Technical University of Denmark

A technical evaluation of Jan Beyea's report: "A study of some of the consequences of hypothetical reactor accidents at Barsebäck"

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Abstract

This report contains a critical review of Jan Beyea's report: A Study of Some of the Consequences of Hypothetical Reactor Accidents at Barsebäck (Princeton University, January 1978).

The conclusion of the evaluation is that the early consequences in particular are much overestimated because of rough approximations and the inclusion of unrealistic sets of parameters.

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INTRODUCTION

In February 1978 the Swedish Energy Commission issued a report with the title "A Study of Some of the Consequences of Hypothetical Reactor Accidents at Barsebäck". This report was prepared for the Commission by Jan Beyea, Center for Environmental Studies, Princeton University, as a critical check of the official Swedish calculations.

At the request of the Commission, a draft of the Beyea report was commented upon by Risø in October 1977. These comments were forwarded to the Energy Commission, who thereafter forwarded them to Beyea. In a similar fashion, comments were made on Beyea's draft report by AB Atomenergi, Sweden, and by the Sandia Laboratories, USA.

These comments led the author to revise his presentation on a few points, but, in spite of the criticism raised, the conclusions of the provisional report remained unaltered in the final report.

In the following, comments are given on the points in the Beyea report that are the main reason why its results for early consequences deviate significantly from the results of other, similar calculations, hereunder those described in Risø Report No. 356: "Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-Melt Accidents at the Barsebäck Reactor".

METHOD

In the Risø Report the relevant parameters were chosen so as to maximize the doses in the Copenhagen area, in as much as the choice took into account the correlation of the parameters and the probability distribution of their magnitudes. Thereafter the doses were calculated as a function of distance from Barsebäck, assuming that the concentration in the plume is normally distributed both vertically and horizontally in the plane at right angles to the wind direction.

Beyea calculates the doses at a number of distances from Barsebäck in the wind direction. These distances are stated for the area within 50 km of Barsebäck, where he uses the distances 5, 10, 15, 20 --- up to 50 km. He considers the calculated doses to apply to areas that lie symmetrically around the calculation points and have the width of the plume ($3\ \sigma_y$) and a length of 5 km (in the wind direction). This implies a very rough picture of the geographical distribution of the doses. For example, Beyea's intervals are particularly inappropriate in connection with Copenhagen. As figure 1 shows, one of his calculation points is placed on the coast of the Sound. The dose that is calculated at this point will not be the average dose for the sub-area that receives the highest doses in Copenhagen. Due to the threshold effect for early consequences, this may give en overestimation of these consequences.

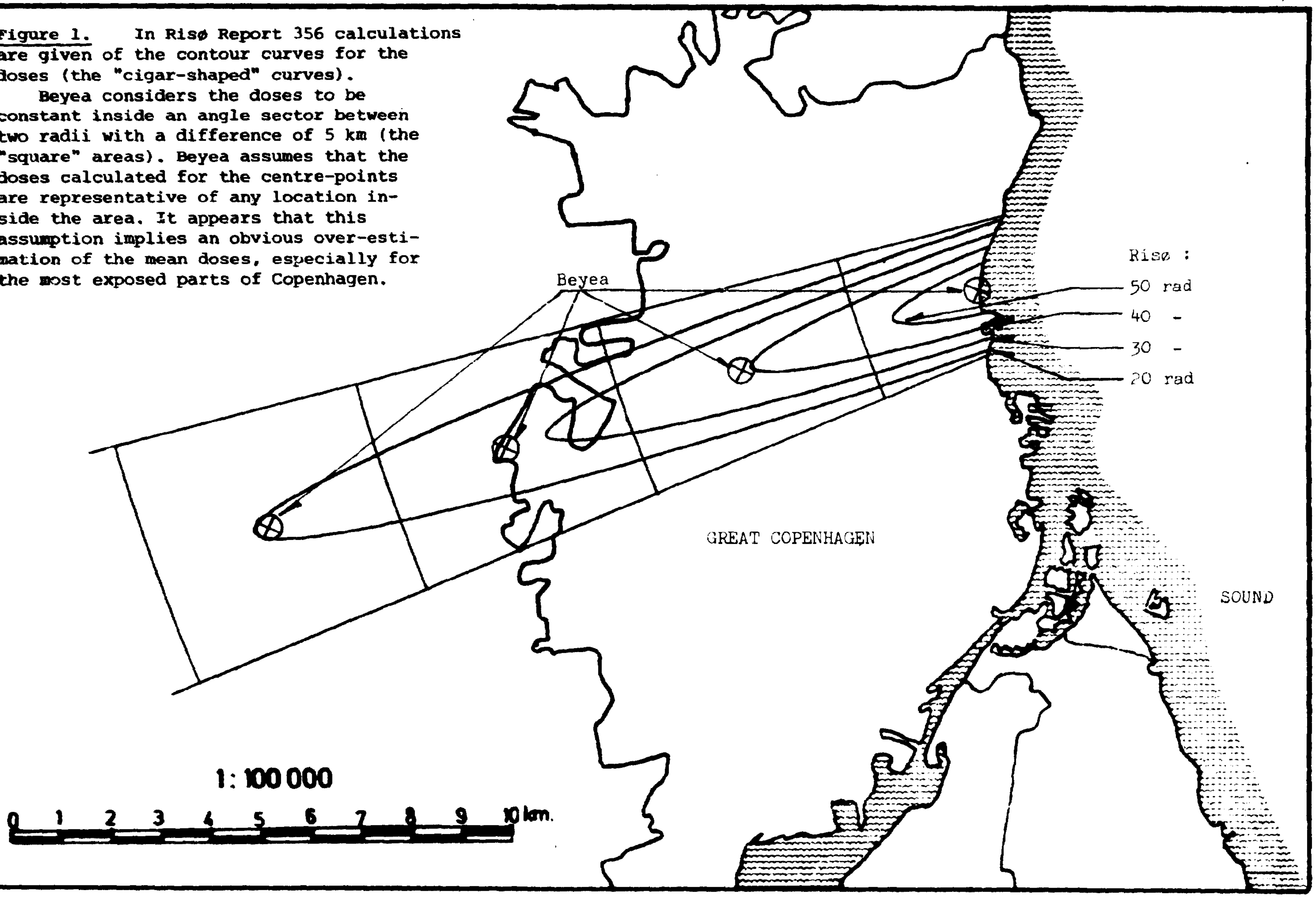
Beyea varies the model parameters over a large interval, making totally 1000 calculations with parameter values chosen by Monte Carlo technique. We doubt that 1000 calculations are enough to give a good picture of the significance of the parameters when so many parameters are varied independently. In addition, the choice of the parameter intervals is unrealistic in several cases. This point is further discussed later in the present report.

