6	0	2.3	2.4	2.8	3.6	3.5	3.3	3.4	4.2	3.5
F	%	0.7	2.3	0.4	0.5	0.2	0.2	0.4	0.3	0.5	1.8	1.2	1.6	0.6
	u		0.3	1.7	1.3	1.0	1.5	1.6	1.4	1.5	1.5	1.4	1.4	1.0
G	%	0.1	0.6	0	0	0.2	0	0.1	0.0	0.1	0.2	0	0	0
	u		0.0	0	0	1.0	0	0.5	1.5	1.4	1.5	0	0	0

<u>Fig. 3.9.</u> Precipitation 0.1 - 1 mm/h. Probability 9.1% No. of observations 17233

Stability \ Sector		ALL	1	2	3	4	5	6	7	8	9	10	11	12
ALL	%		4.2	3.8	4.9	4.9	10.5	14.5	25.1	19.0	4.1	2.8	2.3	3.8
	u		7.3	9.2	8.6	8.0	9.4	9.4	9.2	8.1	5.2	4.7	5.7	6.0
A	%	0.0	0	0	0	0	0	0	0	0	0	0	0	0
	u		0	0	0	0	0	0	0	0	0	0	0	0
B	%	0.1	0.4	0	0	0	0.1	0	0.1	0	0.4	0.5	0	0
	u		0	0	0	0	3.1	0	1.0	0	4.1	1.0	0	0
C	%	0.6	3.2	0	0	0.9	0.3	0.1	0.3	0.6	2.3	1.1	1.3	0.8
	u		0.3	0	0	0.9	0.5	2.1	1.5	2.1	1.2	1.3	1.0	1.5
D	%	98.4	94.6	99.6	99.4	99.1	98.7	99.7	99.1	98.1	94.0	96.7	96.7	98.0
	u		7.7	9.2	8.6	8.1	9.5	9.4	9.2	8.2	5.4	4.8	5.9	6.7
E	%	0.6	0.4	0.4	0	0	0.6	0.1	0.4	1.2	1.5	1.1	0.7	0.8
	u		2.1	2.1	0	0	2.7	2.6	2.3	3.2	3.7	2.3	2.1	2.6
F	%	0.3	1.4	0	0.6	0	0.3	0.1	0.1	0.2	1.9	0.5	1.3	0.4
	u		0.0	0	1.5	0	1.3	1.5	1.5	1.5	1.4	1.5	1.0	1.0
G	%	0.0	0	0	0	0	0	0	0.1	0	0	0	0	0
	u		0.0	0	0	0	0	0.0	1.5	0	0	0	0	0

Fig. 3.10. Precipitation 1 - 5 mm/h. Probability = 3.5% No. of observations 6559

Stability \ Sector		ALL	1	2	3	4	5	6	7	8	9	10	11	12
ALL	%		4.0	8.7	7.7	7.4	6.4	13.4	20.4	15.4	4.3	3.0	4.7	4.7
	u		8.0	8.2	6.6	7.2	7.3	10.2	9.1	8.0	4.3	4.6	5.2	7.9
A	%	0.0												
	u													
B	%	0.0												
	u													
C	%	0.7							1.6					7.1
	u								2.1					1.5
D	%	97.7	100	96.2	100	100	100	100	96.7	100	92.3	88.9	92.9	92.9
	u		8.0	8.5	6.6	7.2	7.3	10.2	9.2	8.0	4.5	4.9	5.5	8.4
E	%	1.0		3.8					1.6			11.1		
	u			2.1					5.7			2.1		
F	%	0.7									7.7		7.1	
	u										1.5		1.5	
G	%	0.0												
	u													

Fig. 3.11. Precipitation of intensity between 5 and 10 mm/h. The total probability for this case was found to be 0.1% (the total number of accurrences observed was 299). These cases were distributed over wind direction (first horizontal row, where the probabilities amount to 100), stability categories (first column, where the probabilities again amount to 100), and finally over both direction and stability. In the latter case the probabilities amount to 100 in each sector. Also given is the average wind velocity for these cases.

Dataset \ Stability	A	B	C	D	E	F	G	%
All data	0.3	1.9	4.6	81.2	8.0	3.0	1.0	100
No rain	0.3	2.1	5.1	78.9	9.0	3.4	1.2	87.3
Rain: 0.1-1	0.0	0.2	1.1	96.8	1.2	0.7	0.1	9.1
(mm/h) 1-5	0.0	0.1	0.6	98.4	0.6	0.3	0.0	3.5
5-10	0.0	0.0	0.7	97.7	1.0	0.7	0.0	0.1

Fig. 3.12. All sectors. Weather categories outside the marked area occurred less than 0.05% of the time corresponding to 5 hours per year. Due to truncations the sum is not always 100%.

Dataset \ Stability	A	B	C	D	E	F	G	%
All data	0.1	3.0	4.3	87.3	3.5	1.4	0.4	6.6
No rain	0.1	3.9	5.5	83.9	4.4	1.7	0.5	5.06
Rain: 0.1-1	0.0	0.0	0.4	98.5	0.5	0.4	0.1	0.96
(mm/h) 1-5	0.0	0.0	0.1	99.7	0.1	0.1	0.0	0.51
5-10	0.0	0.0	0.0	100	0.0	0.0	0.0	0.01

Fig. 3.13. Sector 6 (Wexford). For explanation see Fig. 3.12.

Supplement 7 gives the statistics for the observed amount of rain per hour over a given period in accumulated probabilities as a function of the period. As an example, the probability of totalling less than 2 mm per hour over a period of three hours is 99.0%, and that of less than 1 mm is 96.8%, which gives a probability of 2.2% of totalling between 1 and 2 mm of rain per hour over three hours.

Note that the interval 0.1 mm contains the probability for totalling an amount less or equal to 0.1 mm per hour, i.e. it includes all situations without precipitation. The upper interval marked 101 includes all situations with an amount greater than 10 mm per hour.

To facilitate calculations of the very small probabilities for large amounts of precipitation, a table of frequencies of occurrence is included. A table of probabilities is also included.

When F and G are recorded together with rain, this may in general be the result, besides recording errors, of the different time of recording the rain and stability data, respectively. For example, rain may be observed from 1305-1310 whereas the stability data are always obtained on the hour (or from 10 minutes before the hour to the hour) - in this case 1350-1400.

Incidents of extreme rainfall - The 22 years of data were searched for incidents where the reported amount of rain exceeded 10 mm in one hour In all, 28 such incidents were found. Figure 3.14 shows the dates of the incidents together with the recorded amounts of precipitation, wind speed and direction (degrees and sectors), visibility, cloud cover, cloud height, and present and past weather. Examination reveals that all 28 incidents contain internally consistent data, hence they must be regarded as physically realistic incidents.

The preferred direction lies in sectors 5 to 9, i.e. south-east to west. Twenty of the 28 incidents occurred in these sectors. The largest and second largest amounts, 33 and 27 mm, were observed in sector 2, i.e. with a north-east wind.

Date				Wind speed	Wind direction		Visi-bility	Precip.	Present weather	Past weather	Cloud cover	Cloud height
Year	Month	Day	Hour	m/s	degrees	s	km	mm/h			1/8	100 feet
1957	9	24	21	10	120	5	1.2	11.2	heavy r.	rain	8	3
1958	5	9	5	1.5	290	10	2.4	10.1	steady r.	rain	8	9
1960	9	28	24	3.5	240	9	11	11.4	steady r.	showers	8	3
1960	10	2	11	8.5	140	5	2	11.1	modr. r.	rain	8	8
1961	10	6	9	12.5	160	6	19	12.3	showers	rain	7	13
1963	8	19	13	2	250	9	>70	12.2	showers	showers	6	23
1963	11	7	3	3	250	9	4.8	12.7	after thunder	thunder	7	7
1965	5	4	12	4.5	230	8	14	12.8	showers	showers	7	16
1965	11	13	9	4.5	130	5	9	10.4	showers	thunder	7	22
1966	10	10	9	10	330	12	2	12.6	steady r.	rain	8	4
1966	10	12	17	2	190	7	12	10.7	slight r.	rain	8	12
1966	10	13	15	5	130	5	9	10.8	showers	showers	8	14
1967	7	31	21	1	250	9	1.6	11.0	steady r.	rain	8	3
1967	9	24	9	6.5	200	7	3.2	14.8	modr. r.	rain	8	1

Fig. 3.14.

Date				Wind speed	Wind direction		Visi- bility	Pricip.	Present weather	Past weather	Cloud cover	Cloud height
Year	Month	Day	Hour	m/s	degrees	s	km	mm/h			1/8	100 feet
1968	5	23	13	2	230	8	11	12.2	thunder	thunder	6	15
1970	11	17	15	15	40	2	1.5	10.6	slight r.	rain	8	2
1972	7	21	6	7.5	40	2	7	33.0	thund. & r.	rain	8	25
1973	7	16	15	3	180	7	1.2	22.5	steady r.	rain	8	5
1973	7	16	16	4.5	50	2	2.2	27.0	steady r.	rain	8	6
1973	9	18	17	21.5	20	1	1.5	10.4	steady r.	rain	8	6
1974	8	31	15	5	120	5	3	10.6	thund. & r.	thunder	8	5
1974	8	31	16	3.5	110	4	2.5	22.6	r. aft. thund.	thunder	8	3
1974	9	1	1	1	140	5	6	10.8	r. aft. thund.	thunder	8	7
1974	9	1	2	4.5	160	6	6	11.9	rain	rain	8	9
1975	7	17	13	2	180	7	4	13.9	steady rain	rain	7	2
1976	12	30	6	7.5	250	9	4	13.3	sleet	snow	8	10
1978	10	10	22	2.5	60	3	45	17.7	aft. thund.	thunder	7	17
1978	12	11	11	9	180	7	4	11.2	steady rain	rain	8	10

Fig. 3.14. continued

The observed rain intensity-amount-frequency relationships are in good agreement with those found by J.J. Logue (1971). For example, for Shannon Airport, Logue found that once in 20 years a rain intensity of 0.76 mm/min, totalling an amount of 20 mm, can be expected. For Rosslare the corresponding data are 22 years, 0.74 mm/min and 17.7 mm.

Incidents of extreme atmospheric stability - Following the stability criteria given by Turner (1964), one year of data from the Rosslare station, starting on January 1, 1979, was searched for situations with very stable stratification (categories F and G) and with a duration of at least three hours. There were 81 such cases and the strip-chart recording of wind speed and direction was studied for each of them.

These very stable situations are of interest because they may combine low wind speed and lack of small-scale turbulence, i.e. lack of a dispersion mechanism on a scale comparable to or smaller than the width of a hypothetical plume from a point source. Under such circumstances the concentration in the plume will not change with distance from the source, and if, in addition, wind direction remains constant for several hours, local high concentrations can occur tens of kilometres downstream from the source. It is believed that atmospheric conditions giving rise to these so-called pencil plumes do exist. An excellent example is given by Gifford (1968). Standard methods to determine concentrations will then underestimate the concentrations because the root-mean-square lateral width σ_y assigned to the Gaussian plume formula is too large. If, on the other hand, there are large-scale wind direction fluctuations then the plume will move very much like a serpent. This "meandering" will usually give rise to an efficient broadening of the plume, so that standard estimates of the integrated concentration at a particular point "downstream" will be too high. The exact definition of "too high" will be strongly influenced by integration time.

Inspection of the stripchart recordings led to a classification of the 81 cases in three broad categories:

1) cases in which there is small-scale turbulence, wind speed not zero,
2) cases without small-scale turbulence, wind speed not zero, and
3) cases in which the wind speed is nearly zero.

For category 1 the relative diffusion because of small-scale turbulence will disperse the plume more than is expected in categories F and G. Consequently, standard methods lead to overestimation of concentrations in these categories. Cases in category 3 are characterized by the very small transport that occurs away from the source. The validity of the Gaussian plume model is very questionable here, but since only locations near the source (within 5 km) are affected, there seems no reason for further discussion of cases in this category. Candidates for the "pencil plume" case should be looked for in category 2.

There were 49 cases in category 1, 15 in 2, and 17 in 3. Of the 15 cases in category 2, σ_y was determined for the two which from visual inspection seemed to have the smallest variation in wind direction. Using a method described by Kristensen et al. (1980), σ_y was determined by means of consecutive ten-minute averages of wind speeds and directions, read off from the strip charts. One case occurred in January and one in August, the latter giving the smallest σ_y. This quantity is shown (full lines) in Fig. 3.15 as a function of distance x for one- and three-hour averaging times. For comparison are shown the σ_y's (dashed lines) determined by a standard method described by Thykier--Nielsen (1980). Figure 3.15 shows that even in the case believed to come closest to the "pencil plume" model, the σ_y is larger than the standard estimate of σ_y.

On the basis of detailed data from 1979 it seems reasonable to assume that standard methods for determining σ_y for a Gaussian plume under very stable conditions will underestimate the horizontal width and therefore overestimate the concentration downwind. This conclusion is consistent with the findings of Kristensen et al. (1980) for Denmark.

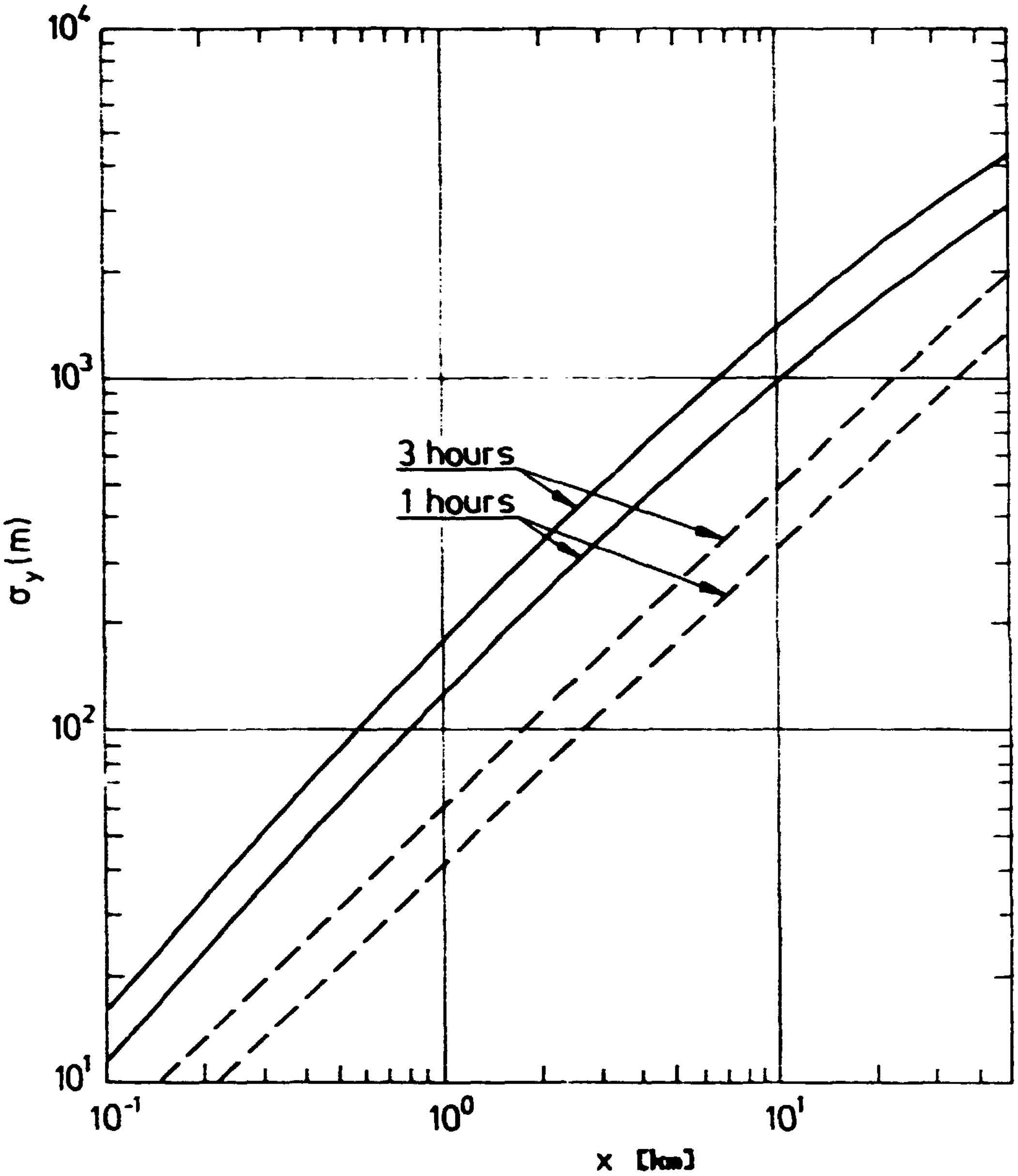


Fig. 3.15. The lateral dispersion parameter σ_y under very stable conditions (F and G) as a function of the distance x from the source for integration times equal to 1 and 3 h. Full lines represent σ_y estimated from Rosslare data for August 27, 1979. Dashed lines show the corresponding σ_y found by a standard method. The wind direction in this case was in a sector relevant to the Wexford area.

3.4. Choice of meteorological parameters for the dose calculations

The meteorological parameters entering into dispersion calculations cannot be chosen independently of one another because the situations modelled have to be physically realizable. In the stability classification scheme, for example, the wind speed is confined to a certain interval in each class. This describes the average behaviour of the atmospheric boundary layer. In the atmosphere, however, there might be isolated cases where the turbulent structure corresponds to A or F, although the wind speed is greater than 3 m/s. Similarly, the turbulent structure may not correspond to D even though the wind speed is greater than 6 m/s, and the sky is completely overcast; for example, a situation where there is strong cold air advection. For this reason some of the combinations in the parameter study in Chapter 8 fall outside the nominal range. They are included to demonstrate the effect of such unusual conditions.

3.4.1. Deposition

Regarding deposition, there are characteristic values for these processes too in the various dispersion categories. Thus, in general, precipitation in category D is associated with prolonged periods of frontal rain, while precipitation in the unstable categories is associated with short-lived and scattered shower activity. As stable stratification is characterized by suppression of vertical turbulence, especially vertical convection, precipitation - particularly in F and G - is very unlikely.

With respect to deposition, it is impossible to make a single calculation giving worst case results for all distances from the source. Choosing a high deposition rate results in greater amounts of material being deposited close to the source, therefore giving higher deposition doses in its immediate vicinity, but lower ones at larger distances. A lower deposition rate, on the other hand, leads to smaller doses nearby, but doses at larger distances are then increased as more material remains in the plume for subsequent deposition. At a given distance, however, a particular deposition rate can be calculated that would result in the highest dose at this distance. From an analytical model (Jensen, 1980) this is explicitly expressed as

$$d = (\ln D)^{-1} \tag{11}$$

where d is a deposition parameter (either $v_g/\alpha u$ or $l_g H + \alpha x/\alpha u$), D is the nondimensional distance $\alpha x/H$, and α the vertical spreading angle of the plume. Typically, α is ~ 1/33. The results of this formula agree well with those obtained with the PLUCON model (Thykier-Nielsen, 1980) for moderate distances ($x < 50$ km).

<u>Bounds on the dry deposition velocity v_g</u> - The deposition velocity estimates obtained in this way are not always physically obtainable. Thus v_g is bounded by the relation (Chamberlain, 1953; Jensen, 1981)

$$v_g < \left(\frac{u_*}{u}\right)^2 u , \tag{12}$$

from the downwards diffusive capability of the atmosphere alone (u_*/u is a characteristic of the turbulent intensity of the atmosphere). Thus, in class B, u_*/u is typically 0.06 and u is 2 m/s; it then follows that

$$v_g < 0.7 \text{ cm/s (in class B).}$$

In class F the turbulence intensity is typically only half this value. Hence

$$v_g < 0.2 \text{ cm/s (in class F).}$$

In practice the deposition velocities are less than these estimates, as the ground surface is not a perfect absorber but has an uptake resistance.

<u>Characteristic values for the wash out coefficient l_g</u> - For the wash-out process such upper bounds exist only in terms of likely precipitation intensities; in general, the larger the intensity,

the larger the wash-out. The occurrences of various rain intensities are found in Supplements 6 and 7.

For a gas the efficiency depends on the solubility of the gas in water and the time constant with which a saturated solution is obtained. For a very active gas like bromine, Engelmann (1968) gives

Rain intensities [mm/h]	0.06	0.1	0.5	1	3	10	100
$l_g[s^{-s}]$	10^{-5}	1.3×10^{-5}	3×10^{-5}	4×10^{-5}	10^{-4}	2×10^{-4}	10^{-3}

which can be obtained from his Figure 5.11. Iodine, which is one of the gaseous elements relevant to nuclear accidents, is less active. For free iodine the coefficient is about two orders of magnitude less than shown above, and, for example, for the compound CH_3I the coefficient is a further two orders smaller (Nielsen, 1980).

For particles, the wash-out efficiency depends on particle size and distribution of raindrop size. As raindrop size is empirically related to rain intensity, and because the particles ensuing from an accident are estimated to have sizes in the micrometer range, l_g becomes a function of intensity alone. Actual values approximate those quoted in the table above.

It should be noted that the worst condition, say at a distance of 17 km from an accident at Carnsore, is not represented by the largest possible rain intensity. From Eq. (11) above, with $H = 100$ m and $u = 6$ m/s, the worst possible value of l_g is of the order of 10^{-4} s^{-1}, corresponding to a rain intensity of perhaps 5 mm/h. Larger rain intensities will result in smaller doses, even if the effect of run-off is disregarded.

3.4.2. Meteorological input for the accident study

Meteorological input for the parameter study

In this section relevant values of the meteorological input for the parameter study in Chapter 8 are proposed. Parameters should be varied so that only one is changed at a time, whereby its significance is clearly shown. However, other variables should be changed if necessary to make the corresponding physical situations realizable. The parameter variation study is performed for a PWR 2 release (duration half an hour).

Stability - The effect of varying this parameter is illustrated by making dose calculations for each of the Pasquill classes. The wind speed used in each class is the average value for that class and for wind direction sector 6 as it appears from analysis of the Rosslare meteorological data (Fig. 3.7). The conditions are as follows

Stability	A	B	C	D	E	F
Wind speed m/s	1.5	3.4	3.1	7.0	3.8	1.8

Because the study is performed for a release lasting for half an hour, no plume meandering need be taken into consideration. The study is made for dry conditions with v_g chosen as 1 cm/s in all stability categories. As already mentioned, this is greater than it may physically be under stable situations. Thus, the doses calculated for Wexford in category F may be somewhat overestimated.

Wind speed - The effect of this parameter is illustrated by dose calculations in both classes D and F. The following wind speeds are used:

Class D	6	8	10	12	m/s
Class F	1	2	5		

As mentioned, 5 m/s is atypical for class F conditions although physically possible. The study was done for dry conditions with v_g chosen as 1 cm/s in class D and 0.2 cm/s in class F.

Dry deposition - The effect of dry deposition is illustrated for typical conditions of class D, 6 m/s wind speed, and dry weather. The deposition velocities chosen are

v_g	10^{-2}	3×10^{-3}	10^{-3}	3×10^{-4}	m/s

The larger value corresponds to a probable value as the physical upper bound is some cm per sec in this situation. The lower value corresponds to very little depletion of the plume.

Wash-out - The effect of wash-out is illustrated for the following conditions of class D with rain: 6, 8, or 10 m/s wind speeds, and v_g = 1 cm/s. The wash-out coefficients chosen are

l_g	0	3×10^{-5}	10^{-4}	3×10^{-4}	s^{-1}

corresponding to precipitation rates of the order of 0, 0.5, 3 and 15-20 mm/h, respectively. This is an overestimate for iodine and submicron particles.

Release categories - The effects of the various release categories (PWR 1, PWR 2, ...) are demonstrated for two adverse meteorological conditions: class D with 6 m/s wind speed, v_g = 10^{-2} m/s, and l_g = 3×10^{-4}, the latter corresponding to heavy rain; and class F with 2 m/s wind speed, and v_g = 2×10^{-3} m/s.

Meteorological input for the hypothetical accident studies

In this dose calculation category only average meteorological conditions are considered, i.e., stability class D, 6 m/s wind speed, v_g = 1 cm/s, and dry weather. The reason for this limitation is that these conditions prevail for about 80% of the time. Moreover, the effect of the more extraordinary conditions is illustrated in the parameter study.

3.5. Additional remarks

Sites near bodies of water (such as that at Carnsore Point) may be subject to distinct local wind systems. Under fair weather conditions the wind has a typical daily variation winds being mainly onshore during the day and offshore at night. Onshore and offshore winds experience a change of surface roughness and temperature gradient patterns which may result in fumigation or recirculation under appropriate conditions. An example is shown in Fig. 3.16. A shore-line source emits effluent into the stable air of the onshore portion of a sea breeze. The associated fanning plume drifts inland until it encounters the developing unstable boundary layer of the warmer land, at which point it fumigates. While the resulting smoky mixture is advected further inland, a portion of this polluted mass is carried aloft and back out over the water by the sea breeze counter-current to form an elevated smoke wall.

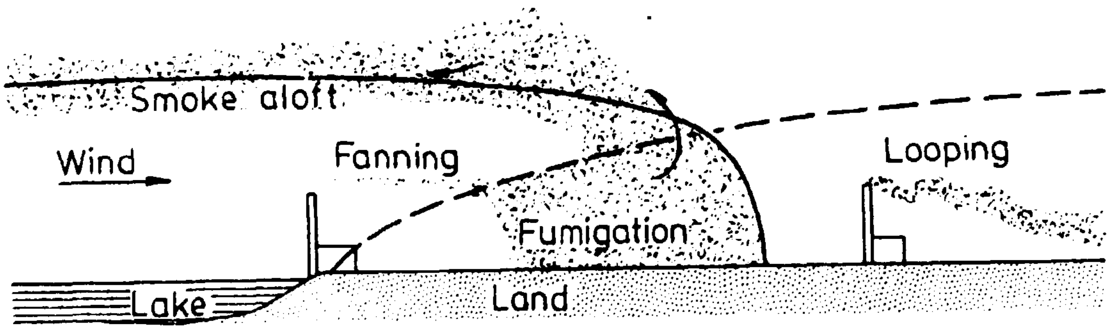


Fig. 3.16. Plume behaviour in the vicinity of a coastline in fair weather conditions (fine spring day).

The onshore flow of marine-modified air has been the subject of many air quality considerations. A useful review is found in Lyons (1975). Owing to several factors it is very unlikely that phenomena such as fumigation and sea-breeze circulation will give rise to doses larger than those calculated for the weather situations selected in this study. The main factor is that the phenomena occur during transitional periods. Fumigation brings the material from the plume down to the ground close to the stack but it also spreads the material upwards (to the apparent lid) and sideways. Hence fumigation might cause a local high concentration over a short period, but because of the strong transitional properties of the phenomenon the resulting doses at a given point in the fumigation zone are often of minor concern.

The effect of the marine inversion, which in situations with large bodies of cold water nearby can limit substantially the height of turbulent mixing, seems also of minor importance with regard to Carnsore Point. This appears from an investigation by W.H. Wann (1973) where the stability at Valentia Observatory determined at the surface was compared with the stability determined for the two layers: 0-200 and 100-400 m. The investigation concluded that, in general, the stability in the higher layer showed a strong tendency to concentrate in the neutral category. The influence of a marine inversion would have appeared in the statistics as a tendency towards the stable category in the higher layer.

REFERENCES

CHAMBERLAIN, A.C. (1953). Aspects of travel and deposition of aerosol and vapor clouds. Atomic Energy Research Establishment. Report HP/R 1261, 35 pp.

ENGELMANN, R.J. (1968). The calculation of precipitation scavenging. In Meteorology and Atomic Energy, edited by D.H. Slade, USAEC Technical Information Center, Oak Ridge, Tennessee, 208-221.

GIFFORD, F.A. Jr. (1968). An outline of theories of diffusion in the lower layers of atmosphere. In Meteorology and Atomic Energy, edited by D.H. Slade, USAEC Technical Information Center, Oak Ridge, Tennessee, 65-116.

JENSEN, N.O. (1980). The simple approach to deposition. Proceedings of "Radioactive releases and their dispersion in the atmosphere following a hypothetical reactor accident", Risø, 22-25 April 1980. CEC, Luxembourg, pp. 331-343.

JENSEN, N.O. (1981). A micrometeorological perspective on deposition. Health Physics, 40, pp. 887-891.

KRISTENSEN, L., PETERSEN, E.L. and JENSEN, N.O. (1980). Lateral dispersion of pollutants in a very stable atmosphere. - The effect of meandering. Atmospheric Environment vol. 15, 5 pp. 837-884.

LOGUE, J.J. (1971). Rain intensity - amount-frequency relationships in Ireland. Technical note no. 34. Meteorological Service, Dublin.

LYONS, W.A. (1975). Turbulent diffusion and pollutant transport in shoreline environments. Lectures on air pollution and environmental impact analyses. American Meteorological Society, Boston, pp. 136-208.

NIELSEN, O.J. (1980). A critical literature review on radioactivity transfer to plants and soil. Report produced under contract no. 1151-79-10 L/V for the CEC. Risø, October 1980, 120 pp.

PASQUILL, F. (1961). The estimation of the dispersion of windborne material. Met. Mag., 90, 33.

PETERSEN, E.L., TROEN, I., FRANDSEN, S. and HEDEGAARD, K. (1981). Wind atlas for Denmark. Risø Report no. 428.

SELLERS, W.D. (1965). Physical Climatology. The University of Chicago Press, Chicago and London, p. 272.

Supplements 1-8, Risø Library, Risø National Laboratory, P.O. Box 49, DK-4000 Roskilde, Denmark.

THYKIER-NIELSEN, S. (1980). The Risø model for calculating the consequences of the release of radioactive material to the atmosphere. Risø-M-2214, 65 pp.

TURNER, D.B. (1964). A diffusion model for an urban area. J. Appl. Meteor., 3, 83-91.

WANN, W.H. (1973). Incidence of stability categories for various stations in Ireland. Technical note no. 37, Meteorological Service, Dublin.

4. RELEASE OF ACTIVITY IN DESIGN-BASIS AND HYPOTHETICAL CORE-MELT ACCIDENTS

When planning this work it was decided to use well known references as far as possible. With regard to descriptions of accidents and their releases to the atmosphere, the descriptions in the American reactor safety study WASH-1400 were followed in principle. Because this study was completed in 1975, a literature search was carried out in addition and some comments on the WASH-1400 findings are included. Finally, Risø National Laboratory has attempted to define a consensus in a "class 9 accident" and its releases based on present knowledge (spring 1981).

4.1. Calculation of radionuclide inventory

The inventory of radionuclides in a reactor core depends, apart from on reactor type, also on a number of parameters. The present study concerns a 2000 MW thermal Light Water Reactor (LWR) that is either a Boiling Water Reactor (BWR) or a Pressurized Water Reactor (PWR).

Nuclide inventories in a BWR and a PWR are compared in Appendix 2. In both cases typical parameters are chosen for enrichment, discharge burn-up, power density and residence times for the fuel. The comparison based on the more important nuclides shows that there is little difference between the two reactor types, and for most nuclides the inventory in the PWR is slightly larger than in the BWR. Based on these calculations, the inventory for this study was calculated using the following parameters:

Reactor type	PWR
Enrichment	3.1%
Power density	34.4 kW/kgU
Burn up	20.6 MWd/kgU

Burn-up is calculated as the average burn-up of the equilibrium core at cycle end. It is assumed that the equilibrium core contains four generations of fuel element having average burn-ups at cycle end of 8.25, 16.5, 24.75 and 33 MWd/kgU. Thus the discharge burn-up is assumed to be 33 MWd/kgU.

Calculations were carried out for a single fuel pin by means of the CCC program (Højerup, 1976a) which includes routines for calculating fission product concentrations (Højerup, 1976b) and actinide concentrations (Mortensen, 1977). The inventory is calculated for the time of which the core becomes subcritical and accidents considered, cf. Appendix 3.

4.2. Release categories

This report presents the consequences of a series of accidents. These range from the worst conceivable in which a core-melt is combined with containment failure to a design-basis accident, defined as a loss-of-coolant accident PWR 9. For the BWR type the three core-melt release types BWR 1, BWR 2 and BWR 3 were considered together with the design-basis accident BWR 5. As the PWR 1 release type is described with both a low and a high rate of energy release, it was decided to describe them both: PWR 1A being that with a low rate of energy release (5.9 MW), and PWR 1B that with a high rate of energy release (152 MW). The release category concept and the corresponding release fractions of different isotope groups, as well as the descriptions of the release categories, are in accordance with USNRC, WASH-1400, Appendix VI.

It should be recalled that the release fractions for a certain release category are not the result of a single accident sequence but represent several similar sequences.

For the release categories considered in this report, the release fractions of the core inventory of eight isotope groups are given in Fig. 4.1 also showing the WASH-1400 accident probabilities.

Release category	Probability per reactor-year	Elevation of release [m]	Containment energy release [MW]	Fraction of core inventory released							
				Xe-Kr	Organic I	I	Cs-Rb	Te-Sb	Ba-Sr	Ru a)	La b)
PWR1A	4×10^{-7}	25	5.9	0.9	6×10^{-3}	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR1B	5×10^{-7}	25	152	0.9	6×10^{-3}	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR2	8×10^{-6}	0	50	0.9	7×10^{-3}	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR3	4×10^{-6}	0	1.8	0.8	6×10^{-3}	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR4	5×10^{-7}	0	0.3	0.6	2×10^{-3}	0.09	0.04	0.03	5×10^{-3}	3×10^{-3}	4×10^{-4}
PWR5	7×10^{-7}	0	0.1	0.3	2×10^{-3}	0.03	9×10^{-3}	5×10^{-3}	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR6	6×10^{-6}	0	n.a	0.3	2×10^{-3}	8×10^{-4}	8×10^{-4}	1×10^{-3}	9×10^{-5}	[illegible]$\times 10^{-5}$	1×10^{-5}
PWR9	4×10^{-4}	0	n.a	3×10^{-6}	7×10^{-9}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0
BWR1	1×10^{-6}	25	38	1.0	7×10^{-3}	0.40	0.40	0.70	0.05	0.5	5×10^{-3}
BWR2	6×10^{-6}	0	8.8	1.0	7×10^{-3}	0.90	0.50	0.30	0.10	0.03	4×10^{-3}
BWR3	2×10^{-5}	25	5.9	1.0	7×10^{-3}	0.10	0.10	0.30	0.01	0.02	4×10^{-3}
BWR5	1×10^{-4}	150	n.a	5×10^{-4}	2×10^{-9}	6×10^{-11}	4×10^{-9}	8×10^{-12}	8×10^{-14}	0	0

Fig. 4.1. Summary of release categories representing ten hypothetical core melt accidents and two design-basis accidents.

n.a. = not applicable

a) includes Ru, Rh, Mo, Tc.

b) includes Y, La, Zr, Nb, Ce, Pr, Nd, Pu, Am, Cm.

(cf. WASH-1400, appendix VI, table 2-1).

Brief descriptions of the various physical processes that define each release category mentioned in Fig. 4.1 are given below. Here the release fractions of iodine and alkali metals are indicated to illustrate the variations in release with release category. For more detailed information on release categories, see USNRC, WASH-1400, appendices V, VII and VIII.

PWR 1A and PWR 1B. This release category can be characterized by core meltdown followed by a steam explosion when molten fuel contacts the residual water in the reactor vessel. The containment spray and heat-removal systems are also assumed to fail, and therefore the containment might be at a pressure above ambient at the time of the steam explosion. It is assumed that the steam explosion would rupture the upper portion of the reactor vessel and breach the containment barrier, with the result that a substantial amount of radioactivity might be released from the containment in a puff over a period of about 10 minutes. The release of radioactive materials would continue at a relatively low rate thereafter. The total release would contain approximately 70% of the iodines and 40% of the alkali metals present in the core at the time of the release. The rates of energy release in the two cases are 5.9 and 152 MW, respectively.

PWR 2. This category is associated with the failure of core-cooling systems and core melting concurrent with the failure of containment spray and heat-removal systems. Failure of the containment barrier would occur through overpressure, causing a substantial fraction of the containment atmosphere to be released in a puff over a period of about 30 minutes. The release of radioactive material would continue at a relatively low rate thereafter. The total release would contain approximately 70% of the iodines and 50% of the alkali metals present in the core at the time of release.

PWR 3. This category involves an overpressure failure of the containment due to failure of containment heat removal. Containment failure would occur prior to the commencement of core melting and then would cause radioactive materials to be released through a ruptured containment barrier. Approximately 20% of the iodines and 20% of the alkali metals present in the core at the time of release would be released to the atmosphere. Most of the release would occur over a period of about 1.5 hours. The release sweeping action of gases generated by the reaction of the molten fuel with concrete. The rate of sensible energy release to the atmosphere would be moderately high.

PWR 4. This category involves failure of the core-cooling system and the containment-spray injection system after a loss-of-coolant accident, together with a concurrent failure of proper isolation of the containment system. This would result in the release of 9% of the iodines and 4% of the alkali metals present in the core at the time of release. Most of the release would occur continuously over a period of two to three hours. A relatively low rate of release of sensible energy would be associated with this category.

PWR 5. This category involves failure of the core-cooling systems and is similar to PWR release category 4, except that the containment spray injection system would operate to further reduce the quantity of airborne radioactive material and to initially suppress containment temperature and pressure. Most of the radioactive material would be released continuously over a period of several hours. Approximately 3% of the iodines and 0.9% of the alkali metals present in the core would be released. The energy release rate would be low.

PWR 6. This category involves a core meltdown due to failure in the core cooling systems. The containment sprays would not operate, but the containment barrier would retain its integrity until the molten core proceeded to melt through the concrete containment base mat. The radioactive materials would be released into the ground, with some leakage to the atmosphere occurring upward through the ground. Direct leakage to the atmosphere would also occur at a low rate prior to containment-vessel melt-through. Most of the release would occur continuously over a period of about 10 hours. The release would include approximately 0.08% of the iodines and alkali metals present in the core at the time of release. The energy release would be very low.

PWR 9. This category approximates a PWR design basis accident (large pipe break), in which only the activity initially contained within the gap between the fuel pellet and cladding would be released into the containment. The core would not melt. It is assumed that the minimum required engineered safequards would function satisfactorily to remove heat from the core and containment. The release would occur over the 0.5-hour period during which the containment pressure would be above ambient. Approximately 0.00001% of the iodines and 0.00006% of the alkali metals would be released. The energy release rate would be very low.

BWR 1. This release category represents a core meltdown followed by a steam explosion in the reactor vessel. The latter would cause the release of a substantial quantity of radioactive material to the atmosphere. The total release would contain approximately 40% of the iodines and alkali metals present in the core at the time of containment failure. Most of the release would occur over a 1/2 hour period. Because of the energy generated in the steam explosion, this category would be characterized by a relatively high rate of energy release to the atmosphere. This category also includes certain sequences that involve overpressure failure of the containment prior to the occurrence of core melting and a steam explosion. In these sequences, the rate of energy release would be somewhat smaller than for those discussed above, although it would still be relatively high.

BWR 2. This release category represents a core melt down resulting from a transient event in which decay-heat-removal systems are assumed to fail. Containment overpressure failure would result, and core melting would follow. Most of the release would occur over a period of about three hours. The containment failure would be such that radioactivity would be released directly to the atmosphere without significant retention of fission products. This category involves a relatively high rate of energy release due to the sweeping action of the gases generated by the molten mass. Approximately 90% of the iodines and 50% of the alkali metals present in the core would be released to the atmosphere.

BWR 3. This release category represents a core meltdown caused by a transient event accompanied by a failure to scram or failure to remove decay heat. Containment failure would occur either before core melt or as a result of gases generated during the interaction of the molten fuel with concrete after reactor vessel melt-through. Some fission product retention would occur either in the suppression pool or the reactor building prior to release to the atmosphere. Most of the release would occur over a period of about three hours and would involve 10% of the iodines and 10% of the alkali metals. For those sequences in which the containment would fail due to overpressure after core melt, the rate of energy release to the atmosphere would be relatively high. For those sequences in which overpressure failure would occur before core melt, the energy release rate would be somewhat smaller, although still moderately high.

BWR 5. This category approximates a BWR design-basis accident (large pipe break) in which only the activity initially contained within the gap between the fuel pellet and cladding would be released into containment. The core would not melt, and containment leakage would be small. It is assumed that the minimum required engineered safeguards would function satisfactorily. The release would be filtered and pass through the elevated stack. It would occur over a period of about five hours while the containment is pressurized above ambient and would involve approximately 6 x 10^{-9}% of the iodines and 4 x 10^{-7}% of the alkali metals. Since core melt would not occur and containment heat removal systems would operate, the release to the atmosphere would involve a negligibly small amount of thermal energy.

4.3. Release conditions

In addition to probability and release magnitude (Fig. 4.1), the parameters characterizing the various hypothetical accident sequences are time of release, duration of release, warning time for evacuation, height of release, and rate of energy release of the plume.

The time of release (Fig. 4.2) is the time interval between the start of the hypothetical accident (reactor shut-down) and the release of radioactive material from the containment building to the atmosphere. It is used to calculate the initial decay of radioactivity from the time of shut-down.

Release category	Time of release [h]	Duration of release [h]	Warning time [h]
PWR 1 A	2.5	0.5	1.0
PWR 1 B	2.5	0.5	1.0
PWR 2	2.5	0.5	1.0
PWR 3	5.0	1.5	2.0
PWR 4	2.0	3.0	2.0
PWR 5	2.0	4.0	1.0
PWR 6	12.0	10.0	1.0
PWR 9	0.5	0.5	n.a.
BWR 1	2.0	0.5	1.5
BWR 2	30.0	3.0	2.0
BWR 3	30.0	3.0	2.0
BWR 5	3.5	5.0	n.a.

Fig. 4.2. Time of release, duration of release and warning time, for the 12 release categories according to USNRC (WASH-1400), 1975.

n.a. = not applicable

The duration of release (Fig. 4.2.) is the total time during which radioactive material is emitted into the atmosphere. It is used to account for continuous releases by adjusting for horizontal dispersion due to wind meander. The parameters of time and duration of release represent the temporal behaviour of the release in the dispersion model.

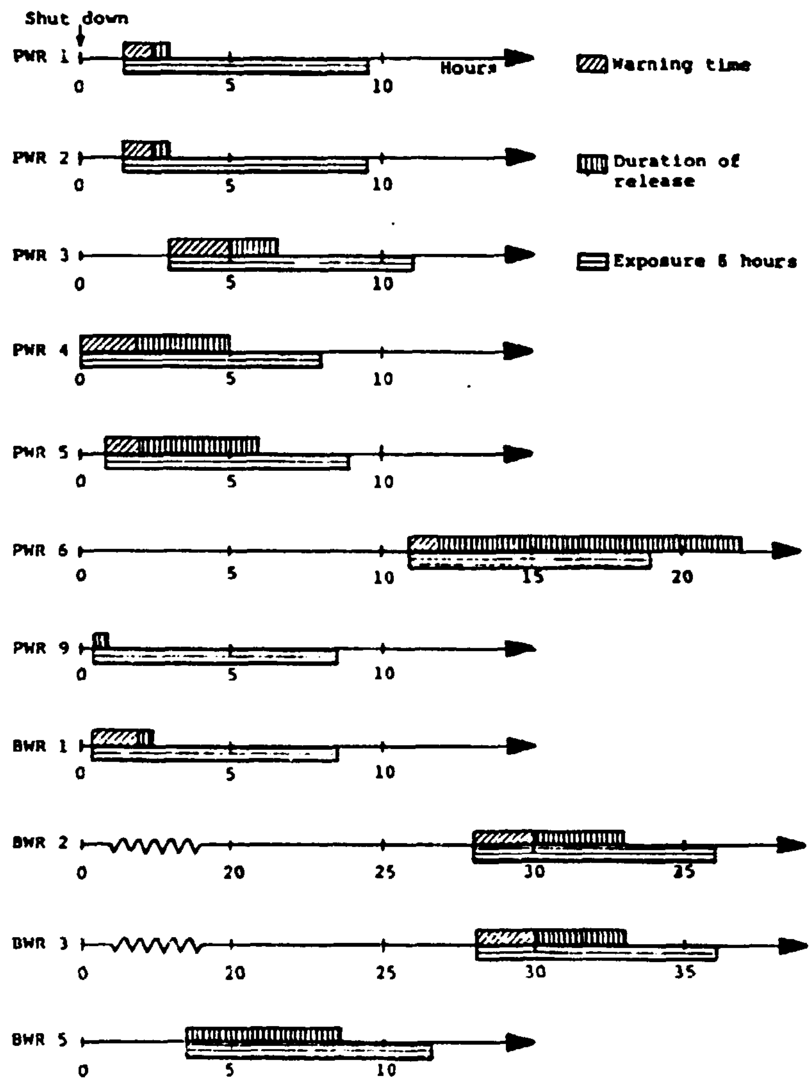


Fig. 4.3. Warning time, duration of release, and exposure time (8 hours) as a function of time after shut-down for 12 release categories in accordance with USNRC (WASH-1400), 1975.

The warning time for evacuation (Fig. 4.2) is the interval between awareness of impending release and the actual release of radioactive material from the containment building.

The height of release and the rate of energy release in the plume (Fig. 4.1) affect the manner in which the plume would be dispersed in the atmosphere.

The exposure period of eight hours is assumed to start simultaneously with the start of the warning time.

Figure 4.3 shows the three different periods of time, warning time, duration of release, and exposure time, as a function of time after shut-down for the release categories considered.

