Journal of Hazardous Materials, 13 (1986) 187—196
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

THE ASSESSMENT OF MAJOR HAZARDS: GENERALISATION OF THE IMPACT MODEL FOR THE ESTIMATION OF INJURY AND DAMAGE AROUND A HAZARD SOURCE

F.P. LEES, B.R. POBLETE

Department of Chemical Engineering, Loughborough University of Technology, Loughborough, Leicestershire LE11 3TU (Great Britain)

and G.B. SIMPSON

Department of Engineering Mathematics, Loughborough University of Technology, Loughborough, Leicestershire LE11 3TU (Great Britain)

(Received June 10, 1985; accepted in revised form October 6, 1985)

Summary

An analytical model which describes the impact of a hazard on the surrounding area has been given previously. The basis of the model is a uniform population density, the inverse square law for the decay of the intensity of the physical effect and the lognormal distribution, or probit equation, for the relation between the causative, or injury, factor and the probability of injury. It was shown that if these assumptions hold, the number of people injured may be approximately estimated by calculating the radius for 50% injury and assuming that all persons inside the circle suffer injury while all those outside it escape injury, and that a simple correction factor can be derived to compensate for the error in this method. It is shown in the present paper that the restriction of the inverse square law for the decay of the intensity of the physical effect can be relaxed and that for the more general case where the decay is inversely proportional to some power n of the distance, the correction factor is $\phi = \exp(2\sigma^2/n^2)$, where σ is the spread parameter of the lognormal distribution.

Introduction

An analytical model for the impact of a hazard on the surrounding area has been described previously [1]. The model is based on a uniform population density, the inverse square law for the decay of the intensity of the physical effect and the lognormal distribution, or probit equation, for the relation between the causative, or injury, factor and the probability of injury. This model was compared with an approximate model which is sometimes used to estimate the number of injured. In this approximate model the radius r_{50} at which there is 50% probability of injury is determined and it is then assumed that all persons inside the circle suffer injury while all those outside it escape injury. It was shown using the more exact model that the correction factor to be applied to the approximate model

0304-3894/86/$03.50

is $\phi = \exp(\sigma^2/2)$, where σ is the spread parameter of the lognormal distribution. It was also shown that the simpler models for the physical phenomena which are of interest in hazards work tend to yield an approximately inverse square law relation for the decay of the intensity of the physical effect and examples were given for fire, explosion and toxic release.

It is the purpose of the present paper to show that the restriction of the inverse square law for the decay can be relaxed and to treat, and to derive the correction factor for, the more general case in which the decay is inversely proportional to some power n of the distance.

Hazard impact model

The model is similar to that described in eqns. (11)—(13) of the previous paper [1] except that the decay index 2 is replaced by n in the latter equation. It therefore consists of the following equations:

$$N_{\text{i}} = \int_0^\infty 2\pi d_{\text{p}} P(r) r \mathrm{d}r \tag{1}$$

$$P = \frac{1}{(2\pi)^{1/2}\sigma} \int_0^x \frac{1}{x} \exp[-(\ln x - m^*)^2/2\sigma^2] \mathrm{d}x \tag{2}$$

$$x = (r_{\text{o}}/r)^n \tag{3}$$

where d_{p} is the population density (persons/m^2), m^* the location parameter of the lognormal distribution, N_{i} the total number of people injured, P the probability of injury, r the distance (m), r_{o} the radius of the physical phenomenon (m) and x the normalised injury factor.

In principle, r_{o} is intended to represent the radius of the physical effect, where this is a meaningful concept as with, say, a fireball, and hence the radius at which the probability of injury is unity. The choice of r_{o}, however, is unrestricted. It is recommended that it be chosen so as to give a probability of injury close to unity.

It can be shown that eqns. (1)—(3) yield the result

$$N_{\text{i}} = \pi r_{50}^2 d_{\text{p}} \exp(2\sigma^2/n^2) \tag{4}$$

The derivation of eqn. (4) is given in the Appendix.

Equation (4) may be written in the form

$$N_{\text{i}} = \pi r_{50}^2 d_{\text{p}} \phi \tag{5}$$

with

$$\phi = \exp(2\sigma^2/n^2) \tag{6}$$

where ϕ is a correction factor which allows for the effect of the variance and of the decay index.

Decay relationships

The decay relationships which describe the decay of the intensity of the physical effect with distance were given in the previous paper for the simpler models for fire, explosion and toxic release. It was shown that these models give an approximately inverse square law relation for the decay of the intensity (thermal radiation, overpressure, concentration). However, some of the current more complex and realistic models for these phenomena, which are described below, give different decay indices. Moreover, in some cases the injury factor is not the intensity itself but some function of it. It is necessary, therefore, to examine these relations in more detail.