RISE OF THE HOT RADIOACTIVE CLOUD

Beyea's report does not include any calculation of the height that the hot cloud would reach as a result of buoyancy. The height is picked randomly in the interval between zero and an upper limit, which is representative of the extent of the atmospheric boundary layer. The height is ascribed the same probability over the whole interval. Thus the results are quite unrealistically influenced by the large consequences that can be conceived as results of extreme values of the plume rise combined with

Figure 1. In Risø Report 356 calculations are given of the contour curves for the doses (the "cigar-shaped" curves).

Beyea considers the doses to be constant inside an angle sector between two radii with a difference of 5 km (the "square" areas). Beyea assumes that the doses calculated for the centre-points are representative of any location inside the area. It appears that this assumption implies an obvious over-estimation of the mean doses, especially for the most exposed parts of Copenhagen.



extreme values for the dry deposition velocity (see figure 4).

The author defends this method (page II-11) by reference to an article by G.A.Briggs, an atmosphere physicist, whose work on smoke plume rise is generally acknowledged. The quotation is taken from the introduction to the article, where Briggs opposes the numerous, often unusable formulas for calculating smoke plume rise that have appeared. However, the same article ends up with a derivation of the formula used in Risø Report No. 356 to calculate the plume rise. Briggs remarks that this formula is "widely supported by field observations and by some modelling experiments. Perhaps over 90% of field observations of buoyant plumes are approximated by this formula". WASH-1400 (the CRAC manual) and Risø both use the Briggs formula for calculating the plume rise.

Briggs formula includes the final height. To advoid an iteration in the calculations, it is generally chosen to calculate conservatively, i.e., to insert a height that is so small that the maximum concentration is not underestimated. In all Risø's calculations this height was set to 25 m, which is less than the smallest plume rise calculated (43 m).

In the discussion of the plume rise used by Risø (table II-1, page II-10), Beyea assumes that the heat release is proportional to the thermal reactor power. The heat content of an accidental release depends, however, on many factors, among others the design of the reactor (content of water in the reactor tank and the wet well) and the duration of the accident. In WASH-1400 no simple correlation between heat release and reactor power is assumed, and therefore no such down-scaling was made in Risø Report No. 356. The method suggested by Beyea cannot, however, be called unreasonable.

In Risø's provisional comments it was pointed out that Beyea did not take into account the self-heating of the release due to radioactive decay. In the activity release under consideration, the radioactive decay would develop a power of 2000-5000 kw, which would imply a further lift of the cloud. This additional lift is not taken into account in the calculations made at Risø, but it is pointed out that, in the majority of the cases, the doses are therefore overestimated. As Beyea emphasizes (page II-11), the results are very sensitive to the plume rise, hence it is surprising that he still neglects this effect in his final report.