For all release categories except PWR 6, the eight-hour exposure time is longer than warning time + duration of release. It should be noted that for the two design-basis accidents, PWR 9 and BWR 5, no warning times are given and hence these are not taken into account.

4.4. Amount of activity released

The amount of activity released in each release category is estimated on the basis of the core inventory at two points of time after reactor shut-down: at the beginning and at the end of the release period. In the calculation of the amount of each single isotope released, the release fraction, as given in Fig. 4.1, and the half-life of the isotope are taken into account. Appendix 3 describes the calculation of the activity release, and the amount of each single isotope released is shown for each release category.

4.5. Recent investigations

Until 1975 the only study in which an attempt was made to estimate the amounts of radionuclides released following a core-melt accident was the WASH-1400 study. Following this a Risk Study was made in Germany (Birkhofer et al., 1979). The latter study used the same models for the release of radionuclides as used in WASH-1400 because knowledge at the time of its publication did not sufficiently support new models. However, it now appears that results of research mainly carried out in the USA and West Germany may lead to reconsideration of both the probabilities of certain accident sequences and the amounts of material released.

The consequences of a reactor accident are very dependent on whether the containment fails or not, and if it does fail then at what time the failure takes place and in what mode.

Recent research, at the moment primarily directed towards PWRs, has led to an estimated probability of containment failure following a core melt-down that is smaller than the WASH-1400 results.

Experimental work at the Sandia Laboratory in USA (Berman et al., 1980) indicates that the probability of a steam explosion is two orders of magnitude lower than assumed in WASH-1400. The probability of the most serious PWR release category in WASH-1400, category 1, is thus reduced by two orders of magnitude.

Theoretical and experimental work at the Kernforschungszentrum Karlsruhe, Germany, (Rininsland et al., 1980) shows that, for a German PWR, the time from a core-melt until overpressure failure of the containment due to steam and gas generation and hydrogen combustion is 2-3 days. The concrete base mat of the containment is not likely to melt through. It has also been shown that the concentration of radioactive materials in the containment atmosphere will decrease by 3-5 orders of magnitude over 2-3 days. Thus the amount of radionuclides available for release to the environment at the time of containment failure is very small. It appears that the release during the accident will be determined by the leak rate from the containment. For an isolated containment, the design leak rate may be 0.25% of total volume per day. If the leak rate equals the design leak rate, the amount of radionuclides released in accident sequences which in WASH-1400 would be category 2 and 3 releases will be 10^{-2} - 10^{-3} times the WASH-1400 results. This is the result of the longer time interval between core melt and containment failure in the new calculations, and also the use of more refined models for calculating aerosol behaviour in the containment.

It must be realized that accidents without structural failure of the containment may lead to releases in categories 2 and 3. The dominant accident sequence in WASH-1400 leading to a PWR 2 release is one in which failure of the check valves separating the high-pressure injection system inside the containment from the injection system outside the containment leaves an open passage from the core to the environment. Proper design should make it possible to avoid, or to make the probability very low for the opening of such pathways.

Thus it may appear in future that the PWR 1, 2 and 3 releases make a very small contribution to the risk from core meltdown accidents, and that the most serious consequences of a core-melt would result from failure to isolate the containment.

In WASH-1400 the PWR release category with a melted core and a non-isolating containment (and failure of the containment radioactivity removal system as well) is PWR 4. Without going into a detailed study of accident sequences leading to the PWR 4 release, it is here considered to represent this situation.

The probability of the release will of course differ from that given in WASH-1400 and will have to be found by means of a full analysis of the actual plant.

Even the PWR 4 release category may prove to be a conservative representative of the "worst conceivable reactor accident". As pointed out by Gjørup (1983), a reconsideration of the releases of iodine and cesium given in the WASH-1400 study makes it likely that these release fractions are greatly overestimated.

After the Three Mile Island accident it was noted that the release of iodine to the atmosphere was 10^5 to 10^6 times less than the release of noble gases, although the inventories of iodine and noble gases were of the same order of magnitude.

Three of the scientists involved in the several analyses made by the technical staff of the Kemeny Commission believe that the very small escape of iodine to the environment can be explained in the following manner. Iodine diffused out of the fuel rods through the failed cladding and vaporized. The escaping iodine, if not already in the iodide form, then encountered a chemically-reducing environment which converted it to iodide. The iodide went into solution when it contacted water; it persists in solution as non-volatile iodide as long as oxidizing conditions do not prevail.

Calculations made at several laboratories indicate that CsI is the stable form of iodine in LWR fuel. Further, cesium is always present in great (about tenfold) excess over iodine. So the iodine is released predominantly as CsI rather than as molecular I_2.

Furthermore, if water is accessible, iodide will dissolve in the water so that its concentration in the gas phase will be much smaller than its concentration in the water.

This explanation could account for the much smaller escape of iodine that was observed at TMI compared to the amount predicted to escape.

In marked contrast to the TMI accident, a large fraction of the iodine escaped to the environment during the Windscale accident (1975) which occurred in the absence of water.

The release of iodine may therefore be lower than previously estimated, possibly by orders of magnitude. Taking this factor into account, doses with reduced iodine releases are calculated in Chapter 8. Nonetheless it must be stressed that these are considered assumptions, and that accident sequences must be re-examined in detail before a general acceptance of reduced iodine releases can be expected.

REFERENCES

BECHER, P.E. et al., (1981). Calculation of Dose Consequences of a Hypothetical Large Accident at a Nuclear Power Reactor. Risø-M-2299.

BERMAN, M., CORRADIN, M., MITCHELL, D., NELSON, L., and SHERRY R. (1980). U.S. Steam Explosion Research: Risk Perspective and Experimental Results. Presented at the 1980 Projekt Nukleare Sicherheit, Jahreskolloquium, Kernforschungszentrum, Karlsruhe.

BIRKHOFER, et al., (1979). Die Deutsche Risikostudie. Der Bundesminister für Forschung und Technologie. GRS-A 329.

GJØRUP, H.L., MICHEELSEN, B., THYKIER-NIELSEN, S. (1983). Consequences of Large Reactor Accidents Calculated on the Basis of Empirical Data. IAEA-CN-42/315.

HØJERUP, C.F. (1976a). The Cluster Burn up Programme CCC and a Comparison of its Results with NPD Experiments. Risø-M-1898.

HØJERUP, C.F. (1976b). FISPRO - an Algol Procedure for Calculation of Fission Products. Risø-M-1899.

MORTENSEN, L. (1977). ACTPRO - an Algol Procedure for Calculation of Actinide Densities. Risø RP-5-77.

RININSLAND, H., FIEGE, A., HORSCH, F., and HOSEMANN, J.P. (1980). Fortschritt der Reaktorsicherheitsforschung in Projekt Nukleare Sicherheit. Presented at the 1980 Projekt Nukleare Sicherheit, Jahreskolloquium, Kernforschungszentrum, Karlsruhe.

UNSNRC, (1975). U.S. Nuclear Regulatory Commission. WASH-1400: Reactor Safety Study. With appendices (Springfield, Virginia).

5. EXPOSURE PATHWAYS AND DOSIMETRIC MODELS

5.1. Exposure pathways

The radioactive material contained in a nuclear power plant may expose the surrounding population to radiation via several pathways. These are shown in Fig. 5.1 and can be divided into three groups:

1. Air pathways: gaseous effluents
2. Water pathways: liquid effluents
3. Direct radiation pathways, i.e. external radiation from the plant or from transport of radioactive materials to and from the plant.

The total radiation dose to a person from a given release of radioactive material is calculated as the sum of doses from all exposure pathways in question.

In a reactor accident air pathways are the only ones of importance as in this case the radioactive material is released either directly from the reactor building or from the stack. There are five possible air pathways:

a) External exposure from the radioactive cloud as it passes overhead.
b) Internal exposure from activity inhaled during passage of the cloud.
c) External exposure from activity deposited on the ground during passage of the cloud.
d) Internal exposure from consumption of foodstuffs contaminated by activity deposited from the cloud.
e) Internal exposure from the inhalation of resuspended activity.

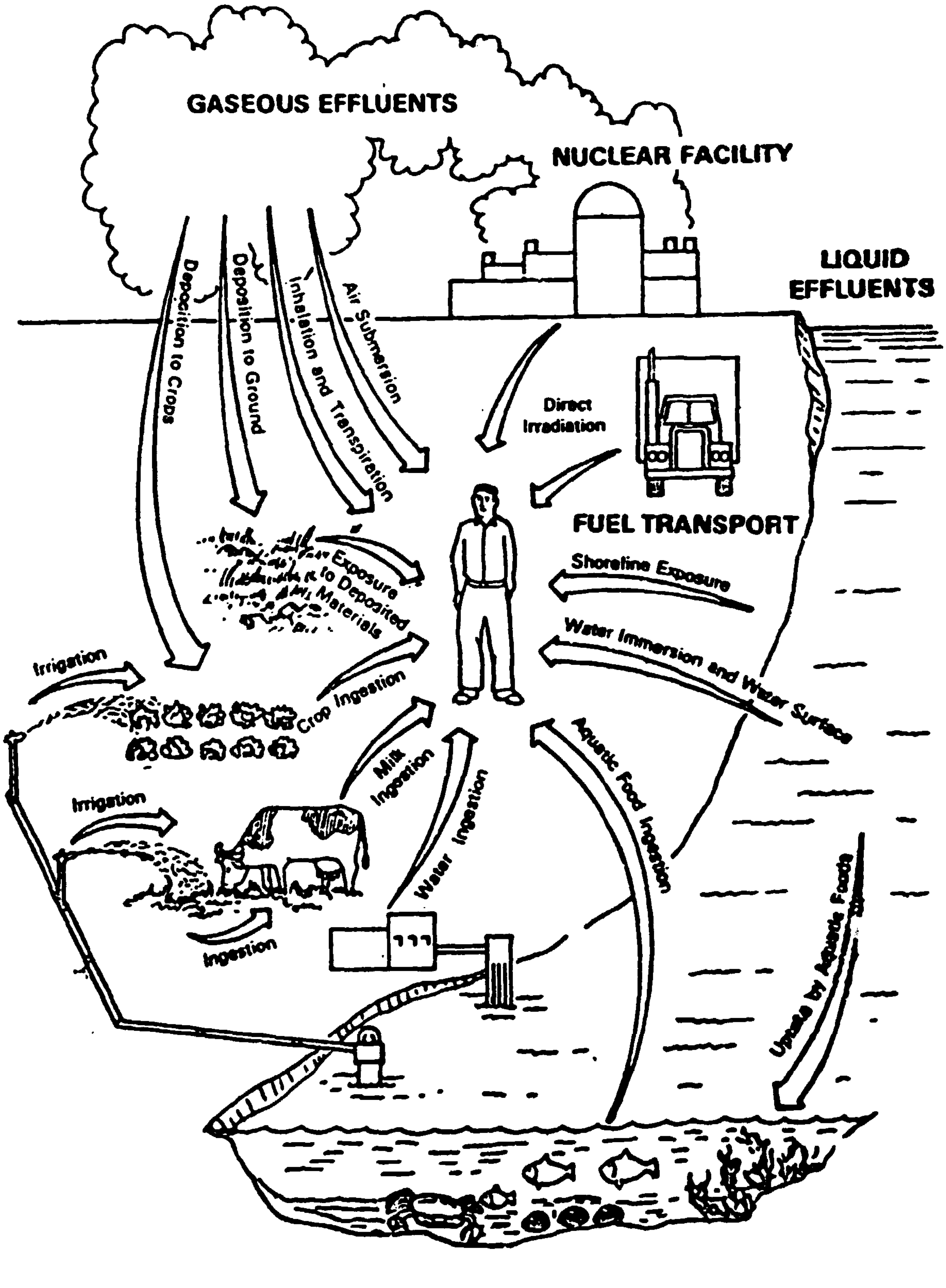


Fig. 5.1. Exposure pathways to man.

Doses from the ingestion of contaminated foodstuffs are not considered as these can be avoided by restricting food production in the affected area.

Even in the absence of such restrictions, the dose would be small compared with that from pathways a), b) and c) (UNSCEAR 1977).

The importance of doses from inhalation of resuspended activity relates primarily to the restriction on land usage that may be required following a reactor accident.

This pathway is disregarded for two reasons. Firstly, if the doses from inhalation of resuspended activity are sufficiently large, countermeasures such as clean-up or evacuation could be implemented. Secondly, the magnitude of doses via this pathway, even in the absence of countermeasures, is at most only of the same order as that from the inhalation of activity during passage of the cloud. For a further discussion of this problem, see USNRC (WASH-1400), 1975, and Kelly et al., 1977.

Thus only doses from pathways a) to c) are considered in this study of hypothetical reactor accidents. The dosimetric models for pathways a) to c) are described in 5.3.

5.2. Quantities and units

The amount of radioactive material and the dose from exposure to radiation are the most important quantities when considering the consequences of releases of radioactive material.

The amount of radioactive material is measured by the number of nuclear transformations in a quantity of the material per unit of time. This number denotes the activity of the material.

SI units are used throughout this report. The special unit of activity in the SI system is the Becquerel, Bq, and this is equal to one transformation per second.

Two quantities are important for doses: absorbed energy dose in gray (Gy), and biological effective dose in gray multiplied by the relative biological effectiveness (RBE) of the radiation considered. The latter quantity was introduced so that doses with differing biological effectiveness can be added. Such differences may result from type of radiation, dose rate, or dose magnitude. The relative biological effectiveness is discussed in NCRP report M-4, 1967, ICRU report 25, 1976, by Smith et al. 1976, and by Page et al., 1977. The SI unit for biological effective dose is the Sievert (Sv). The relations between the SI units and the old units for amounts of radioactive material and dose are as given below:

SI unit	Old unit
1 Bq (Becquerel)	2.7×10^{-11} Curie
1 Gy (Gray)	100 rad
1 Sv (Sievert)	100 rem

Absorbed dose is used where only one type of radiation contributes to the dose. Doses to specific organs are evaluated as absorbed dose in Grays. Whole-body doses are evaluated as biological effective doses in Sievert. It should be noted that the doses considered here only result from β/γ-radiation that has a RBE of 1, i.e. one Sv is approximately equal to one Gy.

5.3. Dosimetric models

5.3.1. Dispersion model

5.3.1.1. 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. 5.2) is used in this study. A discussion of this model from a meteorological point of view is given in Chapter 3. A detailed description of the dose consequence model, PLUCON 2, which is based on the Gaussian dispersion model and is used in this study, is given in Thykier-Nielsen, 1980. Only a general outline of the model is given here.

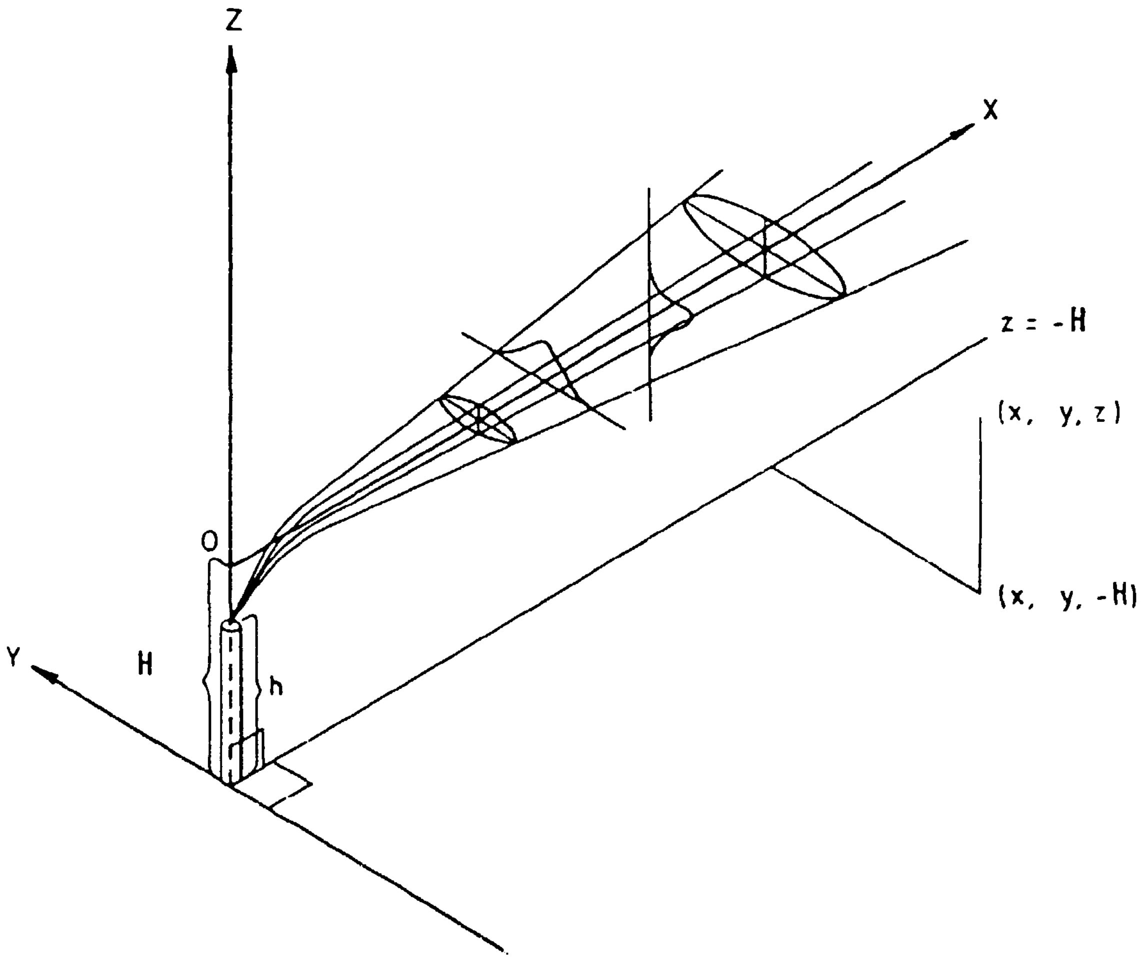


Fig. 5.2. The plume from a chimney stack described by the Gaussian diffusion model. The stack height is h and the effective dispersion height is H.

The model has been verified out to distances of 20 - 30 km where it is able to predict doses and concentrations within a factor of 2 - 3. Concentrations and doses are normally overestimated at larger distances. Overestimation increases with distance and can be up to a factor of 10 at 50 km. Therefore only doses out to a distance of 30 km from Carnsore Point were calculated in this study.

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:

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

as

$$Sg(x,y,z,s,u) = \frac{1}{2\,\pi\,u\,\sigma_y(x,s)\,\sigma_z(x,s)} \times \exp(-\frac{y^2}{2\,\sigma_y(x,s)^2})$$

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

where

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

Formula (2) is modified in cases where a mixing layer markedly affects dispersion. The existence of such a mixing layer implies that the vertical material distribution changes from a Gaussian to a homogeneous distribution with increasing distance from the source point.

However, in the present study, which only considers doses out to a distance of 30 km, the existence of a mixing layer is of little importance. This is because the height of the mixing layers in the atmospheric stability categories considered here is such that significant effects of the layer are seen only at distances larger than 30 km.

A constant wind direction is assumed in the model in the present study. The possibility of a meandering effect in case of longer-term releases (e.g. PWR 4,5,6 and BWR 2,3 and 5) is not taken into account. Meandering gives rise to an unknown broadening of the plume and consequently a lower level of concentration. In such cases the calculated individual doses would be lower than estimated.

5.3.1.2. Plume height. Formula (2) in Fig. 5.2 suggests that the plume might rise above the point from where it is released. The plume height (H(x) in formula (2)) is determined by the heat contained in the activity release and the speed with which the thermal energy is released, together with the temperature gradient in the lowest layer of the atmosphere.

Plume height is calculated according to a procedure given by Briggs (Thykier-Nielsen 1980).

Figure 5.3 shows the height of the plume above ground in the meteorological situations used for the calculations. It should be noted that the plume rise calculated in this study is conservative, i.e. too small compared with the results of recent studies (Briggs, 1969, and Kaiser, 1980).

Pasquill stability	A	B	C	D				E			F		
Stability parameter s	–	–	–	–				4.97×10^{-4}			1.24×10^{-3}		
Wind speed [m/s]	6	6	6	6	8	10	12	1	2	5	1	2	5
Release													
PWR 1 A P = 5.9 h = 25	75	75	75	75	63	55	50	162	133	105	126	105	84
PWR 1 B P = 152 h = 25	378	378	378	378	290	237	202	429	345	261	323	261	199
PWR 2 P = 50 h = 0	181	181	181	181	136	109	91	279	221	163	205	163	120
PWR 3 P = 1.8 h = 0	25	25	25	25	18	15	12	92	73	54	68	54	40
PWR 4 P = 0.3 h = 0	8.4	8.4	8.4	8.4	6.3	5.1	4.2	51	50	30	37	30	22
PWR 5 P = 0.1 h = 0	4.4	4.4	4.4	4.4	3.3	2.6	2.2	35	28	21	26	21	15
PWR 6 P = 0 h = 0	0	0	0	0	0	0	0	0	0	0	0	0	0
BWR 1 P = 38 h = 25	179	179	179	179	140	117	102	279	227	174	212	174	135
BWR 2 P = 8.8 h = 0	64	64	64	64	47	38	32	156	124	91	115	91	67
BWR 3 P = 5.9 h = 25	75	75	75	75	63	55	50	162	133	105	126	105	84

Fig. 5.3. Final effective dispersion height, H(m), as a function of stability class, wind speed and release category (P = thermal effect (MW), h = release height (m)).

The stability parameter, s, used in the calculation of the effective dispersion height is given by

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

where $\partial\theta/\partial z$ is the potential temperature gradient for the atmosphere, g is the acceleration due to gravity, and T(^{o}K) is the temperature of the atmosphere (Briggs, 19?9, and Thykier-Nielsen, 1980).

Note that the plume rise is not assumed to change with stability category when the atmosphere is unstable, i.e., the final plume height is the same for Pasquill categories A, B, C and E, all other parameters being equal.

5.3.1.3. Deposition. Some of the material in the plume may be deposited on the ground during transport in the wind direction. The deposition mechanisms are quite complicated but in principle a distinction may be made between dry and wet deposition.

Dry deposition is a result of several physical mechanisms in diffusion, sedimentation by gravity, etc. Here the socalled source depletion model is used to calculate the amount of material deposited on the ground (Slade, 1968). This model, which is that most commonly used, assumes that material is removed from the entire plume. Losses owing to dry deposition are instantaneously mixed throughout the entire vertical extent of the plume.

The flux of material to the ground is assumed to be proportional to the ground level air concentration where the constant of proportionality is the deposition velocity, v_g.

v_g depends largely on wind speed and turbulence intensity, but the physical, chemical, photochemical and biochemical processes taking place at the surface during material deposition are also very important. Typically values lie in the range 10^{-4} m/s to 10-2 m/s.

If there is precipitation over the area where the material in question is dispersed, then wet deposition (below cloud scavenging) is added to the dry deposition. Precipitation will "wash out" a fraction of the material in the plume. The rate at which wash-out takes place is characterized by a wash-out coefficient l_g, which is defined as the relative change in amount of activity in the plume per time unit. l_g depends mainly on precipitation intensity, particle diameter, and solubility of the material concerned. Typically values of l_g lie in the range 10^{-7} s^{-1} to 10^{-4} s^{-1}.

When there is precipitation, and consequently wet deposition, there will always simultaneously be dry deposition. However, when considering radioactive materials released in a reactor accident, wash-out will always be the dominating mechanism.

5.3.2. Inhalation doses

During the passage of the plume, a person standing on the ground will inhale an amount of radioactive material proportional to the passage time and the concentration at the location in question.

The inhaled activity will enter the respiratory tract and the lungs. Depending on physical size and chemical form, part of the activity is subsequently translocated to other organs of the body. Some of the activity then decays to stable isotopes, while some is excreted biologically. The dose from inhaled activity is thus absorbed over a period of time that varies from a few weeks to several years depending on the isotope in question. The total inhalation dose integrated over a given period of time after inhalation of the activity, is calculated as the sum of the amount of the individual isotopes inhaled, multiplied by a dose-conversion factor.

The dose-conversion factor for a given isotope, which is equal to the dose per intake unit (in, e.g., Bq) integrated over a given period of time after intake, involves a very complicated calculation. It includes physical and chemical data for the isotope in question and data for physiological functions of the body.

Dose-conversion factors are taken from authoritative sources (USNCR, 1975, and ICRP, 1979). The sources of data for dose-conversion factors for different organs are given below.

Bone marrow:	USNRC (WASH-1400)
Lung:	USNRC (WASH-1400)
Gastro-intestinal tract:	USNRC (WASH-1400)
Thyroid:	USNRC (WASH-1400 and NUREG CR-150/ORNL TM-190)
Whole body:	ICRP pub. 30

Inhalation doses are reduced by the filtration effect of buildings. Here a reduction factor of 0.2 is used for filtration. This is derived from recent Danish investigations (Gjørup and Roed, 1980).

A discussion of the significance and consequences of doses to different organs is given in Section 5.3.5.

5.3.3. External dose from the cloud

Isotopes decay in association with the emission of radiation in the form of γ-photons and β-particles. However, owing to the slight ability of β-radiation to penetrate material and the low radiosensitivity of the skin - the tissue most exposed to this radiation - β-doses are of little significance compared to γ-doses. Attention is therefore focussed on doses from γ-radiation.

The external γ-dose from the cloud is calculated by assuming the cloud to be composed of an infinite number of point sources and deriving the total dose by integration. Attenuation and multiple scattering of the γ-rays in air are included in the calculation of the dose from each point source. The γ-dose in air is equal to the γ-flux density multiplied by the mass absorption coefficient for each of eight γ-energy groups. To obtain the dose in tissue, the dose in air should be multiplied by a correction factor equal to the ratio between the electron density in the tissue and that in air and a further correction factor for the internal body organs. Such correction factors are not applied in this study. The external γ-doses given here are doses in air, and thus somewhat larger than the real doses to the body organs.

The correction factors which are equal to the ratio between absorbed dose in the organ considered and the exposure in air depend on photon energy. According to O'Brien and Sanna (1976), typical values are 0.52 for bone marrow, 0.8 for skin and 0.56 as an average for the whole body. The external doses from the cloud calculated in this study should thus be reduced by 20% to 40% to obtain the absorbed doses in the organs considered.

In contrast to the exposure from inhaled activity, the external exposure from the cloud ceases when the plume has passed by.

Inside buildings, the external gamma dose from the plume would be considerably reduced because of the shielding effect of structures. In this report it is assumed that people remain inside brick buildings during the entire passage of the plume. A shielding factor of 0.6 is therefore applied. This factor is given in WASH-1400 as representative of single-family houses and multistorey buildings of brick (USNRC, 1975). The shielding effect of Irish houses has not been investigated, but it is presumed to be about the same as that of American brick houses.

5.3.4. External dose from deposited activity

As described in Section 5.3.1.3, some of the contents of the plume will be removed during its travel downwind by dry deposition and, if there is precipitation, by wet deposition. The material is deposited on the ground where its radioactivity is gradually reduced by decay to stable isotopes and by other mechanisms, e.g., weathering and run-off. Run-off is of little significance outside built-up areas and is thus ignored in this study. Weathering is the term used to describe the mechanism whereby activity gradually sinks into the soil. In the present study weathering is accounted for by use of a formula given by Gale (USNRC, 1975, and Thykier-Nielsen, 1980), according to which the amount of activity is reduced by a factor of 0.5 within 1.5 years.

The external γ-dose from deposited activity is calculated using the same principles as for the external dose from the plume; the ground is divided into a number of point sources and their dose contributions integrated. The dose in air is conventionally calculated at a point 1 m above the ground (see Thykier-Nielsen, 1980, for further details). Correction factors for tissue and internal organs are not used, see Section 5.3.3.

β-doses are disregarded for the reasons mentioned in Section 5.3.3.

The external gamma dose from the ground described above is calculated assuming that the ground is an infinite smooth surface. To account for the shielding effect of the roughness of the ground, a correction factor of 0.7 is applied to the dose calculated.

In this study it is assumed that people would remain inside brick houses for the first eight hours after warning time. The external γ-dose from the ground is therefore reduced by a shielding factor of 0.2 (USNRC WASH-1400, 1975). The total reduction factor for the external γ-dose from the ground is thus $0.7 \times 0.2 = 0.14$. It should be noted that structures provide more effective shielding from radiation from the ground than from that from the plume.

The external gamma radiation from the ground continues for an extended period after the plume has passed.

5.3.5. Doses to specific organs

The doses to specific organs are calculated as the sum of the three dose components described in the preceding sections.

Inhalation dose
External gamma dose from the cloud
External gamma dose from deposited activity

The relative importance of the three dose components, the time variation of doses, and the important nuclide categories vary with atmospheric conditions, with distance downwind from the release point, and with organ. The more important features of the dose in each organ considered are discussed in turn.

Bone marrow

Large radiation doses damage the bone marrow and other blood-forming organs and thereby impare the ability to produce new blood cells. It is generally believed (USNRC WASH-1400, 1975) that damage to bone marrow is the most important contributor to early death from large doses to the whole body. This implies that radiation damage to the lungs or to the gastro-intestinal tract is unlikely to be lethal unless accompanied by bone-marrow damage. Therefore the acute bone-marrow dose is calculated as the sum of the external gamma dose from the passage of the plume, plus the external gamma dose from the activity on the ground integrated over 8 hours, plus the internal dose received during the first 30 days after inhalation of activity from the cloud. The main part of the dose to the bone marrow is received within 30 days.

Lungs

For the accidental releases considered, the probability of death from a lung dose will always be substantially lower than that from the associated bone-marrow dose. The actinides (which are incorporated into the lymph nodes), the lanthanum group, and to a lesser extent the ruthenium group, are the major contributors to the dose to the lungs. 50% to 80% of the inhalation dose will be absorbed within a year.

The dose to the lungs is therefore calculated as the sum of the external gamma dose from the passage of the cloud, plus the external gamma dose from deposited activity integrated over 8 hours, plus the internal dose from inhalation integrated over 1 year.

As the risk of acute injury depends on the rate at which the lung dose is accumulated, this method of calculation gives a conservative result.

Gastro-intestinal tract

Fatalities resulting from local irradiation of the gastro-intestinal tract would be caused by destruction of the intestinal cell population leading to denudation of the gut lining, manifestations such as diarrhoea and haemorrhage, and finally death.

The contents of the GI-tract are normally replaced relatively rapidly, and the inhalation dose in this area will largely be absorbed within a week. The more important nuclides contributing to the internal dose are the lanthanum group, the actinides and the ruthenium group.

The dose is calculated as the sum of the external gamma dose from passage of the cloud, plus the external gamma dose from activity deposited on the ground integrated over 8 hours, plus the internal dose received within 7 days.

Thyroid

Very large doses of ^{131}I to the thyroid would cause an accelerated release of thyroid hormone. In extreme cases severe thyrotoxicosis might develop, leading to heart failure and death. The long-term consequences of large doses to the thyroid may be hyperthyroidism or cancer. ^{131}I contributes about two-thirds of the dose to the thyroid. As ^{131}I has a half-life of 8 days, and the other radioactive isotopes of iodine under consideration, have a half-life of less than one day, the largest part of the inhaled dose will be absorbed after roughly one month.

The dose is calculated as the sum of the external gamma dose from passage of the cloud, plus the external gamma dose from deposited activity integrated over 8 hours, plus the internal dose from inhaled activity integrated over 30 days. The internal dose is the dominant dose component.

The inhalation dose is calculated for adults; the dose for children, depending on age, may be up to three times greater.

Whole body

In order to assess the possible long-term consequences of irradiation of the whole body a calculation was made of the 50-year committed dose equivalent resulting from intake (inhalation) of activity. The 50-year committed dose equivalent is defined as

$$H_{50B} \equiv \sum_{T} w_T H_{50T}$$

where

H_{50B} = 50-year committed whole-body dose equivalent
H_{50T} = 50-year committed dose equivalent for target tissue (organ) T.
w_T = Weighting factor for target organ T.

The summation is performed over all organs appearing in Fig. 5.4.

Data for H_{50B}, H_{50T} and w_T were taken from ICRP Publication 30, 1979. The weighting factors are given in Fig. 5.4.

The total 50-year committed whole-body dose is calculated as the sum of the external gamma dose from the cloud, plus the external gamma dose from deposited activity integrated over 8 hours, plus the 50-year committed whole-body dose equivalent from inhalation of activity during passage of the cloud.

This 50-year committed whole body dose is then used in assessing the possible stochastic effects (late effects) of the hypothetical releases.

Tissue (organ)	Weighting factor (W_T)
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

Fig. 5.4. Weighting factors for different organs

REFERENCES

BRIGGS, G.A. (1969). Plume rise. USAEC Critical Review Series. TID-25075. 81 p.

GJØRUP, H.L. and ROED, J. (1980). Notes on the Relationship between Outdoor and Indoor Exposure Integrals for Air Pollution of Outdoor Origin. Risø-M-2234. 17 p.

ICRP (1979). International Commission on Radiological Protection. Limits for Intakes of Radionuclides by Workers. ICRP publication 30. Part I (Sutton) 117 p.

ICRU (1976). International Commission on Radiation Limits and Measurements. Conceptual Basis for the Determination of Dose Equivalent. ICRU Report 25. 21 p.

KAISER, G.D. (1980). United Kingdom Atomic Energy Authority. (UKAEA, Harwell). Personal communication.

KELLY, G.N., JONES, J.A. and HUNT, B.W. (1977). An Estimate of the Radiological Consequences of National Accidental Releases of Radioactivity from a Fast Breeder Reactor. NRPB-R53. 166 p.

KILLOUGH, G.G. et al. (1978). Estimates of the Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities. Vol. 1. NUREG CR-150/ORNL-NUREG-TM-190 (Washington D.C.) 316 p.

NCRP (1967). National Council on Radiation Protection and Measurements. Report on Subcommittee M-4: Dose-Effect Modifying Factors in Radiological Protection. NCRP BNL 50073 (T-471) (Washington D.C.) 34 p.

O'BRIEN, K. and SANNA, R. (1976). The Distribution of Absorbed Dose Rates in Humans from Exposure to Environmental Gamma Rays. Health Phys. 30, 71-78.

PAGE, C.H. and VIROUREUX, P. (ed.) (1977). SI, The International System of Units. 3rd edition. HMSO, London. 56 p.

SLADE, D.H. (ed.) (1968). Meteorology and Atomic Energy. TID-24190 (Tennessee) 445 p.

SMITH, H. and STATHER, J.W. (1976). Human Exposure to Radiation Following the Release of Radioactivity from a Reactor Accident: A Quantitative Assessment of the Biological Consequences. NRPB-R52 (Harwell) 39 p.

THYKIER-NIELSEN, S. (1980). The Risø Model for Calculating the Consequences of the Release of Radioactive Material to the Atmosphere. Risø-M-2214. 65 p.

UNSCEAR (1977). United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and Effects of Ionizing Radiation (New York) 725 p.

USNRC (1975). U.S. Nuclear Regulatory Commission. WASH-1400. Reactor Safety Study. Appendix VI: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. NUREG-75/014 (Springfield, Virginia) 150 p + supplements.

6. DOSES FROM DESIGN-BASIS ACCIDENTS

6.1. Introduction

The doses from and consequences of the two design-basis accidents, PWR 9 and BWR 5, are discussed in this chapter. The probabilities, release heights, rates of energy release, and effective dispersion heights are shown in Fig. 6.1. Detailed comments on the releases, their magnitudes and their probabilities are given in Chapter 4.

The PWR 9 release occurs without warning time over a period of half an hour as a cold ground release consisting of essentially noble gases with little iodine and Cs-Rb (see Fig. 4.1). Shutdown takes place half an hour before the release commences.

In the BWR 5 release, a period of 3.5 hours is assumed to elapse before the beginning of the five-hour release period, again without warning time. Like the PWR 9 case, the release is dominated by noble gases (see Fig. 4.1). The release is assumed to take place through a 150 m stack without sensible heat.

The essential environment-related factors affecting the consequences are atmospheric conditions and the time the plume takes to pass the area of interest. Considering from the release categories described in Chapter 7, it was decided to combine the two design-basis accident releases - each with a rather low probability of occurrence - with the most probable atmospheric situation found for Carnsore Point. This situation is defined in Chapter 3.4 and is described by the following parameters:

Pasquill stability category D,
Wind speed $u = 6$ m/s (21.6 km/h)
Dry deposition velocity $v_g = 10^{-2}$ m/s
Wet deposition velocity $1_g = 0\ s^{-s}$ (no rain)

Using the PLUCON 2 model calculations were made of bone-marrow doses to individuals as a function of downwind distance from the release point as well as doses to specific organs. A detailed description is given for each release category.

Release category	Probability per. reactor year	Release height h[m]	Rate of energy release [MW]	Effective dispersion height
PWR 9	4E-4*	0	n.a.**	0
BWR 5	1E-4	150	n.a.	150

* 4E-4 understood as 4 in 10 000 per reactor year.
** n.a. = not applicable.

Fig. 6.1. Probabilities of occurrence per reactor year, release heights, h, speeds of sensible energy release from the containment and effective dispersion heights, H, for the two design-basis accidents PWR 9 and BWR 5.

Collective doses to the bone marrow and the whole body were further calculated for the two release categories. For the BWR 5 release a correction for long-term release, in relation to a 30-minute release, was taken into account in the model by correction of the dispersion parameters. Moreover, the model assumes a constant wind direction and hence no meandering effects are taken into account. Meandering gives rise to an unknown broadening of the plume and consequently a lower concentration level. In this case the calculated individual doses would be lower than estimated here.

The other important parameters applied in the calculations (described in detail in Chapter 5) are

Respiration rate: 3.5×10^{-4} m^3/s (adults in working hours)
Reduction factor for those inside buildings, inhalation: 0.2
Reduction factor for those inside buildings, gamma plume: 0.6
Reduction factor for roughness of the ground and those inside buildings, gamma deposition: 0.14
People in the area remain indoors in brick houses for the first eight hours the after start of warning time.

6.2. Doses to individuals

6.2.1. Bone-marrow doses

For both release categories doses to the bone-marrow are calculated (see Section 5.3.5) in the plume centre-line for distances downwind from 0.5 to 30 km from the release point. The three dose components: inhalation dose, external gamma dose from the plume and external gamma dose from deposited radioactivity (in the following called inhalation, gamma plume and gamma deposition) as well as their sums are calculated. The plume centre-line doses represent the highest doses at a given distance in a given release situation. In order to compare the bone-marrow doses from the two different releases, the sum curves are shown on the same diagram in Fig. 6.2.

It is essential to note two factors: for the first, the amount of noble gases released in the BWR 5 case is more than two orders of magnitude greater than in the PWR release. Secondly, there is the difference in release height and hence in plume height (the sensible heat release is negligible in both cases). The PWR release is a cold ground level release with the high concentration plume centre-line falling together with the line of interest for dose calculation, 1 m above ground level. The high concentration gives its full contribution to all three dose components: gamma plume, inhalation and gamma deposition from the beginning of the area of interest, i.e. 500 m from the release point. In the BWR 5 case, however, the pencillike plume positioned at a height of 150 m acts like a line source. It emits long-range penetrating radiation, some of which gives rise to the gamma-plume dose at ground level.

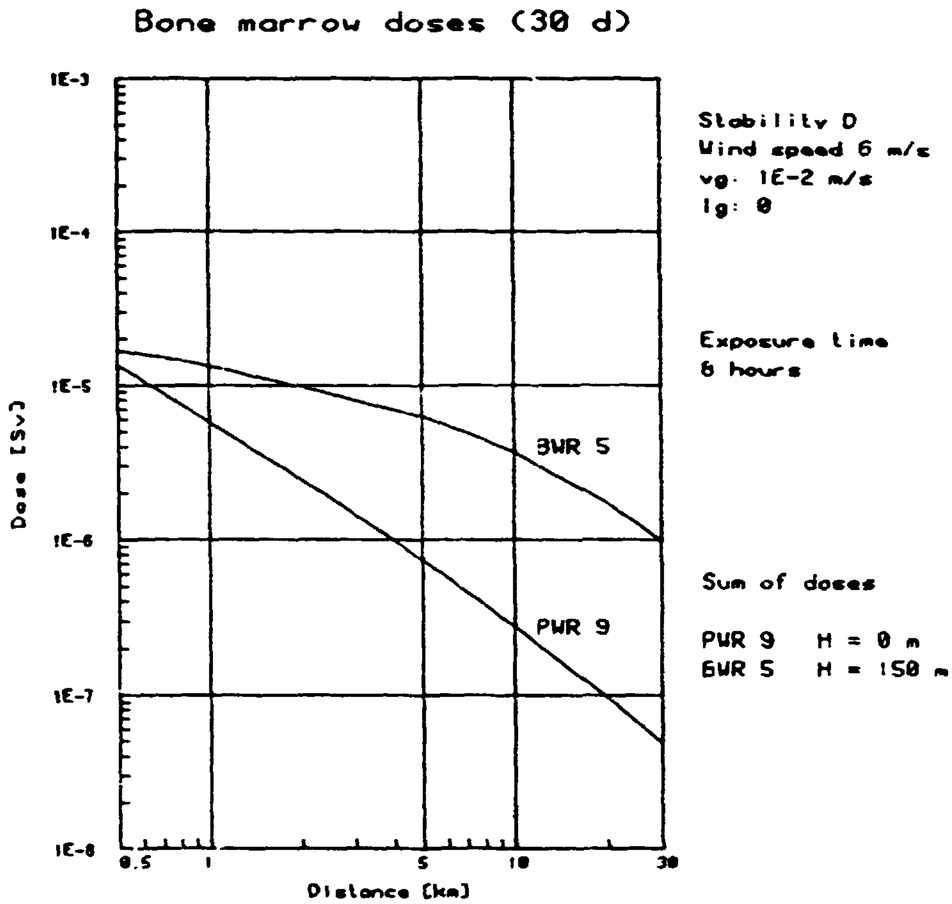


Fig. 6.2. Centre-line bone-marrow doses (integrated over 30 days) as a function of downwind distance in a PWR 9 release and a BWR 5 release.

The maximum dose is found along the projection of the plume centre-line with the highest value closest to the source at a distance of 500 m. As distance increases, the plume is increasingly dispersed, which means that the concentration of radioactive material decreases concurrently. This gives rise to a far more significant fall in the levels of the dose components in the case of the PWR 9 ground level release than in the 150 m plume in the BWR 5 release which - seen from the ground level centre-line - can still emit radiation from most of its length.

Hence the small difference in doses at 500 m between the two releases (as seen in Fig. 6.2), in spite of the much greater BWR 5 release, can be ascribed to two circumstances: 1) The ground level release in the PWR 9 release gives rise to almost equal doses from all three components, while the only component contributing to the BWR 5 release, the gamma plume, is significantly attenuated by the distance of 150 m or more. 2) The atmospheric mass between the source of radiation and the reception point for doses in the BWR 5 case. At 30 km distance, the difference in doses between the two releases increases to about a factor of 20.

6.2.1.1. Release category PWR 9. Figure 6.3 shows the contribution to the bone-marrow dose from the three components: inhalation, gamma plume and gamma deposition. In the ground level plume, inhalation doses can be delivered immediately and deposition can accumulate. The three components are of almost equal importance close to the release point, though the gamma plume contributes most and this becomes rather more dominant with increasing distance. At 30 km, the contribution of the gamma plume is approx. a factor 10 greater than that of the other two components.

The resulting sum of doses must be considered low, between 1E-5 and 2E-5 Sv (1-2 mrem), after 8 hours at 500 m distance, falling more than two decades at 30 km, to 5E-8 Sv, a non-detectable level. The doses shown are centre-line individual doses that fall drastically with increasing crosswind distance. Finally it should be borne in mind that the model gives an overestimation of doses at greater distances.

No short-term health consequences can be expected as a result of the calculated individual dose levels.

