CRITERIA FOR USE IN THE ASSESSMENT AND CONTROL OF MAJOR HAZARDS

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The UK Legislation on "Control of Industrial Major Accident Hazards" includes the requirements for quantified risk assessments.

The paper derives criteria which can be applied to risk assessment for those major consequences which could result in hurt to on-site personnel and members of the public. These criteria are justified in the light of other societal risks (both imposed and voluntary) and are integrated into the cumulative risk to any individual. The methodology described is applicable to releases of toxic gases. However, the approach can also be used in assessments involving small gas-cloud explosions.

INTRODUCTION

It has long been realised that possible accidents at chemical plants present a risk to plant operators but this was not regarded as a cause for public concern. However, in recent years disasters in various parts of the world have heightened the realisation of the dangers to society due to accidents at chemical plants. The groups at risk from such possible accidents are now recognised as:-

(a) Plant operators
(b) Individual members of the public living near to a plant
(c) The population in the area surrounding a plant

The UK Legislation on "Control of Industrial Major Accident Hazards", (CIMAH) (1), lays particular emphasis on the duties of manufacturers to safeguard the latter two categories.

Within the CIMAH legislation there is both direct and indirect requirement for quantiifed safety assessments to be carried out by the manufacturers. It is implicit that any quantified assessment, in order to have meaning, must have a target or criterion against which it can be judged for acceptability.

This paper indicates a methodology by which a manufacturer can derive off-site criteria on the basis of his on-site safety record and a comparison with other socially acceptable risks.

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THE RISK EQUATION

First, consider what it is that the operators of major hazards plants will be expected to do under the new legislation. By operators we mean the people responsible for preparing the Safety Case for submission to the Health and Safety Executive. The safety case, in our opinion, will be required to quantify the risk to the public from possible accidents at the plants, and so the first requirement is an equation which defines the risk. There are many facets of risk but in the context of the CIMAH document we are concerned with the risk of death to an individual member of the public which is defined by the equation.

$$\text{Risk} = \text{Frequency} \times \text{Consequence}$$

or in formal notation,

$$I(h) = f(h) \times P(k|h) \qquad (1)$$

The estimation of the frequency of the hazard associated with a plant may involve detailed safety assessments using event tree/fault tree techniques.

The consequence is the probability that an individual is killed given that the hazard occurs. The estimation of this probability may involve sophisticated mathematical modelling of the effects of the hazard on the population in the area surrounding a plant.

In order to judge whether the above calculated risk is acceptable we need some measure of acceptability, or 'risk acceptance criterion' as it is sometimes called, against which to compare the calculated risk. If such a criterion was specified then it could be used in two ways.

a) For an existing plant the criterion would be met if:-

$$f(h) \times P(k|h) = I(h)_{\text{CALCULATED}} \leq I(h)_{\text{CRITERION}} \qquad (2)$$

b) For a new plant at the conceptual or planning stage the criterion could be used in the risk equation to calculate the 'acceptable' frequency of the hazard.

$$f(h)_{\text{ACCEPTABLE}} \leq \frac{I(h)_{\text{CRITERION}}}{P(k|h)} \qquad (3)$$

The question now is "How does an operator decide on a suitable criterion for risk?".

Whether or not the HSE are prepared to indicate criteria and having done so whether such criteria can be meaningfully used against any safety assessment is open to debate.

We therefore, offer the manufacturers a methodology which can be applied to either of two options:-

(i) a means of generating their own, logically derived, criteria,

or (ii) the use of on-site assessments to show compliance with externally imposed criteria relating to off-site risks.

RISK CRITERIA

The risk to plant operators is regarded as a voluntary risk in that they consciously expose themselves to the potential hazard (duly minimised) for financial reward. However, to the individual outside the site the risk is involuntary. Although it may be philosophically argued that the societal risk is voluntary, e.g. the benefit of the plant product to society as a whole, this may be outweighed to those members of society in the immediate neighbourhood of the potential hazard. Therefore, this risk is also involuntary.

Risk criteria are discussed below in relation to plant operators, individuals and society local to a potentially hazardous chemical plant.

Risk Criterion for Plant Operators

Plant operators are given a qualitative assurance that their risk is as low as reasonably achievable because the plant is designed, constructed and operated in accordance with recognised Codes of Practice.