It is assumed that the intensity of the physical effect decays with distance according to the power law relation

$$w = k_W / r^{n_W} \quad (7)$$

where n_W is the decay index for the intensity and w the intensity. The injury factor is assumed to be a power function of the intensity

$$v = k_{VW} w^{n_{VW}} \quad (8)$$

where n_{VW} is the power index for the injury factor and v the injury factor.

It follows from eqns. (7) and (8) that the injury factor decays with distance according to the relation

$$v = k_V / r^n \quad (9)$$

where

$$k_V = k_{VW} k_W{}^{n_{VW}} \quad (10)$$

$$n = n_W n_{VW} \quad (11)$$

where n is the decay index for the injury factor.

The separation of the relationship for the decay of the injury factor into two, one relation for the decay of the intensity and one relation between the intensity and the injury factor, is desirable where possible, since it allows the two relations, each of which may involve error, to be considered separately. It is not always possible to make this separation, however. For toxic gas, for example, where the injury factor is some concentration–time function, it may be necessary, particularly with instantaneous releases, to calculate this function from the outset.

For fire, the inverse square law for the decay of thermal radiation is well established so that the index n_W equals 2. This applies for fireballs, pool fires and flares. The injury factor v, however, is usually given (e.g. Eisenberg et al. [2]) as

$$v = I^{4/3} t \quad (12)$$

where I is the thermal radiation (W/m^2) and t the exposure time (s).

For explosion, the decays of the peak overpressure and the impulse depend on the model used. For the TNT equivalent model, which is well established (e.g. Baker et al. [3])

$$p^{o} = f(z) \tag{13}$$

$$I_{p} = f(z) \tag{14}$$

with

$$z = r/W^{1/3} \tag{15}$$

where I_p is the impulse (N s/m^2), p^o the peak overpressure (N/m^2), W the mass of explosive (kg) and z the scaled distance (m/kg$^{1/3}$). The curves given by Baker et al. [3] correspond over the overpressure range 1—0.1 bar to decay indices of 1.7 and 0.9 for peak overpressure and impulse, respectively.

For unconfined vapour cloud explosion (UVCE), there is no established model. Investigations of actual UVCEs provide some information. For the Flixborough explosion, for example, the curve given by Sadée et al. [4] gives over the overpressure range 1—0.1 bar a decay ratio for peak overpressure of 1.7. On the other hand some theoretical models such as those of Wiekema [5] and Ebert and Becker [6] give for peak overpressure decay indices of about unity.

The injury factor for explosion is usually given as p^o or I_p, depending on the injury considered.

For toxic release the situation is more complicated, because the modelling both of gas dispersion and of toxic effects is complex. It is necessary in dispersion modelling to distinguish between neutral density and heavy gas, instantaneous and continuous release, and different stability conditions, and in injury modelling between concentration, dosage and other concentration—time functions.

The form of the injury factor for toxic gas depends on the particular gas concerned. Some typical relations are

$$v = C \tag{16a}$$

$$= Ct \tag{16b}$$

$$= C^2 t \tag{16c}$$

where C is concentration (kg/m^3). In practical situations people are exposed to a range of concentrations over a period of time. This is taken into account by the following more general relationship (Eisenberg et al. [2])

$$v = \int C^m \mathrm{d}t \tag{17}$$

where m is an index.

It is convenient to consider first as the injury factor concentration C. As shown in the previous paper [1] using the Sutton models [7], for a neutral density gas in neutral stability conditions the decay indices for concentration downwind on the centreline are 2.6 for an instantaneous release and 1.75 for a continuous release. For heavy gas dispersion there are a large number of models. Currently the box model is probably the most favoured and of the numerous variants among the most widely used are DENZ [8] for an instantaneous release and CRUNCH [9] for a continuous release. In these models there is a density-influenced phase followed by a passive dispersion phase. The models are complex and have been solved numerically, although more recently some analytical results have been derived [9–11]. The general nature of the models is best indicated by considering a particular case. An instantaneous release of 200 te of ammonia in Pasquill D stability conditions and wind speed 3 m/s has been investigated using the DENZ model and a continuous release of 23.9 kg/s of chlorine in Pasquill D conditions and wind speed 5 m/s using CRUNCH. The concentrations downwind on the centre line for the latter case are shown in Fig. 1. This curve has a characteristic shape, which shows an increasing decay up to the transition point and a constant decay thereafter. This behaviour appears to be typical of both instantaneous and continuous releases, similar cases being described by others (e.g. McQuaid [12]). For the two specific cases quoted