6.2.1.2. Release category BWR 5. Figure 6.4 shows the total bone marrow dose and its components in the case of a BWR 5 release. In the case of a 150 m high pencil-like plume, by far the most

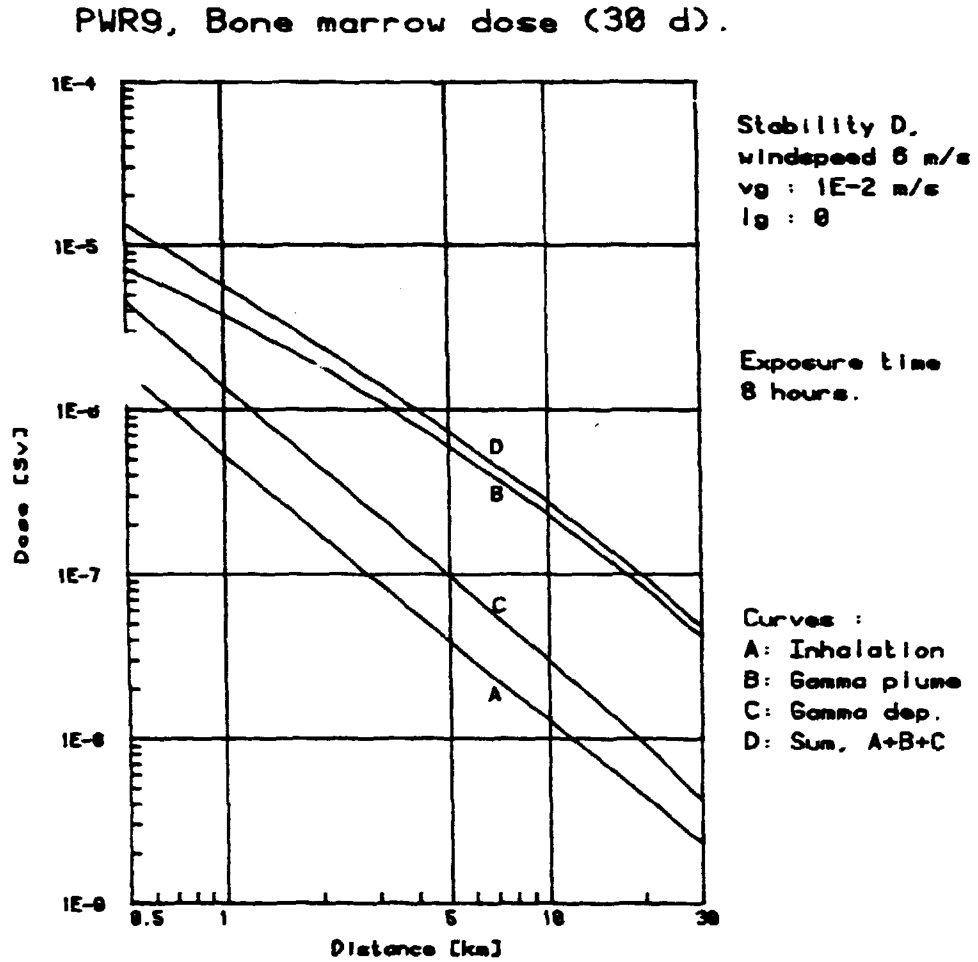


Fig. 6.3. Centre-line doses to the bone marrow (30 d) as a function of distance in the PWR 9 design-basis accident release category. Release height = 0 m.

dominant component is the gamma plume. The very small release fraction of aerosol activity reaches ground level between one and two km downwind.

The contribution from aerosols to the bone-marrow dose rises slowly over some km to reach a maximum at 5-10 km downwind. The levels are insignificant - 2-3 decades below that of the gamma plume component. The resulting dose levels after 8 hours of ~ 2E-5 Sv (2 mrem) at 0.5 km, falling to 1E-6Sv (0.1 mrem) at 30 km, must be considered very low.

As in the case of the PWR 9, no short-term health consequences can be expected from the calculated dose levels for a BWR 5 release.

6.2.2. Doses to specific organs

The impact of doses on specific organs, including doses to the whole body, their relative importance and the method of dose calculation, is described in detail in Section 5.3.5.

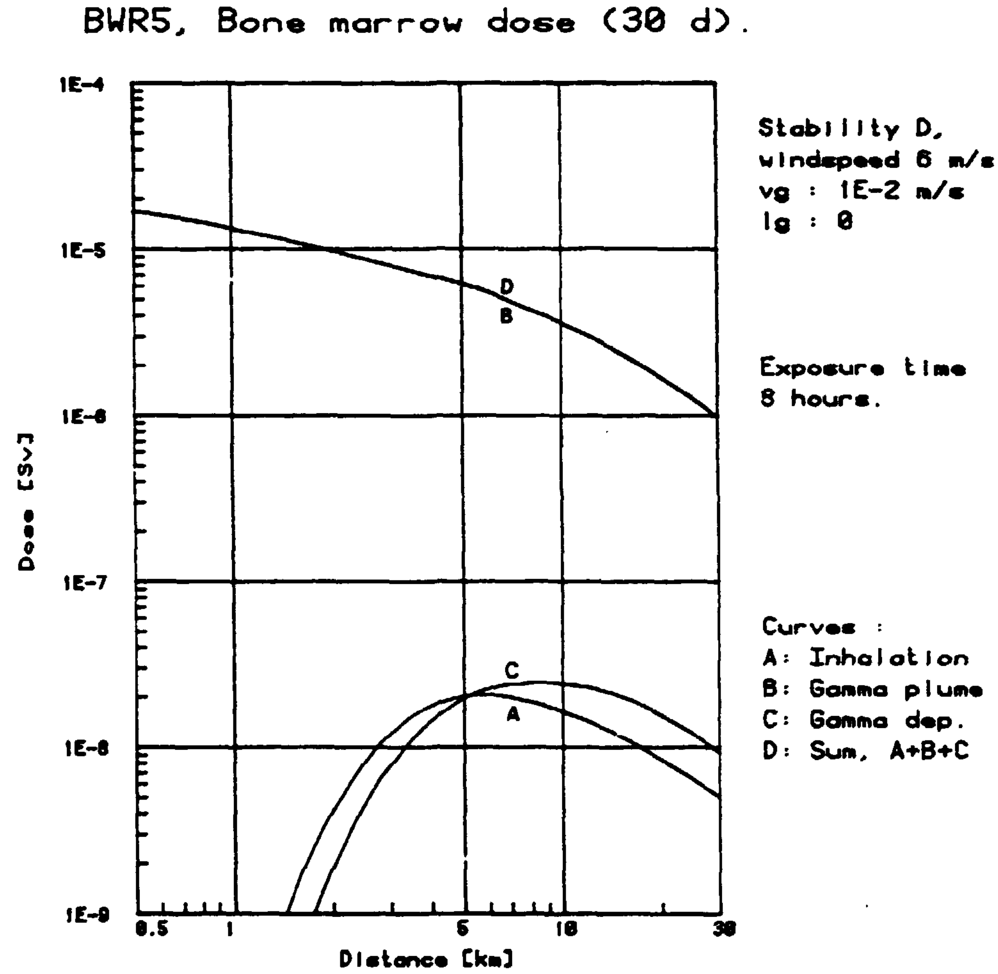


Fig. 6.4. Centre-line doses to the bone marrow (30 d) as a function of distance in the BWR 5 design-basis accident release category. Release height = 150 m.

Individual doses to the following specific organs were calculated:

A: Whole body (integrated over 50 years)
B: Bone marrow (integrated over 30 days)
C: Lungs (integrated over 1 year)
D: Gastro-intestinal tract (integrated over 7 days)
E: Thyroid (integrated over 30 days)

The five specific organ doses obtained in the plume centre-line in the two release categories PWR 9 and BWR 5 are shown in Figs. 6.5 and 6.6. The centre-line individual doses are to be considered the maximum doses for a given distance.

The curves marked F, which show the bone-marrow doses, including external radiation, are the same as the sum-curves marked D in the corresponding Figs. 6.3 and 6.4. For the bone-marrow doses and whole-body doses, the Gray unit is equal to the Sievert.

It must be emphasized, that the organ doses shown in Figs. 6.5 and 6.6 (incl. the whole-body doses) are calculated without the external radiation component, except the curves marked F which are the bone-marrow doses including external radiation (the values in curve B plus external radiation).

In the PWR 9 release, the total gastro-intestinal tract dose will be very close to the calculated total bone-marrow dose, curve F. The total thyroid dose will increase by a little more than 10% compared with curve E. The total whole-body dose and the total lung dose will be about double the level of the F-curve; this is calculated by adding curves A and C, respectively, to curve F, which is almost similar to the external dose.

The reason for the high thyroid dose compared to the other organs is the relatively high radiosensitivity of the thyroid combined with the relatively high proportion of iodine in the release.

In the BWR 5 release, all the organ doses including external radiation will be equal to the F curve because the external radiation is more than two decades greater than the inhalation and deposition components.

No consequences can be expected to any organs from the calculated organ doses in either release category.

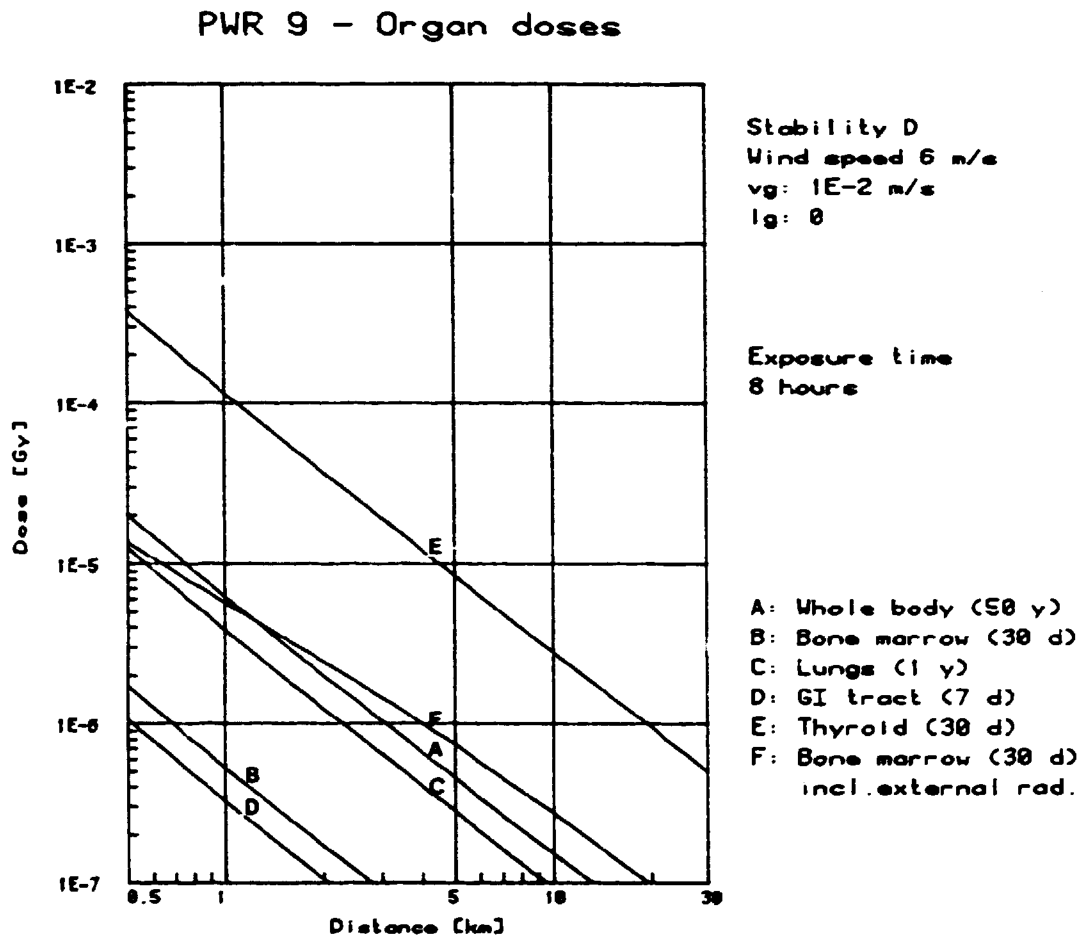


Fig. 6.5. Specific plume centre-line organ doses as a function of downwind distance for the design-basis accident release PWR 9.

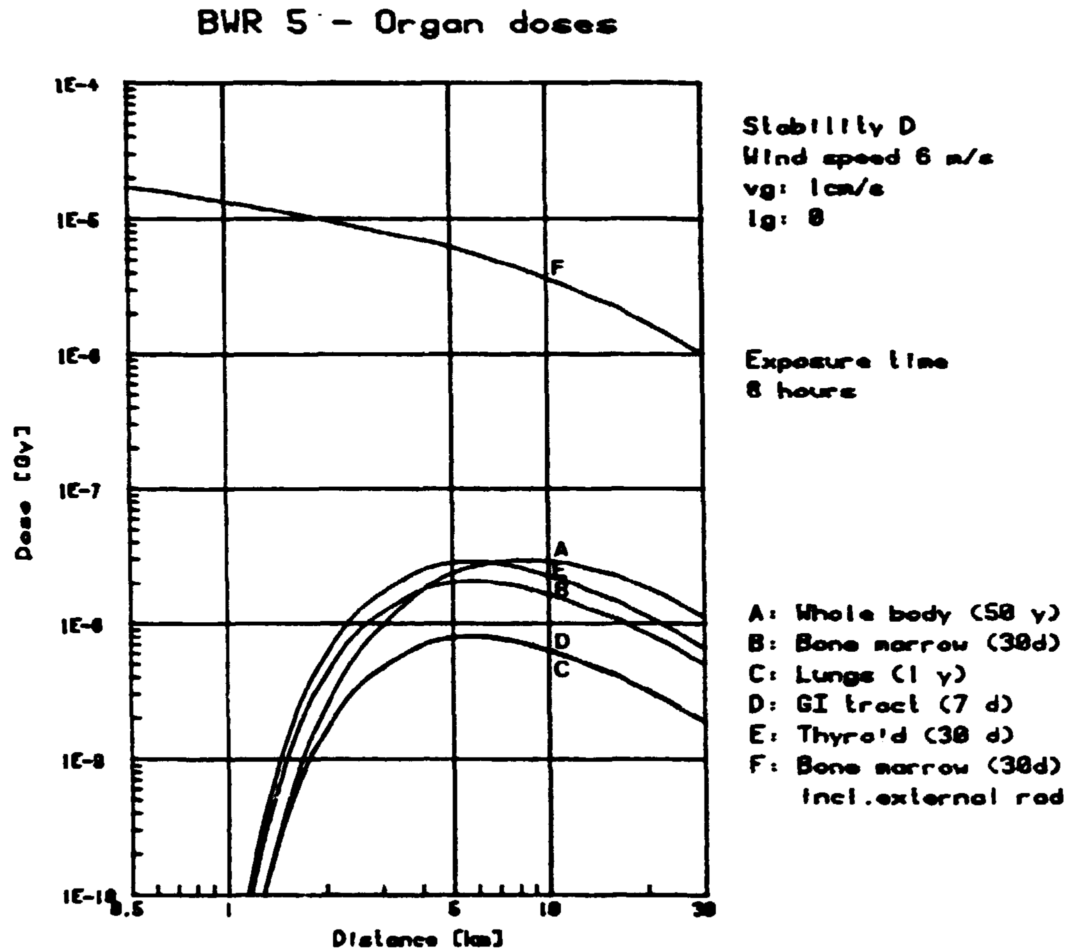


Fig. 6.6. Specific plume centre-line organ doses as a function of downwind distance for the design-basis accident release BWR 5.

6.3. Collective doses

Collective doses, being the sum of doses to the individuals in a given group, are calculated in manSievert. Chapter 2 describes the distribution of the resident population around Carnsore Point in detail in a polar coordinate system with centre in the site and with an angle of 22.5°, giving a total of 16 sectors.

In the PLUCON 2 program the population doses are calculated for each sector segment in the following way. The population in a segment is considered uniformly distributed over the segment. Then the product of the individual dose at any point and the population figure at this point are calculated. Finally the products are summated over the segment. As mentioned in section 5.3.1.1, only the population out to a distance of 30 km is considered.

For each of the two release categories collective dose calculations are made for the six 22.5° sectors (see Chapter 2) covering more than three inhabitants within 30 km. Among these six sectors the highest population distribution is found in the sector that includes the county town of Wexford and whose centre-line points in the 337.5° direction (see Section 2.2).

6.3.1. Collective doses in the PWR 9 release category

The whole-body doses and bone-marrow doses for the six release directions chosen are shown in Fig. 6.7. The total collective doses are accumulated out to a distance of 30 km from the release point. The figure also shows the number of persons receiving individual doses greater than E-6 Sv and their corresponding collective doses.

Further, taking the 337.5° release direction towards Wexford as an example, calculations show that the essential part of the collective dose is delivered within this 22.5° sector. Of the total collective bone-marrow dose of 1.5 E-3 manSv, the contribution from neighbour sectors is negligible:

PWR-9 release	Whole-body doses			Bone-marrow doses		
Release direction	Total dose manSv	Exposure above E-6 Sv persons	manSv	Total dose manSv	Exposure above E-6 Sv persons	manSv
22.5°	1.1E-4	26	7.1E-5	7.1E-5	19	3.6E-5
270°	1.1E-4	0.2	1.8E-7	7.7E-5	0	0
292.5°	4.0E-4	18	6.5E-5	2.6E-4	11	3.0E-5
315°	3.9E-4	15	6.8E-5	2.5E-4	8	3.1E-5
337.5°	2.3E-3	88	1.9E-4	1.5E-3	21	5.4E-5
360°	4.8E-4	88	2.1E-4	3.1E-4	47	8.7E-5

Fig. 6.7. Whole-body and bone-marrow doses in a PWR 9 accident release assumed to take place along the centre-lines of each of the six 22.5° sectors. The total accumulated collective doses, the number of persons exposed to an individual dose of more than E-6 Sv and their corresponding collective doses are shown for the two dose categories. The atmospheric situation is assumed to be: Stability category D, u = 6 m/s, vg = 1E-2 m/s and lg = 0.

Sector	292.5°	315°	337.5°	360°	22.5°
Dose manSv	1.5E-8	1.1E-6	1.5E-3	1.7E-6	2.5E-16
%	-	~ 0.1	~ 99.8	~ 0.1	-

The distribution with downwind distance for the 337.5° release direction of the 1.5E-3 manSv is shown in detail in Fig. 6.8.

Distance interval (km)	Collective bone-marrow dose	
	E-5 manSv	(%)
0.5 - 1	1.9	1.2
1 - 1.5	1.5	1.0
1.5 - 2	1.2	0.8
2 - 3	2.0	1.3
3 - 4	3.0	2.0
4 - 5	4.2	2.8
5 - 7.5	4.9	3.2
7.5 - 10	3.4	2.2
10 - 12.5	1.1	0.7
12.5 - 15	1.4	0.9
15 - 20	108.4	71.1
20 - 25	16.9	11.1
25 - 30	2.6	1.7
Sum	152.4	100.0

Fig. 6.8. Collective bone-marrow doses distributed in the 13 distance intervals in the 337.5° direction in a PWR 9 design-basis accident release.

6.3.2. Collective doses in the BWR 5 release category

For the six release directions chosen, Fig. 6.9 shows the collective doses to the whole body and to the bone marrow.

Figure 6.9 shows that there is no difference between the doses to the whole body and the bone-marrow doses. This is because the external radiation is more than two decades greater than the inhalation and deposition components as shown in Fig. 6.6.

With respect to the PWR 9 release, the greatest collective dose is found for the 337.5° release direction towards Wexford.

Further, the calculations for the 337.5° release direction show that the essential part of the collective dose is delivered within this 22.5° sector. Of the total collective bone-marrow dose of 3.4E-2 manSv, the contributions from the neighbour sectors are:

Sector	292.5°	315°	337.5°	360°	22.5°
Dose manSv	1.7E-6	3.7E-4	3.26E-2	6.1E-4	9.9E-8
%	-	~ 1.1	~ 97.1	~ 1.8	-

However, compared with the PWR 9 release, the relative contribution from the adjacent sectors is more than ten times greater for the BWR 5 release. The reason for this is the effective dispersion height of 150 m, which gives the possibility of irradiation of adjacent sectors.

The distribution with downwind distance for the 337.5° release direction of the 3.4E-2 manSv is shown in detail in Fig. 6.10.

BWR-5 release	Whole-body doses			Bone-marrow doses		
Release direction	Total dose manSv	Exposure above 5E-6 Sv persons	manSv	Total dose manSv	Exposure above 5E-6 Sv persons	manSv
22.5°	1.5E-3	47	3.5E-4	1.5E-3	47	3.5E-4
270°	2.2E-3	2	1.3E-5	2.2E-3	2	1.3E-5
292.5°	6.8E-3	44	3.1E-4	6.8E-3	44	3.1E-3
315°	7.6E-3	54	3.7E-4	7.6E-3	54	3.6E-4
337.5°	3.4E-2	203	1.3E-3	3.4E-2	203	1.3E-3
360°	7.3E-3	179	1.2E-3	7.3E-3	179	1.2E-3

Fig. 6.9. Collective whole-body and bone-marrow doses in a BWR 5 accident release assumed to take place along the centre-lines of each of the six 22.5° sectors. The total accumulated collective doses, the number of persons exposed to an individual dose of more than 5 E-6 Sv, and their corresponding collective doses are shown for the two dose categories. The atmospheric situation is assumed to be: Stability category D, u = 6 m/s, v_g = 1E-2 m/s and 1_g = 0.

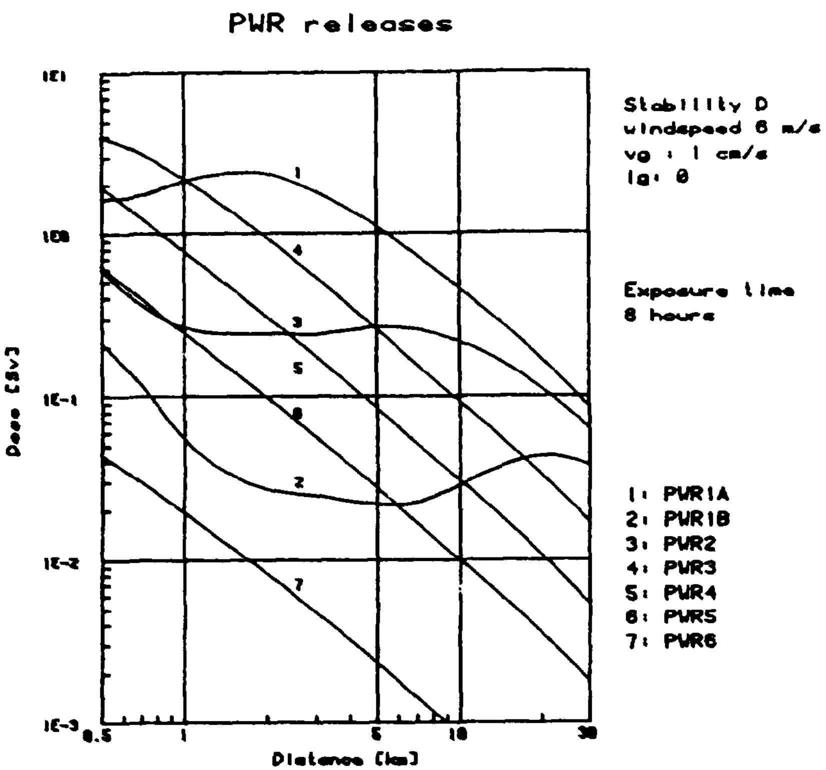


Fig. 7.2. Centre-line doses (maximum doses) to the bone marrow (30 d) as a function of distance for seven PWR releases.

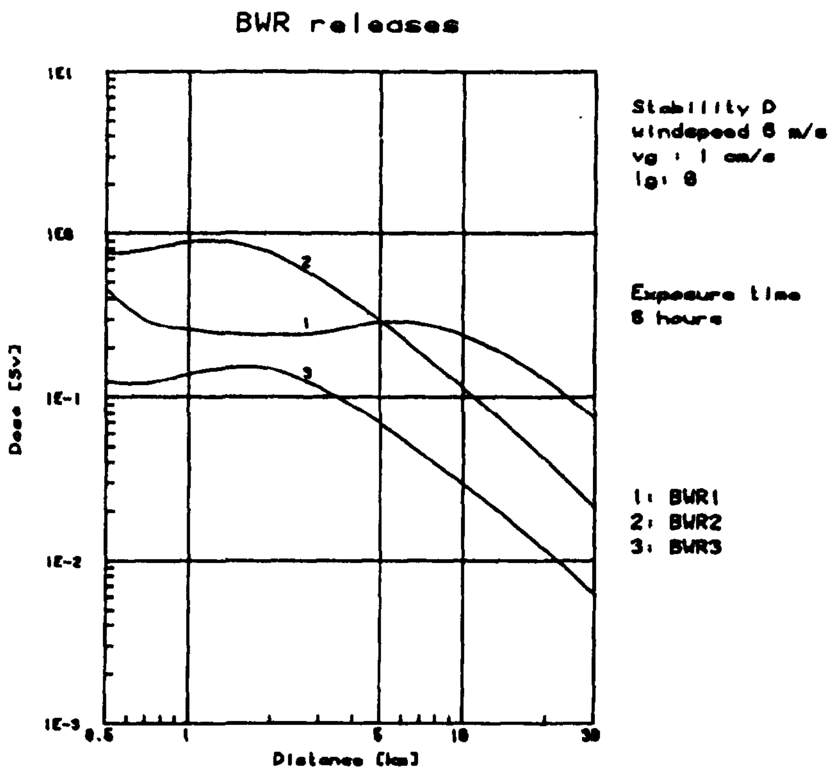


Fig. 7.3. Centre-line doses (maximum doses) to the bone marrow (30 d) as a function of distance for three BWR releases.

Similar trends can be seen for the PWR 1B, PWR 2 and BWR 1 that have high energy releases and high effective release heights. Finally, similar trends can be found for the four cold releases PWR 3 - PWR 6.

Some conclusions may be drawn from Figs. 7.2 and 7.3 bearing in mind that each release category represents a hypothetical accident with extensive damage to the reactor and in some cases also to the containment barriers, that the probability of occurrence of each is very low, and also that only one accident could take place.

From the release point (from 0.5 km) and up to a distance of one km, the cold PWR 3 release results in the highest individual bone-marrow doses in the dose range 4 to 2 Sv. It must be pointed out that in an accident very few people would be exposed at such close range.

At distances larger than one km, the cold release PWR 1A gives rise to the highest doses. Centre-line doses of more than 1 Sv are found within little more than 5 km from the release point.

The greatest BWR release - the BWR 2 - first reaches the same level as the PWR 3 at a distance of 5 km.

At distances greater than 5 km, the hot BWR 1 reaches the same level as PWR 2.

A detailed description follows of the centre-line bone-marrow doses (maximum doses) calculated for each of the ten release categories. The model is able to predict doses and concentrations within a factor of 2-3, and at larger distances the findings are normally overestimated (cf. Section 5.3.1.1).

Gamma plume is generally found to be the dominating dose component except in the PWR 3 release where gamma deposition dominates out to a distance of nearly 3 km.

7.2.1.1. Release category PWR 1A

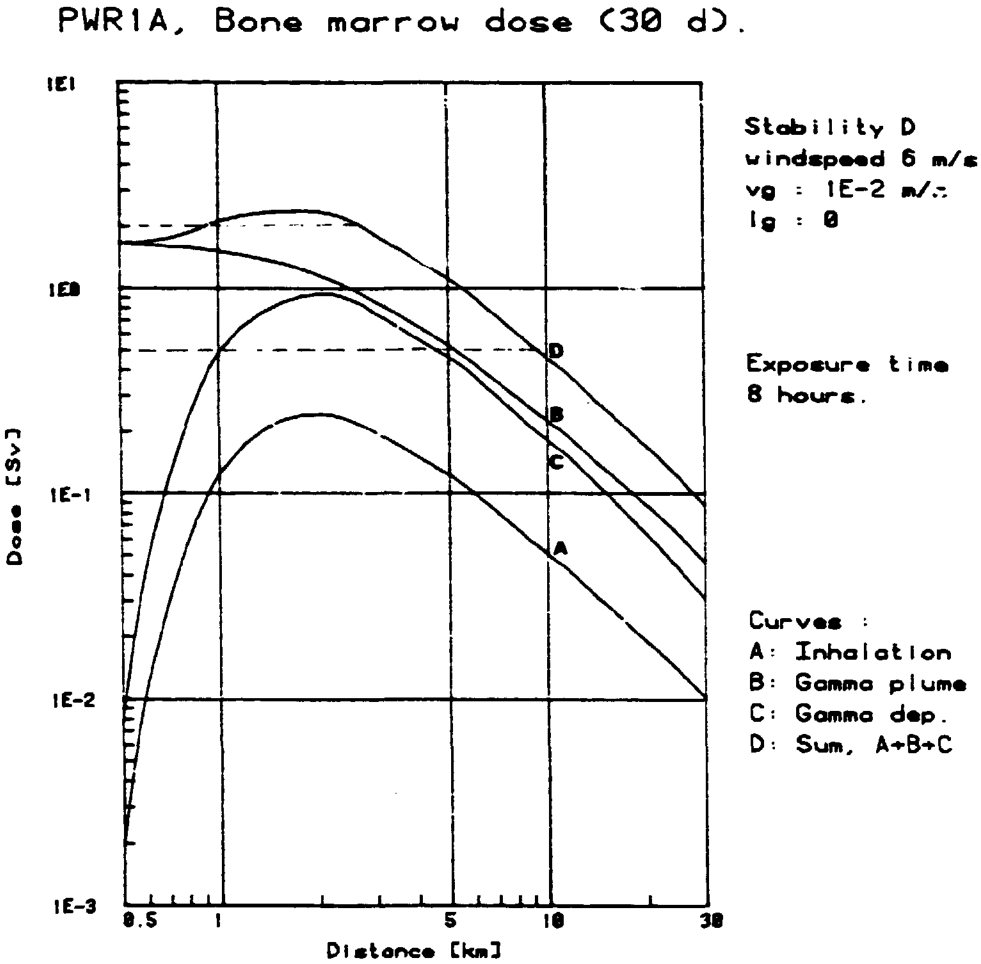


Fig. 7.4. Centre-line doses to the bone marrow (30 d) as a function of distance in the PWR 1A release category.

In the cold PWR 1A release (see Fig. 7.1) with release height h = 25 m, the effective dispersion height, H = 75 m, is reached at a downwind distance of 360 m. The gamma plume component dominates up to about 3 km. The relatively low-hanging plume reaches ground very quickly after the release point and gives rise to contributions from gamma deposition and inhalation, which reach their maximum at a distance of approx. 2 km from the release point. At larger distances downwind the gamma plume and gamma deposition components contribute nearly equally to the resulting bone-marrow dose.

Comparing Fig. 6.10 with Fig. 6.8, it appears that the relative contribution to the collective bone-marrow dose is greater for the PWR 9 release in the distance interval 0.5 km - 7.5 km while the relative contribution to the collective dose is greater for the BWR 5 release in the distance interval 7.5 km - 30 km. This is explained in Fig. 6.2 where the dose decreases much faster with increasing distance in the PWR 9 case than in the BWR 5 case.

Distance interval (km)	Collective bone-marrow dose	
	(E-5 manSv)	(%)
0.5 - 1	0.9	0.3
1 - 1.5	0.9	0.3
1.5 - 2	0.8	0.2
2 - 3	2.2	0.7
3 - 4	3.9	1.2
4 - 5	5.8	1.7
5 - 7.5	9.3	2.8
7.5 - 10	10.3	3.1
10 - 12.5	7.9	2.4
12.5 - 15	6.0	1.8
15 - 20	234.3	69.9
20 - 25	42.3	12.6
25 - 30	10.7	3.2
Sum	335.4	100.0

Fig. 6.10. Collective bone-marrow doses distributed in the 13 distance intervals in the 337.5° direction in a BWR 5 design-basis accident release.

7. DOSES FROM HYPOTHETICAL CORE-MELT ACCIDENTS

7.1. Introduction

This chapter deals with doses and the consequences of hypothetical core-melt accidents.

For a given hypothetical accident, two essential factors affecting consequences must be taken into account: type of accident and atmospheric conditions.

Considering the first factor: for the two reactor types in question, the ten accidents (described in detail in chapter 4) combine the worst conceivable possibilities of accidents to the reactor core with the worst conceivable possibilities of containment failures. The ten release categories are all characterized by core melt-down. Probabilities for the occurrence of such worst conceivable accidents are accordingly very low: they are shown in Fig. 7.1, and comments are given in Chapter 4.

The PWR 1 (A and B) and BWR 1 accidents include a steam explosion in the pressure vessel which results in a breach of the containment barrier with rapid and very large releases as a result.

In the PWR 2 and BWR 2 accidents overpressure results in severe failure of the containment barrier and the concurrent core meltdown gives rise to releases to the atmosphere of very large fractions of the core inventory of radioactive materials (Fig. 4.1). In the BWR 2 case it is expected that 30 hours would elapse before the 3-hour release took place (Fig. 4.3).

Cases PWR 3 to 6 are core-melt accidents with decreasing severity of release, depending on the decreasing leak rates of the containment barrier. In the PWR 6 release, the containment barrier would retain its integrity until the molten core proceeded to melt through the concrete containment base mat into the ground (often called the "China syndrome"). The release would take place over 10 hours with a rather low release rate through the ground upward to the atmosphere. It is assumed that the release starts 12 hours after reactor shut-down.

In the BWR 3 release, 30 hours of cooling after shut-down would elapse before the release takes place over three hours.

The ten release categories have different release rates of sensible energy from the containment.

The PWR 1B, PWR 2 and the BWR 1 releases have high rates of energy release of, respectively, 152, 50 and 38 MW, and could be called "hot" releases. The heat in each release gives rise to buoyancy of the plume. Here the final effective dispersion heights, H, are significantly greater than in the other releases, which could be called "cold" releases with rather low values of H (Fig. 7.1).

Atmospheric conditions at the time of a release constitute the second essential factor affecting the consequences.

To combine hypothetical release categories of very low probability with extreme weather conditions, also having very low probability was not considered reasonable. Therefore each of the ten release categories of low probability was combined with the most probable atmospheric situation found at Carnsore Point. This combination is discussed in detail in this section.

The meteorological situation applied to the ten release categories is the most common one described in Section 3.4:

Pasquill stability category D,
Wind speed u = 6 m/s (21.6 km/h)
Dry deposition velocity $v_g = 10^{-2}$ m/s
Wet deposition velocity $1_g = 0\ s^{-1}$, no rain

Calculations were made using the PLUCON 2 model of bone-marrow doses to individuals as a function of downwind distance from the release point. A detailed description is given for each of the ten release categories.

Doses to specific organs are then described in four selected release categories (PWR 1A, PWR 2, PWR 6 and BWR 2). The relative importance to the dose distribution of different radionuclide groups is then described, followed by a description of dose-level ranges for bone-marrow and whole-body doses in each of the ten release categories.

Collective doses to the bone marrow and whole-body doses are calculated for the ten release categories. The number of persons subjected to doses within certain levels was found in order to estimate the possible number of deaths from acute effects of radiation as well as the number of late cancer cases by applying certain internationally accepted, conservative risk factors.

As described in Section 5.3.1.1, it was decided to calculate only the doses out to a distance of 30 km from Carnsore Point.

As described in Section 5.3.1.2, in the model the plume is assumed to rise to a given height (the effective dispersion height, H) that depends on stability category, wind speed and energy release. When the plume reaches this height it is assumed that its centre-line remains constantly at the height H.

Figure 7.1 shows the final effective dispersion height, H, for the 10 release categories in the meteorological situation considered in this chapter (the values are taken from Fig. 5.3).

Figure 7.1 also shows the distance, d, in m from the release point at which the plume centre-line is assumed to reach H. The value of d is calculated in accordance with a procedure of Briggs.

Release category	Probability per reactor year	Release height h [m]	Energy release from containment P [MW]	Effective dispersion height H [m]	Distance corre-sponding to H d [m]
PWR 1A	4E-7*	25	5.9	75	360 cold
- 1B	5E-7	25	152	378	1300 hot
- 2	8E-6	0	50	181	850 hot
- 3	4E-6	0	1.8	25	225 cold
- 4	5E-7	0	0.3	8.4	200 cold
- 5	7E-7	0	0.1	4.4	200 cold
- 6	6E-6	0	-	0	200 cold
BWR 1	1E-6	25	38	179	660 hot
- 2	6E-6	0	8.8	64	420 cold
- 3	2E-5	25	5.9	75	360 cold

Fig. 7.1. The probabilities of occurrence per reactor year, the release height h and the rate of sensible energy release from the containment are shown for the 10 release categories with core melt-down. The corresponding effective dispersion height H, and the distance d from the release point at which the effective dispersion height is reached, are shown for the atmospheric conditions applied in this section (Pasquill D, $u = 6$ m/s, $v_g = 10^{-2}$ m/s, $l_g = 0\ s^{-1}$),

*4E-7 is understood as 4 in 10,000,000 per reactor year.

Mention should be made of the more important parameters applied in the calculations (described in detail in Chapter 5):

Respiration rate: 3.5 x 10^{-4} m^3/s (adults in working hours)
Reduction factor for those inside buildings, inhalation: 0.2
Reduction factor for those inside buildings, gamma plume: 0.6
Reduction factor for roughness of the ground and those inside buildings, gamma deposition: 0.14
People in the area are assumed to remain inside brick houses for the first 8 hours after the start of warning time.

The model makes a correction for a long-term release, in relation to a 30-minute release, by correcting the dispersion parameters.

7.2. Doses to individuals

7.2.1. Bone-marrow doses

In order to evaluate any acute radiation effects it is necessary to know the bone-marrow dose to individuals. For the 10 release categories, doses to the bone marrow are calculated (see Section 5.3.5) in the plume centre-line for distances downwind from 0.5 to 30 km from the release point. Calculations are made of the three dose components inhalation dose, external gamma dose from the plume and external gamma dose from deposited radioactivity (in the following called inhalation, gamma plume and gamma deposition) as well as their sums. The plume centre-line doses represent the highest doses at a given distance in a given release situation. In order to compare the 10 release types, the sum curves are shown in Figs. 7.2 and 7.3. Figure 7.2 shows the PWR and Fig. 7.3 the BWR releases types.

Figure 7.1 shows that the energy releases and effective release heights of the cold releases PWR 1A, BWR 2 and BWR 3 are of the same order of magnitude. Their dose patterns are also seen to be similar (Figs. 7.2 and 7.3). The differences in dose levels result from the different activity releases and decay times.

Dose level, Sv	0.1	0.5	1.0	2.0
Area surrounded by the isodose curve, km^2	45.5	5.4	1.7	0.17
Distance to start of area, km	0.5	0.5	0.5	0.9
Distance to endpoint, km	27.3	9.3	5.4	2.6
Maximum half-width, m	1130	390	222	75
Distance of maximum width, km	17	5.5	3.1	2.0

Fig. 7.6. Data on the isodose curves shown in Fig. 7.5.

7.2.1.2. Release category PWR 1B

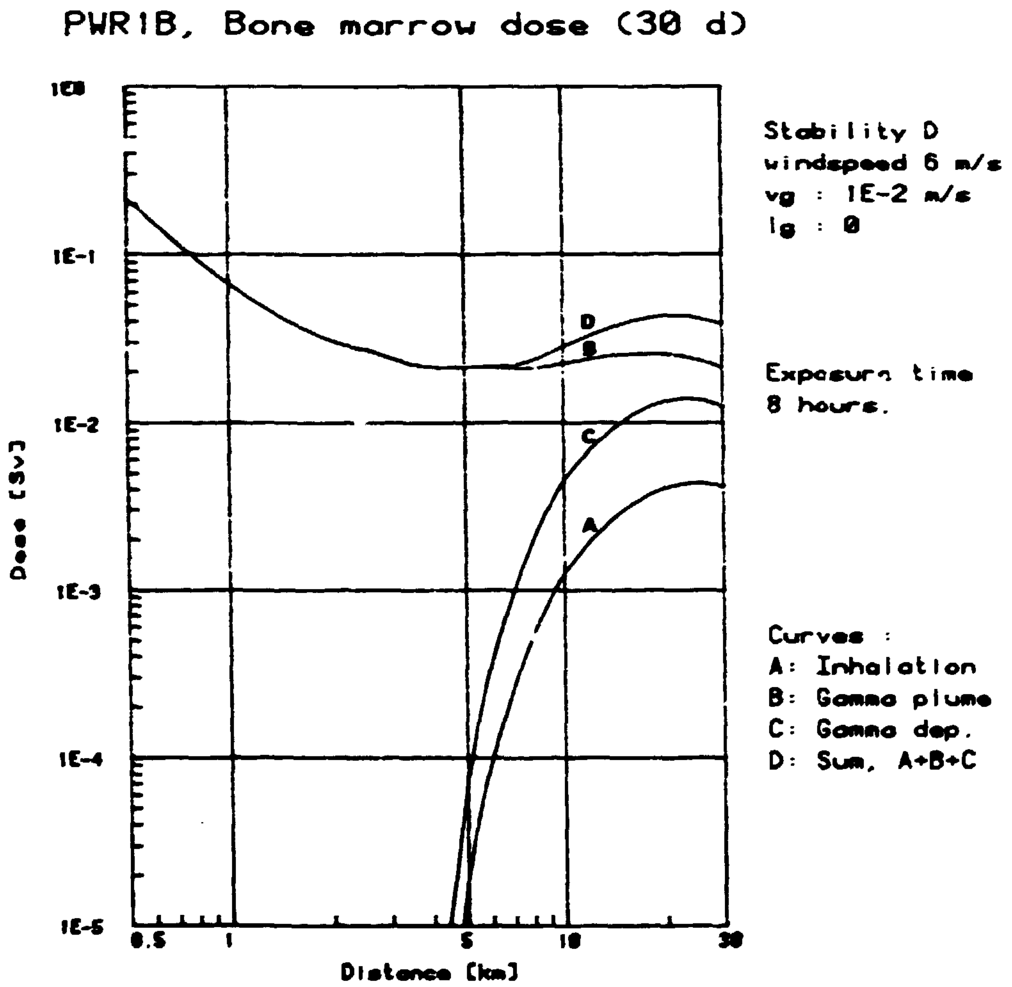
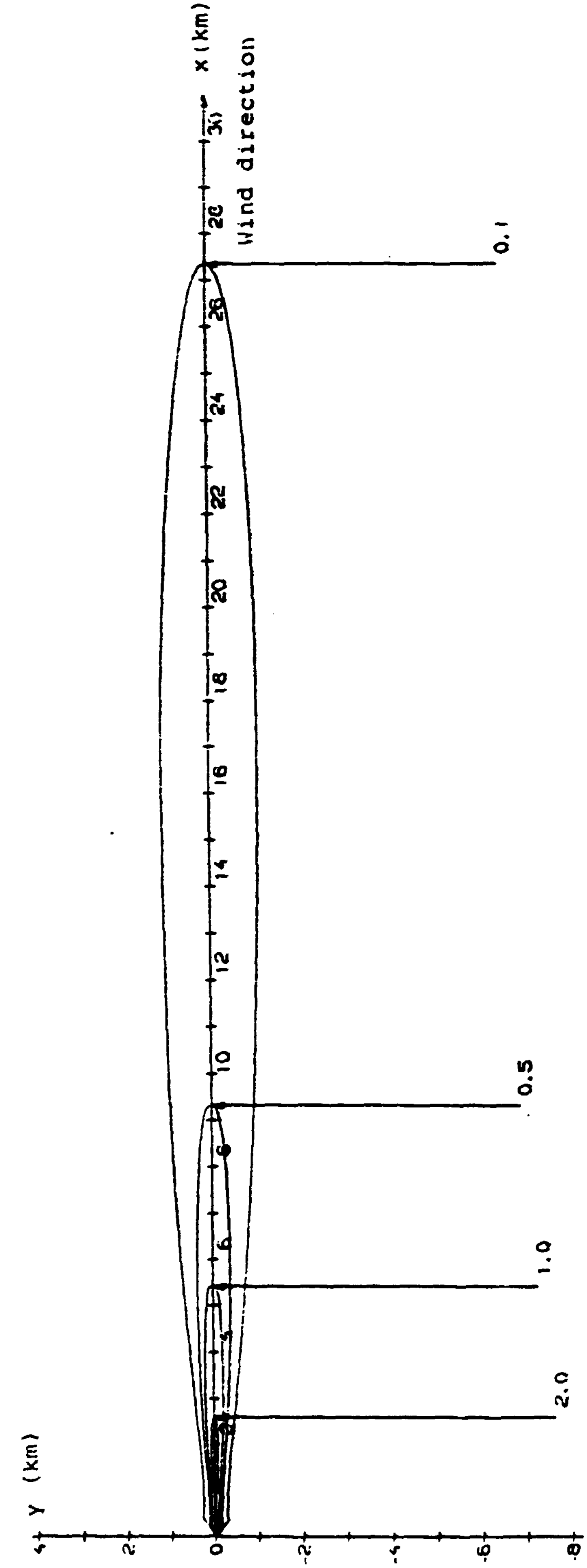


Fig. 7.7. Centre-line doses to the bone marrow as a function of distance in the PWR 1B release category.



The figures showing the centre-line doses represent the maximum downwind doses calculated for each release category. In order to illustrate the spatial dose distribution, isodose curves were calculated for the release giving the highest dose picture - the cold PWR 1A release.

The isodose curves for the values of 2, 1, 0.5 and 0.1 Sv, are shown in Fig. 7.5. The scales of the axes are in km (Fig. 7.4 shows the corresponding levels of 2 and 0.5 Sv by means of dotted lines).

Figure 7.6 shows the areas and the maximal widths of the four isodose curves together with the corresponding distance from the release point.

Fig. 7.5. Isodose curves (bone-marrow dose) for the PWR 1A release cat-

The release height h is 25 m in the PWR 1B release category. The very high rate of energy release of 152 MW from the containment gives rise to a marked buoyancy of the plume, resulting in an effective dispersion height H as high as 378 m, reached at a downwind distance of 1300 m. Although the release comprises a very large fraction of the core inventory, the markedly dominant dose component is gamma plume because of the high plume centre-line. First at 4-5 km downwind does the plume reach ground level and give rise to inhalation and gamma deposition doses. The maximum contribution from the two dose components is reached beyond 20 km.

Up to a distance of more than ten km, the PWR 1B dose is more than one decade less than the dose from the cold PWR 1A release, and at a distance of 30 km it is still more than a factor 2 lower.