However, a useful quantitative criterion against which the risks to employees has been judged is the fatal accident rate, FAR. The fatal accident rate is the number of fatalities occuring in 10^8 man hours. As a statistic it is the number of deaths from industrial injury in a group of 1000 workers during their working lives, (2).

The fatal accident rate in the UK chemical industry is about 4 per 10^8 man hours. About half the FAR is due to the common accidents which occur on most plants (e.g falling off a ladder or getting run over) and about half to special hazards which are peculiar to each plant. Thus, if we are sure that we have identified all the special hazards of a particular plant then their total FAR can amount to 2 per 10^8 man hours.

Thus, implicitly, we have a criterion, which is acceptable to plant operators (and trade unions), of 2 fatalities per 10^8 man hours for the special hazards. The criterion will be met if,

$$\begin{aligned} f(h) \times P(k|h) &= f(h) \times P(e|h) \times P(k|e) \\ &\leqslant (FAR)_S \times W(e) \\ &\leqslant W(h) \end{aligned} \qquad (4)$$

For present purposes assume that

$$W(e) = 2000 \text{ hours}$$

$$P(e|h) = \frac{W(e)}{8760} = \frac{2000}{8760}$$

$$P(k|e) = 1.0$$

Thus,

$$f(h) \times \frac{2000}{8760} \times 1.0 \leqslant \frac{2}{10^8} \times 2000$$

$$= 4 \times 10^{-5} \text{ per year}$$

$$= W(h) \qquad (5)$$

If this risk is acceptable, which it is, then by definition the frequency of the hazard must be acceptable. Thus,

$$f(h)_{\text{ACCEPTABLE}} \leqslant 1.75 \times 10^{-4} \text{ per year} \qquad (6)$$

It is interesting to note that the above risk appears to be in line with the First Report of the Health and Safety Commission's Advisory Committee on Major Hazards (3) which expresses the view that a risk of 10^{-4} per year of a serious accident in a chemical plant causing death or injury might perhaps be regarded as just on the borderline of acceptability. (Note that the committee does not make it clear whether the reference is to plant operators or individuals. We believe that it should refer to plant operators).

Risk Criterion for an Individual Member of the Public

In the present context, individual risk refers to the probability of death per year to an individual member of the public when in the vicinity of a plant from accidents, and also the risk specifically arising from that plant.

At present there are insufficient statistics to permit an individual to arrive at his limit of tolerance of the risk of death due to accidents at a plant, and hopefully this situation will always be the case.

Let us, therefore, consider the application of the 'acceptable' frequency of the hazard which satisfied the operator risk target in the context of off-site individuals. Full details of the calculation of individual risk are given in Appendix 1. However, for present purposes the simplifying assumptions given in Appendix 2 are used. Thus, substituting the value of f(h) from equation (6) into equation (A2.1) we have

$$I(h, s, r) = f(h) \times P(s) \times P(k|e, r)$$

$$= (1.75 \times 10^{-4}) \times \left(\frac{1}{12}\right) \times (0.1)$$

$$= 1.5 \times 10^{-6} \text{ per year} \qquad (7)$$

We now have to consider whether this calculated risk can be used as a criterion, i.e. is it acceptable to an individual member of the public?. To aid a decision on this question reference was made to several opinions which have appeared in the literature (4) (5) (6) (7).

The general consensus of opinion is that a risk of 10^{-6} per year is not taken into account by individuals in making decisions and is, therefore, acceptable.

It is concluded here, therefore, that if it can be demonstrated that the calculated risk to an individual is about 10^{-6} per year, based on a hazard frequency which satisfies the target for the risk to a plant operator, then the risk due to accidents at the plant would also be acceptable to an individual member of the public.

However, before we can say that the hazard frequency is low enough, we must demonstrate that it would also be acceptable to the population in the area surrounding the plant.

Societal Risk Criterion

In the present context, societal risk refers to the possibility of a number of people dying as a result of accidents at a chemical plant.

In the past the risk from chemical plants has been as low as reasonably practicable and the level of success can be judged against the sparse statistics on any dire consequences to the public as a result of plant accidents. Nevertheless, accidents have happened but society seems to regard such accidents in a different light to 'conventional' accidents. Thus, any societal risk criterion must be set at such a level as to give the public an additional assurance that the risks from known potentially hazardous plants are considerably lower than those from the more conventional hazards to which they are already exposed.

