Journal of Hazardous Materials, 17 (1988) 239–245
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

A SIMPLE METHOD FOR DETERMINING THE MAXIMUM CONSEQUENCES OF NOTIONAL TOXIC AND RADIOTOXIC GAS DISCHARGES

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(Received August 1986; accepted in revised form March 27, 1987)

Summary

Methods for determining the consequences of toxic release accidents usually require access to, or the preparation of, lengthy computer programs. A method is presented here whereby the maximum conceivable individual risk from a toxic release accident (as would result if the discharge was instantaneous, neutrally buoyant, and at ground level) can be easily determined by hand calculation only. The method involves replacing the Gaussian cloud with an idealized hemispherical cloud of uniform concentration. Applications of the method to conventional toxins (such as ammonia or chlorine) and carcinogens, as well as external radiation from radioactive cloudshine, are discussed.

1. Introduction

The use of Gaussian models for determining time-averaged concentrations in atmospheric dispersion calculations is well established. For a given size of discharge, the most severe consequences will result if the discharge is at ground level and is instantaneous. In practice, however, an "instantaneous" discharge will often result in gravitational slumping, which in turn causes the discharge to behave in a similar manner to a continuous discharge, since gas is slowly entrained into the air from the slumped vapour [1,2]. Alternatively, an instantaneous discharge may result in the plume rising from the ground due to initial upward momentum or elevated temperature [3]. Both plume rise and slumping will, at least, not lead to an increase in the doses received by personnel downwind of the accident, above the values that would occur if the plume was neutrally buoyant (with the notable exception of those in the immediate vicinity of a slumped cloud). Thus the maximum consequence, in terms of total affected area, of a notional toxic gas release will occur if the gas is released instantly, with neutral buoyancy, and at ground level.

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0304-3894/88/$03.50

The questions that are often uppermost in such scenarios are "To what range should evacuation be considered?" or else "What will be the maximum individual risk at distance x from the source?" It is the object to this paper to present a simple method, using hand calculations only, whereby these questions may be answered, presupposing that accurate toxicological information is available. The method consists of replacing the Gaussian cloud with an idealized hemispherical cloud with the same total mass of toxic gas and of *uniform* concentration. The radius of such a cloud (to yield the same individual doses to people on the ground) can be related to downwind distance, using existing data [4] for Gaussian cloud dispersion coefficients; the effects of such a cloud upon persons on the ground can be more simply calculated since uniform concentration is assumed. The method can be applied to determine upper-bound consequences due to "conventional" toxins, carcinogens and radioactive cloudshine. In particular, the method greatly simplifies calculations relating to cloudshine.

2. Analysis for toxins and carcinogens

The time-averaged concentration χ due to the instantaneous release of quantity Q of material is given by [5]

$$\chi=\frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[-\tfrac{1}{2}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}+\frac{z^2}{\sigma_z^2}\right)\right] \tag{1}$$

where x, y and z are the downwind, crosswind and vertical distances from the centre of the cloud, and σ_x, σ_y and σ_z are the respective dispersion coefficients. The dispersion coefficients are a function of downwind distance from the source, atmospheric stability, and ground roughness. σ_x and σ_y are usually considered equal for instantaneous releases (i.e. radial symmetry), and σ_z is smaller. For the purposes of this paper, discussion will be restricted to the case of open terrain only.

Maximum dose to persons on the ground ($z=0$) will be on the axis of the cloud, i.e. $y=0$. That dose will be given by

$$D=\int_0^\infty \chi^n \mathrm{d}t=\frac{1}{u}\int_{-\infty}^{\infty}\chi^n \mathrm{d}x \tag{2}$$

where u is the windspeed and n is a coefficient. This coefficient is usually taken to equal 2.75 for "conventional" toxins such as chlorine or ammonia [1]. For carcinogens the dose is usually assumed to be directly proportional to the concentration ($n=1.0$) [6,7].

For a person on the centreline of the cloud, and assuming that the dispersion coefficients remain sensibly constant as the cloud passes overhead, eqn. (1) may be substituted into eqn. (2) and the integration carried out. Hence

$$D=\left[\frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\right]^n \frac{\sigma_x}{u}\left(\frac{2\pi}{n}\right)^{\frac{1}{2}} \tag{3}$$

An expression similar to this was derived in Appendix 15 of the first Canvey report [8].

However, for an idealized hemispherical cloud of radius R and uniform concentration, the corresponding expression will be

$$D=\left(\frac{Q}{\frac{2}{3}\pi R^3}\right)^n \frac{2R}{u} \tag{4}$$

Using the data of Hosker [4] for σ_y and σ_z (as functions of downwind distance x and Pasquill stability category), and assuming radial symmetry of the cloud (such that σ_x equals σ_y), it is possible, by setting eqn. (3) equal to eqn. (4), to produce graphs of idealised cloud radius R against downwind distance x for given values of toxicity coefficient n, such that the dose to an individual from the idealized cloud would be the same as that from the Gaussian cloud. Such graphs for "conventional" toxic gases ($n=2.75$) and for carcinogens ($n=1.0$) are presented in Figs. 1(a) and (b), respectively.