7.2.1.3. Release category PWR 2

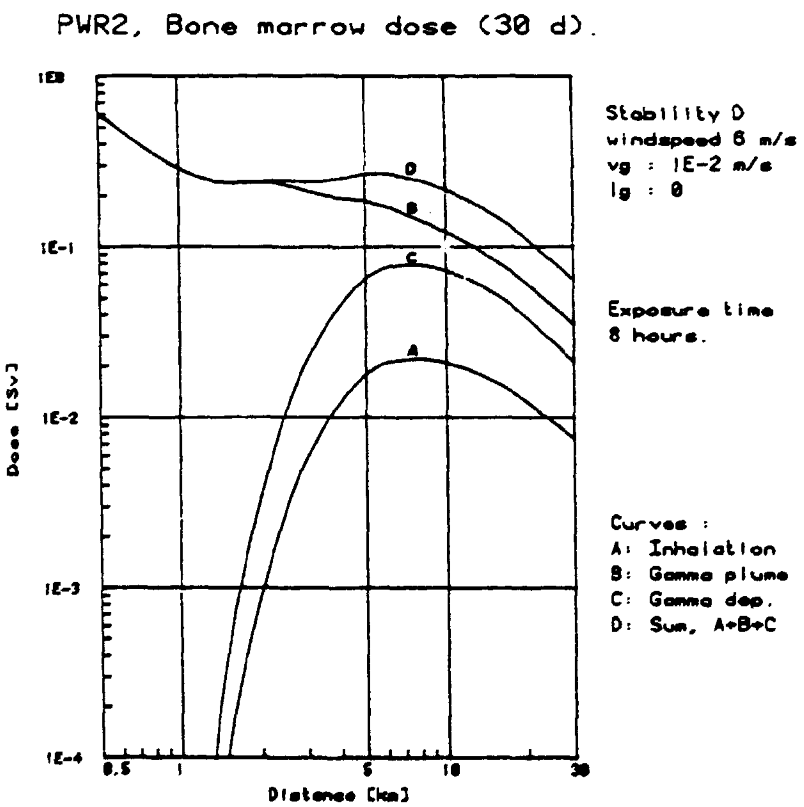


Fig. 7.8. Centre-line doses to the bone marrow as a function of distance in the PWR 2 release category.

The PWR 2 release has the relatively high rate of energy release of 50 MW. The plume reaches the calculated effective dispersion height H of 181 m at a downwind distance of 850 m. With the release height of 0 m, the plume gives rise to inhalation and gamma deposition doses at a distance of little more than one km, having maximal contributions at a distance of between five and ten km. The gamma plume component dominates all the way downwind in the weather situation selected.

7.2.1.4. Release category PWR 3

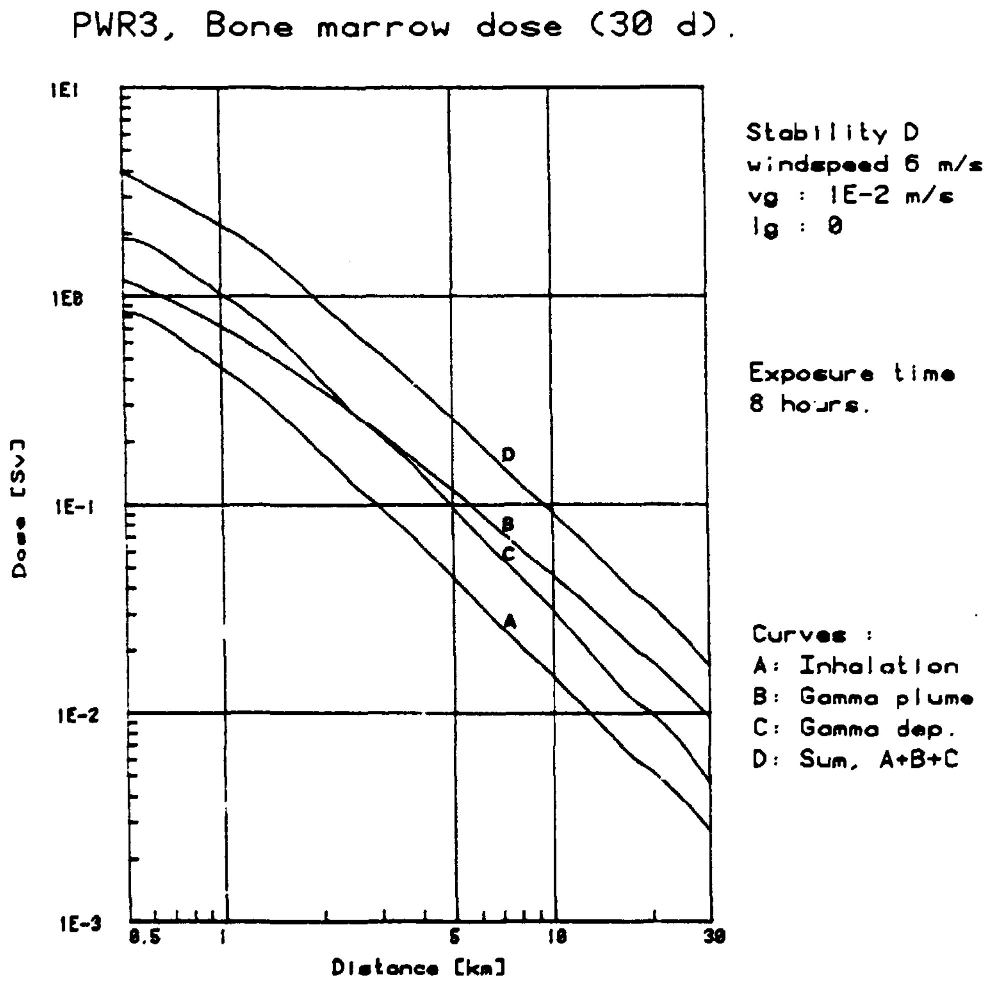


Fig. 7.9. Centre-line doses to the bone marrow as function of distance in the PWR 3 release category.

Of the ten release categories considered, PWR 3 gives the highest doses downwind in the vicinity of the release point up to a distance of 1 km (see Fig. 7.2) with contributions from 4 to 2.5 Sv. The release must be considered as cold with a rate of energy release of 1.8 MW. The release height is 0 m, and the effective dispersion height H of 25 m is reached at a downwind distance of 228 m. Dispersion of the ground-level plume, however, gives rise to a fall of more than a decade in the total dose level within a downwind distance of 5 km. The three dose components contribute almost equally to the dose immediately after the release.

7.2.1.5. Release category PWR 4

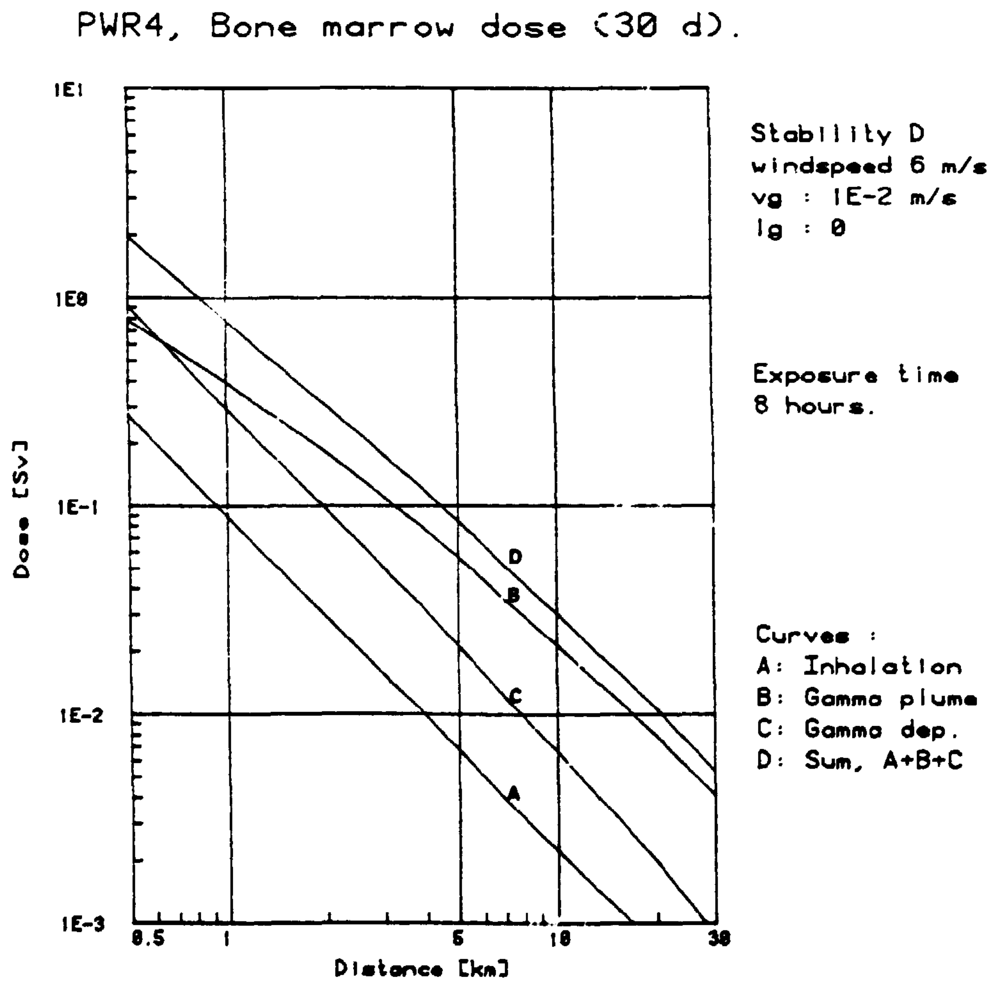


Fig. 7.10. Centre-line doses to the bone marrow as a function of distance in the PWR 4 release category.

The PWR 4 release category has a low rate of energy release from the containment of 0.3 MW at a ground-level release height, and a calculated effective dispersion height of 8.4 m reached 200 m downwind. Gamma plume is the dominant dose contributor. Dispersion of the ground-level plume gives rise to a fall in the total dose level of a factor of 20 within 5 km downwind.

7.2.1.6. Release category PWR 5

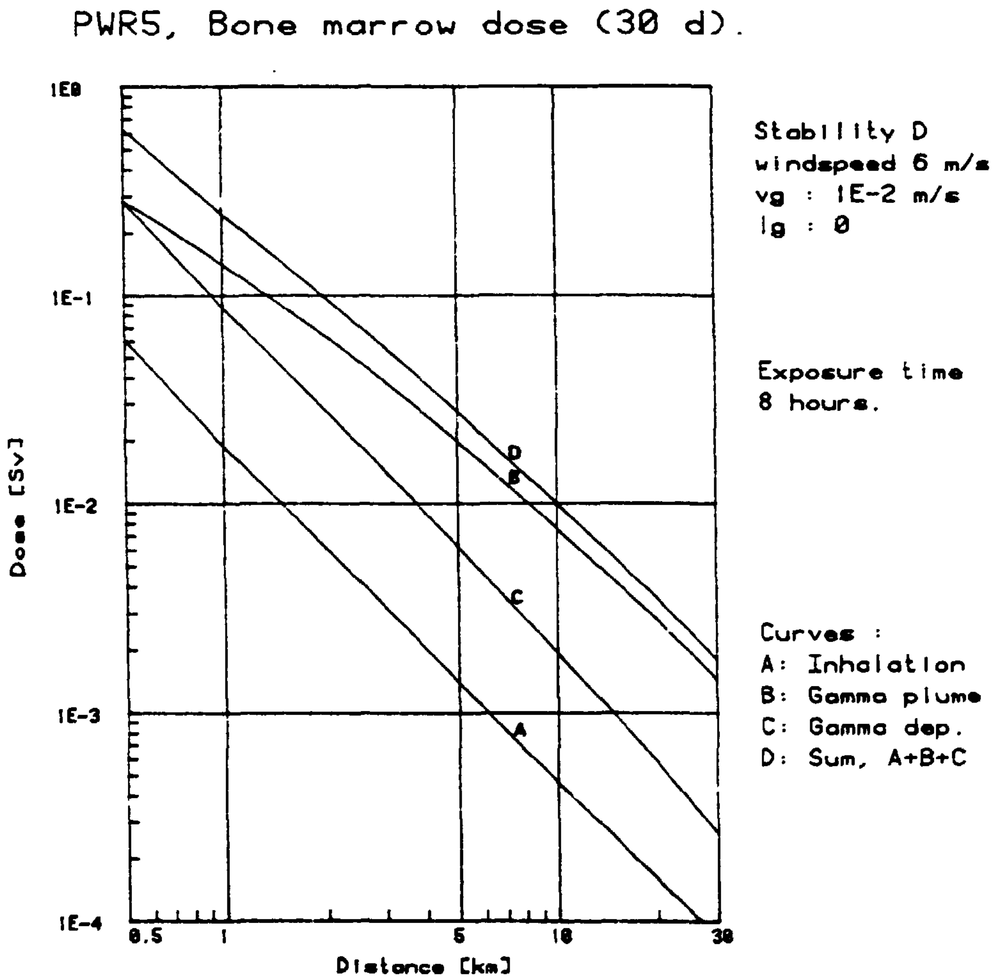


Fig. 7.11. Centre-line doses to the bone marrow as a function of distance in the PWR 5 release category.

The PWR 5 release is a low energy, ground-level release where the dose is dominated by the gamma plume component. This is because of the dominance of noble gases in the release of activity. The dose decreases rapidly with increasing downwind distance as did those of the cold releases discussed earlier.

7.1.2.7. Release category PWR 6

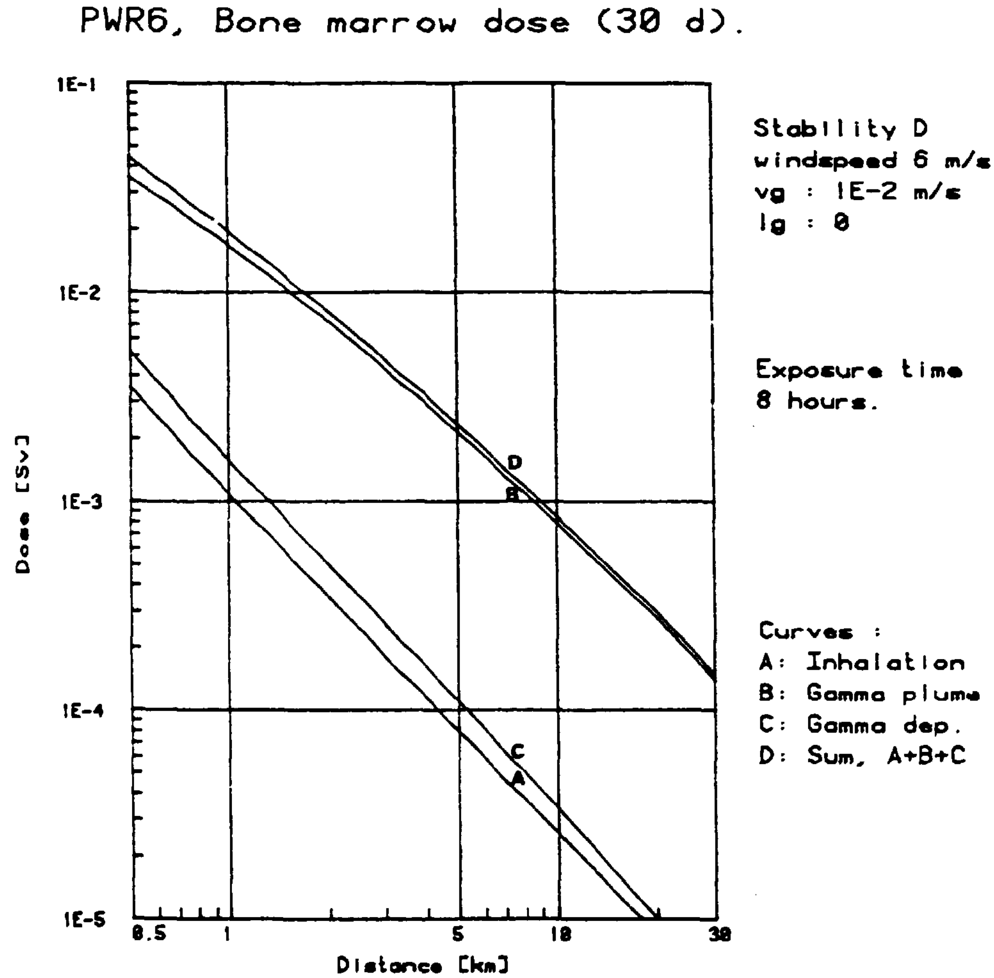


Fig. 7.12. Centre-line doses to the bone marrow as function of distance in the PWR 6 release category.

PWR 6 is a ground-level release at ambient temperature. As this penetrates into the ground, noble gases are the main activity components. The gamma plume is by far the most dominant component downwind. The gamma deposition component is of relatively minor importance because of the 10-hour duration of the release plus the 1-hour warning time, which period of time is very long compared to the exposure time of 8 hours.

7.1.2.8. Release category BWR 1

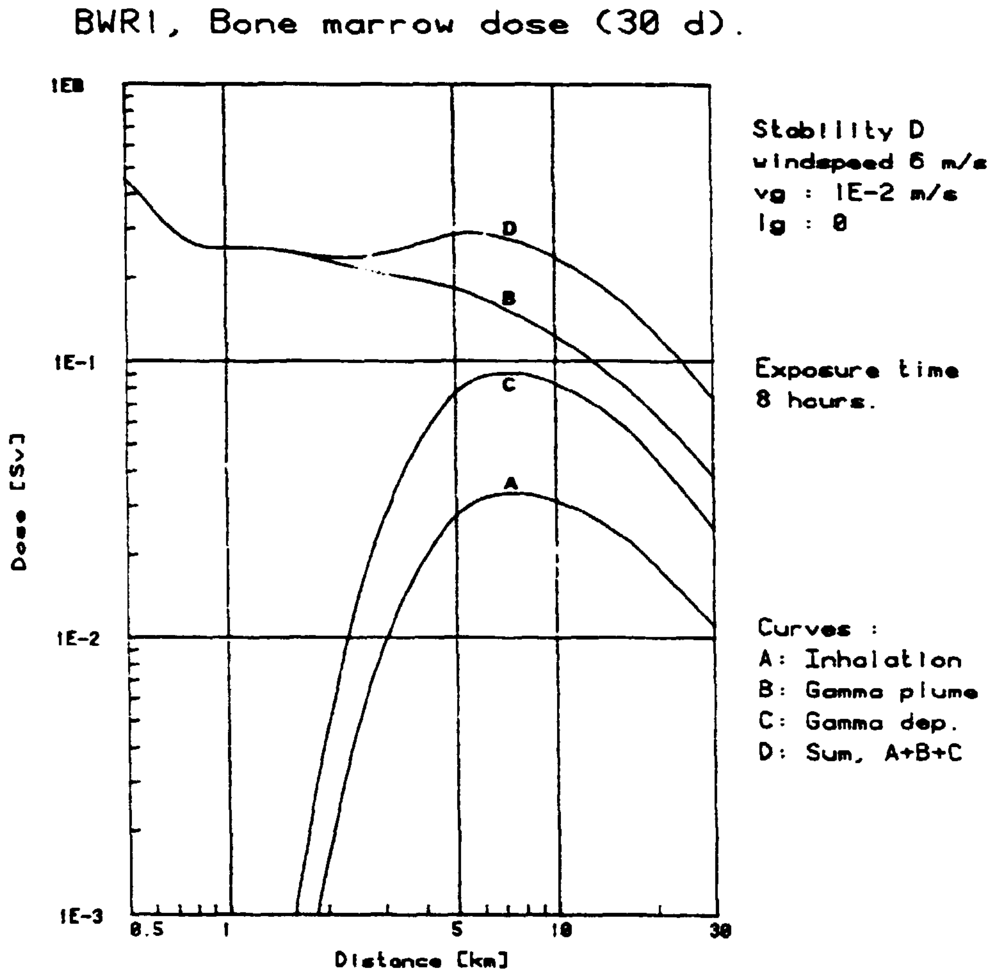


Fig. 7.13. Centre-line doses to the bone marrow as a function of distance in the BWR 1 release category.

The BWR 1 release is characterised by the high rate of energy release - 38 MW - which with a release height of 25 m results in a calculated effective dispersion height of 179 m, reached at a downwind distance of 660 m. As the plume first reaches ground level at a distance of approx. 1.5 km, gamma plume is the only dose component up to this distance from the release point. Inhalation and gamma deposition reach maximums between five and ten km downwind.

7.2.1.9. Release category BWR 2

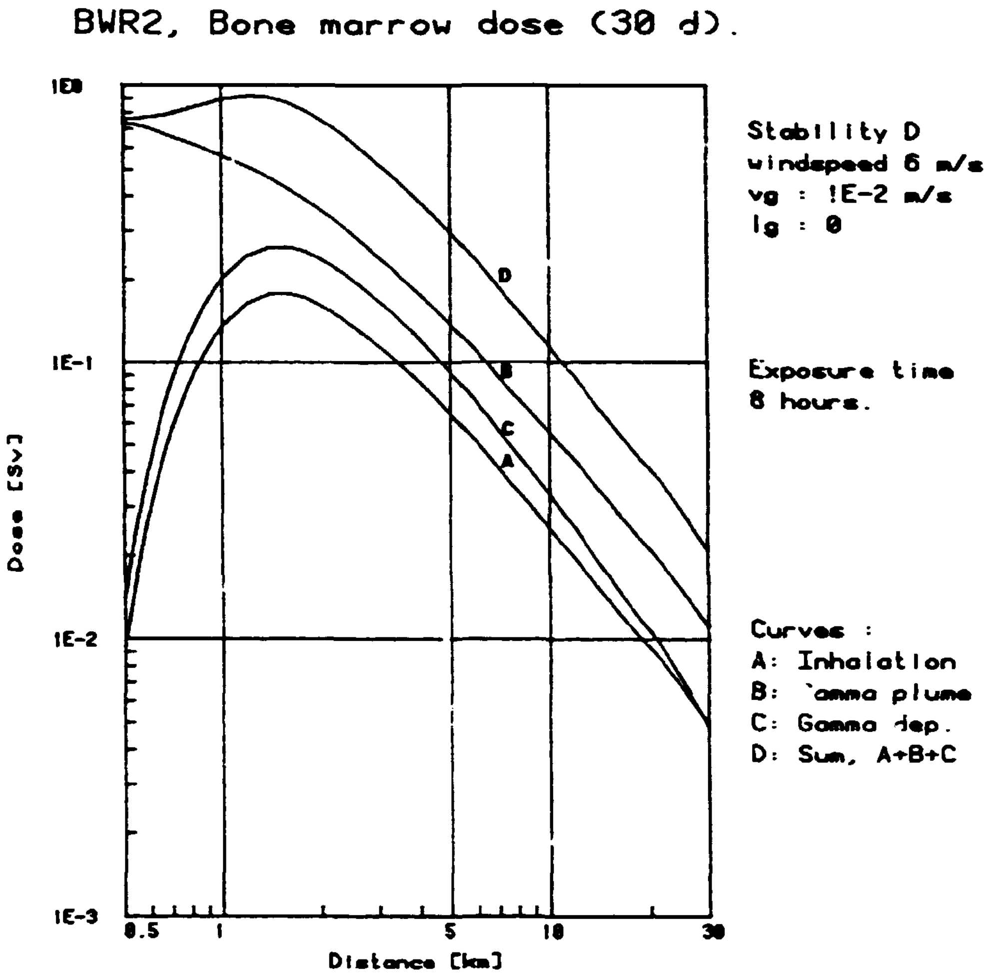


Fig. 7.14. Centre-line doses to the bone marrow as a function of distance in the BWR 2 release category.

As seen in Fig. 7.14, the BWR 2 release gives the highest doses to ground level within a distance of five km from the BWR types considered. The BWR 2 release has a release height of 0 m and an energy release rate from the containment of 8.8 MW. The calculated effective dispersion height is rather low, 64 m, reached 420 m downwind. Gamma plume is the dominant dose component. Inhalation and gamma deposition reach maximums at a distance of between one and two km.

7.2.1.10. Release category BWR 3

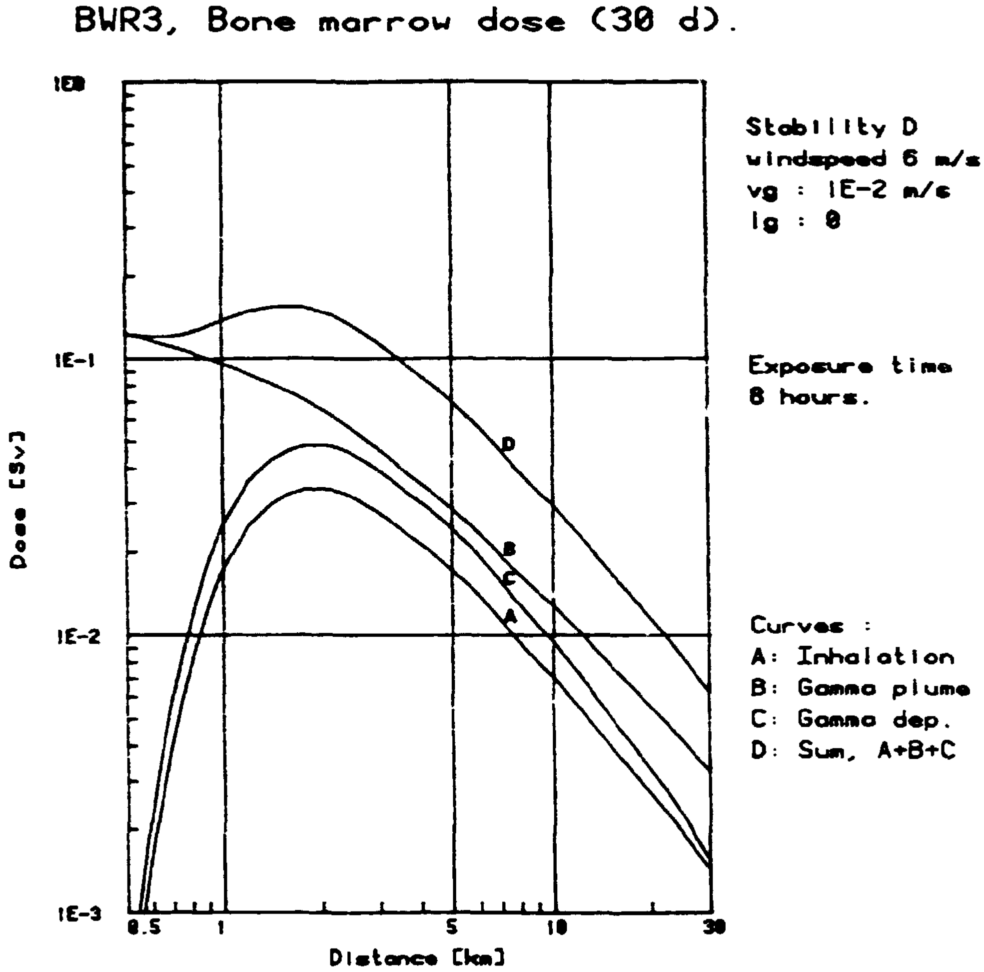


Fig. 7.15. Centre-line doses to the bone marrow as a function of distance in the BWR 3 release category.

In the BWR 3 case the release height is 25 m and the energy release rate from the containment - 5.9 MW - is less than in the other two BWR cases. The calculated effective dispersion height H of 75 m is reached at 360 m downwind. Gamma plume is the dominating dose component. Inhalation and gamma deposition reach a maximum about 2 km downwind.

7.2.2. Doses to specific organs

The impact of doses on specific organs, their relative importance and the method of dose calculation are described in detail in Section 5.3.5.

Release categories PWR 1A, PWR 2, PWR 6 and BWR 2 were selected for detailed investigation. PWR 1A and BWR 2 were chosen because they give the highest doses for the two reactor types. PWR 6 was selected as representing the "minor" PWR cold release with the highest probability of occurrence (6×10^{-6} per reactor year). PWR 2 was chosen for the sake of completeness as this release type was the "work horse" in the parameter study described in Chapter 8.

Individual doses to the following specific organs were calculated:

A: Whole body (integrated over 50 years)
B: Bone marrow (integrated over 30 days)
C: Lungs (integrated over 1 year)
D: Gastro-intestinal tract (integrated over 7 days)
E: Thyroid (integrated over 30 days)

The five specific organ doses obtained in the plume centre-line in the four release categories are shown in Figs. 7.16 - 7.19. The centre-line individual doses are considered the maximum doses for a given distance.

The curves marked B, which show the bone-marrow doses, are the same as the sum-curves marked D in the corresponding Figs. 7.4, 7.8, 7.12 and 7.14.

As the PWR 1A and BWR 2 releases have similar, low energy releases and dispersion heights, their dose patterns, seen in Figs. 7.16 and 7.19, are found to be generally similar.

The somatic effects of doses to specific organs are described in Section 7.5.3.

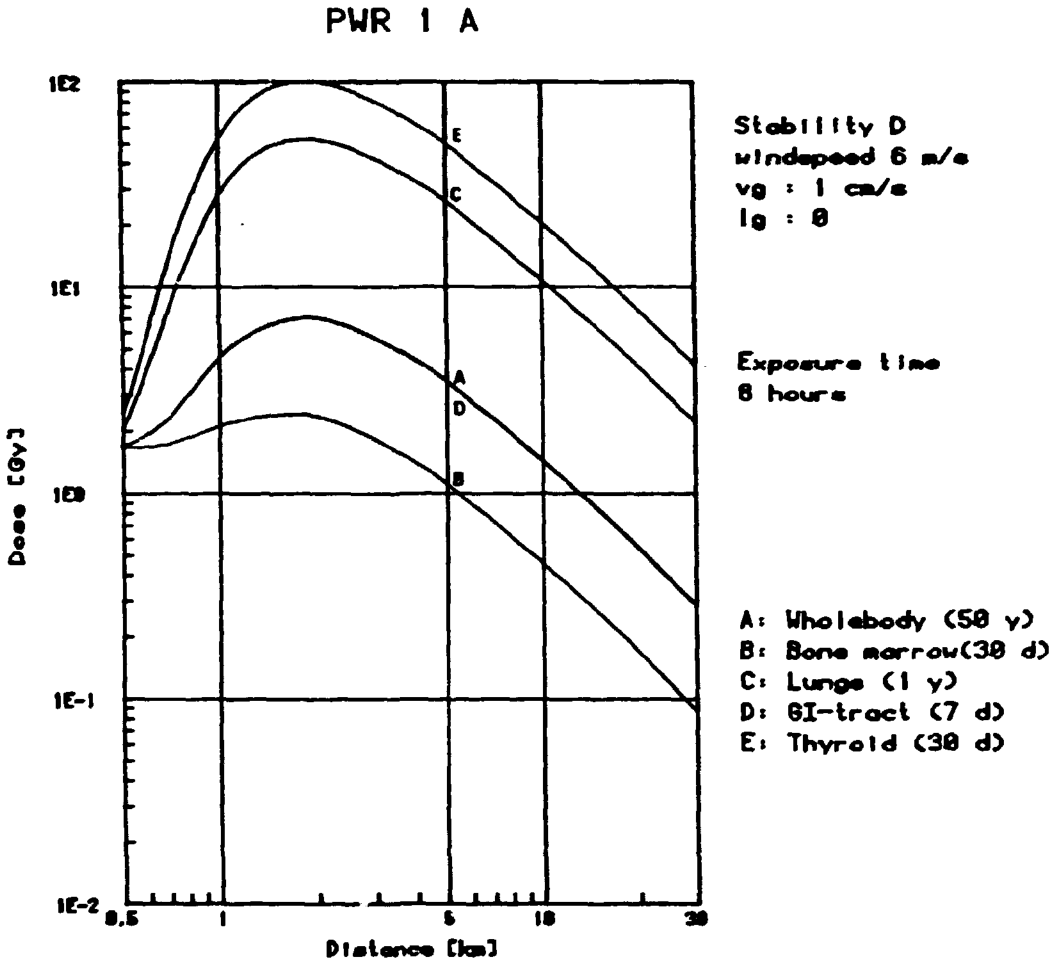


Fig. 7.16. Specific plume centre-line organ doses as a function of distance for the PWR 1A release category.

The cold release leads to maximum inhalation inside the short distance of 2 km, and the very high proportion of iodines and aerosols of ruthenium isotopes in the release (see Fig. 4.1) gives rise to maximum thyroid and lung doses of the order of, respectively, 100 and 40 Gy.

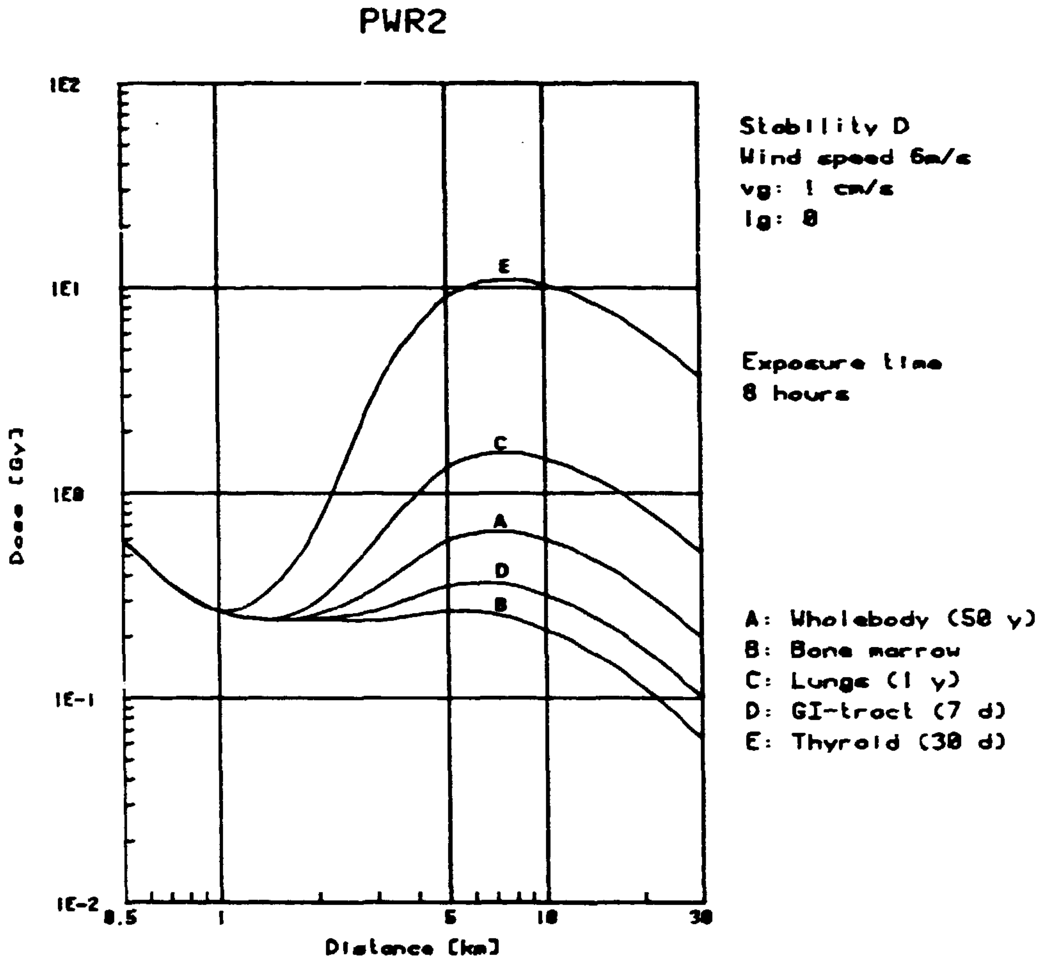


Fig. 7.17. Specific plume centre-line organ doses as a function of distance for the PWR 2 release category.

Maximum organ doses are found at distances of 5-10 km. The maximum levels are:

10-11 Sv to the thyroid, 1.5 Sv to the lungs, 0.4 Sv to the gastro-intestinal tract.

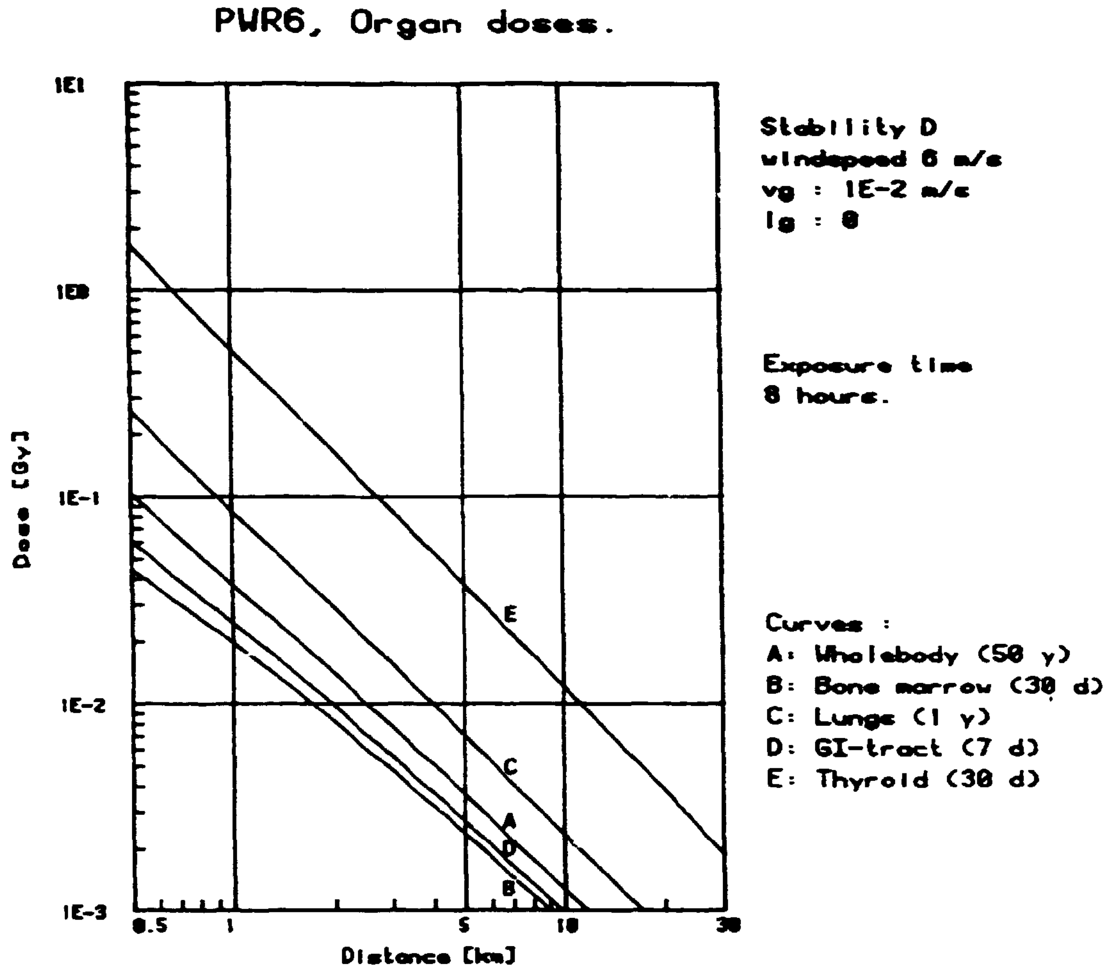


Fig. 7.18. Specific plume centre-line organ doses as a function of distance for the PWR 6 release category.

Note: The ordinate scale differs from that in Figs. 7.16, 7.17 and 7.19.

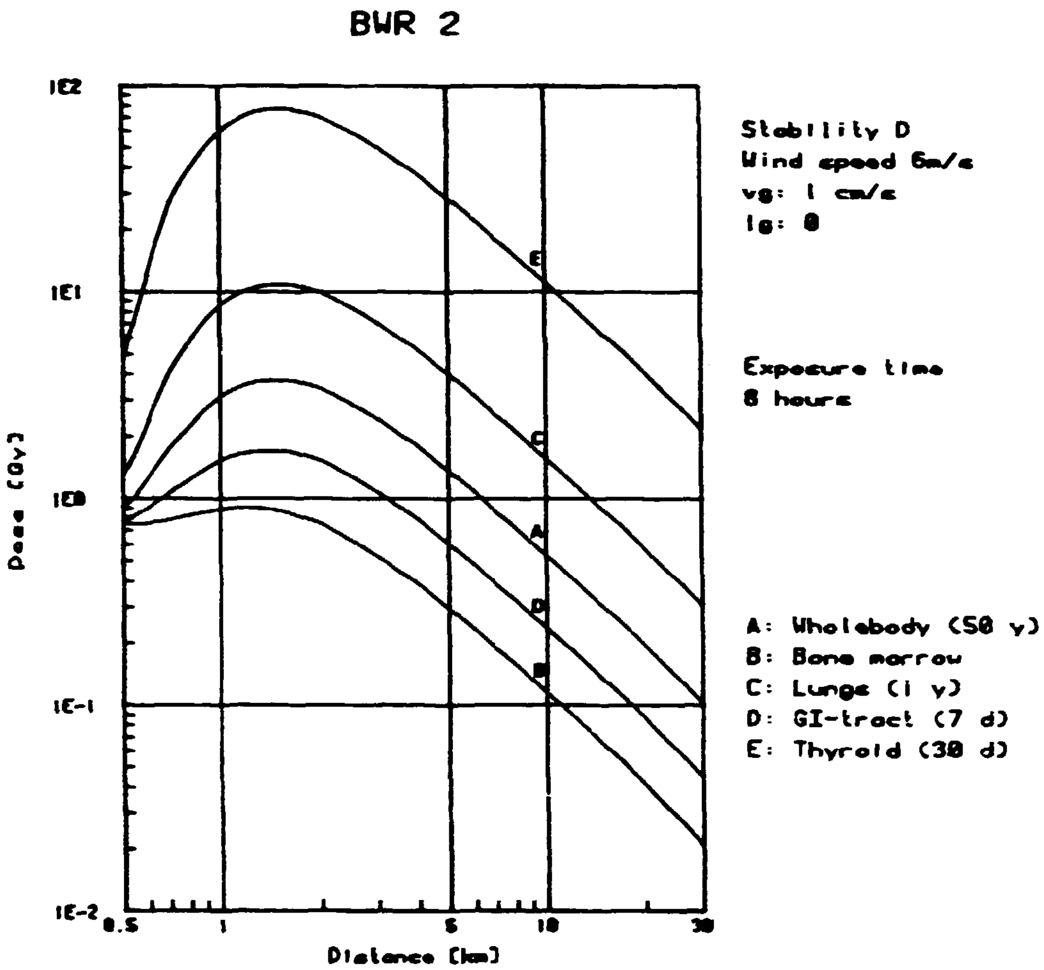


Fig. 7.19. Specific plume centre-line organ doses as a function of distance for the BWR 2 release category.

The lower lung dose, as compared to the PWR 1A doses, results from the relatively smaller fraction of ruthenium isotopes in the BWR 2 release.

7.2.3. Ranges of individual dose levels

For the ten release categories considered here, the PLUCON 2 model was used to calculate the ranges in km from the release point of different dose levels for doses to the bone marrow and for whole-body doses. As described in Section 5.3.5, the bone-marrow dose is the most important contributor to acute effects such as illness and early death. Similarly the whole-body dose is the basis for evaluation of any possible long-term consequences, such as delayed cancer death. The ranges for the two dose types are shown in Figs. 7.20 and 7.21.

Dose level	Sv (rem)	$5 \cdot 10^{-2}$ (5)	0.1 (10)	0.3 (30)	0.5 (50)	1 (100)	2 (200)	3 (300)	4 (400)
Release category		Range from the release point in km							
PWR 1A		>30	27.3	13.3	9.3	5.4	2.6	0	0
PWR 1B		1.1	0.7	0	0	0	0	0	0
PWR 2		>30	21.5	0.86	0.57	0	0	0	0
PWR 3		15.1	9.4	4.5	3.1	1.9	1.1	0.7	0
PWR 4		7.1	4.4	2.0	1.4	0.8	0	0	0
PWR 5		3.3	2.0	0.9	0.6	0	0	0	0
PWR 6		0	0	0	0	0	0	0	0
BWR 1		>30	23.7	0.7	0	0	0	0	0
BWR 2		17.4	10.9	4.9	3.1	0	0	0	0
BWR 3		6.5	3.4	0	0	0	0	0	0

Fig. 7.20. Range in km of eight bone-marrow dose levels for the ten release categories under the atmospheric release conditions: Pasquill stability class D, u = 6 m/s, v_g = 10^{-2} m/s, no rain.

Dose level	Sv (rem)	$5 \cdot 10^{-2}$ (5)	0.1 (10)	0.3 (30)	0.5 (50)	1 (100)	2 (200)	3 (300)	4 (400)	5 (500)
Release category		Range from the release point in km								
PWR 1A		>30	>30	29	21	12.8	7.7	5.6	4.3	3.4
PWR 1B		>30	>30	0	0	0	0	0	0	0
PWR 2		>30	>30	21.6	12.2	0	0	0	0	0
PWR 3		>30	20.5	9.9	7.1	4.5	2.8	2.2	1.8	1.5
PWR 4		13.7	8.7	4.3	3.1	2.0	1.2	0.9	0.8	0.7
PWR 5		6.1	3.9	1.9	1.4	0.8	0.6	0	0	0
PWR 6		0.8	0.5	0	0	0	0	0	0	0
BWR 1		>30	>30	24.3	14.6	0	0	0	0	0.
BWR 2		>30	>30	14.7	10.4	6.2	3.5	2.3	0	0
BWR 3		17.7	10.7	4.4	2.3	0	0	0	0	0

Fig. 7.21. Range in km of nine whole-body dose levels for the ten release categories under the atmospheric release conditions: Pasquill stability class D, u = 6 m/s, $v_g = 10^{-2}$ m/s, no rain.

7.3. Relative importance of radionuclides released

For the release categories considered, a calculation was made in order to evaluate the relative influence on dose of different, selected isotope groups. Five groups were considered: noble gases, iodines, cesium isotopes, strontium isotopes, and the remaining isotopes.