For present purposes, quantified risk can be defined as the product of the frequency of an event and the consequences given that the event occurs. In this case the event is the death of a number of people due to an accident at a chemical plant. Thus, a given level of risk can result from a range of combinations from high frequency - low consequence events to low frequency - high consequence events.

Society already accepts the risks from such a spectrum of combinations as a result of high technology activities which are demanded by society itself to maintain the present quality of life i.e. the necessities of life are no longer the 'bare necessities'. In this sense some risks which had previously been considered to be involuntary risks can now be regarded as voluntary as far as society is concerned. Thus, a range of multiple fatality accidents are already part of modern life and are accepted as such.

Statistics for this type of multiple fatality accident are available for various human activities (8) (9) and there is also a limited amount of data for accidents at chemical plants (10). These data are presented as the cumulative frequency of N or more fatalities versus the number of fatalities as shown for example on Fig. 1.

In a review of these statistics Gill (10) used the following argument to arrive at a societal risk criterion as an aid to the design of new chemical plant. Examination of the curves on Fig. 1 shows that the UK data are about 25 times lower than the world-wide data for 'conventional' accidents. World-wide data on multiple fatality accidents 'associated with a plant or site' which could be said to be attributable to the activities of the chemical industry are shown as Curve 1 on Fig. 2. In order to arrive at the curve for the UK it was considered reasonable to reduce the world-wide data by a factor of 25 i.e. a similar factor to that between the UK and world-wide data for "conventional" multiple fatality accidents, as shown by Curve 2 on Fig. 2.

On the basis of chemical industry performance to date the frequencies indicated on Fig. 2 appear to be acceptable to the public and authorities. It should be remembered that the overall picture of off-site safety in the chemical industry has not been one of constant enquiry and controversy. It would therefore seem reasonable that criteria or 'target' frequencies based on past performance would be an acceptable approach, particularly if the target called for an improvement along the lines of "As Low As Reasonably Achievable".

However, Curve 2 on Fig. 2 is an estimation of the existing performance for multiple fatality incidents within the whole of the UK chemical industry. If we assume for present purposes that there are 250 plants in the UK then the contribution from each of these plants to the total societal risk from the industry as a whole should not exceed $^{1}/_{250}$ of that given on Curve 2. Thus, the criterion for an individual site or plant is estimated by dividing the data on Curve 2 by 250 as shown on Curve 3 on Fig. 2.

As an example of the use of such a criterion let us use the simplifying assumptions given in Appendix 2 to calculate the societal risk due to possible accidents at a chemical plant. Full details of the calculation of societal risk are given in Appendix 1.

A hazard frequency, f(h), of 1.75×10^{-4} per year has already been shown to be 'acceptable' to plant operators and an individual member of the public. This frequency was used in equations A2.2 and A2.3 to calculate the societal risk which depends on the population.

If the population in each sector is,

$$Q(s, r) = 100$$

then the number of deaths conditional on the wind blowing into a sector when the hazard occurs is

$$N(h, s) = Q(s, r) \times P(k|h, r) = 100 \times 0.1 = 10$$

Thus,

$$F(n \geqslant 10)_{CALC.} = f(h) \times P(n \geqslant 10)$$

$$= 1.75 \times 10^{-4} \times 1.0$$

$$= 1.75 \times 10^{-4} \text{ per year}$$

In this case the calculated societal risk is lower than the criterion on Fig. 2 i.e. $F(n \geqslant 10)_{CRITERION} = 6 \times 10^{-4}$ and so the hazard frequency is also acceptable to society.

However, if the population in each sector is 1,000 then the corresponding values are

$$N(h, s) = 100$$

and $$F(n \geqslant 100)_{CALC.} = 1.75 \times 10^{-4} \text{ per year.}$$

TABLE 1 SOURCE-TERM LISTING, BASE-CASE

NB. *=Equivalent Continuous Release. C=Controlled by RSOV. U=RSOV fails or absent.

