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Effect of Cross-Plume Concentration Model on Calculated Accident Consequences

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Abstract:

For reasons of numerical computation, the Gaussian plume model, which is used to describe the dispersion of released atmospheric contaminants, is replaced by a step function. In the U.S. Reactor Safety Study this function is a simple top-hat distribution (distribution width: 2 x $3.0\sigma_y$). To improve upon the top-hat treatment a cross-plume concentration distribution with four distinct concentration steps was used in Phase A of the German RSS (distribution steps at: $0.5\sigma_y$, $1.0\sigma_y$, $2\sigma_y$ and $3\sigma_y$). To determine the effect of the cross-plume concentration model on calculated accident consequences, a series of reactor accident calculations was performed using the Phase A German RSS consequence model and eight different cross-plume concentration models which include the U.S. RSS and the German RSS concentration distribution functions.

The results show that the U.S. top-hat distribution overestimates relative to the German RSS model the early fatalities and slightly underestimates the late fatalities. From all the computation results the conclusion can be drawn that for the calculation of early fatalities a 2-step distribution (for site specific calculation a 4-step distribution) might be adequate, whereas for the calculation of late fatalities a top-hat distribution is adequate.

Der Einfluß des azimutalen Konzentrationsmodells der Abluftfahne auf die berechneten Unfallfolgen

Kurzfassung

Aus Gründen der numerischen Behandlung wird die Gauß-förmig angenommene azimutale Konzentrationsverteilung der Abluftwolke durch eine Stufenfunktion angenähert. In der amerikanischen "Reactor Safety Study" ist dies eine einfache Kastenfunktion mit der Breite $2 \cdot \sigma_y$. Um gegenüber dieser einfachen Verteilung eine Verbesserung zu erzielen, wird in der deutschen Reaktor-Sicherheits-Studie/Phase A eine 4-Stufen-Funktion angewandt mit Stufen bei $0.5\sigma_y$, $1.0\sigma_y$, $2.0\sigma_y$ und $3.0\sigma_y$. Um den Einfluß der verschiedenen Stufen-Funktionen auf die berechneten Unfallfolgen abzuschätzen, wurde eine Reihe von Rechnungen durchgeführt. Diesen Rechnungen wurden neben den beiden Stufen-Funktionen weitere sechs sich voneinander unterscheidende Modelle zugrunde gelegt.

Die Ergebnisse dieser Untersuchung zeigen, daß das amerikanische Modell relativ zum deutschen Modell die Frühschäden überschätzt und die Spätschäden leicht unterschätzt. Aufgrund aller Ergebnisse kann der Schluß gezogen werden, daß zur Berechnung der Frühschäden eine 2-Stufen-Funktion (bei standortspezifischen Berechnungen eine 4-Stufen-Funktion) adequat ist, während zur Berechnung der Spätschäden eine Kastenfunktion ausreichend ist.

1) Introduction

The dispersion of released atmospheric contaminants is normally treated using a Gaussian plume model[1]. To simplify this treatment, the U.S. Reactor Safety Study (RSS)[2] replaced the Gaussian cross-plume shape with a uniform, or top-hat, distribution as shown in Figure 1. The concentration of radionuclides within the top-hat was determined by assuming 1.) a distribution width of $3\sigma_y$ [+)] (i.e., $-1.5\sigma_y \leq y \leq 1.5\sigma_y$) and 2.) that areas enclosed by the top-hat and Gaussian are identical. For a Gaussian of peak concentration P, the top-hat concentration was therefore

$$\frac{1}{3\sigma_y} \cdot \int_{-\infty}^{+\infty} P \cdot e^{-y^2/2\sigma_y^2} \, dy = P \cdot \frac{(2\pi)^{1/2}}{3} \simeq 0.836 \cdot P$$

This simplification has two effects on the calculation of accident consequences. First, consequences calculated using the top-hat are limited to the assumed width of the distribution, whereas in actuality they might occur over either wider, or narrower, areas. Second, all persons affected by the plume at a given distance are exposed to the same average radionuclide concentrations rather than the actual distribution of concentrations from 0 to some peak value. The calculation of early fatalities, which are a threshold effect, may be sensitive to these effects.

To improve upon the top-hat treatment, a cross-plume concentration distribution with four[++)] distinct concentration steps was used in Phase A of the German RSS. The distribution is shown in Figure 2. The concentration value within each inner step is the average of the Gaussian over the width of that step. For example, from $y = 1\sigma_y$ to $2\sigma_y$, the average concentration is

$$\frac{1}{1\sigma_y} \int_{1\sigma_y}^{2\sigma_y} P \cdot e^{-y^2/2\sigma_y^2} \, dy \simeq 0.341 \cdot P$$

+) σ_y is the lateral (cross-wind) atmospheric dispersion parameter (i.e., the standard deviation of concentration in the cross-plume direction).