DRY DEPOSITION OF RADIOACTIVITY ON THE GROUND

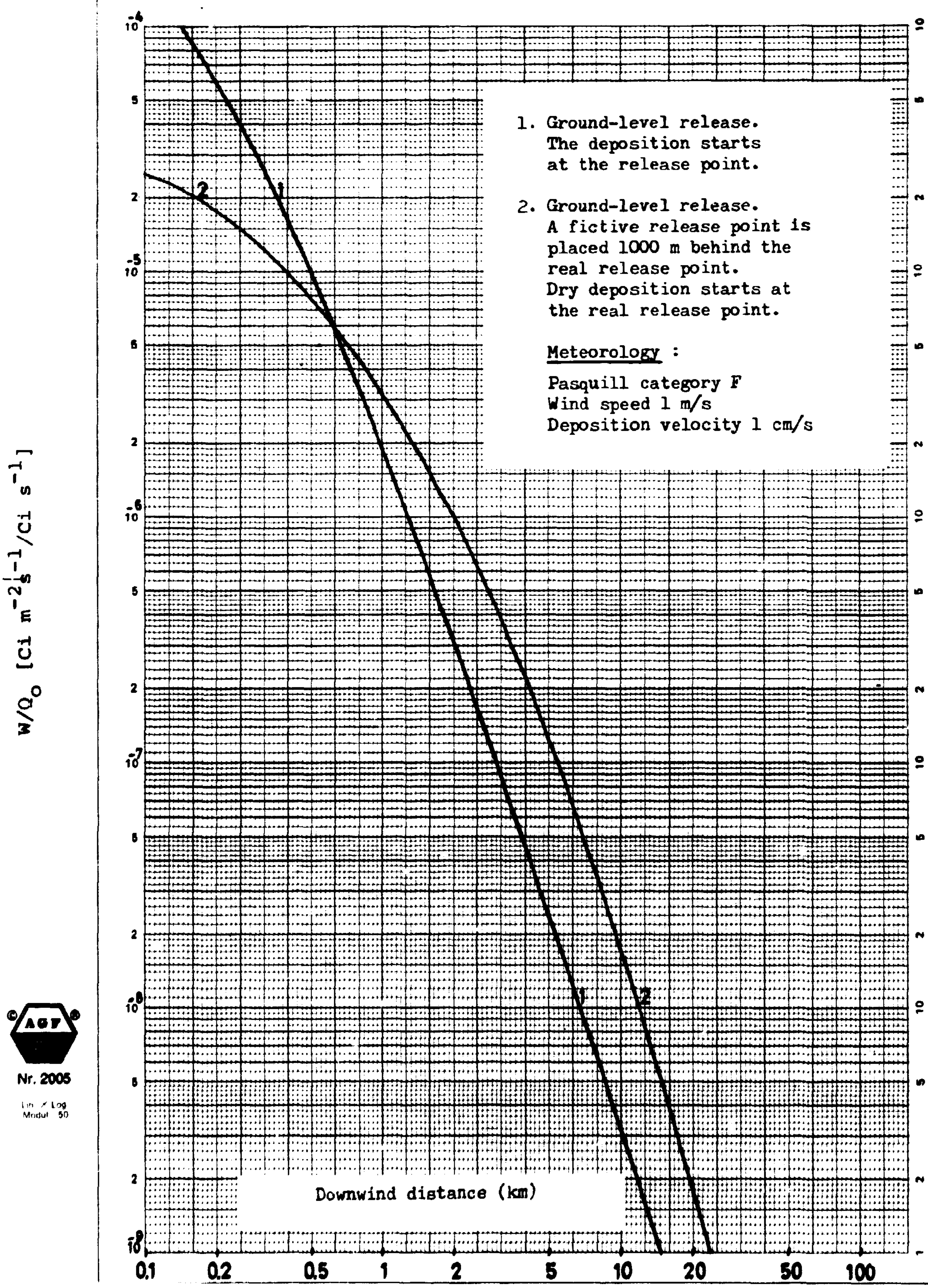
Beyea's method of calculating the radioactivity dry-deposited on the ground deviates considerably from the method of calculation used by Risø. This difference means that, for releases at ground level (such cases are included in Beyea's calculations) combined with large deposition rates (see the section on deposition velocity), the activity deposited becomes more than 1000 times greater than that calculated by Risø. In stable weather situations this applies to distances up to 50 km from the point of release. As the maximum consequences, according to Beyea, are those that originate from radiation from activity deposited in stable weather situations (page J-14), this difference can lead to extremely deviating results.

The difference between the calculation methods used by Beyea and those used by Risø may briefly be described as follows:

Beyea takes into account building turbulence (initial dispersion) by calculating the distribution of the activity as if it was released at a 'fictive' release point placed behind the actual release point. The location of this fictive release point is determined by assuming that the vertical dispersion parameter must have a given value at the actual source point. This value is determined on the basis of assumptions about the dimensions of the building, and is thus independent of atmospheric stability. In connection herewith, dry deposition is calculated as if it started at the actual release point, so that there is no deposition for the distance between the fictive and the actual release point.