ITEM	EVENT	RELEASE (Kg/s)	DURATION (min)	FREQUENCY ($x 10^6/y$)	COMMENTS
Storage Vessels	Burst	50*	10	1	Over bund. pseudo-plume
Only 1 live at once.	Burst	25*	10	1	Into bund. pseudo-plume
Typical	50mm hole, liq.	25*	10	1.6	pseudo-plume
stock :	50mm hole, gas	6.4	20	2.4	2 x flash
20 te	25mm hole, liq.	19	8.8	3.2	
	25mm hole, gas	1.6	30	4.8	2 x flash
	13mm hole, liq.	5	30	4	
	13mm hole, gas	0.25	30	6	
	6 mm hole, liq.	1.3	30	16	
	6 mm hole, gas	0.06	30	24	
Tanker Vessels	NEGLECT: Only on-site in 2% of time, so probability of failure on-site is much less than for static tanks.				
Other vessels					none on-site
Pipelines, Guillotine Fractures	AIL (10m)	1	5(C)	0.6	Tanker EFVC works. Live 2% of time.
		9	20	0.006	Tanker EFVC fails, failure 10x BIL per m
	BIL (40m)	4	5(C)	12	Normally live.
		4	20	0.12	Limited to 4kg/s by orifice-plate.
	CIG (20mm)	1	20	6	Normally live
	DIG (20mm)	1.25	20	0.3	Live as AIL
	EIG (50mm)	1.25	20	0.15	Live 0.1%; 10 x failure rate
Pipe Splits	AIL	5	20	6	EFVC on tanker not actuated.
	BIL	4	5(C)	120	
	CIG	0.25	20	60	
	DIG	0.25	20	3	
	EIG	0.25	20	1.5	
Gaskets (equiv. 9mm	AIL	2.4	20	17	17 joints, live 2% of time, failure 10 x normal rate
holes) 3mm thick,	BIL	2	5(C)	220	47 joints; (3 below RSOV so "uncontrollable")
		2	20(U)	15	
1/4 of	CIG	0.13	20	60	12 joints
circumference	DIG	0.13	20	9	9 joints; Live as AIL
	EIG	0.13	20	1.3	26 joints
Transfer Coupling/hose	FC1	1	5(C)	150	50 operations
		9	20	1.5	EFVC fails
	FC2	1.25	20	150	50 operations
Other Vaporiser	Failure leads to liquid from BIL	4	5(C)	100	
		4	20(U)	1	

NOTE: 1. In deducing source-terms, due account is taken of the possibilities for forward and backflow, and the differences between normally-live and intermittent use items.

2. Source-terms are processed thus : (i) Neglect all cases with frequency below $10^{-6}/y$; (ii) aggregate similar cases (here, 0.25 kg/s were aggregated with 0.13 kg/s / 20 min, since the RAT does not cater for releases below 0.2 kg/s).

LIST OF SYMBOLS USED

FAR	= Fatal accident rate for all accidents at a plant, (hr^{-1})
$(FAR)_s$	= Fatal accident rate for special hazards at a plant, (hr^{-1})
$F[n \geqslant N(h)]$	= Frequency of N or more societal deaths due to a hazard, h,at a chemical plant, (yr^{-1})
f(h)	= Frequency of a hazard, h, at a plant, (yr^{-1})
I(h)	= Risk of death to an individual member of the public due to a hazard, h, at a plant, (yr^{-1}). In the formal definition, this risk is also conditional on the angular and radial position relative to the source of the hazard, $I(h, s_S, r_R)$.
$N(h, s_S, w_W)$	= Number of deaths in sector s_S given a Pasquill weather category w_W when a hazard h occurs.
$P(k/h)$	= Probability that a person is killed given that a hazard, h, occurs. In the equations for individual and societal risks this probability is also conditional on the radial position and the Pasquill weather category, $P(k/h, r_R, w_W)$.
$P(e/h)$	= Probability that a person is exposed to the hazard given that a hazard, h, occurs.
$P(s_S, w_W)$	= Probability of the wind blowing into sector s_S in Pasquill weather category w_W.
$P(k \mid e)$	= Probability that a person is killed given exposure to a hazard. In the equation for individual risk this probability is also conditional on the radial position and the Pasquill weather category, $P(k \mid e, r_R, w_W)$.
$P[n=N(h,s_S,w_W)]$	= Probability of exactly N deaths given that the wind blows into sector s_S in Pasquill weather category w_W when hazard h occurs.
$P[n \geqslant N(h)]$	= Probability of N or more deaths in the population given that a hazard, h, occurs.
$Q(s_S, r_R)$	= Population in sector s_S at radius r_R relative to the plant.
W(e)	= Number of hours per year that a plant operator is exposed to a potential special hazard associated with a plant, (hr/yr).
W(h)	= Risk to a plant operator due to special hazards associated with a plant, (yr^{-1})