++) The Gaussian was actually modeled using seven concentration steps. Because of symmetry, however, only four distinct concentration values were utilized.

For the outermost step, the Gaussian was integrated to infinity to include all radioactive material in the distribution tails.

To determine the effect of the cross-plume concentration model on calculated accident consequences, a series of reactor accident calculations was performed using the Phase A German RSS consequence model and eight different cross-plume concentration models. The results of these calculations are compared and discussed here.

2) Effect of Cross-Plume Concentration Models

A series of reactor accident consequence calculations was performed using eight different cross-plume concentration models in which both the number and width of steps were varied. Each model is described in Table 1 by the number of steps it includes, their outer distances (y/σ_y), and their concentrations relative to the centerline concentration P. Consequences were calculated using the German RSS Phase A consequence model and a uniform population density. Calculations were performed for two types of reactor accidents; categories 1 and 2 from the German RSS. Accident category 1 represents a core-melt followed by a steam explosion resulting in a large short duration release with significant plume rise. Accident category 2 represents a core-melt with large containment leakage of 3-hour duration, and negligible plume rise. For each accident category, 115 weather sequences were used to calculate a probability distribution for both early and latent cancer fatalities. The mean and peak values of these distributions are compared in Table 1 for each cross-plume model investigated. All values have been normalized to the corresponding value calculated using the German RSS model.

As indicated in Table 1, the calculated numbers of latent cancer fatalities are in general quite similar for each of the models investigated. This would be expected since the calculation of latent health effects is based on total population dose[+)] (i.e., no dose thresholds), which, except for the use of dose criteria in countermeasure models, is independent of the cross-plume model used. The U.S. top-hat appears to underestimate latent cancer fatalities by a small amount, although a top-hat with step at $2.0\sigma_y$ gives essentially identical results to the German 4-step model. The differences in calculated early fatalities are somewhat larger, with the U.S. top-hat overestimating by from 20 to 45% (the German model is presumed here to be the best estimate of actual consequences). Two of the models with only 2 concentration steps provide similar results to the German 4-step distribution, and might be adequate replacements. However, the use of actual rather than uniform population distributions may change the numerical values presented in Table 1, and therefore the relative conclusions. All effects described appear to be independent of accident category.

+) Latent cancer fatalities were calculated in the German RSS using a linear dose response model. Unlike in the U.S. RSS, no dose effectiveness factors for low doses and/or dose rates were assumed.

Early fatalities are estimated by the German consequence model based on the individual bone marrow dose received within the first seven days of exposure. The model incorporates a dose response function with a linear normal slope, threshold level = 100 rad, LD_{01} = 250 rad, and LD_{50}[+)] = 510 rad. This function differs from that assumed in the U. S. RSS (curve B for supportive medical treatment) which had a threshold of 320 rad and LD_{50} = 510 rad. The series of calculations described above was repeated using the U. S. bone marrow dose response function to determine whether or not the relative effects of cross-plume models would be altered. Selected results of those calculations are presented in Table 2. The relative conclusions drawn earlier still apply.

Finally, to determine the effect of the uniform population density assumption, the calculations of early fatalities were repeated using actual population data from four German reactor sites. The results of those calculations are presented in Table 3. As indicated, the relative effects of the cross-plume models investigated vary somewhat from site to site, and relative conclusions are somewhat more difficult to draw. Nevertheless, when the results for the four sites are averaged, the conclusions drawn earlier still roughly apply.

[+)] The dose that would be lethal to 50 percent of the population.

3) Conclusions

From the preceding results, the following conclusions can be drawn:

1. For average (many site) calculations, the U.S. top-hat distribution overestimates early fatalities and slightly underestimates latent cancer fatalities.

2. For the calculation of latent cancer fatalities, a top-hat distribution with outer distances $y/\sigma_y = 2$ (width $= 4\sigma_y$) is adequate.

3. For the calculation of early fatalities, a 2-step distribution with outer distances $y/\sigma_y = (1.0, 2.0)$ might be adequate.

4. For site specific (1-site) calculation of early fatalities a 4-step distribution may be desirable.

References

[1] Slade, D. H., Editor, Meteorology and Atomic Energy 1968, U. S. Atomic Energy Commission, TID-24190 (1968)

[2] Reactor Safety Study, App. VI: Calculation of Reactor Accident Consequences, WASH-1400 (NUREG 75/014), U. S Nuclear Regulatory Commission, Oct. 1975.