The table, Fig. 7.22, shows the relative bone-marrow dose distribution over the five groups for the release categories considered. The distribution is also shown for the two design-basis

Release category	Noble gases [%]	Iodine [%]	Cesium [%]	Strontium [%]	Others [%]	Total dose [Sv]
PWR 1A	6.0	64	3.1	2.0	25	0.45
PWR 1B	9.3	66	2.1	1.3	21	2.9E-2
PWR 2	7.6	75	4.4	2.8	10	0.21
PWR 3	13	57	4.9	2.7	23	9.2E-2
PWR 4	33	53	2.3	1.6	9.6	3.0E-2
PWR 5	43	47	1.4	0.9	7.7	9.9E-3
PWR 6	86	10	0.6	0.3	3.3	8.5E-4
PWR 9	59	18	13	-	9.8	2.7E-7
BWR 1	8.5	49	3.4	2.2	37	0.24
BWR 2	2.6	68	7.3	6.0	16	0.11
BWR 3	9.8	47	5.6	2.3	35	2.9E-2
BWR 5	91	0.01	-	-	9.2	3.6E-6

Fig. 7.22. The relative contribution to the bone-marrow dose, at 10 km downwind distance, from five isotope groups for all release categories considered.

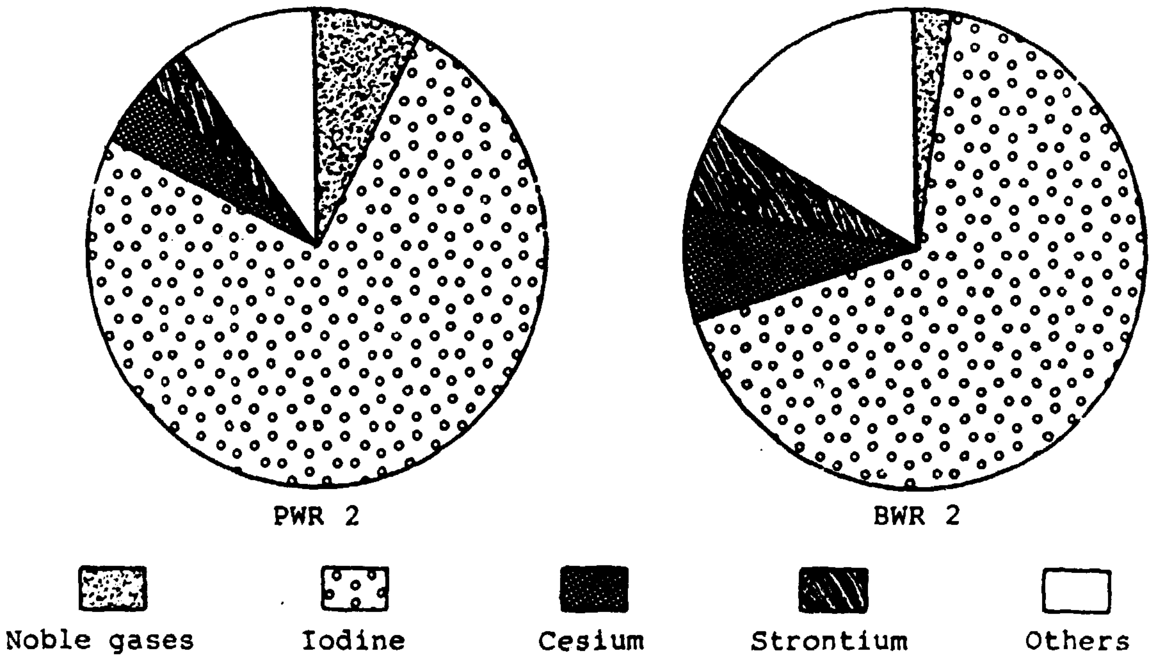


Fig. 7.23. The relative contribution to the bone-marrow dose, at 10 km downwind distance, from five isotope groups for the release categories PWR 2 and BWR 2.

releases PWR 9 and BWR 5 described in chapter 6. The percentages as well as the total doses are given for a distance of 10 km downwind in the plume centre-line.

Figure 7.22 shows that the isotope distribution patterns can be divided into two main groups: the severe core-melt accidents with the corresponding low probabilities (PWR 1A, PWR 1B, PWR 2-5 and the BWR 1-3 cases), and the "China syndrome" PWR 6 accident as well as the two design-basis accidents PWR 9 and BWR 5.

In the latter group the contribution from the noble gases is between 59% and 91%, that from the iodines is low, between 0.01% and 18%, while the group of "other" isotopes contributes between 3.3% and 9.2%. In the PWR 9 release cesium contributes 13% to the very low total collective bone-marrow dose of 2.7×10^{-7} Sv.

In the severe core-melt group, the iodines contribute between 47% to 75% of the total dose. The "other" isotopes contribute between 9.9% and 37%, and noble gases between 2.6% and 43%. The cesium and strontium isotopes are considered low dose contributors of a few per cent each.

Figure 7.23 illustrates the relative contribution to the bone-marrow dose 10 km downwind in the plume centre-line from the five groups in the PWR 2 and BWR 2 release categories.

7.4. Collective doses

Collective doses are calculated in manSievert (manSv). Chapter 2 described the distribution of the resident population in the area. The doses are presented in sectors in a polar coordinate system with centre in the site and with an angle of 22 1/2° between the radii, giving a total of 16 sectors.

The distribution is described in detail in Figs. 2.3 - 2.8. As mentioned in Section 5.3.1.1, only the population out to a distance of 30 km was considered.

Figure 2.3 shows that two people reside in the sector segment in the 45° direction at a distance of between 1.5 and 2 km.

Figure 2.5 shows that three people inhabit Tuskar Rock in the sector segment in the 67.5° direction at a distance of between 10 and 12.5 km. No others reside in these two sectors. Figures 2.7 and 2.8 shows that the next eight sectors towards the sea are uninhabited and that the large majority of people live in just six sectors. Among these, the highest population distribution is found in that which includes the county town of Wexford and whose centre-line points almost exactly in the direction 337.5° (see Section 2.2).

As the collective dose to the few people in sectors 45° and 67.5° can be easily found from the information on individual doses, only the six sectors mentioned above were considered for the calculation of collective doses.

For a given release direction, the program adds each dose contribution found within a sector of 75° at each side of the release direction. The data show that with the Pasquill categories considered in this report, the main dose is delivered within the 22.5° sector in question and that the contributions from adjoining sectors are very small. For the atmospheric situation: stability D, $u = 6$ m/s, $v_g = 10^{-2}$ m/s, $l_g = 0$, and the maximum release (PWR 1A), the collective dose to the bone marrow is found to be 2540 manSv in the 337.5° direction, while the contributions in the adjoining sectors 315° and 360° amount to a total of 2.2 manSv. It can be added that the adjoining sector contribution is mainly found inside a distance of five km from the release point.

The calculation is made for each release category by choosing the release direction on the centre-line of the sector considered.

In order to find the sector in which the highest collective doses are found in the case of a release, calculations were made of the collective doses to the bone-marrow as well as whole-body doses for a PWR 1A release taking place in each of the six directions. The plume centre-line is assumed to cover the centre-line of the sector for each direction.

Release direction	Wholebody dose [manSv]	Bone Marrow dose [manSv]
22.5^{o}	235	80
270^{o}	410	130
292.5^{o}	1240	400
315^{o}	1180	380
337.5^{o}	7990	2540
360^{o}	1240	410

Fig. 7.24. Collective whole-body and bone-marrow doses calculated for a PWR 1A release in each of the six release directions considered out to a distance of 30 km.

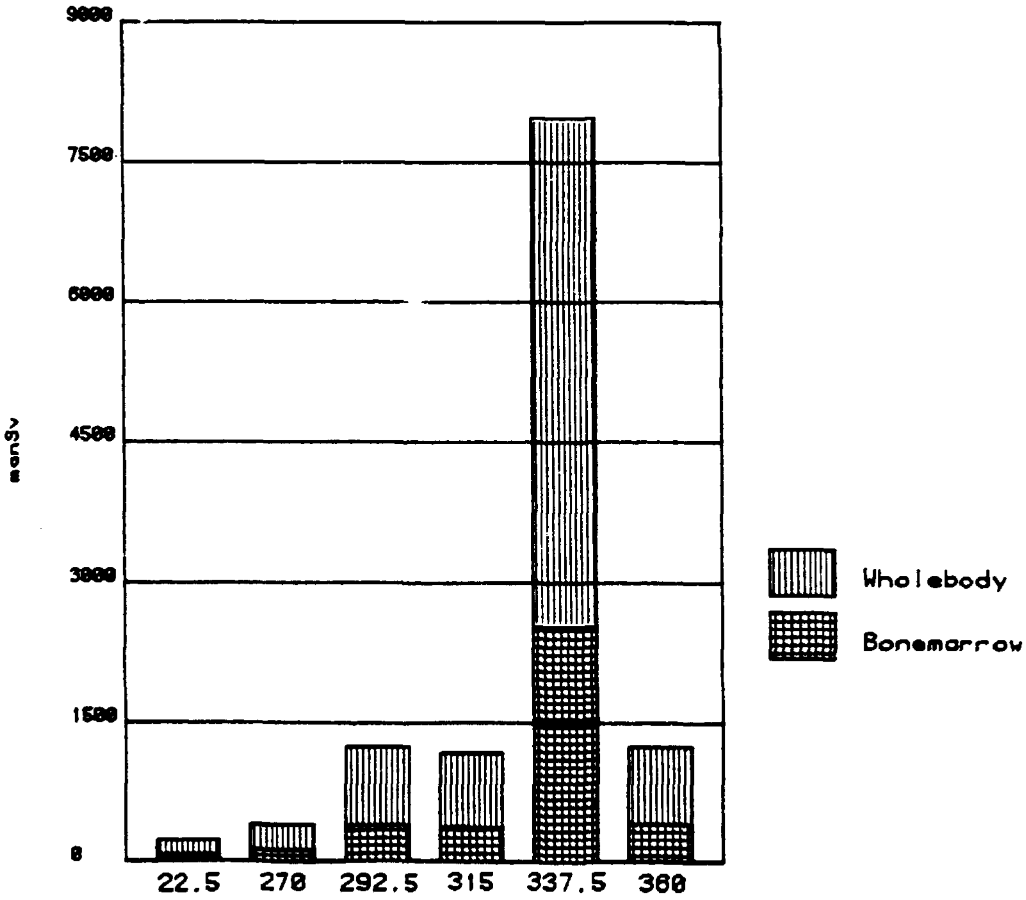


Fig. 7.25. Collective whole-body and bone-marrow doses for the PWR 1A release in six release directions out to a distance of 30 km.

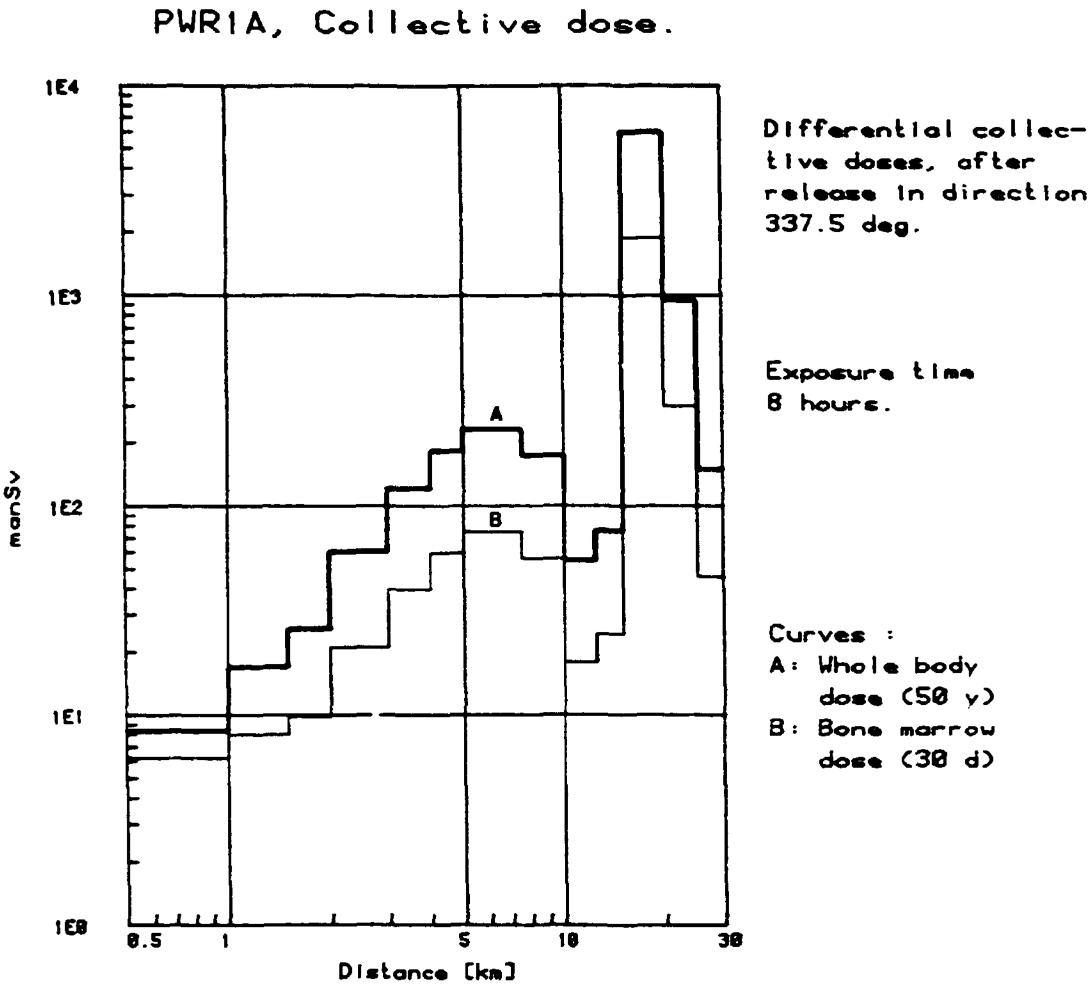


Fig. 7.26. Collective whole-body doses and bone--marrow doses for the PWR 1A release as a function of distance. The steps show the dose contribution within each sector segment.

Figure 7.24 shows the collective doses to the bone marrow and the whole-body doses for a PWR 1A release in each of the six 22.5° sectors considered. The doses are presented in a histogram in Fig. 7.25.

The distribution of the collective dose in the 337.5° release direction as a function of distance is shown in Fig. 7.26. As to be expected, the essential contribution is found at the distance at which Wexford lies.

At stated in Section 5.3.1.1 it should, however, be borne in mind that the dose model is able to predict the doses to within a factor 2-3 inside the chosen distance of 30 km.

Bone marrow dose

Release type	0-5 km [manSv]	5-10 km [manSv]	10-20 km [manSv]	20-30 km [manSv]	Total [manSv]
PWR 1 A	145	131	1920	341	2540
PWR 1 B	4	5	432	97	538
PWR 2	28	46	1230	230	1530
PWR 3	67	41	435	80	623
PWR 4	28	17	153	29	228
PWR 5	10	6	52	10	78
PWR 6	1	1	5	1	8
BWR 1	28	51	1390	261	1730
BWR 2	71	62	585	112	830
BWR 3	15	15	162	32	224

Whole body dose

Release type	0-5 km [manSv]	5-10 km [manSv]	10-20 km [manSv]	20-30 km [manSv]	Total [manSv]
PWR 1 A	416	403	6080	1090	7990
PWR 1 B	4	7	1180	282	1470
PWR 2	46	116	3610	687	4460
PWR 3	231	132	1380	255	2000
PWR 4	86	46	403	77	613
PWR 5	28	15	122	24	189
PWR 6	2	1	7	1	11
BWR 1	51	135	4190	798	5180
BWR 2	306	283	2750	534	3870
BWR 3	54	58	598	117	827

Fig. 7.27. Collective bone-marrow and whole-body doses in the 337.5° release direction for the ten release categories considered. The contribution inside four distance intervals and the total dose are shown.

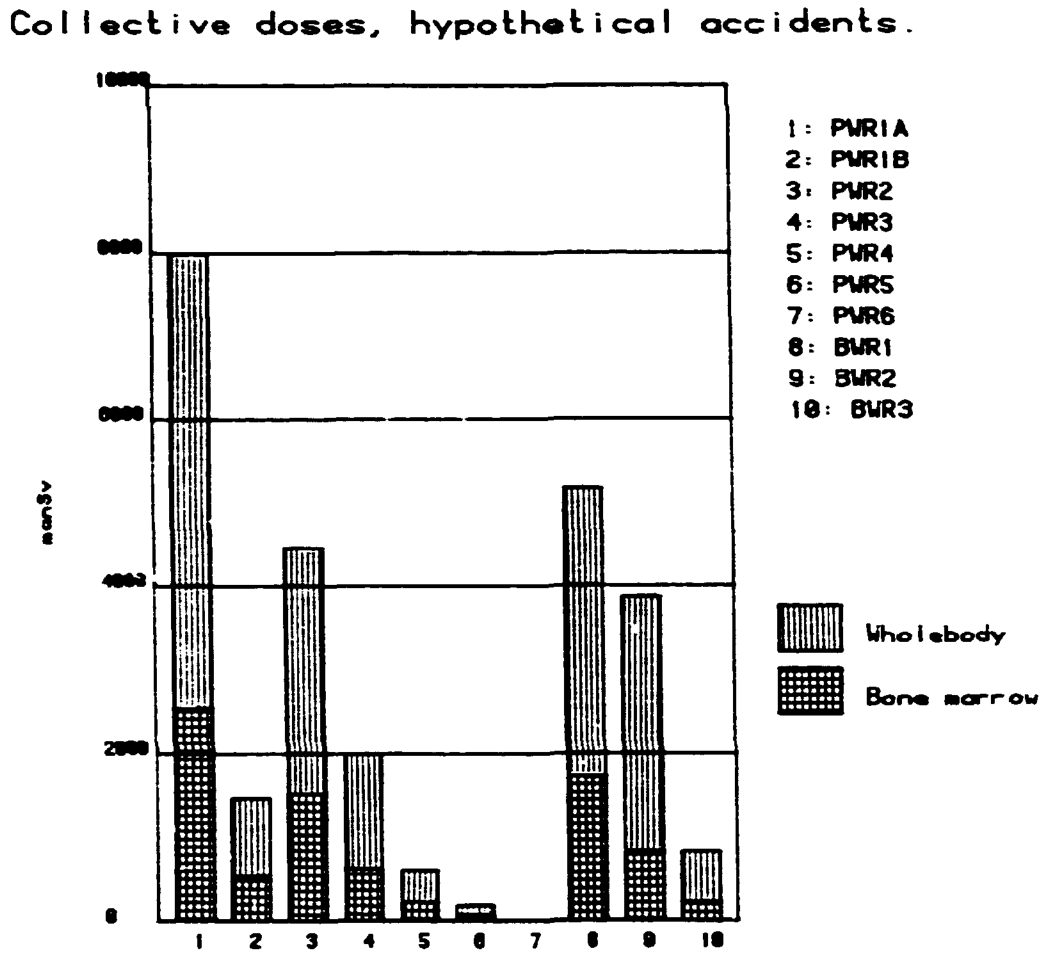


Fig. 7.28. Collective bone-marrow and whole-body doses in the 337.5° release direction for the release categories considered.

Figure 7.27 shows the collective bone-marrow and whole-body doses for all release categories considered for the 337.5° release direction. For each release category the contribution is shown for four distance intervals as well as the total collective dose calculated from the release point out to the 30 km limit. Figure 7.28 shows the two collective dose types in a histogram for comparison.

As the 337.5° direction represents the crucial sector, and as calculations of collective doses consume much computer time, only doses for the 337.5° direction were calculated for the other release categories considered.

7.5. Health effects

The health effects that might be associated with a reactor accident can be divided into three categories:

1) Early somatic effects (nonstochastic effects)
2) Late somatic effects (stochastic effects)
3) Genetic effects.

Early and continuing somatic effects include the early mortalities (and morbidities) usually observed after large acute doses of radiation, and which can occur within days to weeks after exposure. They also include illnesses and deaths manifested within a year or so. In general early somatic effects are associated primarily with individual doses of over 1 Sv - and thus would be limited to persons in the immediate vicinity of the reactor site. *The early somatic effects are estimated on the basis of the* magnitude of individual exposure. Late somatic effects include latent cancer fatalities and are typically expected to be observed after a latency of 2 to 30 years after exposure. Finally, there are the genetic effects which do not manifest themselves in the individuals exposed but rather in their descendants.

In contrast to early somatic effects, both latent cancer and genetic diseases are random phenomena, where the probability of occurrence is some function of the magnitude of the cause, i.e. in the case of radiation the magnitude of exposure. It must also be borne in mind that these effects can be initiated by a large variety of causes other than radiation. Since no clinical distinction can be made between a cancer, or genetic disease, that is induced by radiation and one that occurs spontaneously, the late somatic and genetic effects originating from a major release of radioactive material would manifest themselves as an increase in the normal incidence of the effect in question in the exposed population.

Latent cancers as well as genetic diseases are calculated on the basis of collective doses rather than individual doses. By the use of the so-called linearity principle even small contributions to the collective dose are taken into account. However, some people consider use of the linearity principle (extrapolating the rather well known risk at high doses and high dose rates to areas of smaller doses and dose rates and even to zero) for estimating late cancer risks to be "an alarmist approach" leading to much exaggerated pictures of the radiation risk.

7.5.1. Early somatic effects

In the event of a serious reactor accident, it is generally expected that all possible resources will be mobilized within the country concerned as well as in neighbouring countries. A very high level of treatment can therefore be expected to be available to seriously injured individuals. The WASH-1400 report considers three levels of treatment: minimal, supportive and heroic.

The relation between dose to the bone marrow and early mortality depends on the level of treatment of the exposed individuals. Figure 7.29 shows the relations applied in the WASH-1400 report for supportive and minimal treatment. It also shows the relation applied in the German Risk Study (Birkhofer et al., 1979).

The dose/mortality criteria used in the investigation of release categories treated here correspond to the three levels in WASH-1400. It appears that for heroic, and even for supportive treatment, no early fatalities can be expected in any of the ten hypothetical releases.

The number of individuals receiving bone-marrow doses at certain levels as well as the resulting collective doses were calculated by the PLUCON2 program using data for distribution of the resident population and for the downwind dose pattern. The calculations were used to find the resulting cases of early mortality by applying the appropriate probabilities to different levels of bone-marrow dose.

The probabilities applied are those used in WASH-1400 for early mortalities assuming minimal treatment of the individuals exposed.

All calculations are made for the atmospheric condition: Pasquill stability category D, $u = 6$ m/s, $v_g = 10^{-2}$ m/s, $l_g = 0$ (no rain).

Early somatic effects associated with individual doses of more than 1 Sv would thus be limited to individuals inside a distance of 5.4 km from the release site according to Fig. 7.20.

For the "cold" PWR 1A release category which has been shown to give rise to the largest doses, the calculation was made for releases along the centre-line of the directions 22.5°, 292.5°, 315°, 337,5°, and 360° for the population within 7.5 km from Carnsore Point. The doses received in all other directions are of no influence.

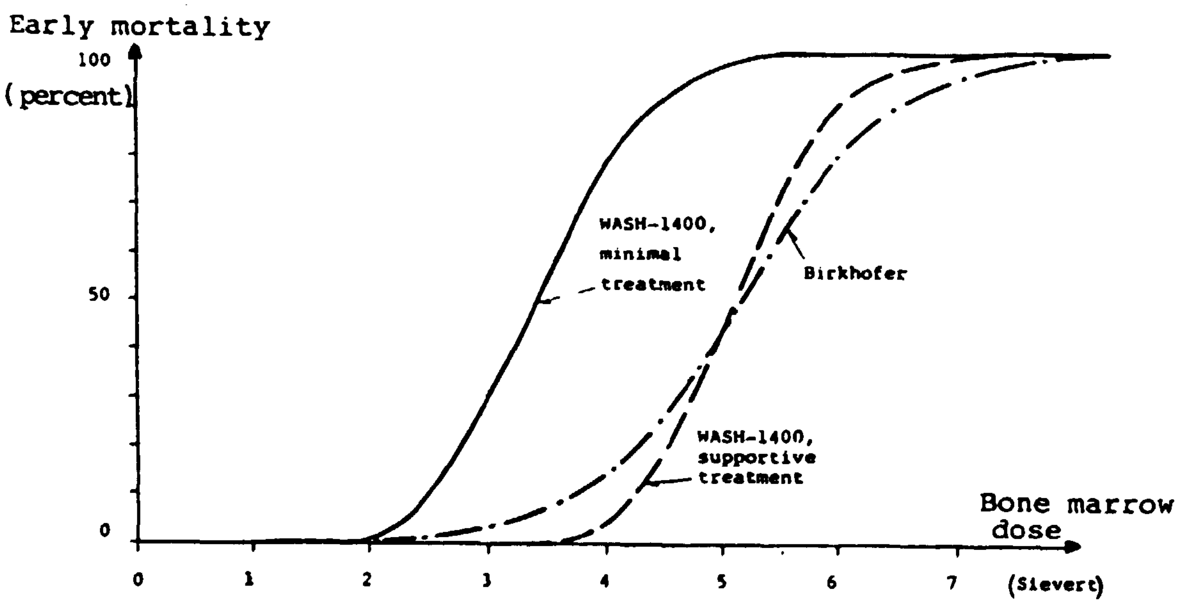


Fig. 7.29. Relations between bone-marrow dose and early mortality as assumed in the WASH-1400 report (for minimal treatment and supportive treatment) and in the German Risk Study (the Birkhofer report).

The collective dose is calculated by combining the population distribution described in chapter 2 with the dose pattern obtained from the Gaussian plume-dose model. The population density inside each of the squares shown in chapter 2 is assumed to be uniform. A calculation is made of the estimated number of persons receiving a dose greater than a defined level. This number is not necessarily an integer, and tenths of persons as well as tenths of cases appear in the following.

7.5.1.1. Release category PWR 1A. In each of the five release directions mentioned above, the total collective dose up to a distance of 7.5 km is calculated. Contributions from doses less than 1 Sv are included in the figures. Figure 7.30 shows the calculated number of individuals receiving a dose of more than 1 Sv and their corresponding exposure.

The cases of early mortality are assumed to follow a Poisson distribution with mean values of 0.1 and 0.2, respectively. This gives the probabilities shown in Fig. 7.31.

Release category	Release direction	Total collective dose 0-7.5 km manSv	Exposure above 1 Sv		
			Number of persons	Collective dose manSv	Calculated cases of early mortality
PWR 1 A	22.5°	65.4	20.0	33.4	0.2
	292.5°	56.1	13.9	20.6	-
	315°	70.5	11.1	15.8	-
	337.5°	220.0	72.3	95.8	0.1
	360°	226.4	74.6	108.7	0.2

Fig. 7.30. A summary of the total collective bone-marrow dose up to a distance of 7.5 km from Carnsore Point, the number of persons subjected to exposure of more than 1 Sv, their collective dose, and the resulting calculated number of cases of early mortality assuming minimal treatment to those exposed. The calculation was made under the assumption that a PWR 1A release takes place in each of five directions.

Release direction	No case of early mortality	1 case of early mortality	2 cases of early mortality
22.5°	82%	16%	2%
337.5°	91%	9%	-
360°	82%	16%	2%

Fig. 7.31. Probabilities of 0, 1 or 2 cases of early mortality. Calculations were made assuming that a PWR 1A release takes place in each of the three directions, with most people found inside a distance of less than 5.4 km from Carnsore Point.

Figure 7.31 shows that the highest calculated probability of one or more cases of early mortality is 18% for a PWR 1A release in the direction 22.5° or 360°.

This is twice as much as the 9% calculated for the 337.5° direction because in the sector segment from 1.5 to 2 km the population numbers 16 persons in the 22.5° direction and 14 in the 360° direction, compared with 4 in the 337.5° direction. Figure 7.6 shows that the range for the 2 Sv level is from 0.9 to 2.6 km, and the maximum width is at a distance of 2.0 km.

7.5.1.2. Other release categories. Figure 7.20 shows that the only release categories giving doses greater than 1 Sv are PWR 1A, PWR 3 and PWR 4. Similar calculations were carried out assuming release categories PWR 3 and 4 and release directions 337.5° and 360°: the results are shown in Fig. 7.32.

Release category	Release direction	Distance considered	Total number of persons	Total collective dose manSv	Calculated cases of early mortality
PWR 1A	337.5°	7.5 km	437	220.0	0.1
PWR 1A	360°	7.5 km	438	226.4	0.2
PWR 3	337.5°	2 km	18	21.6	0.4
PWR 3	360°	2 km	29	20.1	0.4
PWR 4	337.5°	1 km	7	4.2	-
PWR 4	360°	1 km	7	3.0	-

Fig. 7.32. A summary of the total number of individuals and their collective bone-marrow dose up to a distance from the release point of 7.5 km for PWR 1A, 2 km for PWR 3 and 1 km for PWR 4, and the resulting calculated cases of early mortality assuming minimal treatment to those exposed. Calculations were made assuming that the plumes in the three hypothetical release categories travelled in the release direction 337.5° or 360°.

Figure 7.20 shows that the ranges from the release point for the 1 Sv level are 5.4, 1.9 and 0.8 km for the three release categories PWR 1A, PWR 3, and PWR 4; thus calculations can be limited to the sector segment including these distances. The figure also shows that the PWR 3 release is the only one giving doses above 2 Sv. The result of the high PWR 3 dose level is seen in Fig. 7.32. This release gives the highest calculated number of cases of early mortality: 0.4.

0.4 cases of early mortality imply:

67%	probability of no cases of early mortality					
27%	-	-	1 case	-	-	-
5%	-	-	2 cases	-	-	-
1%	-	-	3 cases	-	-	-

The probability of occurrence of a PWR 3 release is 4×10^{-6} per reactor year (Fig. 7.1). The probability of occurrence of the atmospheric condition under consideration (Pasquill D, u = 6 m/s, $v_g = 10^{-2}$ m/s, no rain) in the 337.5° or 360° direction can be found from Fig. 3.8 to be 0.08 per year.

The probability of a PWR 3 release in the 337.5° or 360° direction under these meteorological conditions is hence of the order of

$$4 \times 10^{-6} \times 8 \times 10^{-2} = 3.2 \times 10^{-7} \text{ per reactor year.}$$

The above calculations take no account of evacuation. The total population living at a distance of less than 2 km from Carnsore Point numbers 82 people and there is 2 hours warning time for a PWR 3 release. Two hours is ample time to evacuate the whole of this population. If evacuation is successful the probability of no cases of early mortality increases from 67% to 100%.

7.5.2. Late somatic effects

Recently three large international evaluation groups have published their findings on the late somatic (development of cancers) and genetic effects of ionizing radiation.

The estimates of cancer mortality risk per 10^4 Sv are given by these groups as follows: BEIR (1972): 180, BEIR (1980): 130, ICRP (1977): 100, and UNSCEAR (1977): 120.

These estimates are, however, based on models that certainly lead to overestimation of the cancer risk. The models are suitable for establishing a likely upper limit to the risk, and therefore for establishing so-called "acceptable" or "safe" dose limits i.e. limits assuring that the risk from radiation for the individual is no greater than the risks associated with other activities having good safety records.

Gjørup has pointed out that the real risk could be much less than the risk assumed by the setting of "safe" dose limits (Gjørup, 1980). The interval of uncertainty covers some decades and for small doses and dose rates the possibility that the risk is zero cannot be excluded. For doses less than 1 Sv and dose rates less than 10^{-3} Sv/min, it seems reasonable to estimate the cancer risk to be between 2 and 200 late cancer deaths per 10^4 Sv. As the most probable median value, it seems reasonable to use the logarithmic mean value of 20 cases. The uncertainty could be set at a factor of ten in both directions.

WASH-1400 uses three different values for expected latent cancer deaths per 10^4 Sv: 135 for total dose more than 0.25 Sv, 54 for between 0.10 and 0.25 Sv, and 27 for less than 0.10 Sv.

Two risk values are used in the calculation of late somatic effects in the ten release categories investigated here.

A: A risk of 125 per 10^4 Sv (1 case per 80 Sv) as an average of the two values given by BEIR 1980 and UNSCEAR.

B: A risk of 20 per 10^4 Sv (1 case per 500 Sv) as proposed by Gjørup for dose levels less than 1 Sv and dose rates less than 10^{-3} Sv/min. For higher levels, the value in A is used: 125 per 10^4 Sv.

As described in section 5.3.5, the 50-year committed whole-body dose is used for the assessment of late somatic effects. The whole-body dose is calculated as the external gamma dose from the cloud plus the external gamma dose from deposited activity integrated over 8 hours, plus the 50-year committed whole-body dose equivalent from inhalation of activity during cloud passage.

For the atmospheric conditions Pasquill D, u = 6 m/s, $v_g = 10^{-2}$ m/s, no rain, it is assumed that a reactor accident takes place resulting in one of the ten release categories, and that the plume passes along one of the selected release directions over land.

Figure 7.33 shows the collective doses calculated for the release categories considered in the given release directions. In the calculation the collective dose contribution is split into four distance intervals, thus giving the possibility of calculating the number of latent fatalities within each interval as well as the total number of cases up to a distance of 30 km. Assumed risk factor: A = 125 per 10^4 Sv.

The PWR 1A release gives rise to the highest latent cancer fatality figure of 99.8 in the 337.5° direction with the highest contribution of 76.0 in the 10-20 km interval. Obviously the PWR 1A release is the most serious. Assuming risk value A the severity ranking is:

PWR 1A	99.8
BWR 1	64.7
PWR 2	55.9
BWR 2	48.4
PWR 3	25.0
PWR 1B	18.3
BWR 3	10.4
PWR 4	7.7
PWR 5	2.4
PWR 6	0.1

Latent cancer fatalities are random phenomena whose probability of occurrence for an individual is a function of the dose received. There is no direct relationship between being subjected to irradiation and incurring cancer many years later. As no clinical distinction can be made between a cancer induced by radiation and one that occurs spontaneously, the late somatic effects originating from a major release of radioactive material would manifest themselves as an increase in the normal incidence of cancer for the population exposed.

Distance intervals		0-5	5-10	10-20	20-30	Total 0-30
Release category	Release direction	Collective whole-body doses, man Sv. Corresponding latent cancer fatalities.				
PWR 1A	22.5°	124	111	0	0	235
		1.6	1.4	0	0	3.0
	270°	1.1	0.1	379	30	410
		0.01	0	4.7	0.4	5.1
	290.5°	76	154	711	302	1243
		1.0	1.9	8.9	3.8	15.6
	315°	66	277	479	355	1177
		0.8	3.5	6.0	4.4	14.7
	337.5°	416	403	6080	1086	7985
		5.2	5.0	76.0	13.6	99.8
	360°	434	600	49	158	1241
		5.4	7.5	0.6	2.0	15.5
PWR 1B	337.5°	3.6	6.8	1177	282	1469
		0.05	0.09	14.7	3.5	18.3
PWR 2		46	116	3613	687	4462
		0.6	1.5	45.2	8.6	55.9
PWR 3		231	132	1382	255	2000
		2.9	1.7	17.3	3.2	25.0
PWR 4		87	46	403	77	613
		1.1	0.6	5.0	1.0	7.7
PWR 5		28	15	122	24	189
		0.4	0.2	1.5	0.3	2.4
PWR 6		1.8	1.1	6.9	1.5	11.3
		0.02	0.01	0.09	0.02	0.1
BWR 1		51	135	4191	798	5175
		0.6	1.7	52.4	10.0	64.7
BWR 2		305	283	2749	534	3871
		3.8	3.5	34.4	6.7	48.4
BWR 3		54	58	598	117	827
		0.7	0.7	7.5	1.5	10.4

Fig. 7.33. Collective whole-body doses and calculated corresponding latent cancer fatalities for the release categories considered in the different release directions. Assumed atmospheric conditions: Pasquill D, u = 6 m/s, $v_g = 10^{-2}$ m/s, $l_g = 0$ (no rain). Assumed risk value A = 125 per 10^4 Sv.

Assuming a release direction of 337.5^{o} towards Wexford, Fig. 7.34 shows the total number of persons exposed (see Fig. 7.32) for each of the hypothetical release categories considered in this section. The corresponding total collective whole-body dose and the calculated maximum number of latent cancer fatalities assuming risk value A (see Fig. 7.33) are also shown. The corresponding maximum death rate per 1000 persons ranges from 4.5 in the case of release category PWR 1A to 0.04 in the PWR 6 case.

Release category	Total number of persons exposed	Total collective whole-body dose (manSv)	Calculated number of latent cancer fatalities	Rate per 1000 persons	"Normal" cancers
PWR 1A	22000	7984	99.8	4.5	Wexford town
PWR 1B	21750	1469	18.3	0.84	(1975)
PWR 2	22100	4463	55.9	2.53	78.6
PWR 3	24200	2000	25.0	1.04	
PWR 4	25500	613	7.7	0.3	Wexford county
PWR 5	25800	189	2.4	0.09	(1975)
PWR 6	26800	11.3	0.1	0.04	51.0
BWR 1	21100	5175	64.7	3.07	
BWR 2	26000	3871	48.4	1.86	Irish republic
BWR 3	25500	827	10.4	0.41	(1975) 59.0

Fig. 7.34. Calculated number of latent cancer fatalities assuming that the plumes in the different hypothetical release categories all travel in the same release direction, 337.5^{o}, towards Wexford. Three examples of the natural cancer death rate over 30 years are shown for comparison.

As mentioned earlier, the increase in the cancer death rate resulting from exposure in the case of an accidental release of activity would manifest itself over a span of maybe 30 years.

For comparison, it must be pointed out that in a population as considered here the "normal" incidence of cancer must be expected to be of the order of 1500-1800 fatalities over 30 years. Figure 7.34 shows the "normal" cancer death rate per 1000 persons over 30 years of age for Wexford town, Wexford county and the Irish Republic based on figures for the year 1975 (Report of Vital Statistics, 1975).

Release category in direction 337.5°	Risk value B					Risk value A
	Levels above 1 Sv and 1 E-3 Sv/min		Levels below 1 Sv and 1 E-3 Sv/min		Total number of latent cancer fatalities	Total number of latent cancer fatalities (from Fig. 7.33)
	Collective dose manSv	Number of latent cancer fatalities	Collective dose manSv	Number of latent cancer fatalities		
PWR 1A	7984	100	-	-	100	99.8
PWR 1B	1469	18.3	-	-	18.3	18.3
PWR 2	4463	56	-	-	56	55.9
PWR 3	230	2.9	1770	3.6	6.5	25.0
PWR 4	87	1.1	525	1.1	2.2	7.7
PWR 5	3	0.03	186	0.4	0.4	2.4
PWR 6	none	none	11	0.02	0.02	0.1
BWR 1	5175	64.7	-	-	64.7	64.7
BWR 2	305	3.8	3566	7.1	10.9	48.4
BWR 3	none	none	827	1.7	1.7	10 4

Fig. 7.35. Collective whole-body doses and calculated maximum figures for latent cancer fatalities assuming releases in the 337.5° direction. For risk value B, the numbers are given for levels above 1 Sv and 1 E-3 Sv/min and levels equal to these or below them. The figures for risk value A are shown for comparison (Fig. 7.33).

Application of risk value B is complicated by the two limitations:

1. The doses must be below 1 Sv, and
2. The dose rate level must be less than 1 E-3 Sv/min.

The collective doses at the required dose levels are easily given by means of the computer calculations. The limitation on dose rate is judged by means of the individual gamma plume doses calculated for each release category for the centre-line of the release (the curves marked B: gamma plume in Figs. 7.4 and 7.7-7.15) in connection with the duration of the releases (Fig. 4.2). This use of the centre-line doses adds, however, to the pessimism in the calculation of the number of latent cancer fatalities assuming risk value B. The doses, and hence the dose rates, fall drastically with increasing distance from the plume centre-line. Figure 7.35 shows the results of the calculations for the 337.5° release direction (towards Wexford). For the ten release categories considered, the number of latent cancer fatalities found for risk value A is repeated from Fig. 7.33 in the last column. For PWR 1A, PWR 1B, PWR 2 and BWR 1, the calculations are limited to risk value A as the releases are of short duration and hence the dose rates are greater than 1 E-3 Sv/min. No individual doses are above 1 Sv in the PWR 6 and BWR 3 release categories.

The probability that a particular release category will lead to a release in the 337.5° direction towards Wexford can be indicated by multiplying the meteorological probability of the weather in question occurring in this direction by the probability of occurrence of the release in question.

Figure 7.36 gives these probabilities for the release categories considered in this section.

With reference to the remarks in section 4 on recent experience, it should be pointed out that the probability of the release categories including a steam explosion in the reactor vessel that might cause containment failure (PWR 1A, PWR 1B and BWR 1) may now be considered to be reduced by two orders of magnitude.

Release category	Probability per reactor year
PWR 1A	1.6×10^{-8}
PWR 1B	2.0×10^{-8}
PWR 2	3.2×10^{-7}
PWR 3	1.6×10^{-7}
PWR 4	2.0×10^{-8}
PWR 5	2.8×10^{-8}
PWR 6	2.4×10^{-7}
PWR 9	1.6×10^{-5}
BWR 1	4.0×10^{-8}
BWR 2	2.4×10^{-7}
BWR 3	8.0×10^{-7}
BWR 5	4.0×10^{-6}

Fig. 7.36. Probabilities of the atmospheric conditions under consideration (stability D, wind speed 6 m/s, v_g = 0.01 m/s, no rain) being in the direction of Wexford (0.04 per year) coincident with the probabilities of occurrence per reactor year of the release categories concerned, taken from WASH-1400 (cf. Fig. 4.1 or Fig. 7.1).

Moreover, melt-through of the concrete base mat is unlikely, and this excludes PWR 6.

Core-melt cases with delayed containment failure are also considered to have much smaller consequences because of the reduction by two to three orders of magnitude of the concentration of radioactive material in the containment. PWR 2, PWR 3 and BWR 2 are the relevant release categories here.

Hence the most serious release category which, with reason, should be taken into account is probably PWR 4 considering that categories 1,2 and 3 are likely to have a much lower probability of occurrence than earlier assumed (WASH-1400).

The probability of a PWR 4 release occurring in the direction of Wexford is 0.04 x 5 E-7 = 2 E-8 per reactor year.

7.5.3. Early somatic effects of doses to specific organs

A few organs are specifically sensitive to the dose originating from the inhalation of certain radioactive elements. Inhaled radioactive materials are generally deposited in the lungs, and after their removal from here they pass through the gastro-intestinal tract. Some isotopes are deposited in specific ways, i.e. iodine isotopes in the thyroid gland.

For the PWR 1A, PWR 2, PWR 6 and BWR 2 release categories calculations were made of plume centre-line organ doses to the lungs, gastro-intestinal tract and thyroid gland. The detailed calculation is described in section 5.3.5.

The centre-line organ doses as a function of distance are shown in Figs. 7.16 - 7.19 for the four release categories together with bone-marrow and whole-body doses.

7.5.3.1. Doses to the lungs. The probability of mortality resulting from a lung dose is always substantially lower than that from the associated bone-marrow dose.

The same dose-response curve as appears in WASH 1400 is used here (the criterion curve in Fig. VI 9-3) showing probabilities of mortality within 365 days of

40 Gy - 0.01
50 Gy - 0.02.

Figure 7.16 shows that, for the PWR 1A release category, a lung--dose level between 40 and 50 Gy occurs in the distance rance 1.5 to 3 km. A level above 30 Gy occurs out to a distance of 4 km.

Assuming a release in the 337.5^{o} direction, about 5 people would be exposed to doses of between 40 and 50 Gy. This means an expected 5 x 0.02 = 0.1 cases of early mortality.

In the dose range between 30 and 40 Gy, the number of people exposed is estimated to be about 50. Applying the 40 Gy risk of 0.01, this leads to 50 x 0.01 = 0.5 cases of early mortality.

Figures 7.17 - 7.19 show that, in each of the other release categories, the highest lung dose occurs in the BWR 2 release of approx. 10 Gy that leads to no acute cases of mortality.

7.5.3.2. Doses to the gastro-intestinal tract. Applying the criterion used in WASH-1400 (Fig. VI 9-4) with a zero risk threshold at 20 Gy, Figs. 7.16 - 7.19 show that there will be no cases of mortality resulting from irradiation of the gastro-intestinal tract.

7.5.3.3. Doses to the thyroid. In WASH-1400, App. VI, it is indicated that acute thyroid effects are not found below 250 Gy and furthermore, that "anyone who receives less than a lethal dose to the bone marrow would receive less than 250 Gy to the thyroid".

Figures 7.16 - 7.19 show that the maximum thyroid doses are 100 Gy for the PWR 1A release, and 70 Gy for the BWR 2. No acute thyroid effects are therefore to be expected in any of the release categories under consideration.

7.5.3.4. Genetic effects. There seems reasonable agreement between the latest reports on the genetic risks of radiation. The same international committees that considered cancer risks also evaluated genetic risks.

In ICRP publication 27 the harm to man attributable to the genetic effects of radiation is stated to be 10^{-2} Sv^{-1} of serious genetic ill-health during the first two generations. Equal harm is expected in all following generations. It is considered as the harm to a population of fertile individuals irradiated prior to conception of their offspring. This fraction of the total population is considered generally to be 0.4, implying a genetic risk value of 4×10^{-3} Sv^{-1} (to the first two generations), where the dose is understood as a collective whole-body dose.