Figure 2 shows the difference between the results in a situation with and without a fictive release point, respectively, in a stable weather sitaution with low wind speed (Pasquill F, wind speed u = 1 m/s and deposition velocity v_g = 1 cm/s).

Figure 2. Rate of deposition on the ground normalized to the release rate.



The curves are calculated on the basis of a smoke plume model where the concentration is assumed to be uniformly distributed. The width and height of the plume are given by $\alpha \cdot x^p$ and $\beta \cdot x^q$, respectively, where x is the distance from the release point in the wind direction. The parameters α, β, p and q are fitted to the usual Pasquill-Gifford dispersion parameters.

Curve 1 shows the normalized deposition rate on the ground (deposited amount per unit area per unit time/released amount per unit time from a release at ground level). Curve 2 shows the deposition rate for a release from a fictive release point located 1000 m behind the actual release point, and assuming that the deposition starts at the actual release point. At distances greater than a couple of km from the actual release point, the amount deposited on the ground will be 6 times larger for situations with a fictive release point. With a wind speed of 2 m/s and a deposition velocity of 10 cm/s, the amount deposited will be 1000 times greater, as already mentioned. Corresponding results are found for a Gaussian dispersion model.

It is primarily Beyea's assumption that dry deposition starts at the actual release point that gives rise to the large differences in question. This assumption is questionable. Normally, it must be assumed that turbulence around a building will strongly increase the deposition, so that the deposition is much greater here than in the open country. To take this into consideration, the deposition should at least be calculated as if it started at the fictive release point. If so, the deposition rate on the ground will coincide with curve 1 at downwind distances greater than a few kilometres.

CHOICE OF DRY DEPOSITION VELOCITIES

In the same way as for the plume rise ΔH, Beyea selects the deposition velocity v_g within a broad interval (0.1 - 10 cm/s). He takes v_g as a random variable distributed uniformly on a log scale. The use of a log scale ensures that the low values are treated on an equal footing with the high values. Beyea estimates (page III-7) that the method of choosing ΔH and v_g randomly in a broad interval implies a ten-doubling of the consequences relative to the WASH-1400 method, where ΔH is calculated and v_g is ascribed a mean value.

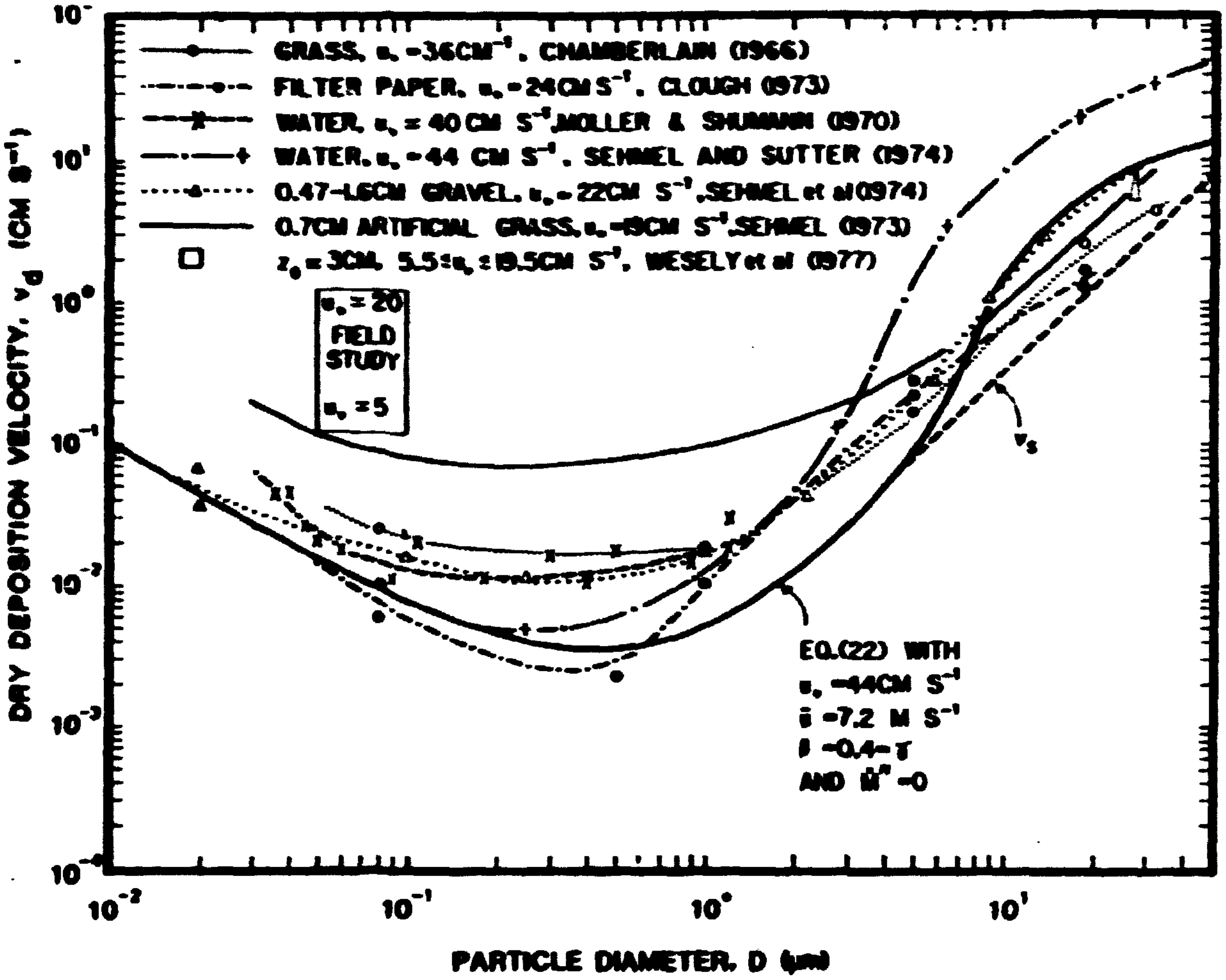
In Beyea's report it is stated (page II-8) that use of his method ensures that the worst cases associated with the unknown parameters are included. If the purpose of Beyea's study is to estimate the consequences of a reactor accident at Barsebäck rather than to make a mathematical parameter study, we consider his method to be unsuitable.