Table 1: Calculated Accident Consequences[a] for Several Cross-Plume Concentration Models

Number of Concentration Steps		Steps y/σ_y	Concentrations (Relative to Peak P)	Early Fatalities[b] Accident 1 Mean	Early Fatalities[b] Accident 1 Peak	Early Fatalities[b] Accident 2 Mean	Early Fatalities[b] Accident 2 Peak	Latent Cancer Fatalities[b] Accident 1 Mean	Latent Cancer Fatalities[b] Accident 1 Peak	Latent Cancer Fatalities[b] Accident 2 Mean	Latent Cancer Fatalities[b] Accident 2 Peak
U.S. RSS	1	1.5	0.84	144	142	120	125	95	93	93	91
	1	1.0	1.25	237	201	204	163	88	87	84	79
	1	2.0	0.63	75	80	66	90	100	98	99	100
	2	1.0, 2.0	0.86, 0.40	102	100	100	105	99	98	97	99
	2	1.0, 2.5	0.86, 0.27	100	101	95	96	100	100	99	101
	2	0.5, 2.0	0.96, 0.52	77	72	89	96	99	97	98	99
German RSS	4	0.5, 1.0 2.0, 3.0	0.96, 0.75 0.34, 0.06	100	100	100	100	100	100	100	100
	4	0.5, 1.0 1.5, 2.5	0.96, 0.75 0.46, 0.17	101	100	103	104	99	100	98	99

[a] Accident consequences calculated with the German RSS phase A model assuming a uniform population density.

[b] Normalized to the mean and peak calculated using the German 4-step cross-plume concentration model. Calculations are made assuming 115 different weather sequences to generate a probability distribution for each consequence. The mean and peak refer to this distribution.

Table 2: Early Fatalities[a] Calculated Using U.S. RSS Bone Marrow Dose Response Function

Number of Concentration Steps		Steps y/σ_y	Concentrations (Relative to Peak P)	Early Fatalities[b] Accident 1 Mean	Early Fatalities[b] Accident 1 Peak	Early Fatalities[b] Accident 2 Mean	Early Fatalities[b] Accident 2 Peak
U.S. RSS	1	1.5	0.84	134	137	121	123
	1	1.0	1.25	233	194	210	162
	1	2.0	0.63	57	60	58	84
	2	1.0, 2.0	0.86, 0.40	97	97	100	101
	2	1.0, 2.5	0.86, 0.27	96	96	96	94
	2	0.5, 2.0	0.96, 0.52	77	73	88	94
German RSS	4	0.5, 1.0 2.0, 3.0	0.96, 0.75 0.34, 0.06	100	100	100	100
	4	0.5, 1.0 1.5, 2.5	0.96, 0.75 0.46, 0.17	100	100	103	104

[a] Accident consequences calculated with the German RSS phase A model assuming a uniform population density

[b] Normalized to the mean and peak calculated using the German 4-step cross-plume concentration model. Calculations are made assuming 115 different weather sequences to generate a probability distribution for each consequence. The mean and peak refer to this distribution.

Table 3: Early Fatalities[a] Calculated Using Actual Population Data from Four German Sites

Number of Concentration Steps		Steps y/σ_y	Early Fatalities[b] Site 1 Mean	Site 1 Peak	Site 2 Mean	Site 2 Peak	Site 3 Mean	Site 3 Peak	Site 4 Mean	Site 4 Peak
Accident 1										
U.S. RSS	1	1.5	143	109	140	98	141	140	146	135
	2	1.0, 2.0	97	94	99	93	101	97	100	98
	2	1.0, 2.5	97	94	99	93	100	97	100	98
German RSS	4	0.5, 1.0, 2.0, 3.0	100	100	100	100	100	100	100	100
Accident 2										
U.S. RSS	1	1.5	94	104	93	103	121	122	112	111
	2	1.0, 2.0	81	90	80	89	101	101	95	98
	2	1.0, 2.0	78	88	78	85	96	94	91	94
German RSS	4	0.5, 1.0, 2.0, 3.0	100	100	100	100	100	100	100	100

[a] Calculated with the German RSS phase A model and German bone marrow dose response function

[b] Normalized to the mean and peak calculated using the German 4-step cross-plume concentration model. Calculations are made assuming 115 different weather sequences to generate a probability distribution for each consequence. The mean and peak refer to this distribution.