These graphs enable the dose D at distance x due to toxic release Q to be determined easily via eqn. (4). The individual risk may then be determined from a probit function for conventional toxins [1,9] or a linear dose–risk relationship for carcinogens.

3. Analysis for radioactive cloudshine

The cloudshine radiation flux at a point $(a, b, 0)$ on the ground may be determined [10], neglecting build-up, from

$$\phi\ (a, b, 0)=\frac{1}{4\pi}\int_0^\infty\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\chi(x, y, z)\,e^{-\mu((x-a)^2+(y-b)^2+z^2)^{\frac{1}{2}}}}{(x-a)^2+(y-b)^2+z^2}\,dx\,dy\,dz \tag{5}$$

where the concentration χ is determined from eqn. (1), and μ is the linear absorption coefficient for air, which is equal to approximately $3.24\times10^{-3}\ m^{-1}$ at typical gamma energies. The dose (Grays) received by a person at position $(a, b, 0)$ will thus be given by

$$D=\mu_m E\int_0^\infty \phi\ dt \tag{6}$$

where μ_m is the mass absorption coefficient for body tissue (0.0027 m^2/kg at typical gamma energies) and E is the gamma energy in joules.

Equations (1), (5) and (6) have been solved numerically (using a

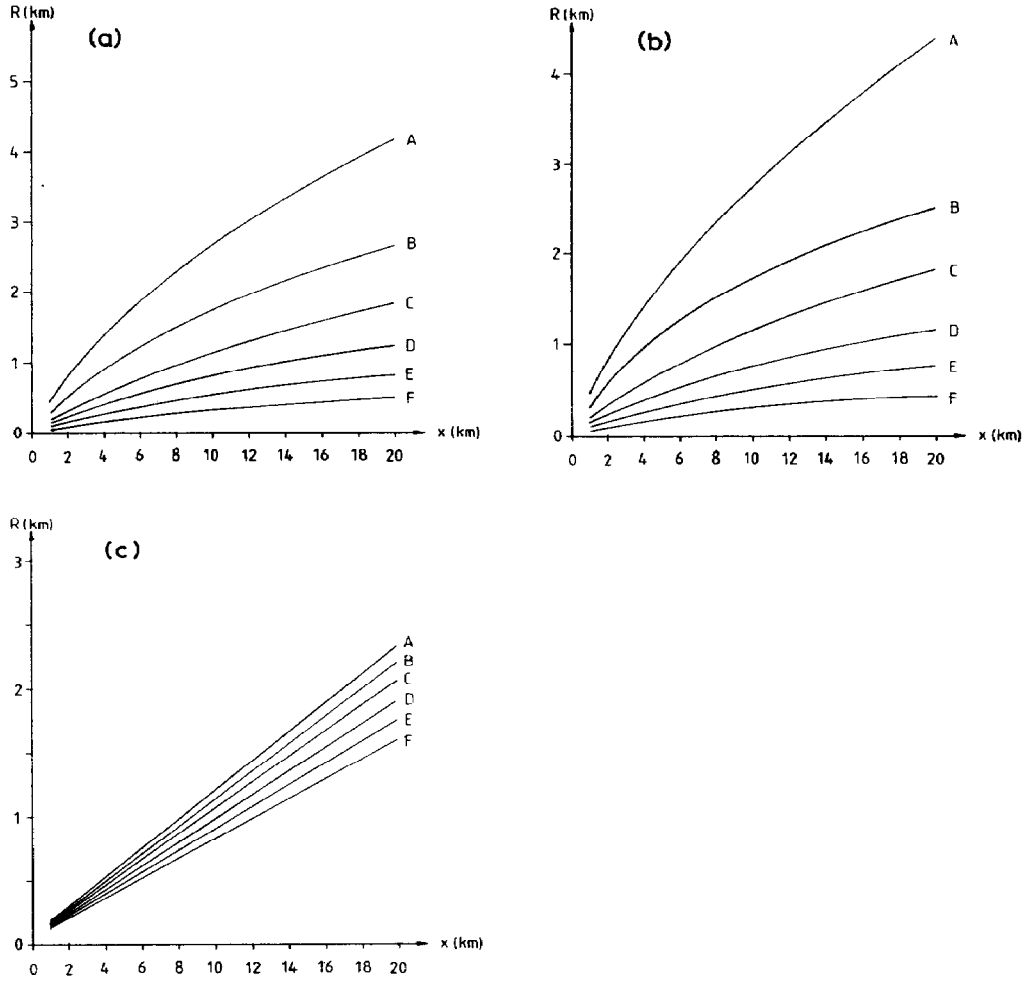

Fig. 1. The radius R of an idealised hemispherical cloud with uniform concentration $Q/\frac{2}{3}\pi R^3$, such that the dose received by a person axially downwind is equal to that which would be received from a Gaussian cloud of similar activity (or toxic mass) Q. Exposure time for the idealised cloud is $2R/u$. For case (c), the dose rate is that at the centre of the idealised cloud. R is given as a function of downwind distance x and Pasquill stability category. The data apply for open terrain. (a) Toxic gas, $n=2.75$; (b) Carcinogenic material, $n=1.0$; (c) radioactive cloudshine, $\mu=3.24\times10^{-3}\,\mathrm{m}^{-1}$.