W.G.N. Slinn, in "Some Comments on Parameterizations for Resuspension and for Wet and Dry Deposition of Particles and Gases for Use in Radiation Dose Calculations", May 1977, states that there are a number of experimental results for the dependence of v_g on the particle size of the material in question. In WASH-1400 (appendix VI page K-1 and K-6) it is stated that the expected particle size in a release from a core melt accident is of the order of magnitude of a few microns in diameter and hardly larger than 10 microns.

This assumption is confirmed by the Karlsruhe reports: Nukleare Aerosole im geschlossenen System (KFK 1985), PARDISEKO III - A Computer Code for Determining the Behaviour of Contained Nuclear Aerosols (KFK 2151) and Projekt Nukleare Sicherheit (KFK 2130, page 276-299), in which are described problems concerning radioactive aerosols created inside a reactor containment during a fuel melt. These reports give results of model calculations based on experimental investigations where UO_2 is evaporated. The size distribution of the nuclear aerosols is stated to be log-normal with a geometric mean diameter of 0.1-0.3 micron.

If, in accordance with these references, it is assumed that the expected particle size in a core melt release lies in the range 0.1-10 micron, then the deposition velocity lies in the range 0.005-1 cm/s for areas of land (cf. fig. 3).

Furthermore, measurements made on Danish territory of the deposition velocity of short-lived fission products (iodine among others) from Chinese nuclear weapons testing show that the deposition velocity for these materials lies in the range 0.1-1 cm/s (Risø Report No. 361: Environmental Radioactivity in Denmark in 1976 by A. Aarkrog and J. Lippert). Although reactor accidents and nuclear weapons testing cannot be directly compared, the particles in question may be expected to be more or less of the same sizes as the material released in a reactor accident. This confirms the assumption that the deposition velocities are less than 1 cm/s. Beyea's choice of deposition velocities as



<u>Figure 3.</u> The influence of particle size on deposition velocity. For areas of land the deposition velocity will be in the interval 0.005 - 1 cm/s for particle sizes between 0.1 μm and 10 μm.

Source: W.G.N. Slinn, Some Comments on Parameterizations for Resuspension and for Wet and Dry Deposition of Particles and Gases for Use in Radiation Dose Calculations.