Very generally expressed, the number of cases of genetic harm in the first two generations after a reactor accident could be said to be approximately one-third the number of latent cancer fatalities shown in Fig. 7.35.

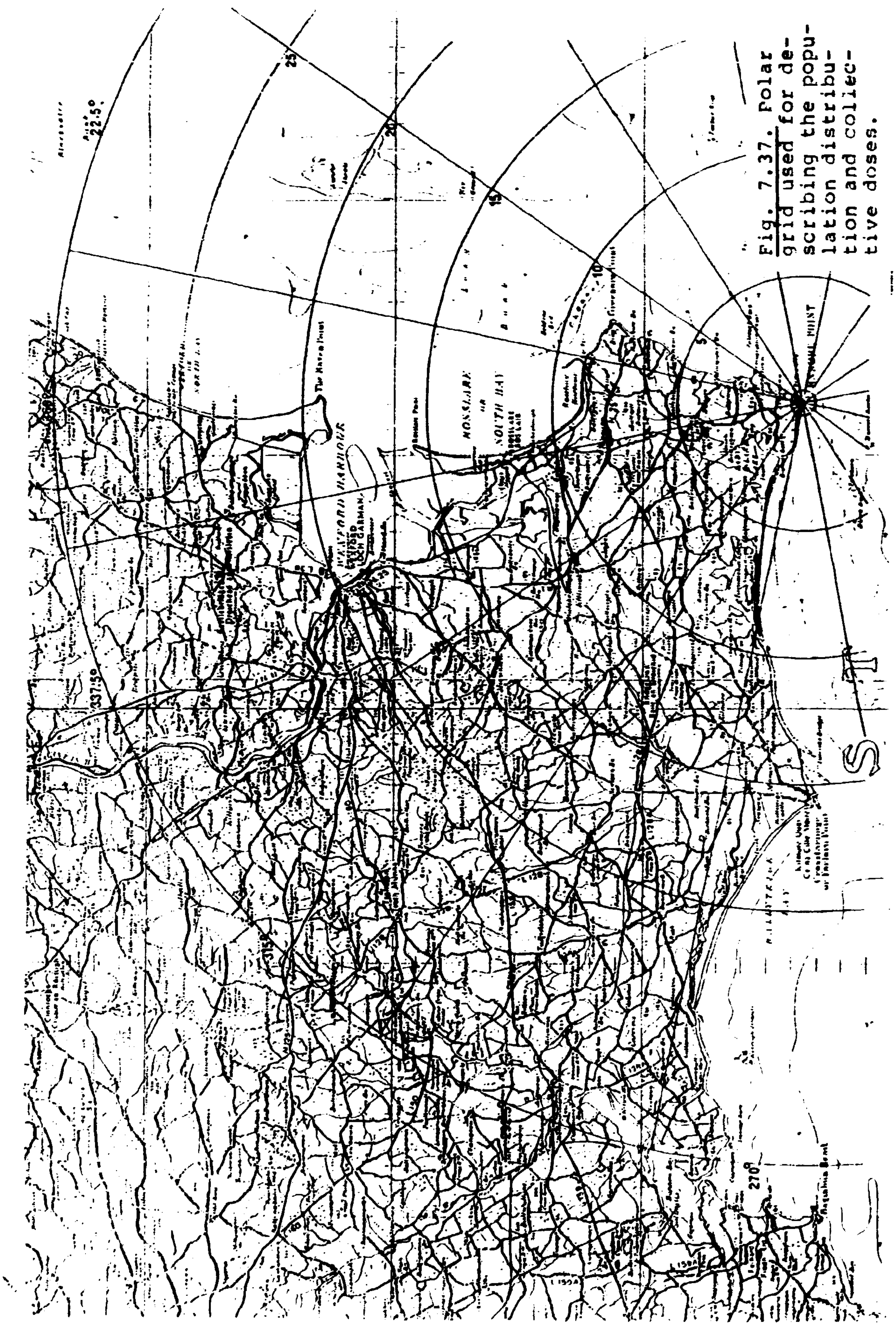


Fig. 7.37. Polar grid used for describing the population distribution and collective doses.

REFERENCES

ADVISORY COMMITTEE ON THE BIOLOGICAL EFFECTS OF IONIZING RADIATIONS (1972). The Effects on Populations of Exposure to Low Levels of Ionizing Radiation. "BEIR report". (National Academy of Sciences, Washington, D.C.) 217 pp.

COMMITTEE ON THE BIOLOGICAL EFFECTS OF IONIZING RADIATIONS (1980). The Effects on Populations of Exposure to Low Levels of Ionizing Radiation "BEIR III report". (National Academy of Sciences, Washington, D.C.) 638 pp.

CENTRAL STATISTICS OFFICE (1980). Census of Population of Ireland, Vol. 1. Population of District Electoral Divisions, Towns and Larger Units of Areas. The Stationary Office, Dublin. Prl. 8692.

GESELLSCHAFT FÜR REAKTORSICHERHEIT (1979), Deutsche Risikostudie Kernkraftwerke (Verlag TÜV Rheinland, Köln) 262 pp.

HEDEMANN JENSEN, P. et al. (1977) Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-melt Accidents at the Barsebäck Reactor. Risø-R-356. 59 pp + appendices.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (1977) Recommendations. ICRP Publication; 26. Annals of the ICRP 1:3. 53 pp.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (1977) Problems Involved in Developing an Index of Harm. ICRP Publication; 27. Annals of the ICRP 1:4. 24 pp.

CENTRAL STATISTICS OFFICE (1975). Report on Vital Statistics (The Stationary Office, Dublin) Prl. 6950. 158 pp.

UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION (1977). Sources and Effects of Ionizing Radiation. (United Nations, New York) 725 pp.

NUCLEAR REGULATORY COMMISSION. (1975) Reactor Safety Study. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. Appendix VI: Calculation of Reactor Accident Consequences. WASH-1400 (App. 6). (USNRC, Washington, D.C.) 471 pp.

8. PARAMETER STUDY

8.1. Introduction

Many parameters are of importance in a description of the dose pattern resulting from accidental releases of large amounts of radioactive material to the atmosphere.

In the preceding Chapters 6 and 7 the design-basis accidents and hypothetical release categories were investigated under fixed atmospheric conditions and demographic patterns: here the influence on dose pattern of varying a number of different parameters is discussed. These can be divided into three groups of a meteorological, demographical or plant-related nature.

Regarding atmospheric conditions, the influence on the dose pattern of the following parameters is described: stability category, wind speed, dry deposition velocity, and wet deposition velocity.

A search was made to find the worst possible weather conditions for the ten hypothetical release categories considered in Chapter 7.

The choices of length of exposure time and the assumed evacuation patterns are related to population distribution. Hence the exposure time is varied; furthermore the influence on dose effects of an assumed evacuation speed was investigated.

A plant-related parameter is the release fraction of the core inventory. Recent information indicates a large degree of conservatism in the WASH-1400 release fractions, especially for iodines and aerosols. A parameter variation of the release fraction is described.

Finally, the dose pattern in what could be called a "reasonable class 9 accident" is described, i.e. accident conditions for a hypothetical release category with release fractions established in the light of information from the latest experience and studies in reactor safety.

Except for the release category variation and the final class 9 accident discussion, the parameter investigation here described was made for release category PWR 2 only. This category was chosen because it is one of the severe WASH-1400 release categories that have a higher probability of occurrence, i.e. 8 x 10^{-6} per reactor year; moreover large fraction of the core inventory is released.

It might be argued that the BWR 2 release has a higher probability of occurrence (6 x 10^{-6} per reactor year) and release fractions of similar size, and thus would be the correct choice. The PWR 2 release, however, takes place only 2.5 hours after shut-down, while 30 hours elapse before the BWR 2 release occurs, giving time for the decay of the short-lived part of the core inventory.

8.2. Atmospheric parameters

8.2.1. Stability category

For the PWR 2 release category, the centre-line bone-marrow doses for an exposure time of 8 hours were calculated for the six Pasquill stability classes A-F. A dry deposition velocity of v_g = 10^{-2} m/s and no rain were used.

Use was made of the most common wind speed in each stability category (as described in Section 3.4.2). Figure 8.1 shows the wind speed, the final effective dispersion height, H, and the vertical dispersion parameter, σ_z, for each stability category at 1 km downwind.

Stability category	A	B	C	D	E	F
Wind speed m/s	1.5	3.4	3.1	7	3.8	1.8
H (m)	725	320	350	150	175	170
σ_z (m)	400	105	55	30	20	15

Fig. 8.1. Corresponding values of Pasquill stability categories, final effective dispersion heights, H, and the vertical dispersion parameter, σ_z, at a distance of 1 km from the release point for the PWR 2 release category.

The curves in Fig. 8.2 show that a stability category F situation leads to the highest doses. Compared to stability D, no rain, the F situation results in doses that are 2-3 times higher with a minimum difference from 7 to 10 km.

The rather hot release reaches the final dispersion height shown in Fig. 8.1 about one km downwind. The vertical dispersion parameter σ_z varies considerably with stability category.

No detailed description of the variation of the dose picture with stability category is given here.

It must be remembered that the centre-line bone-marrow-dose curves are sums of the components: inhalation, gamma plume and gamma deposition.

From Fig. 3.8 the probability of Pasquill stability category F, u = 1.8 m/s and no rain, in a 337.5° direction, i.e. towards Wexford, is found to be 8.6 E-4 per year (~ 0.3 day per year). Therefore the total probabilities for this accident are 8 E-6 x 8.6 E-4, giving 6.9 E-9 per reactor year.

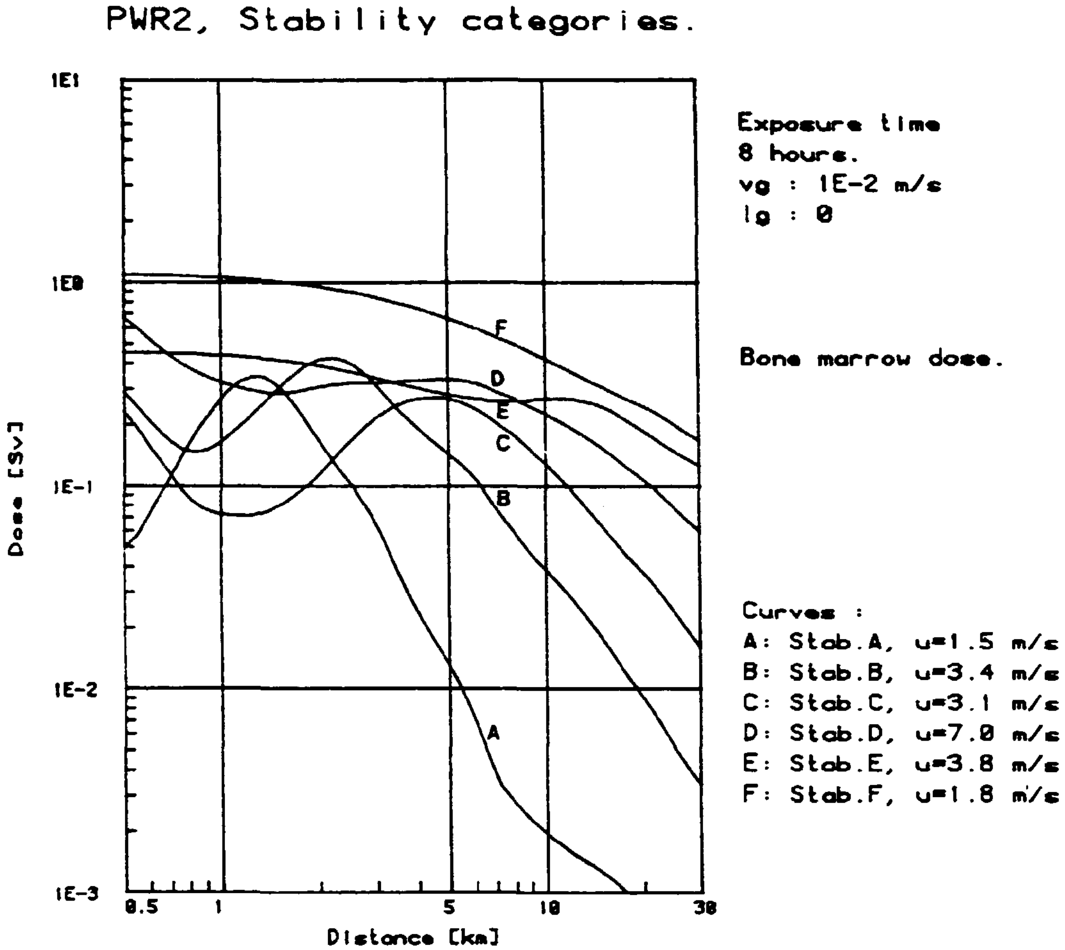


Fig. 8.2. Bone-marrow centre-line doses for the PWR 2 release in six different stability categories.

8.2.2. Wind speed

The influence of wind speed on the centre-line bone-marrow dose in the PWR 2 release was calculated for two Pasquill stability categories, D and F. In both cases no rain was assumed. In the Pasquill D situation with a dry deposition velocity of $v_g = 10^{-2}$ m/s, doses were calculated for four wind speeds: 6, 8, 10 and 12 m/s. Figure 8.3 shows corresponding values of the four wind speeds and the final effective dispersion height, H.

In accordance with formula (2) in Section 5.3.1.1, the concentration in the plume is inversely proportional to wind speed. As a result the highest wind speed is expected to entail the lowest doses, and this is the case at downwind distances greater than 10 km. Figure 7.8, which shows the components of the bone-

Wind speed	u, m/s	6	8	10	12
Dispersion height	H, m	181	135	108	91

Fig. 8.3. Corresponding values of wind speed and final effective dispersion height, H, for Pasquill stability category D.

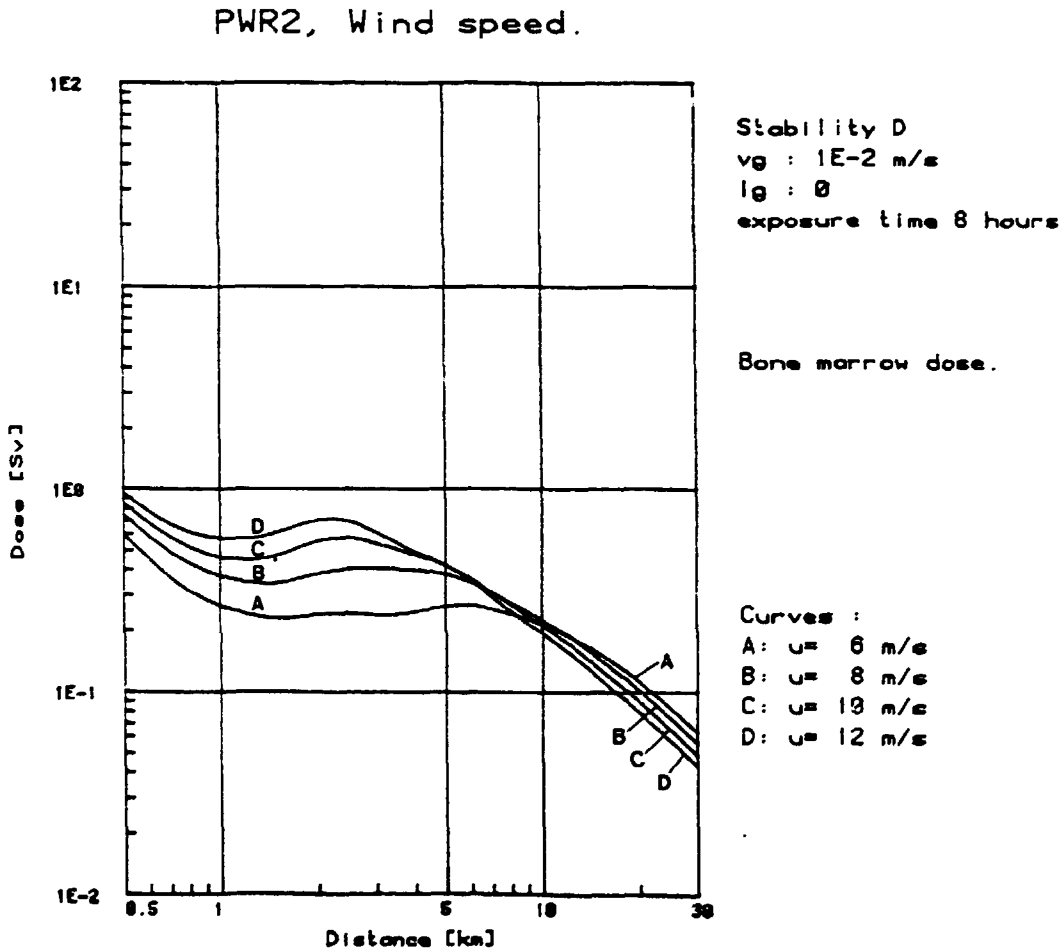


Fig. 8.4. Centre-line bone-marrow doses as function of distance in the PWR 2 release category shown for four wind speeds in Pasquill stability category D.

-marrow dose and whose sum curve, marked D, is identical with curve A on Fig. 8.4, shows that the dominating component is gamma plume, and that the concentration-dependant component, inhalation (Fig. 7.8, marked A), first makes its full but small (compared to the gamma plume) contribution at a downwind distance of 5-10 km, in the same range where the curve shifts occur (Fig. 8.4). The dominating component, gamma plume, is more influenced by the final effective dispersion height, H, which is halved from 181 m for u = 6 m/s to 91 m for u = 12 m/s. The distance to the plume from the ground and the attenuation in the mass of the atmosphere are dominant factors too.

Figure 8.4 shows that the choice of u = 6 m/s used in Chapter 7 gives doses that are lower by an order of 10-30% inside downwind distances up to 10 km than those given by the average wind speed of 7 m/s. At larger distances, u = 6 m/s gives slightly higher doses. However, this only applies to the PWR 2 release category.

For the Pasquill stability category F situation, the dry deposition velocity $v_g = 2 \times 10^{-3}$ m/s was chosen in accordance with Section 3.4.2. The centre-line bone-marrow doses were calculated for wind speeds of 1, 2 and 5 m/s.

Wind speed, u, m/s	1	2	5
Dispersion height, H, m	205	163	120

Fig. 8.5. Corresponding values of wind speed and final effective dispersion height, H, for Pasquill stability category F.

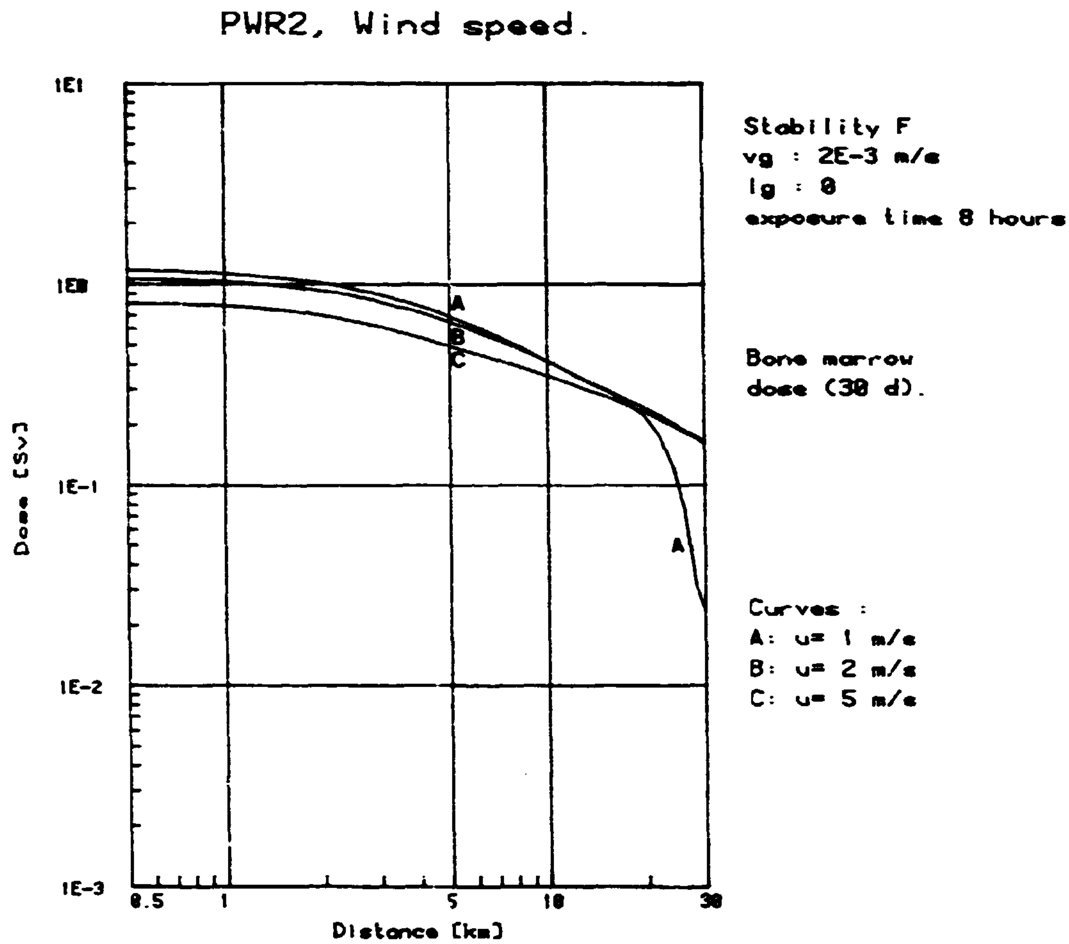


Fig. 8.6. Centre-line bone-marrow doses as function of distance in the PWR 2 release category for three wind speeds in Pasquill stability category F.

With the higher and more uniform final dispersion heights, doses are lowest for the highest wind speed. The sudden drop in curve A is caused by the low wind speed of 1 m/s (= 3.6 km/h), as the exposure time (8 hours) ends d before the plume reaches 25 km. The warning time of one hour (see Fig. 4.3) expires before the release takes place, thus leaving 7 hours for dispersion (7 h x 3.6 km/h = 25.2 km).

8.2.3. Dry deposition velocity

The variation in centre-line bone-marrow dose with different values of v_g, as suggested in Section 3.4.3, is shown in Fig. 8.9.

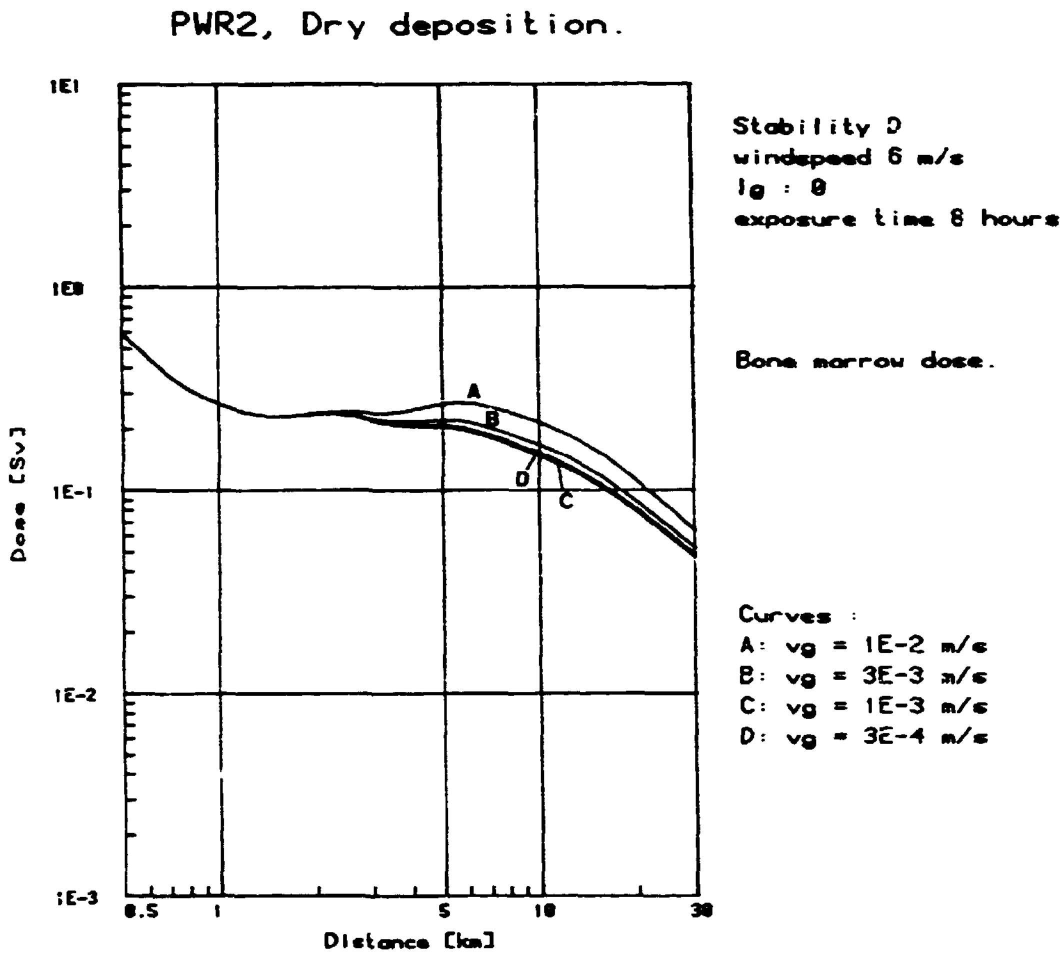


Fig. 8.7. Centre-line bone-marrow doses as a function of distance in the PWR 2 release category. Curves are shown for four different values of the dry deposition velocity v_g.

Little variation is found and the choice of $v_g = 10^{-2}$ m/s used in Chapters 6 and 7 seems to give pessimistic dose values. As can be seen in Fig. 7.8, the deposition component contributes to the dose after about 2 km, reaching its maximum between 5 and 10 km.

8.2.4. Wet deposition

As described in detail in Chapter 3, precipitation gives rise to the removal of material from a plume and to the deposition of this on the ground. A wash-out coefficient or wet deposition rate l_g is defined. It might be construed as the proportion of the amount of material removed in unit of time. Figure 8.8 shows the corresponding values of rain intensity and wet deposition rate l_g, cf. Section 3.4.1.

Rain intensities mm/h	0.06	0.1	0.5	1	3	10	100
l_g s^{-1}	E-5	1.3E-5	3E-5	4E-5	E-4	2E-4	E-3

Fig. 8.8. Rain intensities in mm/h and the corresponding wet deposition rates.

Figures 3.7 to 3.11 in Chapter 3 shows that the probabilities of the occurrence of rain are those seen in Fig. 8.9.

	All sectors %	Sector 337.5° (incl. Wexford) %
All data	100	6.6
No rain	87.3	5.06
0.1-1 mm/h	9.1	0.96
1 - 5 -	3.5	0.51
5 - 10 -	0.1	0.01

Fig. 8.9. Probabilities of the occurence of rain of certain intensities in all sectors and in the 337.5° sector including Wexford. 0.01% corresponds to 0.86 hours per year.

Information on rain of greater intensity than 10 mm/h is given in Section 3.3.3: incidents of extreme rainfall.

Figures 3.9 - 3.11 show that nearly all rain occurs exclusively in Pasquill stability category D.

The wet deposition parameter investigation was therefore carried out for:

Pasquill stability category D

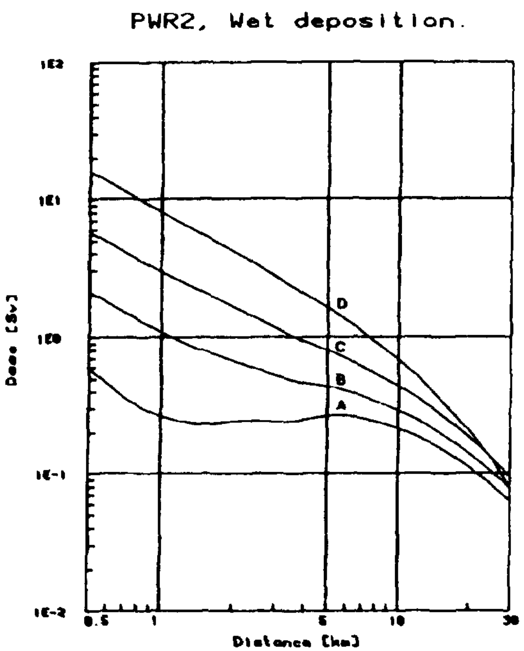
l_g = 0 s^{-1} ~ no rain
l_g = 3E-5s^{-1} ~ 0.5 mm/h
l_g = E-4 s^{-1} ~ 3 mm/h
l_g = 3E-4s^{-1} ~ 15-20 mm/h

As the choice of wind speed has great influence on the resulting doses in the case of precipitation, the above values of l_g were calculated for the three wind speeds u = 6 m/s, 8 m/s and 10 m/s. Figures 8.10, 8.11 and 8.12 show the centre-line bone-marrow doses as a function of downwind distances in the PWR 2 release category for the three wind speeds.

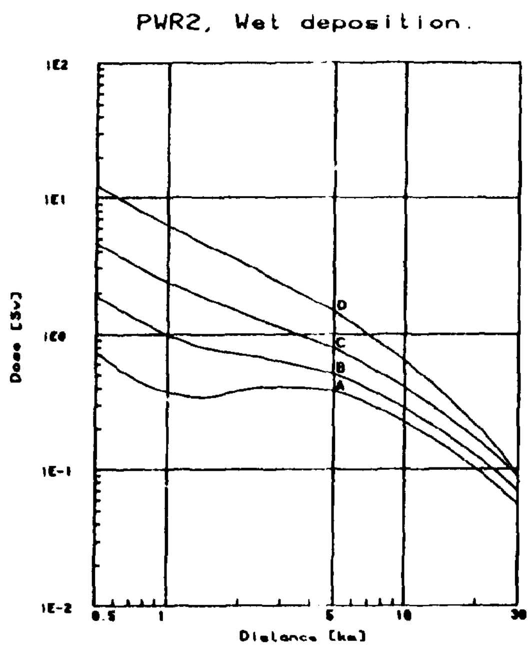
The curves for no rain, marked A, in the three figures are identical with the three corresponding curves in Fig. 8.4 (A, B and C); the curve marked A in Fig. 8.10 is identical with the curve marked D in Fig. 7.8.

The marked growth in bone marrow doses with increasing rain intensity, especially at shorter downwind distances, is a consequence of the resulting increase in activity deposited on the ground: the more rain, the greater is the dominance of the gamma deposition component. Up to a distance of about 10-20 km, the B, C and D curves in Figs. 8.10, 8.11 and 8.12 result almost exclusively from the gamma deposition component.

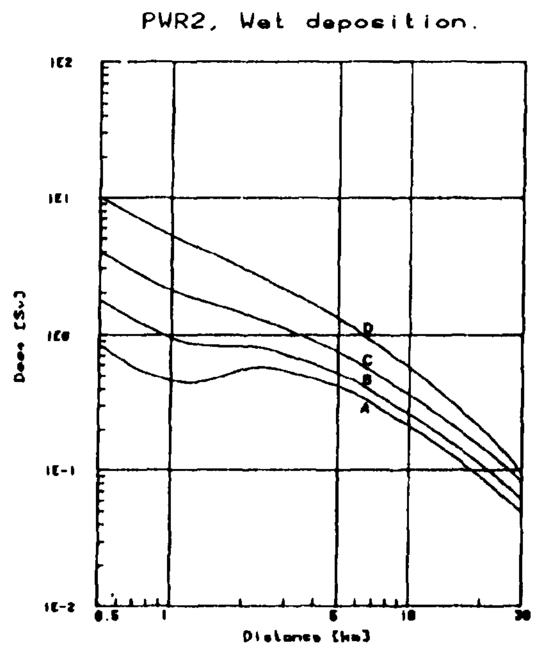
In order to evaluate the influence of rain, a detailed calculation of the worst case was carried out: the D curve in Fig. 8.10 represents Pasquill stability category D, u = 6 m/s, $v_g = 10^{-2}$ m/s, $l_g = 3 \times 10^{-4}$ s^{-1}, corresponding to very heavy rain of 15 - 20 mm per hour. It is further assumed that the rain persists until the plume reaches the limit of the area considered, i.e. 30



u = 6 m/s



u = 8 m/s



u = 10 m/s

Figs. 8.10 to 8.12. The influence of wind speed, u, on the centre-line bone-marrow doses calculated for four different values of the wet deposition coefficient, l_g. Release category PWR 2, stability D, v_g = 1E-2 m/s, and the four l_g values in s^{-1}: 0 (curves A), 3E-5 (curves B), 1E-4 (curves C, and 3E-4 (curves D).

km. With u = 6 m/s = 21.6 km/h, rain is calculated to persist for 30/21.6 = 1.4 hours.

The probability of this taking place when a wind is blowing towards Wexford (Fig. 3.11) is well below 0.01% per year. Assuming a PWR 2 probability per reactor year (Fig. 7.1 or 4.1) of 8 E-6 leads to a probability for such an extreme situation of less than

0.01% x 8E-6 = 8E-10 per reactor year

or less than once per 1,250,000,000 reactor years.

For this worst situation Fig. 8.13, gives the ranges in km of nine dose levels for centre-line bone-marrow doses (30 days) and whole-body doses (50 years).

Dose level Sv (rem)	0.5 (50)	1 (100)	2 (200)	3 (300)	4 (400)	5 (500)	6 (600)	7 (700)	8 (800)
	Range from the release point in km								
Bone marrow (30 days)	12	7.4	4	2.7	2.1	1.6	1.34	1.1	1.0
Whole body (50 days)	14.3	9.2	4.6	2.8	2.1	1.6	n.a	n.a	n.a

Fig. 8.13. Ranges in km of centre-line bone-marrow doses and whole-body doses in the PWR 2 release category for the worst atmospheric situation found: Pasquill D, u = 6 m/s, v_g = 10^{-2} m/s, l_g = 3E-4 s^{-1} (n.a. = not applicable).

Figure 8.14 shows the distribution of people and their allocated collective bone-marrow doses in three distance intervals. Early mortalities by are calculated applying the WASH-1400 relations between bone-marrow dose and early mortality for minimal and surportive treatment (both shown in Fig. 7.29).

Distance interval [km]	Number of individuals	Total dose [man Sv]	Cases with minimal treatment	Cases with supportive treatment
0.5 - 1.0	7	21	2.3	1.8
1.0 - 5.0	218	213	7.2	2.0
5.0 - 7.5	212	109	-	-
Sum	437	343	9.5	3.8

Fig. 8.14. Distribution of number of individuals and their allocated, collective bone-marrow dose in the PWR 2 release category in the extreme atmospheric condition: Pasquill D, u = 6 m/s, $v_g = 10^{-2}$ m/s and l_g = 3 E-4 s^{-1}, and a calculation of early mortalities assuming minimal and supportive treatment respectively.

The results indicate that about 10 early mortalities could be expected following upon minimal treatment and about 4 after supportive treatment. To get an idea of the possible variation in early mortality, the number of cases is assumed to follow a Poisson distribution. This gives the probabilities shown in Fig. 8.15.

Treatment	Number of cases of early mortality			
	0 - 5	6 - 10	11 - 15	16 - 20
Minimal	9%	56%	32%	3%
Supportive	82%	18%	-	-

Fig. 8.15. Probabilities of early mortalities in four intervals assuming minimal and supportive treatment respectively. Calculations were made assuming that a PWR 2 release takes place in a direction of 337.5° with very heavy rain, 15 - 20 mm per hour.

Figure 8.16 shows a calculation for this release situation of latent cancer fatalities similar to the presentation in Fig. 7.34.

		Above 1 Sv	Below 1 Sv
Collective dose in manSv		315	4050
Number of persons exposed		180	221
Number of latent cancer fatalities	Risk value A for the whole dose range 125 cases per 10^4 Sv	A total of 50.6	
	Risk value B $\geq$1 Sv 125 cases per 10^4 Sv <1 Sv 20 cases per 10^4 Sv.	3.7	8.1
		A total of 11.8	

Fig. 8.16. Collective whole-body doses and number of individuals receiving doses in the release situation PWR 2, Pasquill D, u = 6 m/s, $v_g = 10^{-2}$ m/s, l_g = 3 E-4 s^{-1}. The expected number of latent cancer fatalities is calculated for the two risk values A and B applied in 7.5.2.

8.3. Exposure time

In a release situation the exposure time (see Fig. 4.3) at a distance downwind is decisive for the size of the deposition dose.

The influence on the centre-line bone-marrow dose is illustrated in two PWR 2 release situations with different deposition circumstances.

Figure 8.17 shows the centre-line doses for four different exposure times, 2, 4, 8 and 24 hours, for Pasquill D, u = 6 m/s, v_g = 10-2 m/s and no rain. Figure 8.18 shows the same information for a similar situation but with rain: l_g = 3 E-5 s^{-1}, corresponding to about 1 mm/hour.

A warning time of one hour before the start of the release implies that, when T = 2 h, the plume has only one hour in which to travel at a speed of 6 m/sec, corresponding to 21.6 km/h.

Comparing Figs. 8.17 and 7.8, it is obvious that gamma plume radiation dominates within a few km downwind in the situation without rain. Figure 8.18 shows that the deposition dose is significant, and that the resultant bone-marrow dose is nearly proportional to the exposure time.

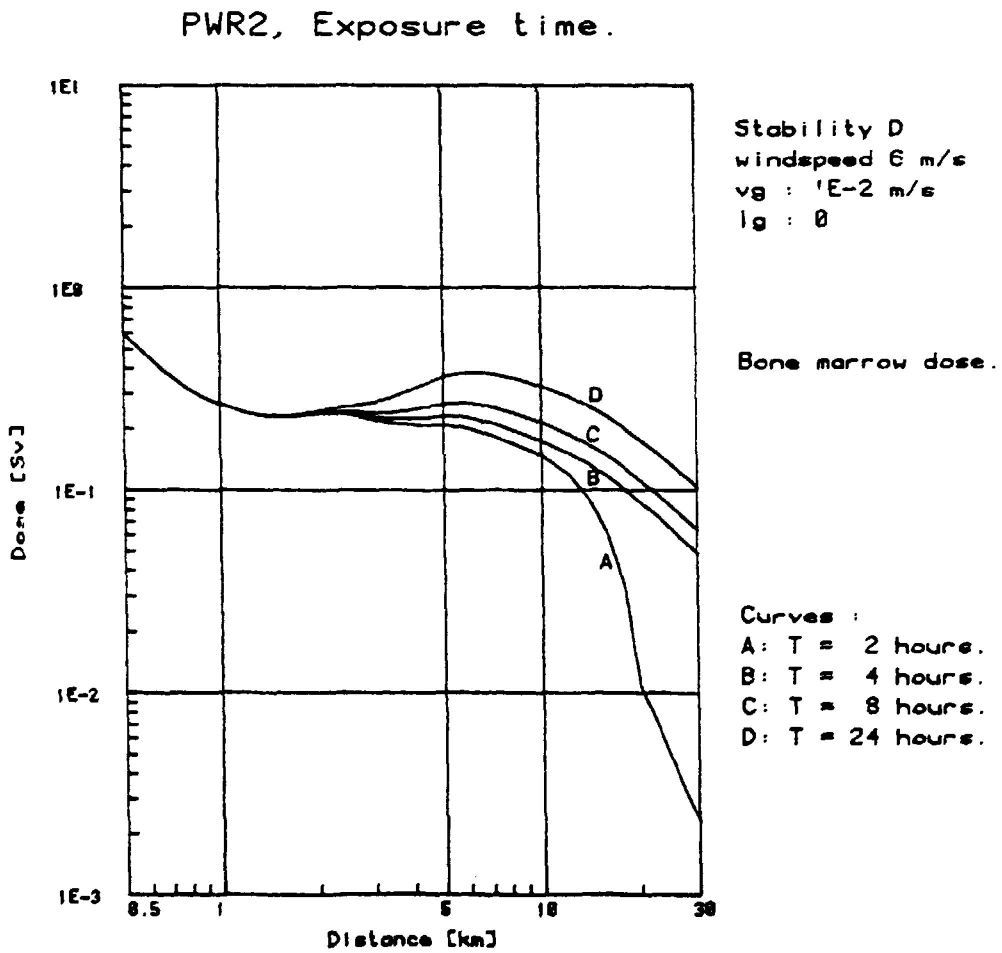


Fig. 8.17. Bone-marrow centre-line doses for various exposure times in the PWR 2 release, no rain.

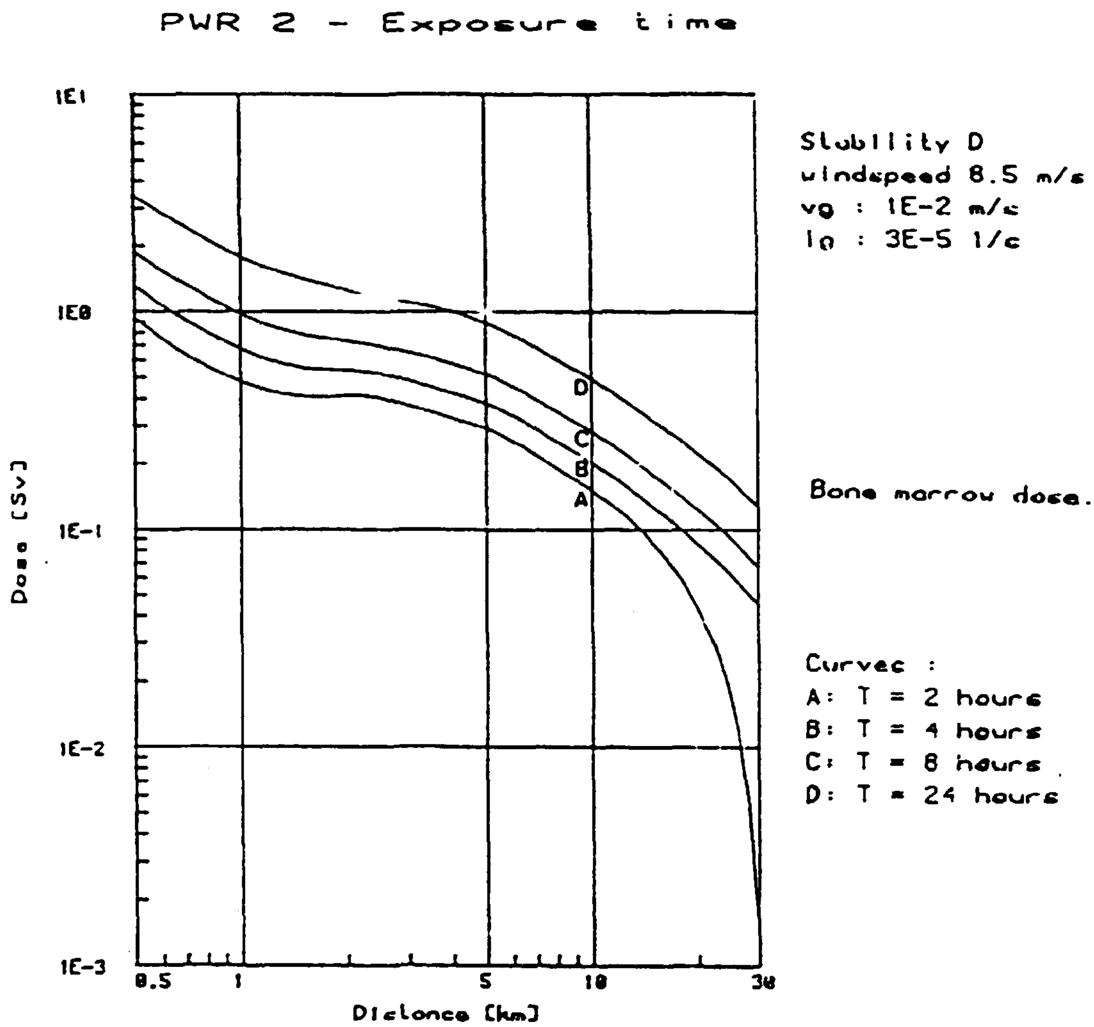


Fig. 8.18. Bone-marrow centre-line doses for various exposure times in the PWR 2 release, with rain (1 mm/h).

8.4. Evacuation pattern

The effects of a proposed evacuation pattern for the resident population up to a distance of 30 km were investigated. The evacuation was assumed to take place in the following three-step pattern:

1) 0-2 hours after warning time: 30% of the population are evacuated at a constant speed,
2) 2-4 hours: a further 40% are evacuated,
3) 4-8 hours: the last 30% are evacuated.

Of essential importance are the lengths of warning time given in Fig. 4.2 for each release category, and the wind speed at and after the start of the release.

Figure 4.2 shows three lengths of warning time: 1, 1.5 and 2 h.

At various downwind distances the percentage of the resident population evacuated - and therefore not exposed to radiation - was calculated for the same wind speed used in Chapter 7, i.e. u = 6 m/s (21.6 km/h). A corresponding reduction factor for

Distance km	Cloud travel time hours	Warning time 1 h			Warning time 1.5 h			Warning time 2 h		
		Cloud arrival time	% evacu-ated	Fraction of population exposed	Cloud arrival time	% evacu-ated	Fraction of population exposed	Cloud arrival time	% evacu-ated	Fraction of population exposed
0	0	1	15		1.5	23		2	30	
0 - 5			16.5	0.835		24.5	0.755		32.5	0.675
5	0.23	1.23	18		1.73	26		2.23	35	
5 - 10			20	0.8		27.5	0.725		37	0.63
10	0.46	1.46	22		1.96	29		2.46	39	
10 - 20			25.5	0.745		34	0.66		44	0.56
20	0.93	1.93	29		2.43	39		2.93	49	
20 - 30			33.5	0.665		43.5	0.565		53.5	0.465
30	1.39	2.39	38		2.89	48		3.39	58	
Warning time valid for release type		PWR 1 A, PWR 1 B, PWR 2, PWR 5, PWR 6			BWR 1			PWR 3, PWR 4, BWR 2, BWR 3		

Fig. 8.19. Fraction of population evacuated before start of exposure for three lengths of warning time for wind speed u = 6 m/s = 21.6 km/h. Likewise a calculation is made for the fraction of the population that would be exposed on arrival of the cloud.

each distance interval is then found which lessens the population, and hence the collective dose calculated for the distance interval considered.