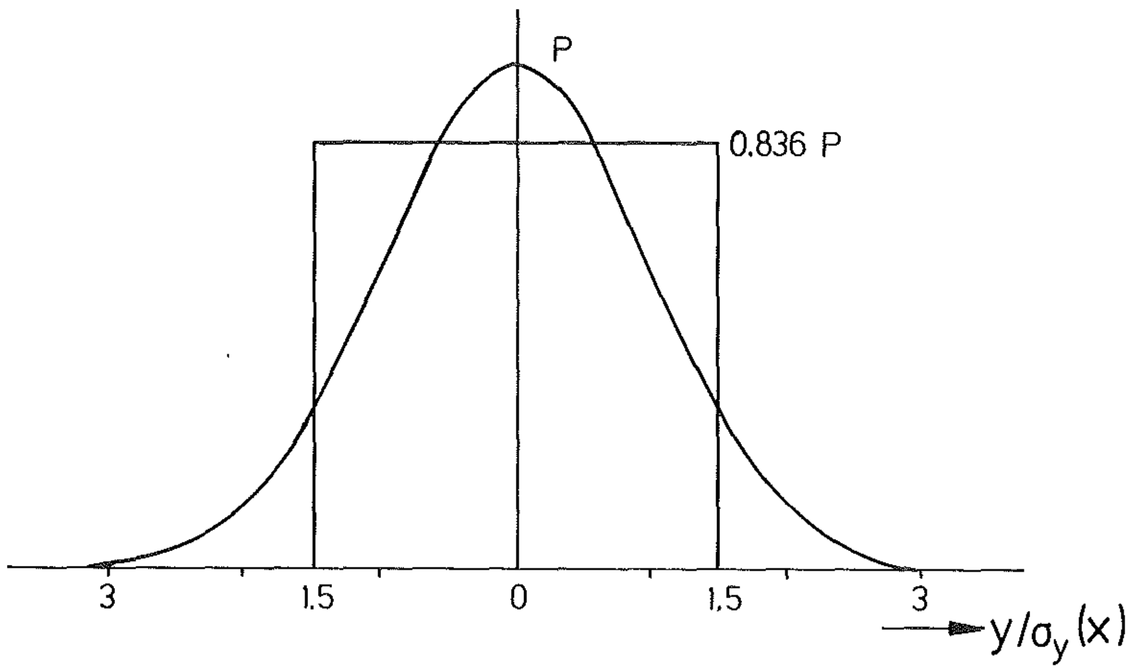

Figure 1: Top-Hat Cross Plume Concentration Distribution Used in U. S. RSS

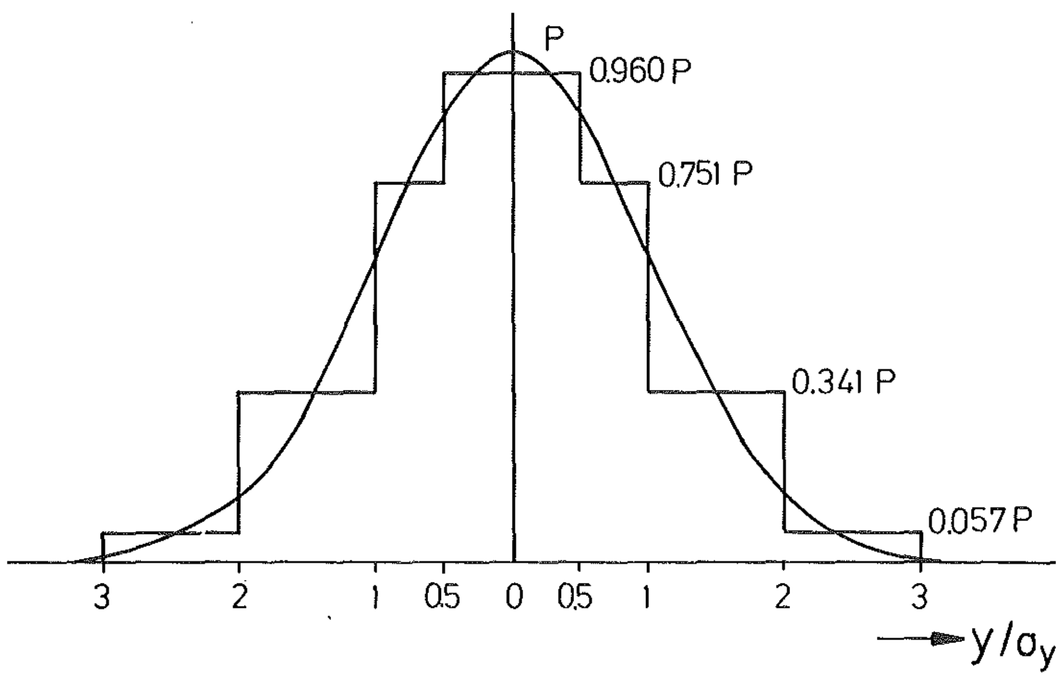

Figure 2: Cross-Plume Concentration Model Used in Phase A of German RSS