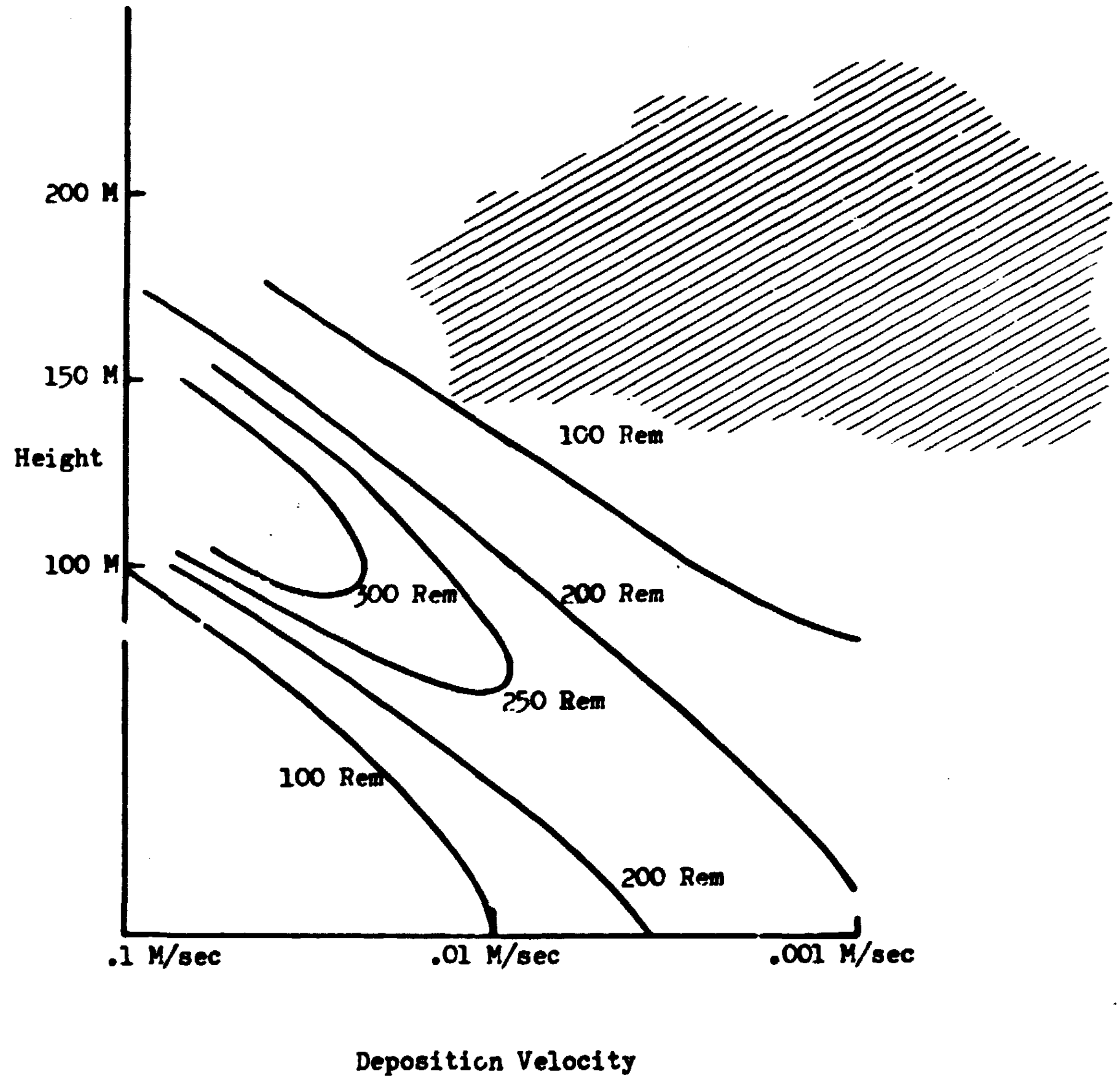


Figure 4. Sample Dose Contours [Figure II-8 in Beyea's report] at 17 miles from a BWR 1 accident. 2 m/sec wind, stability class F, 24 hr ground dose.

In Beyea's calculations all points on the figure are considered possible and therefore he finds doses up to 400 rem. For particle sizes between 0.1 and 10 μm (see figure 3), and with the plume rises calculated from Briggs' formula, the doses will probably lie in the hatched area being less than 100 rem.

large as 10 cm/s is therefore unrealistic.

The influence of deposition velocity/plume rise is shown in Beyea's report on page II-20. On a copy of figure II-8 (figure 4) an area is drawn that comprises the most probable values for deposition rate and plume rise. The value for plume rise used in Risø-M-1905 is 175 m. Even if the amount of heat released is assumed to be halved (as stated by Beyea), the contribution from the decay heat would be sufficent for the cloud to rise to about 175-200 m in the distance stated (cf. F.A. Gifford: The Rise of Strongly Radioactive Plumes, Journal of Applied Meterology 6, 644, August 1967).

As Beyea assumes that the two parameters ΔH and v_g are equally probable over the whole interval, he finds doses of up to 400 rem at a distance of 17 miles, where they may probably be lower than loo rem.

CHOICE OF WET DEPOSITION VELOCITIES

In calculating the activity washed out on the ground during precipitation, Beyea chooses only one value for the wash-out coefficient which, according to WASH-1400, applies to rain intensities of between 2 and 5 mm rain per hour. It would be more correct, and in agreement with the treatment of, e.g., the dry deposition velocity, if a distribution of the wash-out coefficient had been used which corresponded to the distribution of the rain intensity in the area of the Sound.