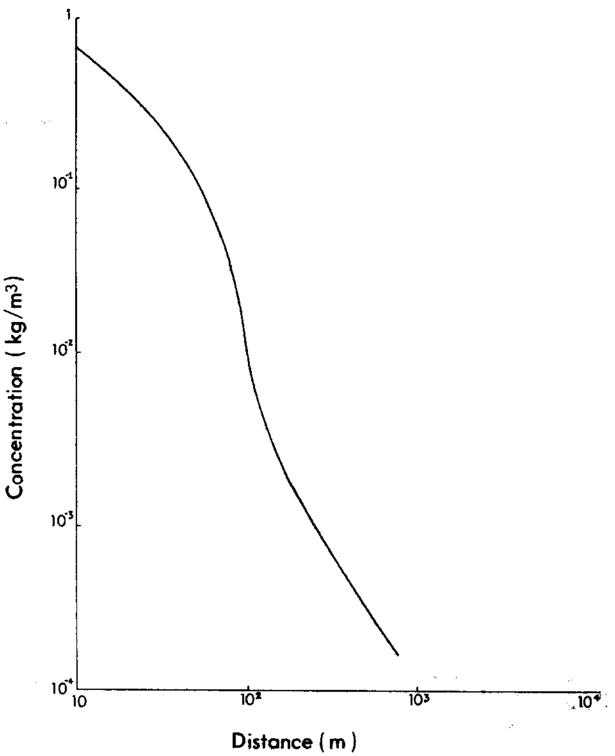

Fig. 1. Decay of concentration with distance for a continuous release of chlorine of 23.9 kg/s using the CRUNCH model [9]. Wind speed 5 m/s, stability conditions Pasquill D.

the decay indices after transition are 1.4 for the instantaneous release and 1.7 for the continuous release. A more detailed treatment of the decay of concentration for heavy gas dispersion and of the implications of this for the model is beyond the scope of this paper.

If the injury factor is dosage Ct, then as shown in the previous paper, for a neutral density gas in neutral stability conditions the decay index for dosage Ct downwind on the centreline is 1.75 for both instantaneous and continuous releases. The decay index for dosage for heavy gas is more complex, but an indication can be obtained by considering the continuous release example just described. As stated above, after transition the decay index for concentration is 1.7 and that for dosage is therefore also 1.7.

If the injury factor is the function C^2t, again the situation is more complex, but an indication can be obtained by considering continuous releases. For both neutral density and heavy gas dispersion the decay index for the function C^2t downwind on the centreline will be the square of that for C. Hence for neutral density gas in neutral stability conditions the decay index is 3.1 $(=(1.75)^2)$ and for the heavy gas continuous release example it is 2.9 $(=(1.7)^2)$.

The values of the decay indices for intensity and for injury factor just discussed are summarised in Table 1.

The normalised intensity i and the normalised injury factor x may be obtained by dividing the intensity w and the injury factor v by the values of these variables at r_o.

Discussion

A model of hazard impact was presented in a previous paper [1]. The principal assumptions were that the population is uniformly distributed, that the intensity—distance relation for the physical effect is the inverse square law and that the injury probability—injury factor relation is the log-normal distribution, or probit equation.

It has been shown in the present paper that the restriction of the inverse square law for decay of the intensity of the physical effect can be relaxed and that the model can be generalised to an inverse power law relation. Moreover, it can also be generalised to handle a power law relation between the intensity and the injury factor. The model is given by eqns. (5) and (6). The correction factor ϕ $(= \exp(2\sigma^2/n^2))$ for variance and decay index given in eqn. (6) reduces to ϕ $(= \exp(\sigma^2/2))$ as given previously for inverse square law decay with $n = 2$.

The decay index for the intensity given by the more complex and realistic models of physical phenomena has been reviewed and it has been shown that it tends to lie in the range 1—2. The decay index for the injury factor has also been reviewed and it has been shown that it tends to lie in the range 1—3.

TABLE 1

Decay index for the intensity and injury factor for some principal hazards

Hazard	Model	Physical effect	Intensity, w	Injury factor, v	Power index, n_w	Decay index	
						Intensity, n_{vw}	Injury factor n
Fire	Fireball, pool fire	Thermal radiation	I	$I^{4/3}t$	4/3	2	2.7
Explosion	TNT	Peak overpressure	p^o	p^o	1	1.7[a]	1.7
		Impulse	I_p	I_p	1	0.9[a]	0.9
	UVCE (Flixborough)	Peak overpressure	p^o	p^o	1	1.7[b]	1.7
	UVCE	Peak overpressure	p^o	p^o	1	1.0[c] 1.1[d]	1.0 1.1
Toxic release	Neutral density: instantaneous release	Concentration	C	C Ct	1 1	2.6[e] 1.75[e]	2.6 1.75
	Neutral density: continuous release	Concentration	C	C Ct C^2t	1 1 2	1.75[e]	1.75 1.75 3.1
	Heavy gas: instantaneous release	Concentration	C	C	1	1.4[f]	1.4
	Heavy gas: continuous release	Concentration	C	C Ct C^2t	1 1 2	1.7[g]	1.7 1.7 2.9