In the PWR 2 release (and PWR 1A + B, PWR 5 and PWR 6) it appears that 16.5% of the population are evacuated from inside a distance of 0-5 km before the arrival of the cloud and that 33.5% are evacuated from inside a distance of 20-30 km without any exposure.

Release category	Distance [km]	Reduction factor	Dose [manSv] full	Dose [manSv] reduced	Latent cancer fatalities Risk value A full	Risk value A reduced	Risk value B full	Risk value B reduced
PWR 1A	0 - 5	0.835	416	347	5.2	4.3		
	5 - 10	0.800	403	322	5.0	4.0		
	10 - 20	0.745	6080	4530	76.0	56.6		
	20 - 30	0.665	1086	722	13.6	9.0		
	Σ		7985	5921	99.8	73.9	-	-
PWR 2	0 - 5	0.835	46	38	0.6	0.5		
	5 - 10	0.800	116	93	1.5	1.2		
	10 - 20	0.745	3613	2692	45.2	33.7		
	20 - 30	0.665	687	457	8.6	5.7		
	Σ		4462	3280	55.9	41.1	-	-
BWR 2	0 - 5	0.675	305	206	3.8	2.6	3.8	2.6
	5 - 10	0.630	283	178	3.5	2.2	0.6	0.4
	10 - 20	0.560	2749	1539	34.4	19.2	5.4	3.1
	20 - 30	0.465	534	248	6.7	3.1	1.1	0.5
	Σ		3871	2171	48.4	27.1	10.9	6.6

Fig. 8.20. Reduction in number of latent cancer fatalities obtained through implementation of the proposed three-step evacuation pattern over eight hours. The calculation is shown for three release categories in the 337.5° direction in Pasquill category D, u = 6 m/s, $v_g = 10^{-2}$ m/s, no rain. The numbers for full dose and full latent cancer fatalities are repeated from Fig. 7.33. Use was made of the risk values A and B, as described in Section 7.5.2.

The influence of the reduction of the collective dose to the exposed population and hence of the latent cancer fatalities, was calculated for three categories of release, all assumed to take place in the release direction 337.5^{o} in category D weather with a wind speed of 6 m/s and no rain. Use was made of the risk values A and B described in Section 7.5.2 of, respectively, 125 and 20 latent cancer fatalities per 10^4 Sv. The results are shown in Fig. 8.20. It can be seen that a reduction of one quarter is obtained in the PWR 1A and PWR 2 releases and more than 40% in the BWR 2.

8.5. Worst hypothetical release situations

In the course of the study a search was made in order to find the worst situations disregarding their probability of occurrence.

In each release category the highest doses were sought at four downwind distances: 1, 5, 15 and 30 km.

In the PWR 3, BWR 2 and BWR 3 releases, two situations were found for each category. Figures 8.21, 8.22 and 8.23 show these cases.

In Fig. 8.21 the worst situation is seen to be the same for PWR 1A, PWR 1B, PWR 2 and PWR 3: Pasquill stability category D, u = 6 m/s, $v_g = 10^{-2}$ m/s and l_g = 3 E-4 s^{-1}, the latter corresponding to a rain intensity of 15-20 mm/h. The probability of this weather situation occurring in any one direction is well below 0.01% per year.

In Fig. 8.22 the worst situation for the PWR 3, PWR 4, PWR 5 and PWR 6 releases was found to be Pasquill stability category F, u = 2 m/s, v_g = 2 E-3 m/s, no rain. Figure 3.8 shows that the probability of this situation occurring in, e.g., Sector 337.5^{o}, is

$$0.873 \times 0.058 \times 0.017 = 0.09\%.$$

Figure 8.23 shows the worst situations found for the BWR 1, BWR 2 and BWR 3 release categories.

For all three release categories, the centre-line bone-marrow doses are shown for the extreme rain situation, Pasquill D, u = 6 m/s, v_g = 10^{-2} m/s and l_g = 3 E-4 s^{-1} (15-20 mm/h). For the BWR 2 and BWR 3 releases doses are also shown in stability category F, v_g = 10^{-2} m/s and wind speed u = 5 m/s, no rain.

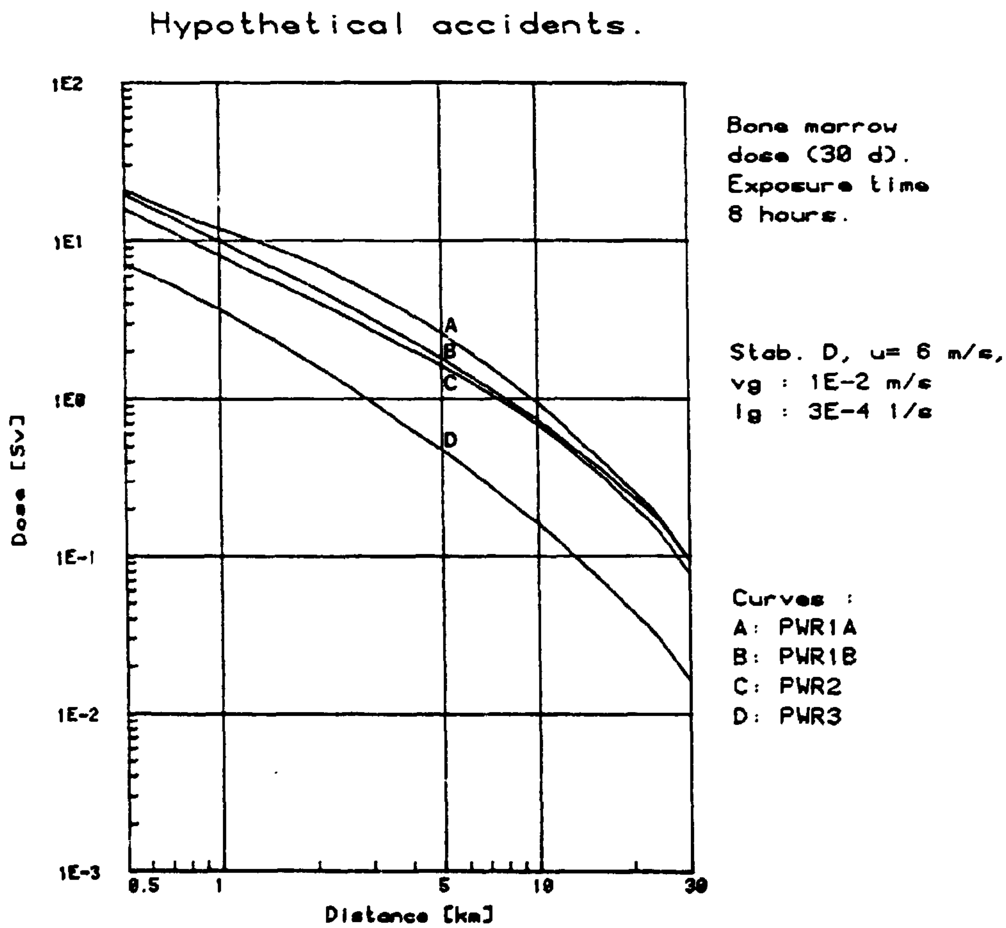


Fig. 8.21. Worst possible release situations for the categories PWR 1A, PWR 1B, PWR 2 and PWR 3, Pasquill stability category D, u = 6 m/s, v_g = 10-2 m/s, l_g = 3 E-4 s-1 (15-20 mm rain/h).

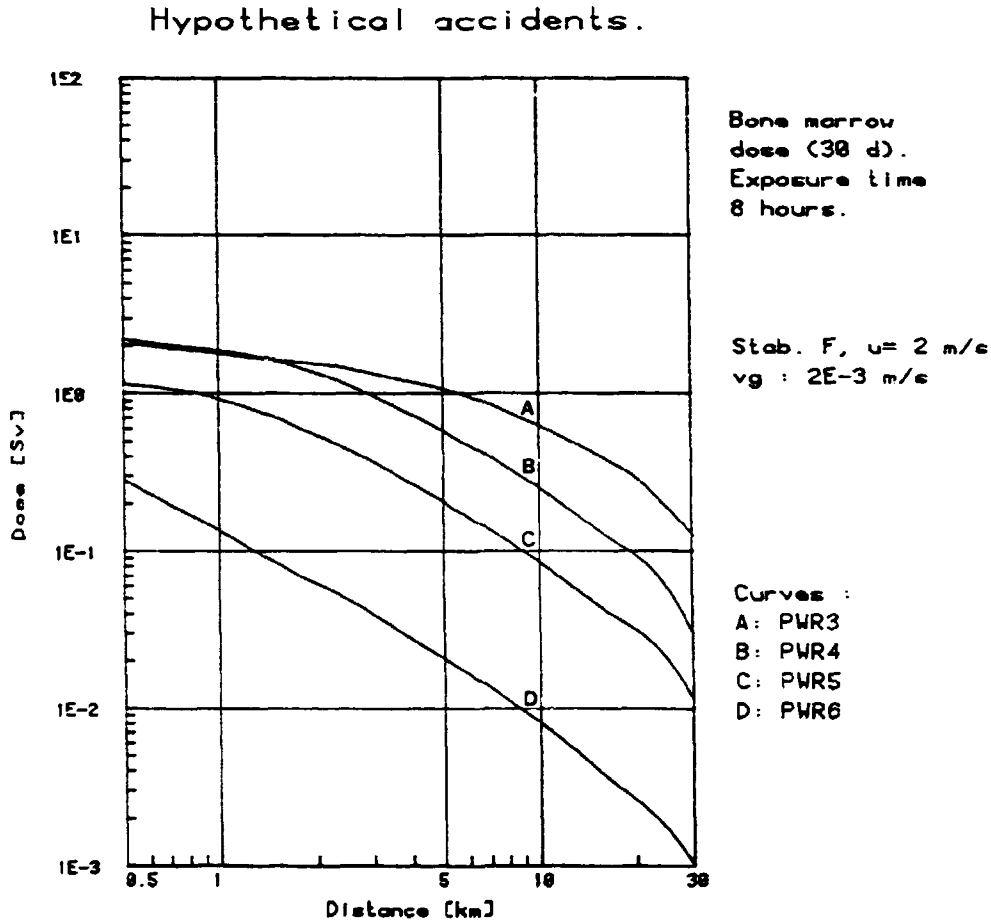


Fig. 8.22. Worst possible release situations for the categories PWR 3, PWR 4, PWR 5 and PWR 6, Pasquill stability category F, u = 2 m/s, v_g = 2 E-3 m/s, no rain.

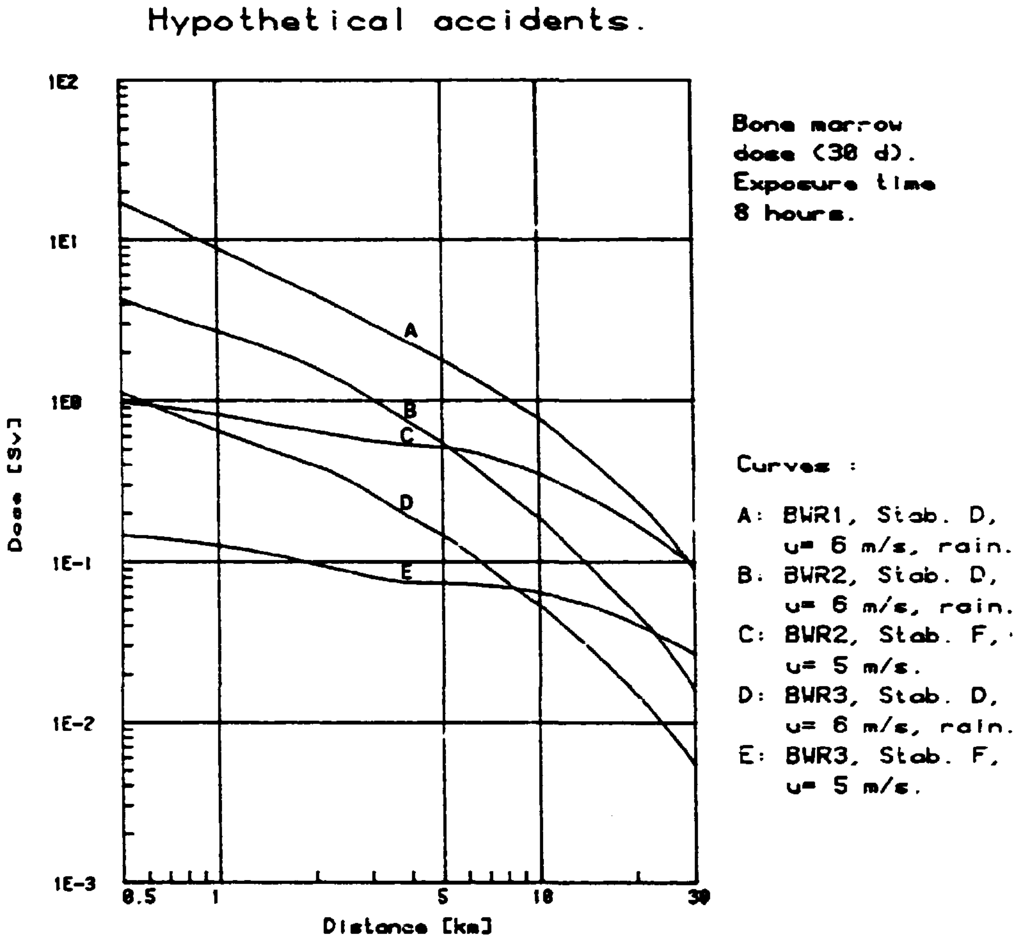


Fig. 8.23. Worst possible release situations for the categories BWR 1, BWR 2 and BWR 3. The three categories are all shown for Pasquill stability category D, u = 6 m/s, v_g = 10^{-2} m/s and l_g = 3 E-4 s^{-1} (15-20 mm rain/hour). BWR 2 and BWR 3 are further shown for Pasquill stability category F, u = 5 m/s, v_g = 10^{-2} m/s, no rain.

8.6. Release fraction variations

Recent studies (e.g. Levenson 1980) indicate a certain conservatism in the WASH-1400 release fractions. The most significant observation from the Three Mile accident in the USA in 1979 was the behaviour of iodines in the containment and the very small iodine release to the atmosphere.

Lacking definite information from larger bodies/organisations at the time of writing, it was decided to perform a parameter calculation on the release fractions. The PWR 2 release category was modified to give the following five releases.

A. PWR 2 with a reduction to 10% of the iodine release
B. The same as A with a further reduction to 10% of other aerosols
C. PWR 2 with a reduction to 1% of the iodine release
D. The same as C with a further reduction to 1% of other aerosols
E. PWR 2 with release of noble gases only.

The five modified PWR 2 releases are shown in Figs. 8.24 - 8.28.

All releases are calculated for Pasquill stability category D, u = 6 m/s, $v_g = 10^{-2}$ m/s, no rain, and for an exposure time of 8 hours; the curves show the centre-line bone-marrow doses.

Figure 8.29 shows the sum curves from the five modified PWR 2 releases in conjunction with the unchanged PWR 2 curve from Fig. 7.8. The resultant doses are very sensitive to any changes in the release fraction of iodine.

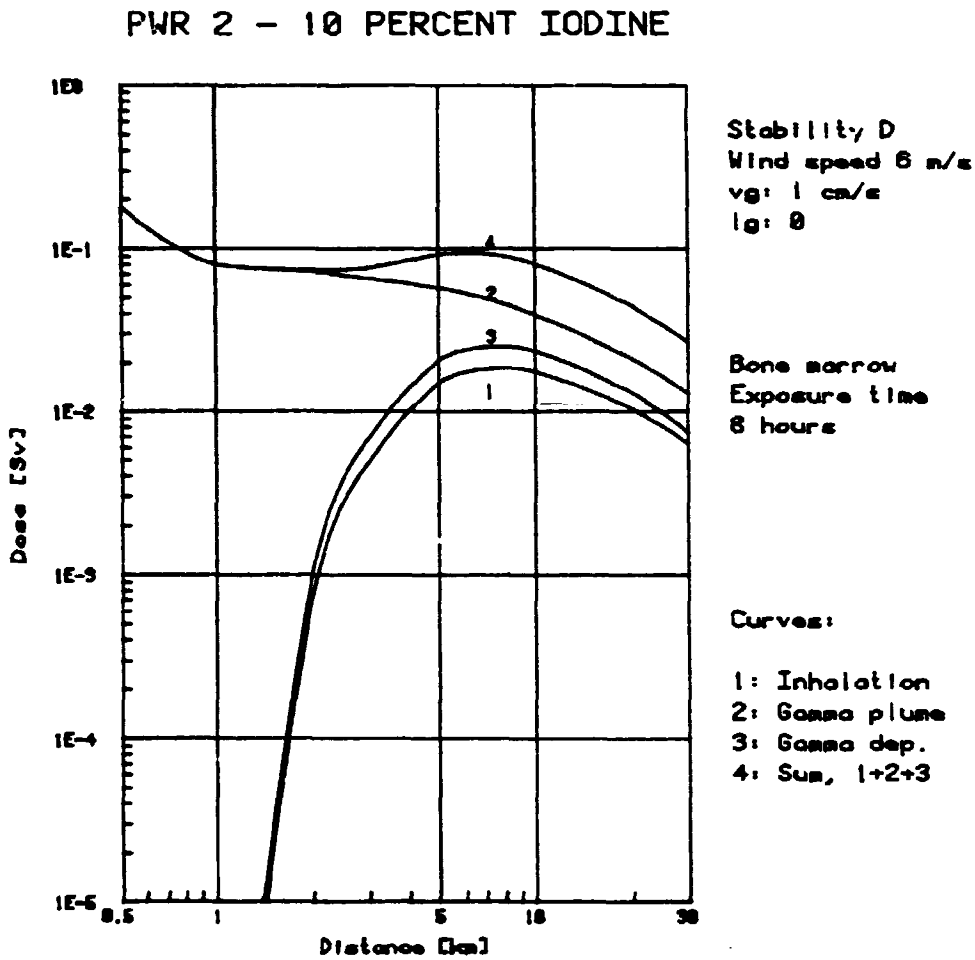


Fig. 8.24. Centre-line bone-marrow doses as a function of distance in the PWR 2 release with a reduction to 10% of the iodines released (cf. A on page 185).

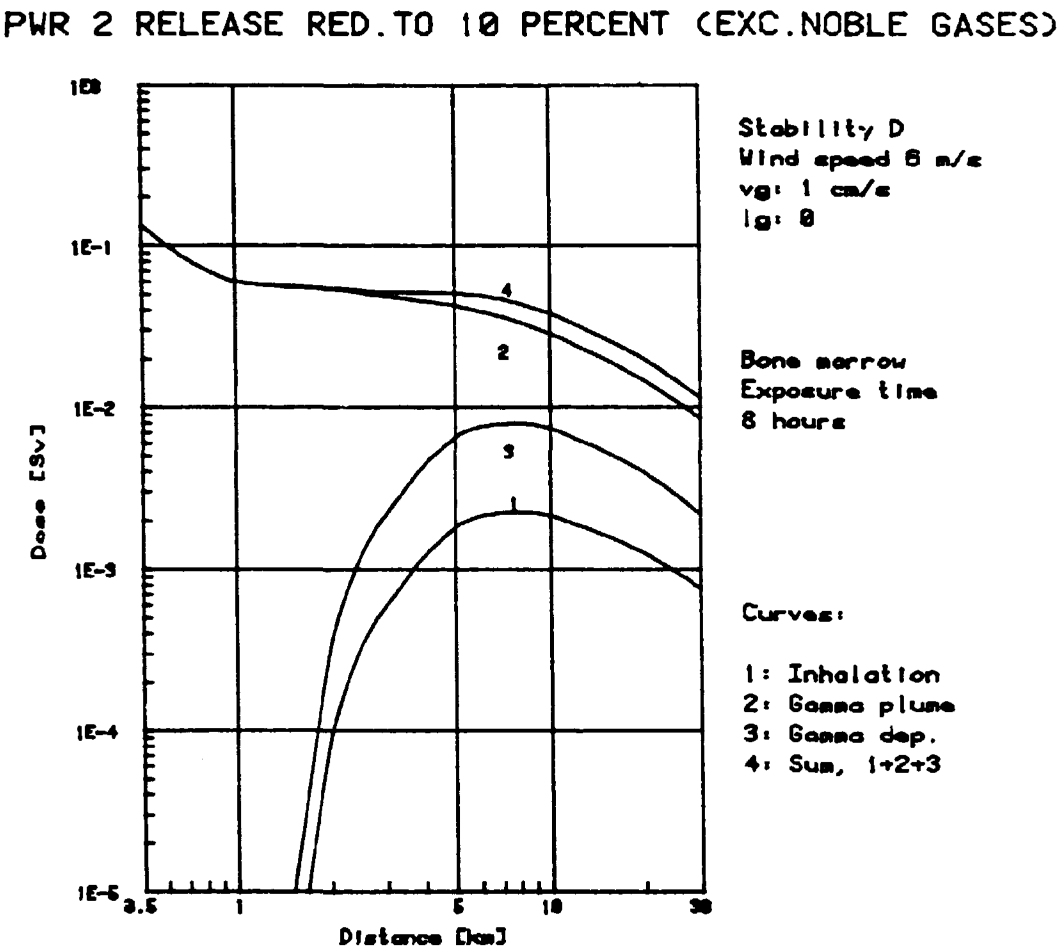


Fig. 8.25. Centre-line bone-marrow doses as a function of distance in the PWR 2 release with a reduction to 10% of iodines and other aerosols released (cf. B on page 185). No reduction of noble gases.

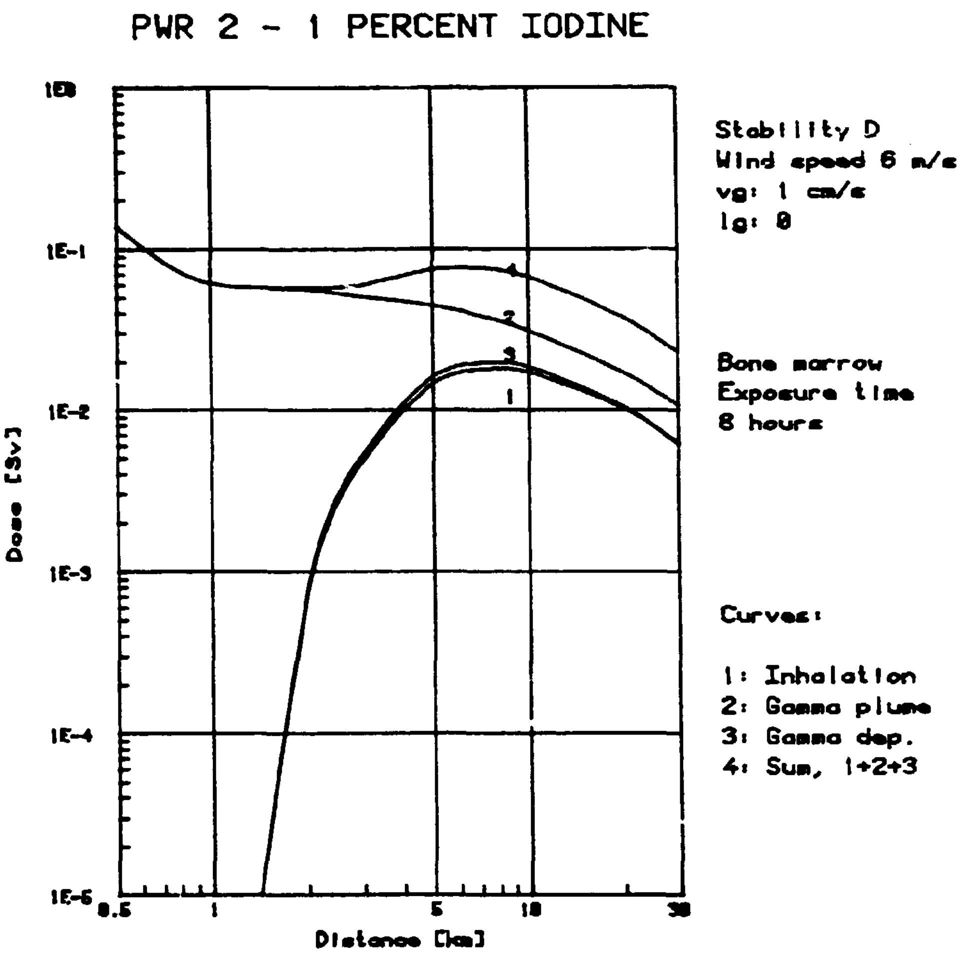


Fig. 8.26. Centre-line bone-marrow dose: as a function of distance in the PWR 2 release with a reduction to 1% of the iodines released (cf. C on page 185).

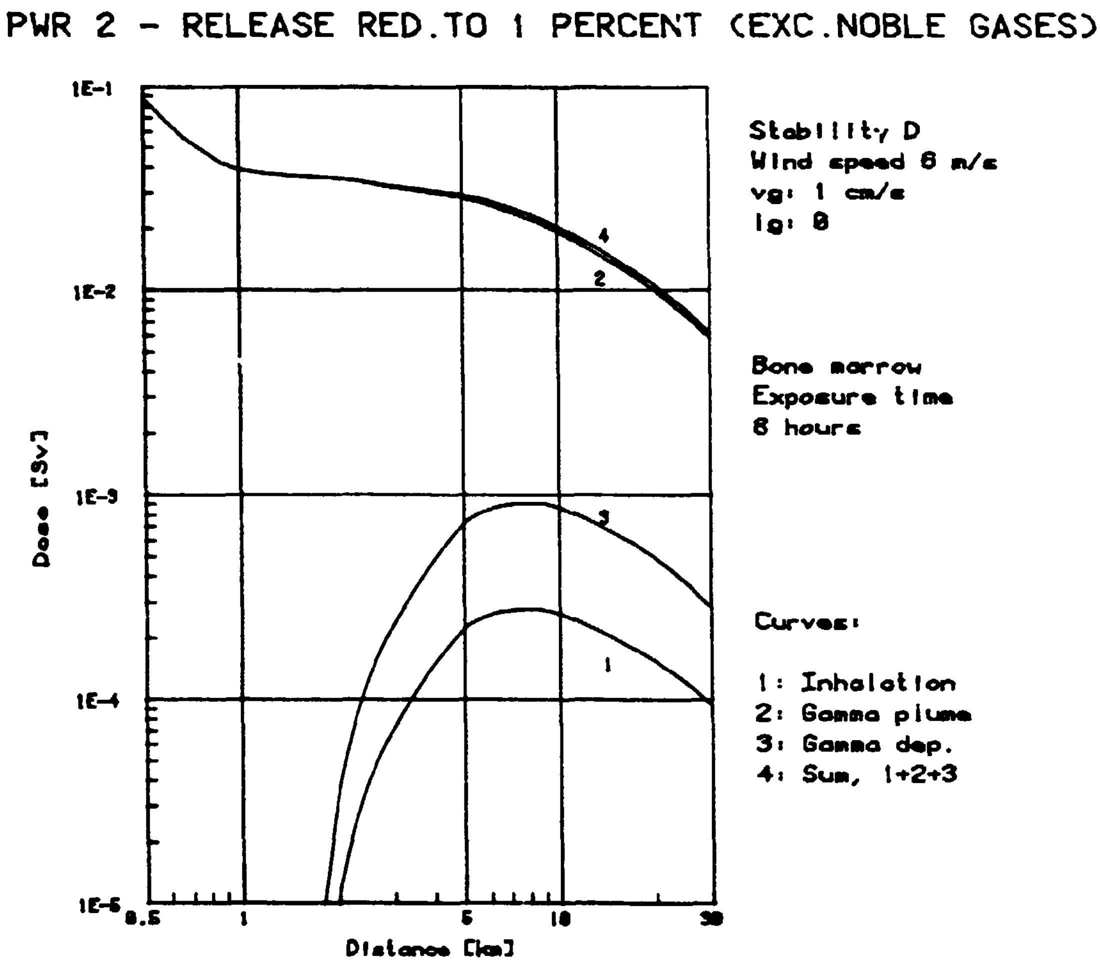


Fig. 8.27. Centre-line bone-marrow doses as a function of distance in the PWR 2 release with a reduction to 1% of iodines and other aerosols released (cf. D on page 185). No reduction of noble gases.

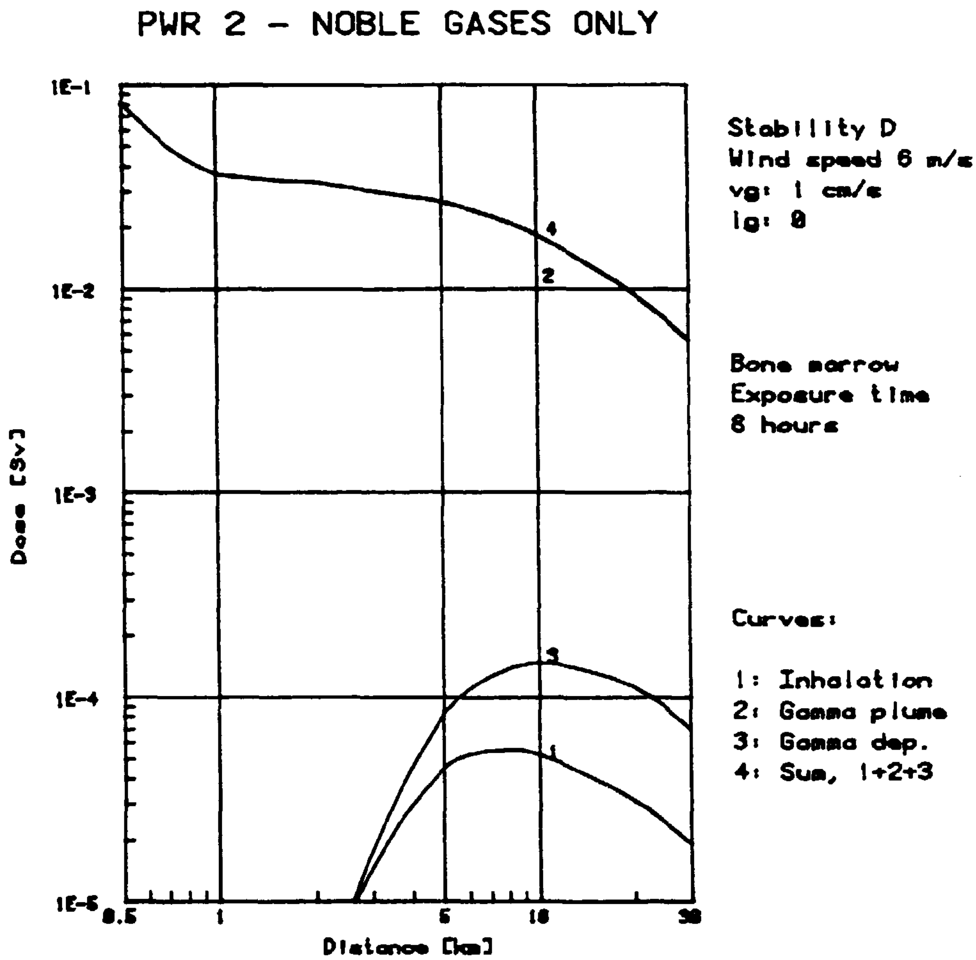


Fig. 8.28. Centre-line bone-marrow doses as a function of distance in the PWR 2 release involving noble gases only (cf. E on page 185).

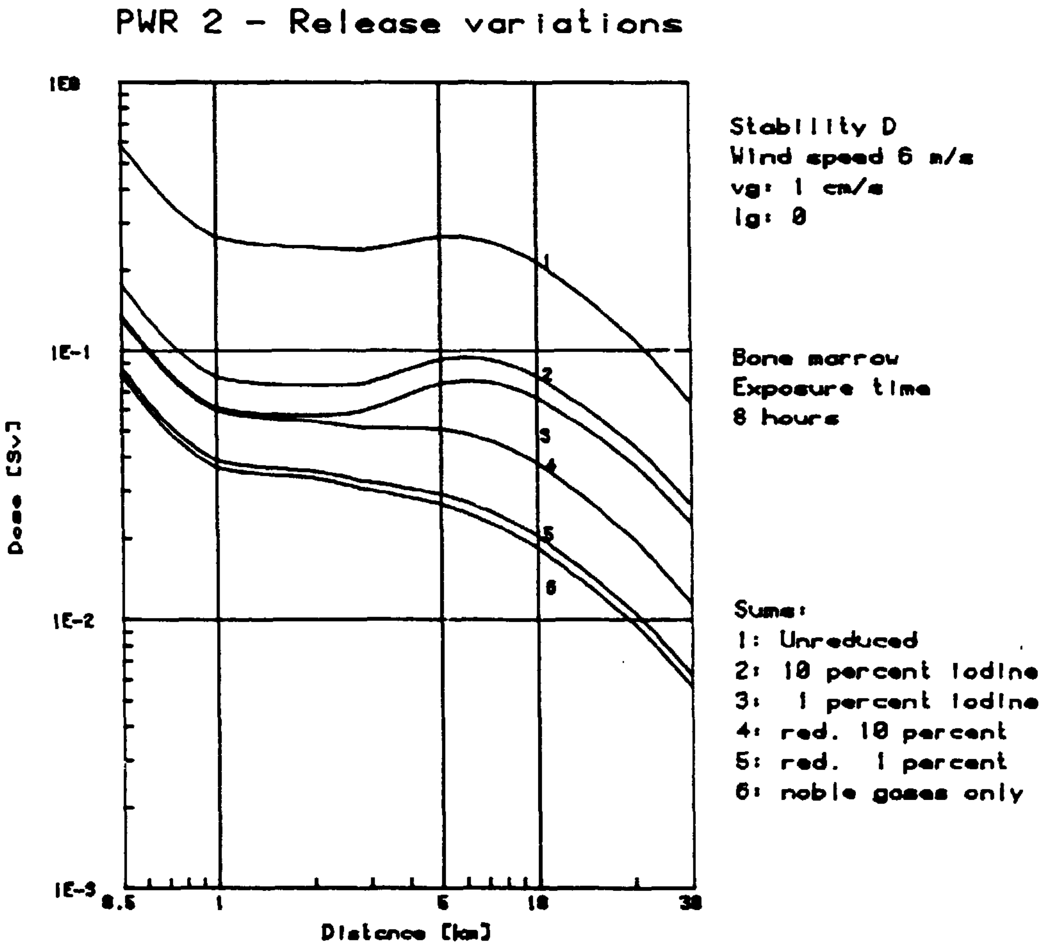


Fig. 8.29. The sum curves relating to the PWR 2 variations B-F (the same as the sum curves on Figs. 8.23 to 8.27) shown together with the unmodified PWR 2 release.

8.7. BEED release

8.7.1. Release fraction

Experimental work at Sandia Laboratory in the USA indicates that the probability of a steam explosion in the reactor vessel, which might cause containment failure, is two orders of magnitude lower than assumed in WASH-1400 (Berman et al., 1980). The probability of the most serious PWR release category in WASH-1400, category 1, is thus reduced by two orders of magnitude. Furthermore, Mayringer (Munich, October 1981), in an analysis of the mechanism of large steam explosisions, excluded their posibility. Hence the WASH-1400 category 1 release is physically excluded.

Theoretical and experimental work at Kernforschungszentrum Karlsruhe, Germany, shows that, for a German PWR, the time from a core melt until overpressure failure of the containment due to steam and gas generation and hydrogen combustion is 2-3 days (Rininsland et al., 1980). Melt-through of the concrete base mat in the containment is unlikely, and it has been shown that the aerosol concentration of radioactive material in the containment atmosphere will decrease in 2-3 days by 3-5 orders of magnitude. Thus the amount of radionuclides available for release to the environment at the time of containment failure is very small, i.e. 10^{-2} to 10^{-3} times the WASH-1400 findings. The longer time interval between core-melt and containment failure in the new calculations is partly responsible for this reduction.

Based on these results it appears that the most probable serious consequences of a core meltdown in a PWR would originate from a PWR 4 release.

Scientists in the USA have recently re-evaluated the information available from reactor accidents such as SL-1, Windscale, and Three Mile Island. These studies (Stratton et al., 1980, Levenson and Rahr, 1980) indicate that it is iodide - probably cesium iodide - rather than iodine that emerges from melting fuel. Cesium iodide is a much less volatile chemical compound that readily combines with the water and steam in light water reactor system. Thus the release of fission products will be less than 1% of the core content except for the noble gases.

In the light of the above reports Gjørup (Risø-M-2299, appenix) analysed in detail the information available on the TMI 2, SL 1 and Windscale accidents.

Based on this work, a release from a reactor system with a reducing atmosphere is suggested for further study. The fission product release is obtained as a Best Estimate from Empirical Data (BEED).

The time at which the release occurs after shut-down, the duration of release and the initial release height are assumed to be the same for BEED as for PWR 4 (Figs. 4.2 and 4.3).

The release fractions in per cent for PWR 4 and BEED are given in Fig. 8.

	PWR4	BEED
Xe-Kr	60	60
I -Br	9	1
Cs-Rb	4	0,1
Te-Sb	3	0,5
Ba-Sr	0,5	0,02
Ru a)	0,3	0,02
La b)	0,04	0,02

Fig. 8.30. Release fractions for the PWR 4 release according to WASH-1400 (Fig. 4.1) and the BEED release category according to Risø-M-2299.

a) includes Ru, Rh, Mo, Tc

b) includes Y, La, Zr, Nb, Ce, Po, Nd, Pu, Am, Cm.

8.7.2. Dose calculations

Dose calculations based on the above release conditions result in doses which in general are a factor 2-4 lower than the PWR 4 releases, except for the noble gases. Figures 8.31 and 8.32 show bone-marrow doses and whole-body doses, respectively. Figures 8.33 and 8.34 show organ doses for the PWR 4 and the BEED release. As expected, the largest reduction (a factor of 10) is seen in the dose to the thyroid because of the significant reduction in the iodine release.

Figure 8.35 shows isodose curves for bone-marrow dose levels of 2, 1, 0.5 and 0.1 Sv, respectively, for the two releases PWR 4 and BEED in the stability category D situation, u = 6 m/s, v_g = 1 E-2 m/s, no rain. The significant reduction in the area subjected to exposure at the different dose levels is obvious.

8.7.3. Release probabilities

In Risø-M-2299 it is argued that the most probable serious consequences of core meltdown in a PWR would not originate from the accident sequences described by PWR 1, 2, and 3, but from an accident sequence that includes a failure of the containment isolation.

In WASH-1400 a melted core and a non-isolating containment (and failure of the containment radioactivity removal system as well) occur in the PWR 4 release. Without going into a detailed study here of accident sequences leading to this situation, the PWR 4 release is taken as representative of such a case.

The probability of this release under these new assumptions, where the probabilities of the WASH-1400 PWR 1, 2 and 3 releases are considered extremely small, is here assumed to equal the sum of the probabilities of PWR 1, 2, 3 and 4, i.e. ~ 1.4 x 10^{-5} per reactor year.

BONE MARROW DOSES

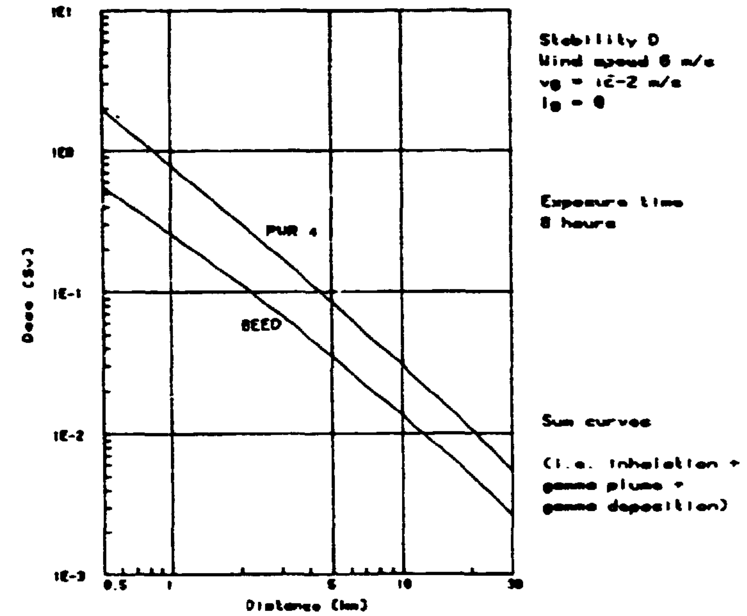


Fig. 8.31. Centre-line bone marrow doses as a function of distance fo r the PWR 4 and BEED releases, respectively.

WHOLE BODY DOSES

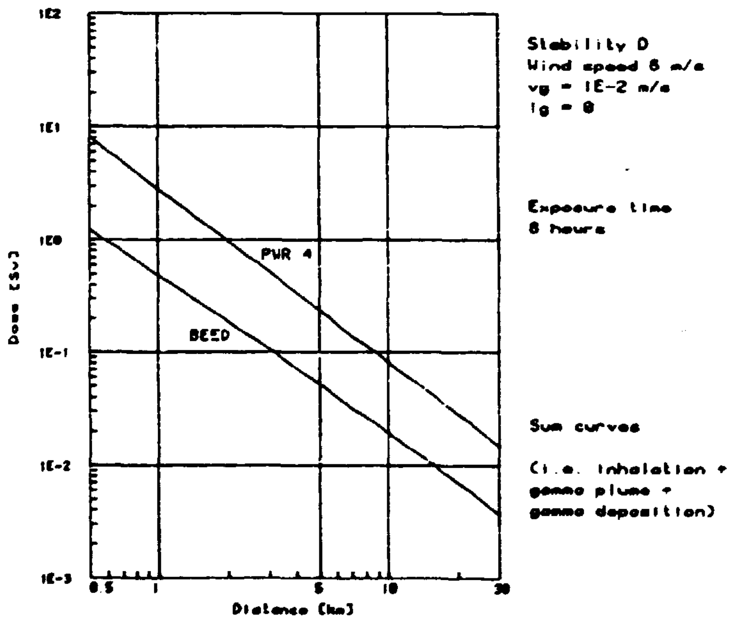


Fig. 8.32. Centre-line whole-body doses as a function of distance for the PWR 4 and BEED releases, respectively.

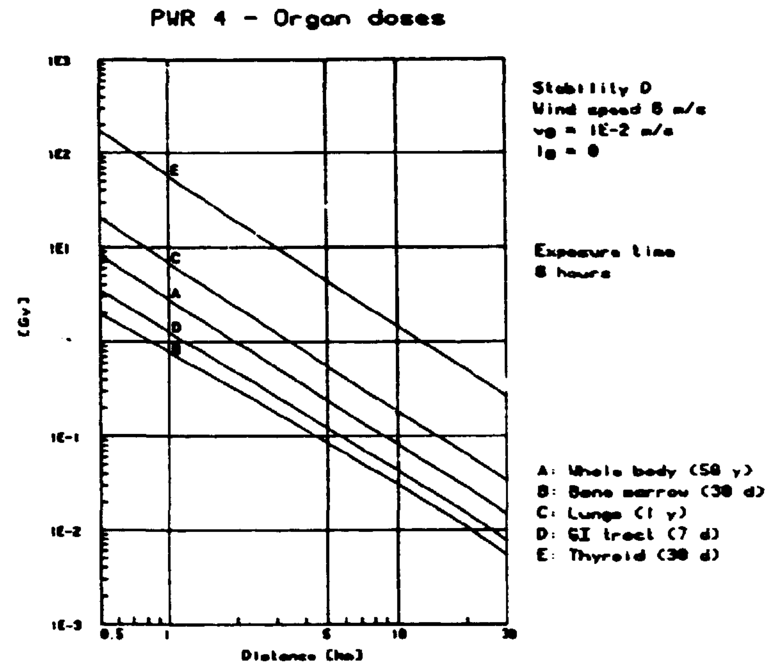


Fig. 8.33. Centre-line organ doses as a function of distance for the PWR 4 release.