Beyea emphasizes (page J-12) that rain does not dominate his results unless his plume rise and dry deposition treatment is rejected. As stated in the foregoing section, we reject this treatment, and hence rain becomes dominant and arguments about wash-out coefficients become significant. In a rain situation, radiation doses to bone marrow are largely proportional to the wash-out coefficient, as the bone marrow dose is dominated by radiation from washed-out activity on the ground.

POPULATION DENSITY AND SHIELDING FACTOR

The method of letting the shielding factor depend on the population density (shielding for wooden houses is used for population densities of <80 people/km^2) is incorrect and leads to an overestimation of the doses in Denmark, the United Kingdom and on the North European mainland. In these areas only very few houses are built of wood, regardless of the population density.

Furthermore, far too rough a method is used for the determination of the population density in the area between 50 km and 1000 km. The population densities given in table II-9, page II-36, are weighted mean values that cover large local variations in population densities. Mean values are calculated for sector sections that cover both areas of water (the North Sea, the Baltic, etc.) as well as large towns (Hamburg, Amsterdam, etc.). The use of the mean population densities stated in the calculation of population doses, and the consequences derived herefrom, will give rise to errors, partly because of the large variations in population densities as mentioned, and partly because even relatively densely populated areas can, by this averaging, be placed under the fictive limit for wooden buildings.

In addition, Beyea's method of calculating individual doses from the passage of the cloud is incorrect. Statistically considered, 20% of the population are out of doors during the day and 80% are inside buildings. However, Beyea uses the approach that, for each geographical sub-area (5 km x $3\sigma_y$), the whole population is considered as being all outside or all inside buildings. It is inadequate to suppose that in 20% of the sub-areas the population is outside and in 80% the population is inside. This method may give reasonable results if the areas considered are small in relation to the characteristic dimensions of the cloud. Beyea's areas, which have the width of the cloud and a length of 5 km, are however so large that, for example, the whole population in the most exposed quarters of Copenhagen may be assumed to be out of doors during the passage of the cloud. A considerable number of his calculations for the Copenhagen area therefore result in too high doses, and thus in excessive consequences.

UNCERTAINTY

When a Monte Carlo method is used, the validity of the results depends on the number of simulations carried out. The adequacy of the number of simulations can only be established by estimating the uncertainty of the results. It is therefore a shortcoming of Beyea's work that this has not been done.

Beyea apparently maintains that the uncertainties can be estimated or eliminated by drawing a smoothed curve (comments to fig. II-lo, page II-39). However, a smoothed curve gives in itself no guarantee of a reliable result. If the shape of the curve had been estimated in advance, and if the results had proved to fit the expectations, then the results would have inspired more confidence. Alternatively, several simulations in blocks of 1000 could be carried out and then drawn. If the curves from the individual blocks agreed mutually, then again there would be more confidence in the results. The text indicates (page II-38) an approach to the last procedure; but even if this is the case, the results are not shown.

Moreover, Beyea maintains that by choosing the parameters at random from uniform distributions, he ensures that the cases with worst consequences will be taken into account (page II-8). This is not so. By using a uniform distribution, instead of a more realistic distribution, he only increases the probability that cases with large consequences will result from the simulations.

The "probability distributions" calculated in Beyea's report are not probability distributions in the normal sense as Beyea himself admits (page I-1, appendix I). As earlier pointed out, it is unreasonable to assume an almost total lack of knowledge of plume rise, as well as of the dry deposition velocity v_g. The "probability distributions" given in Beyea's report therefore only give an impression of how much the doses can vary when some of the parameters are varied.

The considerations of the sensitivity of the results to the assumed probability distributions of the parameters are only correct if these distributions have the true mean value and variance. While range, which is a measure of variance, is varied in Beyea's sensitivity analyses, the mean values, which are decisive for determining at which level the variation takes place, are apparently unvaried.

Moreover, the significance of changes in the wet deposition parameter is not investigated.

Considering how sensitive doses, and especially the consequences of doses are to changes in both plume rise and deposition parameters, it is essential to vary the mean values for these parameters.

THE RELATIONSHIP BETWEEN DOSES AND CONSEQUENCES

As is the case in Risø Report No. 356, Beyea bases the calculation of early fatalities on the probabilities given in WASH-1400. He classifies the doses in intervals of 50 rem, but instead of using the mean probabilities for early fatalities in these intervals, he uses the probabilities corresponding to the largest doses in the intervals.

Beyea admits (page J-13) that this is open to criticism, but he maintains that the effect is not significant. It implies, however, that in calculating the number of early fatalities all doses are increased to a multiple of 50 rem. Because the number of fatalities is an increasing function of the dose, the effect of Beyea's approximation is dose-dependent. When the number of fatalities calculated by Beyea is larger than 1000, the number should be divided by approximately 2. When the number is between 100 and 1000, it should be divided by 5-6, and when the calculated number is less than 100, it should be divided by more than 10, in some cases by infinity.