[a] Over the range 1—0.1 bar [3].
[b] Over the range 1—0.1 bar [4].
[c] Wiekema model [5].
[d] Ebert and Becker model [6].
[e] See Ref. [1].
[f] Specific example of 200 te ammonia release using DENZ [8].
[g] Specific example of 23.9 kg/s chlorine release using CRUNCH [9].

Acknowledgement

One of the authors (FPL) wishes to thank the Science and Engineering Research Council for supporting this work.

List of symbols

C	concentration (kg/m^3)
d_p	density of population (persons/m^2)
i	normalised intensity of physical effect
I_p	impulse (N s/m^2)
k_v, k_{vw}, k_w	constants
m	index for concentration
m^*	location parameter in lognormal distribution
n	decay index for the injury factor
n_v	power index for the injury factor
n_w	decay index for the intensity of the physical effect
N_i	total number of people injured
p^o	peak overpressure of explosion (N/m^2)
P	probability of injury
r	radial distance (m)
r_o	radius of physical phenomenon (m)
t	time (s)
v	injury factor (various units)
w	intensity of physical effect (various units)
x	normalised injury factor
z	scaled distance (m/kg$^{1/3}$)
σ	spread parameter in lognormal distribution (σ^2 = variance)
ϕ	correction factor for variance and decay index
Φ	normal distribution function

Subscript

50	for probability of injury equal to 0.5

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Appendix

The model considered is that in eqns. (1)–(3). The treatment is essentially similar to that given in Appendix 2 of Ref. [1].

The injury factor x_{50} and the radius r_{50} at which the probability of injury is 50% ($P = 0.5$) are obtained from eqns. (9) and (10) of Ref. [1] by putting $Y = 5$ so that

$$x_{50} = \exp m^* \tag{A.1}$$

From eqn. (3)

$$r_{50} = r_o / x_{50}^{1/n} \tag{A.2a}$$

$$= r_o / \exp(m^*/n) \tag{A.2b}$$

Let

$$y = \ln x \tag{A.3}$$

Then

$$P(r) = \frac{1}{(2\pi)^{1/2}\sigma} \int_{-\infty}^{y} \exp\left[-(y - m^*)^2/2\sigma^2\right] dy \tag{A.4}$$

Let

$$z = (y - m^*)/\sigma \tag{A.5}$$

Then

$$P(r) = \frac{1}{(2\pi)^{1/2}} \int_{-\infty}^{z} \exp(-z^2/2) dz \tag{A.6a}$$

$$= \Phi(z) \tag{A.6b}$$

where $\Phi(z)$ is the normal cumulative distribution function.

Then, from eqns. (3), (A.3), (A.5) and (A.6), eqn. (1) becomes

$$N_i = \int_0^{\infty} 2\pi d_p \, \Phi\left[(n \ln r_o - n \ln r - m^*)/\sigma\right] r dr \tag{A.7}$$

Let

$$u = (n \ln r_o - n \ln r - m^*)/\sigma \tag{A.8}$$

Then

$$N_i = \pi r_o^2 d_p \exp(-2m^*/n) \int_{-\infty}^{\infty} (2/n)\sigma \exp(-2\sigma u/n)\, \Phi(u)\, du \tag{A.9}$$

$$= \pi r_o^2 d_p \exp(-2m^*/n) I \tag{A.10}$$

where

$$I = \int_{-\infty}^{\infty} (2/n)\sigma \exp(-2\sigma u/n)\, \Phi(u) du \tag{A.11}$$

From the derivation of eqn. (A2.17) from eqn. (A2.12) in Ref. [1], substituting $(2\sigma/n)$ for σ, it follows that

$$I = \exp(2\sigma^2/n^2) \tag{A.12}$$

Then eqn. (A.10) becomes

$$N_i = \pi r_o^2 d_p \exp(-2m^*/n) \exp(2\sigma^2/n^2) \tag{A.13}$$

and hence from eqn. (A.2)

$$N_i = \pi r_{50}^2 d_p \exp(2\sigma^2/n^2) \tag{A.14}$$

$$= \pi r_{50}^2 d_p \phi \tag{A.15}$$

where

$$\phi = \exp(2\sigma^2/n^2) \tag{A.16}$$