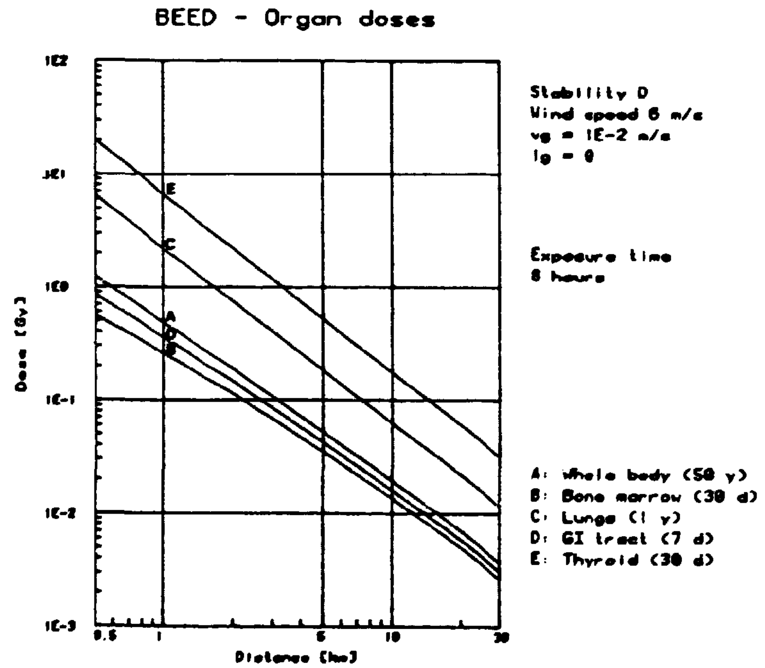
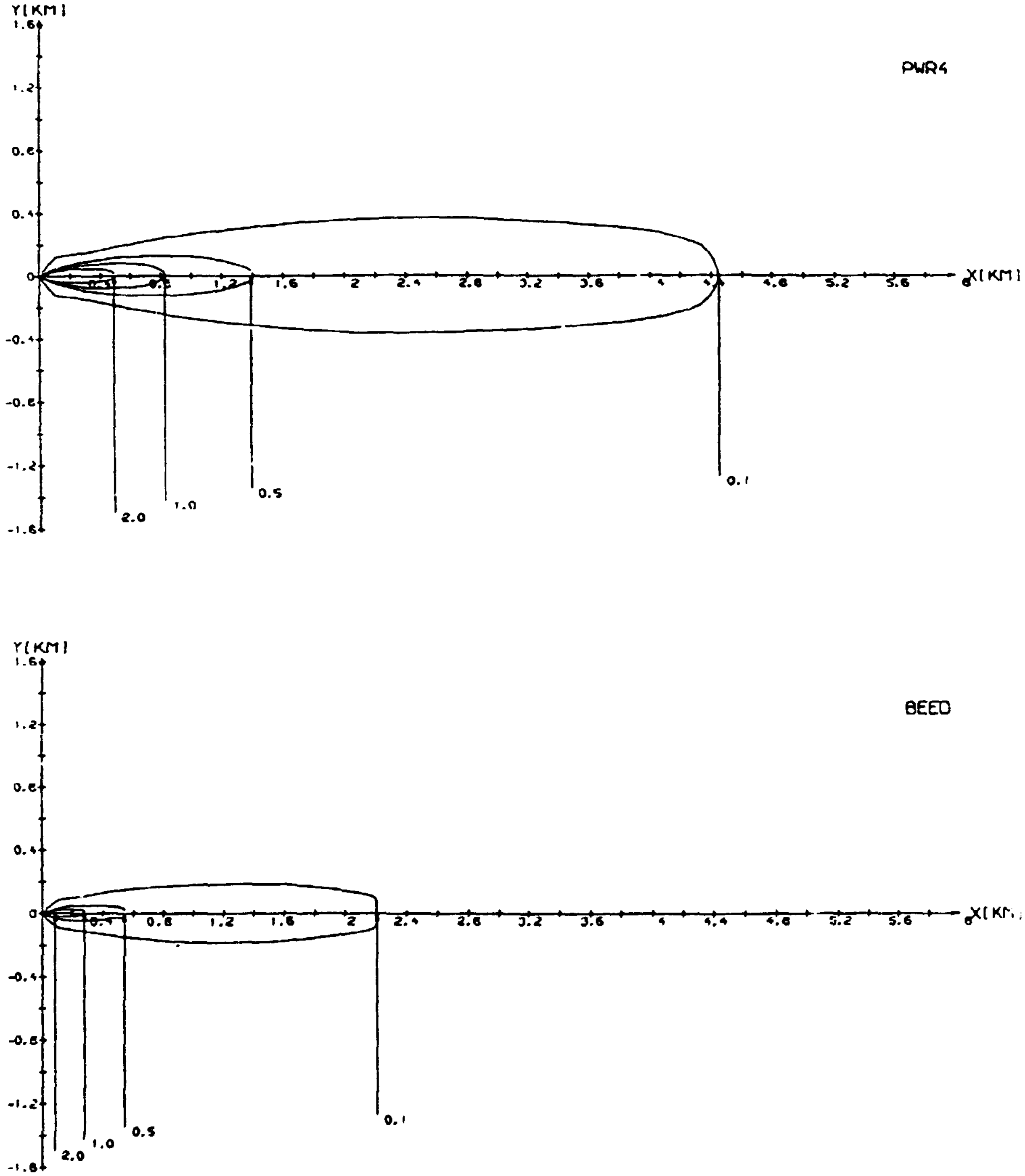


Fig. 8.34. Centre-line organ doses as a function of distance for the BEED release.



<u>Fig. 8.35</u>. Isodose curves (bone-marrow doses) for the PWR 4 and the BEED release. The curves are shown for 0.1, 0.5, 1.0, and 2.2 Sv. Stability D, 6 m/s, v_g = 1 E-2 m/s, no rain.

REFERENCES

BECHER, P.E., et al. (1981). Calculation of Dose Consequences of a Hypothetical Large Accident at a Nuclear Power Reactor. Risø-M-2299, 46 pp.

BERMAN, M. et al. (1980). US Steam Explosion Research. Risk Perspective and Experimental Results. In Sammlung der Vorträge zum Jahreskolloquium, 1980 des Projektes Nukleare Sicherheit. Karlsruhe, am 25. November 1980. 101-166.

LEVENSON, M. and RAHN, P. (1980). Realistic Estimates of the Consequences of Nuclear Accidents. (Electric Power Research Institute, Palo Alto, Cal.) 22 pp.

MAYRINGER, F. (1981) Wie sind Dampfexplosionen im Lichte Neuerer Erkentniesse zu Beurteilen? - Zu Möglichkeit, Ablauf und Wirkung, Paper at: GRS-Fachgespräch 1981, Fortschritte in der Sicherheitsbeurteilung von Kernkraftwerken, München, Bayerisher Hof, 22. und 23. Oktober 1981. 25 pp.

STRATTON, W.R., MALINAUSKAS, A.P., and CAMPBELL, D.O., (1981), Letter to NRC chairman Ahearne dated August 14., 1980. In: Regulatory Impact of Nuclear Reactor Accident Source Term Assumptions. NUREG-0771 (for comment) Appendix A. 4 pp.

APPENDIX 1

Grids for describing the population
distribution in the vicinity of
Carnsore Point.
Data were provided by the ESB.

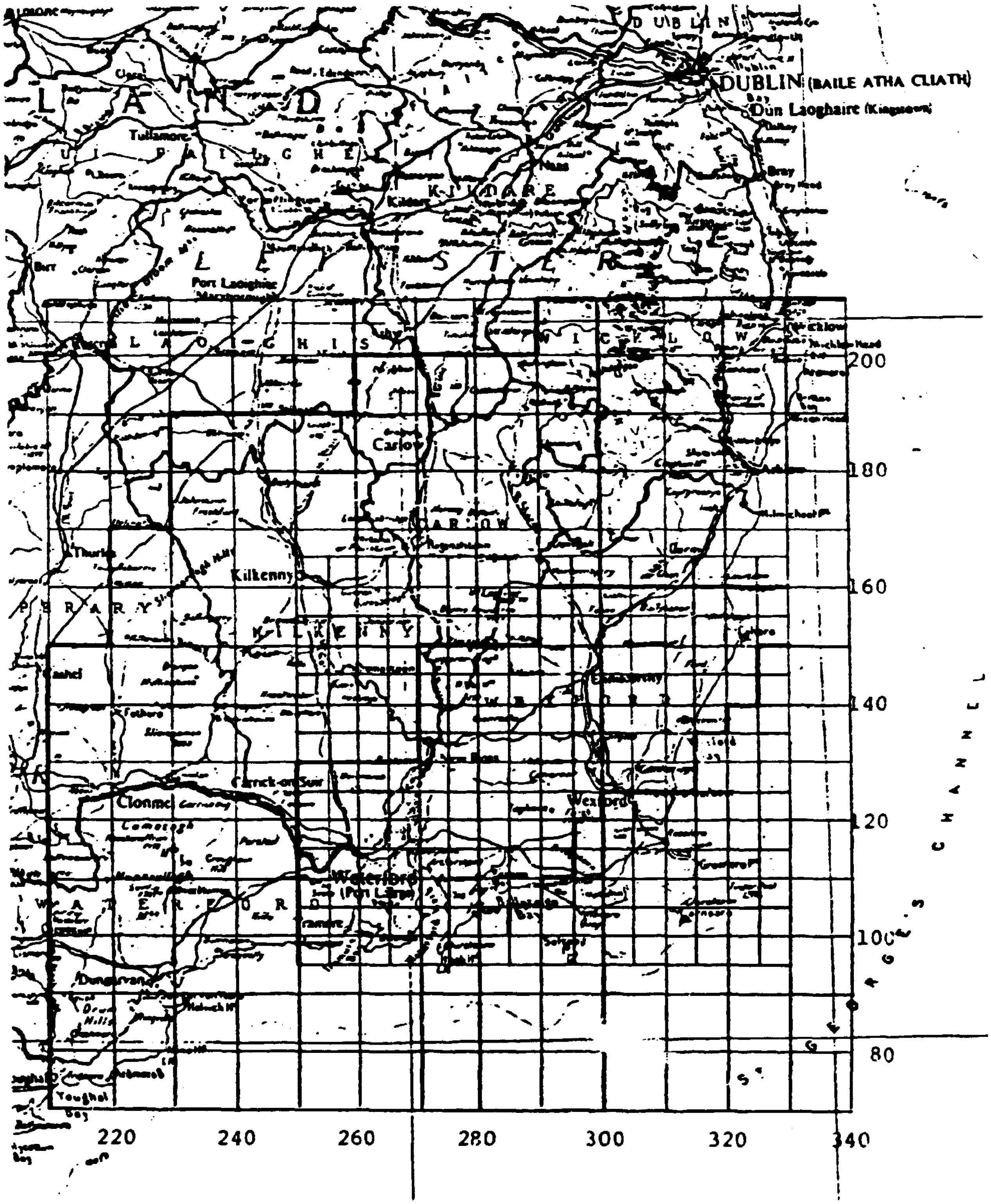


Fig. A.1. Grid for describing the population distribution in the Carnsore area (coordinates according to the National Grid).

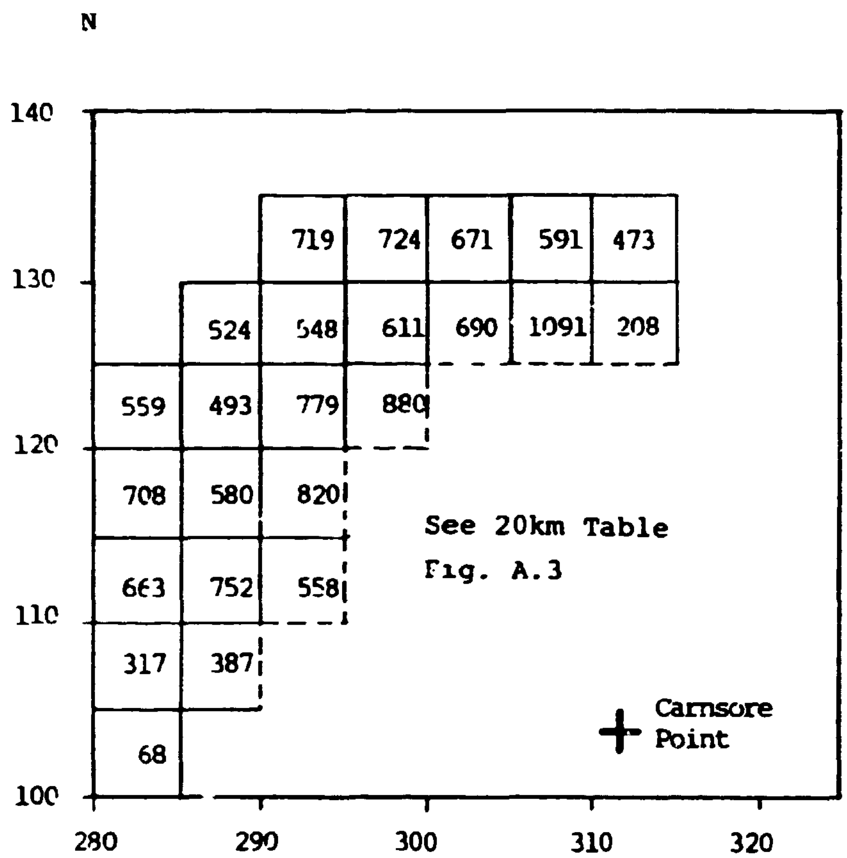


Fig. A.2. Resident population, 1979, in 5 x 5 km squares within 30 km of Carnsore Point. (Coordinate system: National Grid).

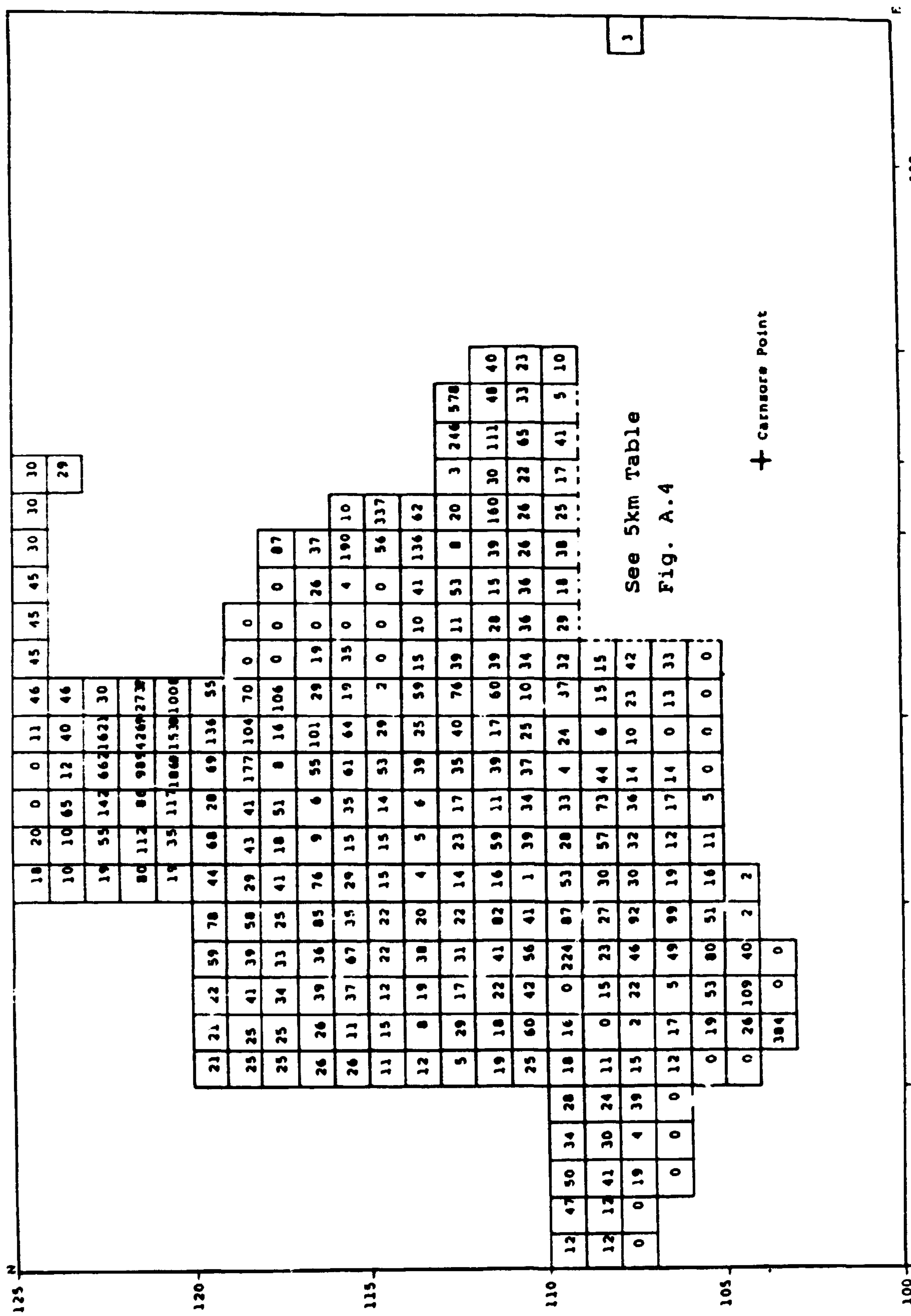


Fig. A.3. Resistent population, 1979, in 1 × 1km squares within 20 km of Carnsore Point. (Coordinate system in National Grid).

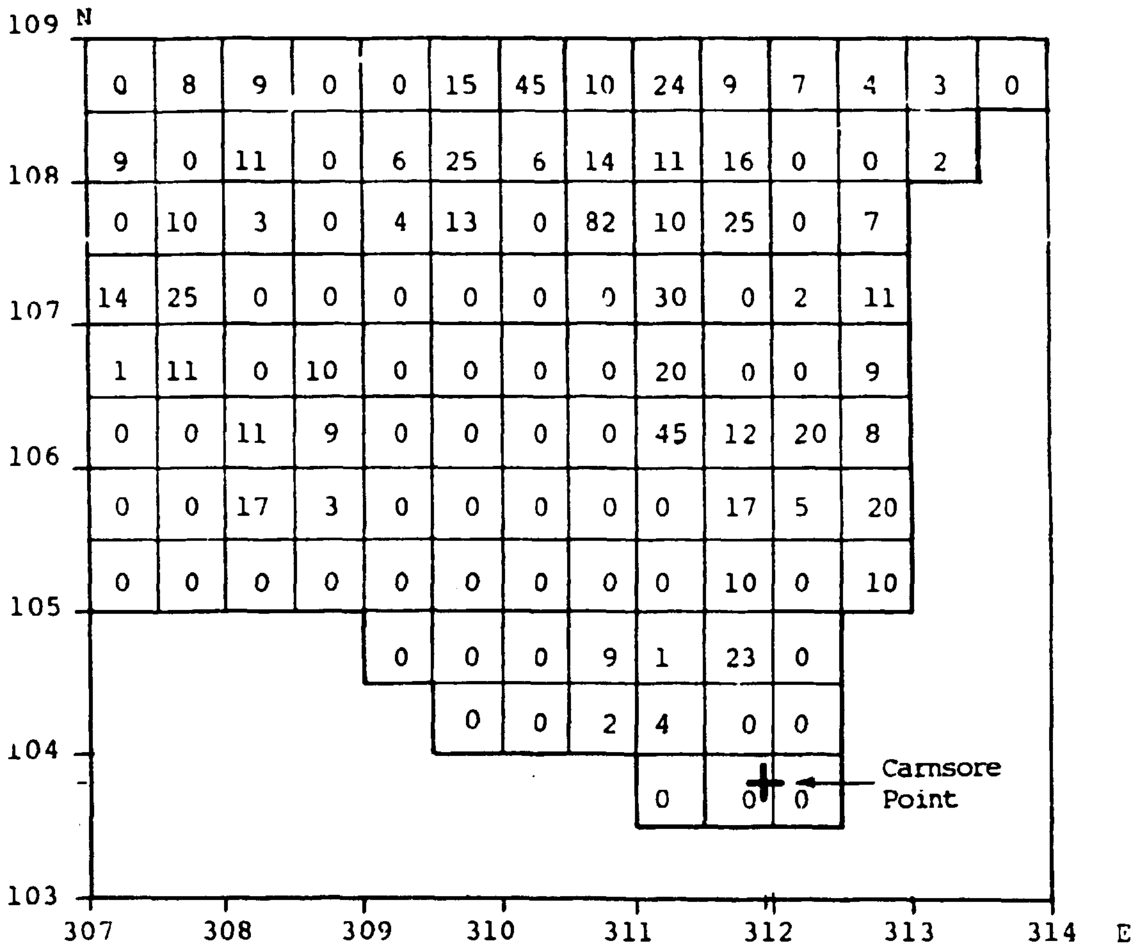


Fig. A.4. Resident population, 1979, in 0.5 x 0.5 km squares within 5 km of Carnsore Point.
(Coordinate system: National Grid).

APPENDIX 2

Forsøgsanlæg Risø
Reaktorteknikafdelingen

RP-4-80
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CALCULATION OF RADIOACTIVE INVENTORY IN A TYPICAL BWR AND IN A TYPICAL PWR. COMPARISON WITH WASH-1400

by

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Modern PWR operation is characterised by:

Discharge burn-up	33 MWd/kgU
Power density	34.4 kW/kgU
Enrichment	3.1 pct.
Fuel residence time	4 years or 960 full power days (with an assumed utilization factor of 66%).

The equilibrium core contains fuel that has had irradiations of between 0 and 33 MWd/kgU. At the start of the annual cycle, the four generations of fuel elements have average burn-ups of:

0, 8.25, 16.5 and 24.75 MWd/kgU (average = 12.4 MWd/kgU).

At the end of the annual cycle the burn-up values are:

8.25, 16.5, 24.75 and 33 MWd/kgU (average = 20.6 MWd/kgU).

BWRs have lower enrichment and power density; discharge burn-up is also smaller. Characteristic values can be:

Discharge burn-up	25 MWd/kgU
Power density	26 kW/kgU
Enrichment	2.6 pct.
Fuel residence time	4 years or 960 full power days with a utilization factor of 66%.

The average burn-up of the BWR then varies between 9.4 MWd/kgU and 15.6 MWd/kgU, with a mean value of 12.5 MWd/kgU.

As the build-up of fission products, especially the transuranics, may depend on a delicate balance between radioactive decay and neutron absorption, the resulting inventory of isotopes in a fuel load will be a function of numerous parameters, such as burn-up, power density, neutron spectrum, initial enrichment, reactor type - just to mention the more important ones.

It follows that it is hardly possible to put numerical values on the concentrations of all nuclides present in any unspecified light-water-reactor core, unless such values are encumbered with unreasonably large uncertainties.

Therefore we decided in the present case to find values for the two dominant reactor types, PWR and BWR, as specified in the text above. Table 1 lists a few of the more important radioactive elements at shut down (i.e. when maximum burn-up has been reached (T = 0)) and at 2,12 and 33 hours after shut-down. At T = 0 they are compared with the values given in WASH-1400, App. VI. It should be noted that the latter refer to a 3200 MWth reactor, run to an average burnup of 17.6 MWd/kgU at a power density of 40 kW/kgU. This corresponds to an energy production of E = 1.40 x 10^6 MWd. In our PWR and BWR cases energy production is greater, namely 1.92 x 10^6 MWd.

The three cases in Table 1 are then characterized in the following way:

	Power MWth	Power dens. kW/kgU	Burn-up MWd/kgU	Mass t U	Energy prod. MWd	Irr.time F.P.days
WASH-1400	3200	40	17.6	80	$1.4 \cdot 10^6$	438
PWR	3200	34.4	20.6	93	$1.92 \cdot 10^6$	600
BWR	3200	26	15.6	123	$1.92 \cdot 10^6$	600

Many of the trans-uranics come into being through long chains involving radioactive transmutations and neutron absorption. They are, therefore, much more sensitive than fission products to all the parameters mentioned above. As an example Table 2 lists a few isotopes, including four of the higher trans-uranics. The differences between them are large. (This might be due to different nuclear data). The WASH-1400 column shows these values multiplied by 1,37, the ratio of the energy production of the PWR and the BWR to that of the WASH-1400 reactor. Although multiplied by this ratio, the WASH-1400 numbers do not turn out to be conservative in all cases.

Table 1. Activities in 3200 MWth reactors. (10^8 Curies).
(1 Ci = $3.7 \cdot 10^{10}$ Becquereli)

		T = 0	T = 2h	T = 12h	T = 33h
Iodine 131,132, 133,134, 135	WASH-1400 PWR BWR	7.15 7.03 6.98	5.41	3.34	2.19
Cesium 134,136 137	WASH-1400 PWR BWR	0.152 0.137 0.118	0.137	0.137	0.135
Tellurium 127,127M 129,129M 131M,132	WASH-1400 PWR BWR	1.76 1.65 1.61	1.59	1.32	1.06
Barium 140	WASH-1400 PWR BWR	1.6 1.54 1.54	1.53	1.50	1.43
Strontium 89,90,91	WASH-1400 PWR BWR	2.08 2.01 2.10	1.86	1.36	1.00
Ruthenium 103,105, 106	WASH-1400 PWR BWR	2.07 2.42 2.25	2.20	1.71	1.57
Cerium 141,143 144	WASH-1400 PWR BWR	3.65 3.77 3.79	3.72	3.46	3.05
Neptunium 239	WASH-1400 PWR BWR	16.4 17.7 16.5	17.4	15.4	11.9

Table 2. Activities of some isotopes (10^8 Curies). 3200 MWth reactors.

	PWR	BWR	WASH-1400	WASH-1400*
Xe 135	0.45	0.31	0.34	0.47
Cs 137	0.061	0.061	0.047	0.064
Pu 241	0.082	0.065	0.034	0.047
Am 241	0.000053	0.000044	0.000017	0.000023
Cm 242	0.0131	0.0089	0.0050	0.0069
Cm 244	0.00027	0.00010	0.00023	0.00032

$$\text{WASH-1400*} = (\text{WASH-1400}) \times \frac{\text{Energy production of PWR (and BWR)}}{\text{Energy production of WASH-1400 reactor}}$$

APPENDIX 3

Calculation of the amounts of radionuclides released in the different release categories considered. As mentioned earlier, a PWR with the specifications mentioned in Appendix 2 also constitutes the basis for BWR release calculations.

Computer calculations are made of the PWR core inventory at shut-down time (Fig. A 1), in half-hour steps up to 10 hours, and in two-hour steps up to 30 hours.

The inventory amounts of radionuclides are a sum of exponential functions which in turn describe an exponential curve - at least during the time periods considered - of the form: a exp. (bt). Hence the amount released of a given radionuclide in a given period can be calculated as

$$Q = \frac{rf}{t_2-t_1} \int_{t_1}^{t_2} a \exp(bt)\, dt = rf \frac{Q_1-Q_2}{\ln Q_1/Q_2}$$

where

- Q = amount of a given radionuclide released during the release period
- rf = release fraction, as given in Fig. 4.1.
- t_1 = start of release
- t_2 = end of release
- Q_1 = amount of isotope at the time $t = t_1$
- Q_2 = amount of isotope at the time $t = t_2$

Figures A 2 to A 12 show the amounts of radionuclides released in the release categories considered.

Activities are given i PBq (petabecquerel = 10^{15}Bq).

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	248	I 131	191o
Kr 85 m	57o	I 132	28oo
Kr 85	14.6	I 133	331o
Kr 87	1o6o	I 134	443o
Kr 88	147o	I 135	381o
Rb 86	1.45	Xe 131 m	26.9
Rb 88	15oo	Xe 133 m	1o1
Rb 89	197o	Xe 133	331o
Sr 89	2ooo	Xe 135 m	738
Sr 9o	1o9	Xe 135	1o5o
Sr 91	254o	Cs 134	111
Y 9o	112	Cs 136	64.5
Y 91	258o	Cs 137	142
Zr 95	34oo	Cs 138	365o
Zr 97	338o	Ba 14o	355o
Nb 95	34oo	La 14o	361o
Nb 97	34oo	Ce 141	331o
Mo 99	365o	Ce 143	314o
Tc 99 m	322o	Ce 144	226o
Ru 1o3	297o	Pr 143	31oo
Ru 1o5	19oo	Pr 144	228o
Ru 1o6	732	Nd 147	131o
Rh 1o5	18oo	Pm 147	312
Rh 1o6	8o2	Pm 149	1o2o
Sb 127	1o7	Np 239	4o84o
Sb 129	587	Pu 238	1.39
Te 127 m	17.o	Pu 239	o.639
Te 127	1o5	Pu 24o	o.697
Te 129 m	1o7	Pu 241	191
Te 129	565	Am 241	o.122
Te 131 m	264	Cm 242	33.8
Te 131	17oo	Cm 244	o.639
Te 132	275o		

Fig. A 1. Core inventory at shut down.

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	169	I 133	2160
Kr 85 m	335	I 134	716
Kr 85	13.1	I 135	2000
Kr 87	210	Xe 131 m	24.1
Kr 88	670	Xe 133 m	90.6
Rb 86	0.574	Xe 133	3000
Rb 88	321	Xe 135 m	387
Rb 89	0.455	Xe 135	1310
Sr 89	100	Cs 134	44.4
Sr 90	5.42	Cs 136	25.7
Sr 91	104	Cs 137	56.9
Y 90	0.336	Cs 138	42.4
Y 91	7.75	Ba 140	177
Zr 95	10.2	La 140	10.8
Zr 97	9.05	Ce 141	9.95
Nb 95	10.2	Ce 143	8.91
Nb 97	9.53	Ce 144	6.76
Mo 99	1420	Pr 143	9.31
Tc 99 m	1280	Pr 144	6.76
Ru 103	1180	Nd 147	3.91
Ru 105	494	Pm 147	0.938
Ru 106	292	Pm 149	2.99
Rh 105	712	Pu 238	0.0041
Rh 106	292	Pu 239	0.0019
Te 129 m	42.6	Pu 240	0.0021
Te 129	181	Pu 241	0.572
Te 131 m	99.4	Np 239	119
Te 131	41.2	Am 241	0.00037
Te 132	1070	Cm 242	0.091
I 131	1330	Cm 244	0.0018
I 132	1920		

Fig. A 2. PWR 1-release.

Start of release 2.5 hours after shut down

Duration of release 0.5 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	169	I 133	2160
Kr 85 m	335	I 134	716
Kr 85	13.1	I 135	2000
Kr 87	210	Xe 131 m	24.1
Kr 88	670	Xe 133 m	90.6
Rb 86	0.717	Xe 133	3000
Rb 88	401	Xe 135 m	387
Rb 89	0.569	Xe 135	1310
Sr 89	120	Cs 134	55.5
Sr 90	6.51	Cs 136	32.1
Sr 91	124	Cs 137	71.1
Y 90	0.447	Cs 138	53.0
Y 91	10.3	Ba 140	212
Zr 95	13.5	La 140	14.5
Zr 97	12.1	Ce 141	13.3
Nb 95	13.6	Ce 143	11.9
Nb 97	12.7	Ce 144	9.01
Mo 99	71.2	Pr 143	12.4
Tc 99 m	64.2	Pr 144	9.01
Ru 103	59.2	Nd 147	5.21
Ru 105	24.7	Pm 147	1.25
Ru 106	14.6	Pm 149	3.98
Rh 105	35.6	Pu 238	0.0055
Rh 106	14.6	Pu 239	0.0026
Te 129 m	32.0	Pu 240	0.0028
Te 129	136	Pu 241	0.763
Te 131 m	74.6	Np 239	159
Te 131	30.9	Am 241	0.00049
Te 132	806	Cm 242	0.121
I 131	1330	Cm 244	0.0025
I 132	1920		

Fig. A 3. PWR 2-release.

Start of release 2.5 hours after shut down

Duration of release 0.5 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	85.0	I 133	560
Kr 85 m	187	I 134	25.9
Kr 85	11.7	I 135	416
Kr 87	36.4	Xe 131 m	21.4
Kr 88	284	Xe 133 m	79.9
Rb 86	0.286	Xe 133	2640
Rb 88	75.2	Xe 135 m	249
Rb 89	0.00011	Xe 135	1310
Sr 89	40.0	Cs 134	22.2
Sr 90	2.17	Cs 136	12.7
Sr 91	3.3	Cs 137	28.4
Y 90	0.335	Cs 138	0.500
Y 91	7.74	Ba 140	70.2
Zr 95	10.1	La 140	10.8
Zr 97	8.00	Ce 141	9.93
Nb 95	10.2	Ce 143	8.37
Nb 97	8.50	Ce 144	6.76
Mo 99	104	Pr 143	9.30
Tc 99 m	95.1	Pr 144	6.76
Ru 103	88.6	Nd 147	3.88
Ru 105	23.2	Pm 147	0.938
Ru 106	21.9	Pm 149	2.89
Rh 105	52.0	Pu 238	0.0041
Rh 106	21.9	Pu 239	0.0019
Te 129 m	31.9	Pu 240	0.0021
Te 129	95.4	Pu 241	0.572
Te 131 m	69.6	Np 239	115
Te 131	12.9	Am 241	0.00037
Te 132	785	Cm 242	0.091
I 131	377	Cm 244	0.0018
I 132	536		

Fig. A 4. PWR 3-release

Start of release 5.0 hours after shut down
Duration of release 1.5 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	97.0	I 133	271
Kr 85 m	200	I 134	62.0
Kr 85	8.77	I 135	238
Kr 87	103	Xe 131 m	16.1
Kr 88	379	Xe 133 m	60.3
Rb 86	0.057	Xe 133	2000
Rb 88	26.2	Xe 135 m	235
Rb 89	0.040	Xe 135	894
Sr 89	10.0	Cs 134	4.44
Sr 90	0.542	Cs 136	2.56
Sr 91	9.82	Cs 137	5.69
Y 90	0.045	Cs 138	2.78
Y 91	1.03	Ba 140	17.6
Zr 95	1.35	La 140	1.45
Zr 97	1.17	Ce 141	1.33
Nb 95	1.36	Ce 143	1.17
Nb 97	1.23	Ce 144	0.901
Mo 99	10.6	Pr 143	1.24
Tc 99 m	9.60	Pr 144	0.901
Ru 103	8.87	Nd 147	0.520
Ru 105	3.33	Pm 147	0.125
Ru 106	2.19	Pm 149	0.395
Rh 105	5.30	Pu 238	5.51E-4
Rh 106	2.19	Pu 239	2.57E-4
Te 129 m	3.20	Pu 240	2.80E-4
Te 129	12.3	Pu 241	0.076
Te 131 m	7.33	Np 239	15.8
Te 131	3.12	Am 241	4.9E-5
Te 132	80.1	Cm 242	0.012
I 131	171	Cm 244	2.5E-4
I 132	245		

Fig. A 5. PWR 4-release

Start of release 2 hours after shut down

Duration of release 3 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
KR 83 m	152	I 133	88.8
KR 85 m	93.4	I 134	16.4
Kr 85	4.38	I 135	75.5
Kr 87	42.4	Xe 131 m	8.o3
Kr 88	17o	Xe 133 m	3o.1
Rb 86	o.o13	Xe 133	992
Rb 88	5.36	Xe 135 m	113
Rb 89	o.oo68	Xe 135	452
Sr 89	2.oo	Cs 134	o.998
Sr 9o	o.1o9	Cs 136	o.5[illegible]
Sr 91	1.9o	Cs 137	1.28
Y 9o	o.oo78	Cs 138	o.477
Y 91	o.181	Ba 14o	3.52
Zr 95	o.237	La 14o	o.253
Zr 97	o.2o1	Ce 141	o.232
Nb 95	o.238	Ce 143	o.2o3
Nb 97	o.211	Ce 144	o.158
Mo 99	2.11	Pr 143	o.217
Tc 99 m	1.91	Pr 144	o.158
Ru 1o3	1.77	Nd 147	o.o91
Ru 1o5	o.619	Pm 147	o.o22
Ru 1o6	o.438	Pm 149	o.o69
Rh 1o5	1.o5	Pu 238	9.6E-5
Rh 1o6	o.438	Pu 239	4.5E-5
Te 129 m	o.532	Pu 24o	4.9E-5
Te 129	1.95	Pu 241	o.o13
Te 131 m	1.21	Np 239	2.74
Te 131	o.5o9	Am 241	8.6E-6
Te 132	13.3	Cm 242	o.oo21
I 131	56.8	Cm 244	4.3E-5
I 132	81.5		

Fig. A 6, PWR 5-release

Start of release 2 hours after shut down

Duration of release 4 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	2.16	I 133	3.86
Kr 85 m	13.4	I 134	2.5E-4
Kr 85	4.38	I 135	1.32
Kr 87	o.o78	Xe 131 m	8.o3
Kr 88	8.31	Xe 133 m	28.4
Rb 86	o.ooll	Xe 133	972
Rb 88	o.o22	Xe 135 m	29.1
Rb 89	o	Xe 135	375
Sr 89	o.179	Cs 134	o.c89
Sr 9o	o.oo98	Cs 136	o.o5o
Sr 91	o.o67	Cs 137	o.114
Y 9o	o.ooll	Cs 138	4.1E-8
Y 91	o.o26	Ba 14o	o.3o8
Zr 95	o.o34	La 14o	o.o36
Zr 97	o.o17	Ce 141	o.o33
Nb 95	o.o34	Ce 143	o.o22
Nb 97	o.o17	Ce 144	o.o22
Mo 99	o.215	Pr 143	o.o31
Tc 99 m	o.2o2	Pr 144	o.o22
Ru lo3	o.2o5	Nd 147	o.o13
Ru lo5	o.olo	Pm 147	o.oo31
Ru lo6	o.o51	Pm 149	o.oo83
Rh lo5	o.lol	Pu 238	1.4E-5
RH lo6	o.o51	Pu 239	6.4E-6
Te 129 m	o.lo6	Pu 24o	6.9E-6
Te 129	o.114	Pu 241	o.oo19
Te 131 m	o.179	Np 239	o.334
Te 131	o.o32	Am 241	1.2E-6
Te 132	2.37	Cm 242	3.oE-4
I 131	3.63	Cm 244	6.2E-6
I 132	4.82		

Fig. A 7. PWR 6-release

Start of release 12 hours after shut down

Duration of release 10 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	7.2E-4	I 133	3.5E-4
Kr 85 m	1.6E-3	I 134	3.7E-4
Kr 85	4.4E-5	I 135	3.8E-4
Kr 87	2.1E-3	Xe 131 m	8.oE-5
Kr 88	3.9E-3	Xe 133 m	3.oE-4
Rb 86	8.6E-7	Xe 133	9.9E-3
Rb 88	8.2E-4	Xe 135 m	1.7E-3
Rb 89	1.6E-4	Xe 135	3.6E-3
Sr 89	2.oE-8	Cs 134	6.7E-5
Sr 9o	1.1E-9	Cs 136	3.9E-5
Sr 91	2.4E-8	Cs 137	8.5E-5
Y 9o	o	Cs 138	8.4E-4
Y 91	o	Ba 14o	3.5E-8
Zr 95	o	La 14o	o
Zr 97	o	Ce 141	o
Nb 95	o	Ce 143	o
Nb 97	o	Ce 144	o
Mo 99	o	Pr 143	o
Tc 99 m	o	Pr 144	o
Ru 1o3	o	Nd 147	o
Ru 1o5	o	Pm 147	o
Ru 1o6	o	Pm 149	o
Rh 1o5	o	Pu 238	o
Rh 1o6	o	Pu 239	o
Te 129 m	1.1E-7	Pu 24o	o
Te 129	5.5E-7	Pu 241	o
Te 131 m	2.6E-7	Np 239	o
Te 131	9.6E-7	Am 241	o
Te 132	2.7E-6	Cm 242	o
I 131	2.oE-4	Cm 244	o
I 132	3.oE-4		

Fig. A 8, PWR 9-release

Start of release 0.5 hours after shut down
Duration of release 0.5 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	2ol	I 133	125o
Kr 85 m	4o2	I 134	555
Kr 85	14.6	I 135	12oo
Kr 87	3o7	Xe 131 m	26.8
Kr 88	843	Xe 133 m	1ol
Rb 86	o.574	Xe 133	331o
Rb 88	355	Xe 135 m	45o
Rb 89	1.79	Xe 135	14oo
Sr 89	1oo	Cs 134	44.4
Sr 9o	5.42	Cs 136	25.7
Sr 91	1o7	Cs 137	56.9
Y 9o	o.559	Cs 138	81.1
Y 91	12.9	Ba 14o	177
Zr 95	16.9	La 14o	18.1
Zr 97	15.4	Ce 141	16.6
Nb 95	17.o	Ce 143	15.o
Nb 97	16.1	Ce 144	11.3
Mo 99	179o	Pr 143	15.5
Tc 99 m	161o	Pr 144	11.3
Ru 1o3	148o	Nd 147	6.52
Ru 1o5	668	Pm 147	1.56
Ru 1o6	366	Pm 149	5.oo
Rh 1o5	892	Pu 238	o.oo69
Rh 1o6	366	Pu 239	o.oo32
Te 129 m	74.6	Pu 24o	o.oo35
Te 129	332	Pu 241	o.953
Te 131 m	176	Np 239	2oo
Te 131	112	Am 241	o.ooo61
Te 132	19oo	Cm 242	o.151
I 131	762	Cm 244	o.oo31
I 132	11oo		

Fig. A 9. BWR 1-release

Start of release 2 hours after shut down

Duration of release 0.5 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	o.o89	I 133	1o7o
Kr 85 m	4.32	I 134	2.3E-7
Kr 85	14.6	I 135	122
Kr 87	3.6E-5	Xe 131 m	26.7
Kr 88	o.6o4	Xe 133 m	85.6
Rb 86	o.686	Xe 133	311o
Rb 88	o.3o4	Xe 135 m	19.9
Rb 89	o	Xe 135	586
Sr 89	197	Cs 134	55.4
Sr 9o	1o.9	Cs 136	3o.1
Sr 91	25.1	Cs 137	71.1
Y 9o	o.444	Cs 138	o
Y 91	1o.2	Ba 14o	331
Zr 95	13.4	La 14o	14.1
Zr 97	3.68	Ce 141	13.o
Nb 95	13.6	Ce 143	6.5o
Nb 97	3.81	Ce 144	8.99
Mo 99	79.o	Pr 143	12.2
Tc 99 m	75.1	Pr 144	8.99
Ru 1o3	86.9	Nd 147	4.83
Ru 1o5	7.7o	Pm 147	1.25
Ru 1o6	21.9	Pm 149	2.76
Rh 1o5	33.1	Pu 238	o.oo55
Rh 1o6	21.9	Pu 239	o.oo26
Te 129 m	31.3	Pu 24o	o.oo28
Te 129	21.o	Pu 241	o.762
Te 131 m	38.4	Np 239	112
Te 131	6.92	Am 241	5.oE-4
Te 132	625	Cm 242	o.121
I 131	156o	Cm 244	o.oo25
I 132	191o		

Fig. A 10. BWR 2-release

Start of release 30 hours after shut down

Duration of release 3 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	o.o89	I 133	119
Kr 85 m	4.32	I 134	2.6E-8
Kr 85	14.6	I 135	13.5
Kr 87	3.6E-5	Xe 131 m	26.7
Kr 88	o.6o4	Xe 133 m	85.6
Rb 86	o.137	Xe 133	311o
Rb 88	o.o61	Xe 135 m	19.9
Rb 89	o	Xe 135	586
Sr 89	19.7	Cs 134	11.1
Sr 9o	1.o9	Cs 136	6.o2
Sr 91	2.51	Cs 137	14.2
Y 9o	o.444	Cs 138	o
Y 91	1o.2	Ba 14o	33.1
Zr 95	13.4	La 14o	14.1
Zr 97	3.68	Ce 141	13.o
Nb 95	13.6	Ce 143	6.5o
Nb 97	3.81	Ce 144	8.99
Mo 99	52.7	Pr 143	12.2
Tc 99 m	5o.1	Pr 144	8.99
Ru 1o3	57.9	Nd 147	4.83
Ru 1o5	5.13	Pm 147	1.25
Ru 1o6	14.6	Pm 149	2.76
Rh 1o5	22.1	Pu 238	o.oo55
Rh 1o6	14.6	Pu 239	o.oo26
Te 129 m	31.3	Pu 24o	o.oo28
Te 129	21.o	Pu 241	o.762
Te 131 m	38.4	Np 239	112
Te 131	6.92	Am 241	5.oE-4
Te 132	625	Cm 242	o.121
I 131	173	Cm 244	o.oo25
I 132	212		

Fig. A 11. BWR 3-release

Start of release 30 hours after shut down

Duration of release 3 hours

Isotope	Amount (PBq)	Isotope	Amount (PBq)
Kr 83 m	5.3E-2	I 133	5.7E-6
Kr 85 m	1.2E-1	I 134	3.7E-7
Kr 85	7.3E-3	I 135	4.2E-6
Kr 87	2.7E-2	Xe 131 m	1.3E-2
Kr 88	1.8E-1	Xe 133 m	5.oE-2
Rb 86	5.7E-9	Xe 133	1.6E+o
Rb 88	1.5E-6	Xe 135 m	1.6E-1
Rb 89	3.9E-11	Xe 135	8.1E-1
Sr 89	1.6E-1o	Cs 134	4.4E-7
Sr 9o	8.7E-12	Cs 136	2.5E-7
Sr 91	1.3E-1o	Cs 137	5.7E-7
Y 9o	o	Cs 138	2.4E-8
Y 91	o	Ba 14o	2.9E-1o
Zr 95	o	La 14o	o
Zr 97	o	Ce 141	o
Nb 95	o	Ce 143	o
Nb 97	o	Ce 144	o
Mo 99	o	Pr 143	o
Tc 99 m	o	Pr 144	o
Ru 1o3	o	Nd 147	o
Ru 1o5	o	Pm 147	o
Ru 1o6	o	Pm 149	o
Rh 1o5	o	Pu 238	o
Rh 1o6		Pu 239	o
Te 129 m	8.5E-1o	Pu 24o	o
Te 129	2.6E-9	Pu 241	o
Te 131 m	1.8E-9	Np 239	o
Te 131	4.1E-1o	Am 241	o
Te 132	2.1E-8	Cm 242	o
I 131	3.9E-6	Cm 244	o
I 132	5.5E-6		

Fig. A 12. BWR 5-release

Start of release 3.5 hours after shut down

Duration of release 5 hours

Sales distributors:
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