ACCIDENT PROBABILITY

Beyea asserts that the only basis that exists for calculating the probability of a catastrophic reactor accident is the fact that by the end of 1976, the total number of world reactor-years of commercial operation for large (500 MWe) nuclear plants was about 300 without the occurrence of any core melt-downs. On this basis he estimates the chance of a catastrophic accident occurring during the lifetime of the two Barsebäck plants to be no greater than one in five (page 1-27).

Accepting this form of argument would bring all technological development to a standstill as the probability of a catastrophe occurring to any technical innovation would be 1.

However, even if this method is applied, there is no argument for only considering reactors of more than 500 MWe. At present, western countries have accumulated experience from approximately 1400 reactor years, of which 700 years are light-water-reactor and 700 magnox-reactor years. In addition, approximately 1500 reactor years of experience have been accumulated with military light-water-reactors. During these more than 2000 light-water-reactor years there has been one accident (Browns Ferry), which in accordance with appendix C of Beyea's report had a probability of between 1:300 (Rasmussen) and 1:70-1:8 (Michael Grupp) of leading to a core melt-down. The probability that such a core-melt accident would have the nature of a catastrophe (i.e. more than one early fatality after 24 hours of exposure, assuming minimal medical treatment after the irradiation) is, according to fig. 1-3, page I-17, less than 1:4. Therefore the probability of a catastrophe at Barsebäck lies between 1:40 000 and 1:1000 during the operational lifetime of the two reactors, if Beyea's method is applied.

SUMMARY AND CONCLUSIONS

The objections to Beyea's calculations may be summarized in three points:

1. Compared to Risø's model, Beyea's model includes some rough approximations that all give rise to unnecessary overestimations of the doses and the consequences - in particular the early ones.

2. Beyea's analyses and conclusions depend critically on the type of a number of meteorological situations and on the meteorological processes dependent on these situations. By considering plume rise, deposition velocity, wind speed, wind direction, stability and precipitation partly as independent quantities, and not taking into account what probability there is for the combination of the parameter values, he obtains results that partly rest on a series of non-physical situations. It is in fact these situations, which give very large doses, that imply a large number of early fatalities, because of the non-linearity between doses and early consequences.

3. Beyea uses the Gaussian dispersion model for distances up to 1000 km, although normally the model is only considered valid within approximately 20-50 km.

In table I-7, page I-21, Beyea summarizes his results of calculations for wind directions towards Copenhagen. Twenty-four hours of irradiation, minimal medical treatment and no rain are assumed. Provided that a large accident has happened at Barsebäck, and that the wind direction is towards Copenhagen, then he finds the following probabilities of early fatalities in Denmark:

BWR 3 accident:	<1%	probability	for	early fatality
BWR 2 accident:	<1%	"	"	" "
BWR 1 accident:	50%	"	"	0 early fatalities
	10%	"	"	> 100 early fatalities
	1%	"	"	> 10000 early fatalities

The difference between these results and the results of Risø Report No. 356 is that Beyea's simulations lead to early fatalities in up to 50% of the BWR 1 accidents, while Risø finds that such fatalities are unlikely on Danish territorry.

In this connection is must be remarked that alone Beyea's choice of ΔH and v_g makes many of his dose calculation results too large (cf. figure 4) - unless Risø's assumptions concerning both ΔH and v_g are incorrect.

Additionally, the doses to the population in the most exposed sub-area will in some cases be overestimated because of the assumption that the whole population is outside during the passage of the plume.

Moreover, the average dose for the most exposed population in Copenhagen is too large -because of the unsuitable placing of the areas in relation to the Sound, cf. fig. 1 - and the calculated average dose is furthermore increased to the nearest multiple of 50 rem in the evaluation of the consequences.

In short, we are of the opinion that 50% of the BWR 1 simulations, which according to Beyea's interpretation may imply early fatalities, can be dismissed on the background of an unrealistic choice of parameters and too rough a method of calculation.

This is not in disagreement with Beyea's statements that "Relatively minor mistakes or questionable assumptions in accident simulations could conceivably have very large effects on predictions" (page I-16), and that his method will hardly underestimate the probability of the worst case consequences by more than a factor of ten, but that, on the other hand, his approach "can overestimate the prompt deaths by a very large numerical factor (including infinity)" (page II-8).

The conclusion of Risø's evaluation of Beyea's report is that its results, as far as early consequences are concerned, are strongly overestimated due to rough approximations and inclusion of unrealistic parameter sets. Moreover, Beyea's report does not point out any errors in the calculations described in Risø Report 356, so we find it proper to maintain that early fatalities are unlikely on Danish territory.

The long-term consequences are less dependent on the choice of parameter values. They are, however, to a certain degree influenced by the different approximations in Beyea's method. Further, it should be remembered that the calculations in Beyea's report rest on the same conservative assumptions as listed in the summary of Risø Report 356.