$30\times30\times30$ array for discretizing the cloud) [11] at different on-axis downwind positions from a notional airborne discharge of radioactivity. The results have been equated with the doses received at the centre of an idealized hemispherical cloud of radius R with the same total activity Q (becquerels), and with uniform concentration, and with exposure time $2R/u$. The flux at the centre of the idealised cloud is given by [10]:

$$\phi = \int_0^R \frac{\chi\, 2\pi r^2\, e^{-\mu r}}{4\pi r^2} dr$$
$$= \frac{Q}{\frac{4}{3}\pi R^3 \mu}(1 - e^{-\mu R}) \quad (7)$$

Hence the dose (Grays) is given by

$$D = \mu_m E \phi \frac{2R}{u} \quad (8)$$

A graph showing the variation of idealized cloud radius R with downwind distance x, for the case of cloudshine, is shown in Fig. 1(c). Hence if the release magnitude Q is known, the dose (Grays) to an individual at distance x can be readily calculated using Fig. 1(c), together with eqns. (7) and (8).

4. Comparison of hazard magnitudes — Sample calculations

The method may be employed to determine equivalent discharges of different types of hazardous materials, to yield the same individual risk at a given point downwind. This calculation has been performed for discharges of chlorine, iodine-131 (internal radiation — carcinogenic effects) and krypton-85m (external radiation — carcinogenic effects) to give 1% individual risk of death (LD_{01}) to a person standing in the open air 2 km downwind from the release

TABLE 1

Comparison of hazard magnitudes

Hazardous material	Quantity to give LD_{01} at 2 km
Cl_2 (prompt deaths)	3.34 tonnes
I-131 (delayed deaths)	1.1×10^{17} Bq[a]
Kr-85m (delayed deaths)	1.5×10^{19} Bq

[a]Neglecting deposition.

Data:

Assumed conditions:	windspeed 5 m/s, neutral conditions, neutral buoyancy.	
Chlorine toxicity:	$n = 2.75$; $a = -17.1$; probit coefficient $b = 1.69$; probit coefficients (concentration in ppm, time in minutes).	[8]
Iodine-131 toxicity:	thyroid cancer dose-risk factor $= 3.1 \times 10^{-4}$ deaths/man Sv [12]; inhalation factor = 270 Gy/GBq; inhalation rate $= 3 \times 10^{-4}$ m^3/s [6]; RBE = 1 Sv/Gy.	
Krypton-85m toxicity:	external radiation dose-risk factor $= 1.25 \times 10^{-2}$ deaths/man Sv; gamma energy = 0.305 MeV; RBE = 1 Sv/Gy; and $\mu_m = 0.0027$ m^2/kg.	

point. Class D conditions, neutral buoyancy and 5 m/s windspeed have been assumed. The results are shown in Table 1. The quantities listed represent ca. 30% of the UK government notifiable inventory of chlorine, ca. 3% of the iodine-131 inventory in a 3000 MW(th) nuclear reactor, and ca. 14% of the total gaseous gamma activity in a 3000 MW(th) reactor, respectively [13,14]. (Values for radioactive inventories are determined assuming 1000 days' irradiation and ca. 100 s of cooling time.)

The calculations for chlorine, iodine-131 and krypton-85m have been performed using Figs. 1(a), 1(b) and 1(c), respectively. In the case of iodine-131, some radiation dose to other parts of the body will occur from both external and internal radiation; however, the predominant exposure pathway is internal thyroid irradiation.

6. Conclusions

A method has been presented for determining, by means of simple hand calculation only, the dose (or individual risk) to a person at a given point axially downwind from an instantaneous airborne discharge of neutrally-buoyant toxic gas, carcinogen, or radioactive material. Numerical values have been determined to enable the calculation to be performed for open terrain.

The method enables quick calculations of individual risk to be performed for various types of toxic hazard. It is also useful as a teaching aid since it enables meaningful cloudshine calculations to be made without writing (or having access to) large computer programs.

List of symbols

D	dose ($ppm^{2.75}$ minutes, or Grays)
E	gamma energy (J)
n	toxicity coefficient
Q	quantity of material released (kg or Bq)
R	idealised cloud radius (m)
r	radial distance (m)
u	windspeed (m/s)
x, y, z	coordinate system
μ	linear absorption coefficient for gamma radiation in air (m^{-1})
μ_m	mass absorption coefficient for gamma radiation in body tissue (m^2/kg)
ϕ	gamma radiation flux ($m^{-2}\,s^{-1}$)

$\sigma_x, \sigma_y, \sigma_z$ dispersion coefficients (m)
χ concentration (ppm, kg/m^3 or Bq/m^3)

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