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Frequency of Multiple Fatality Accidents

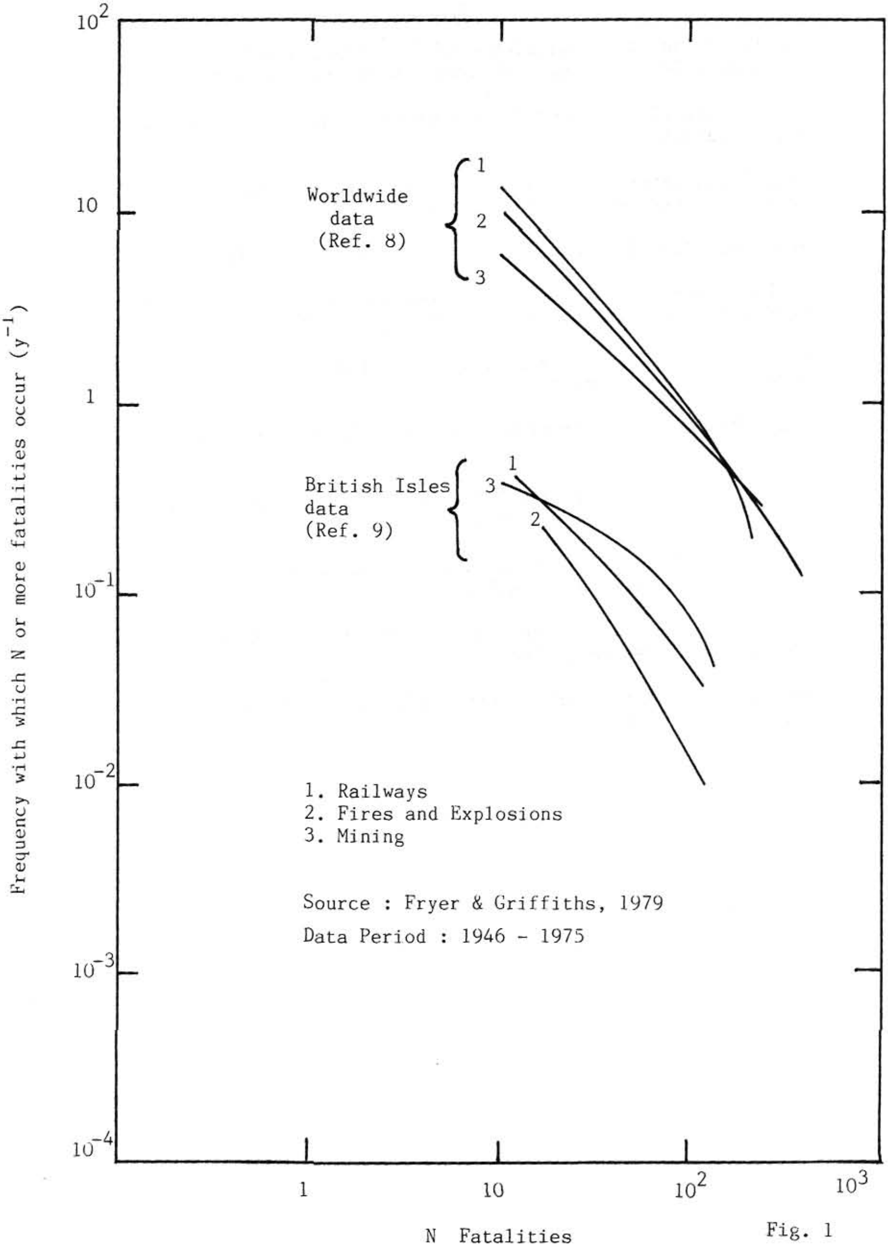

Fig. 1

Frequency of Multiple Fatality Accidents Associated with a Chemical Industry Plant or Site

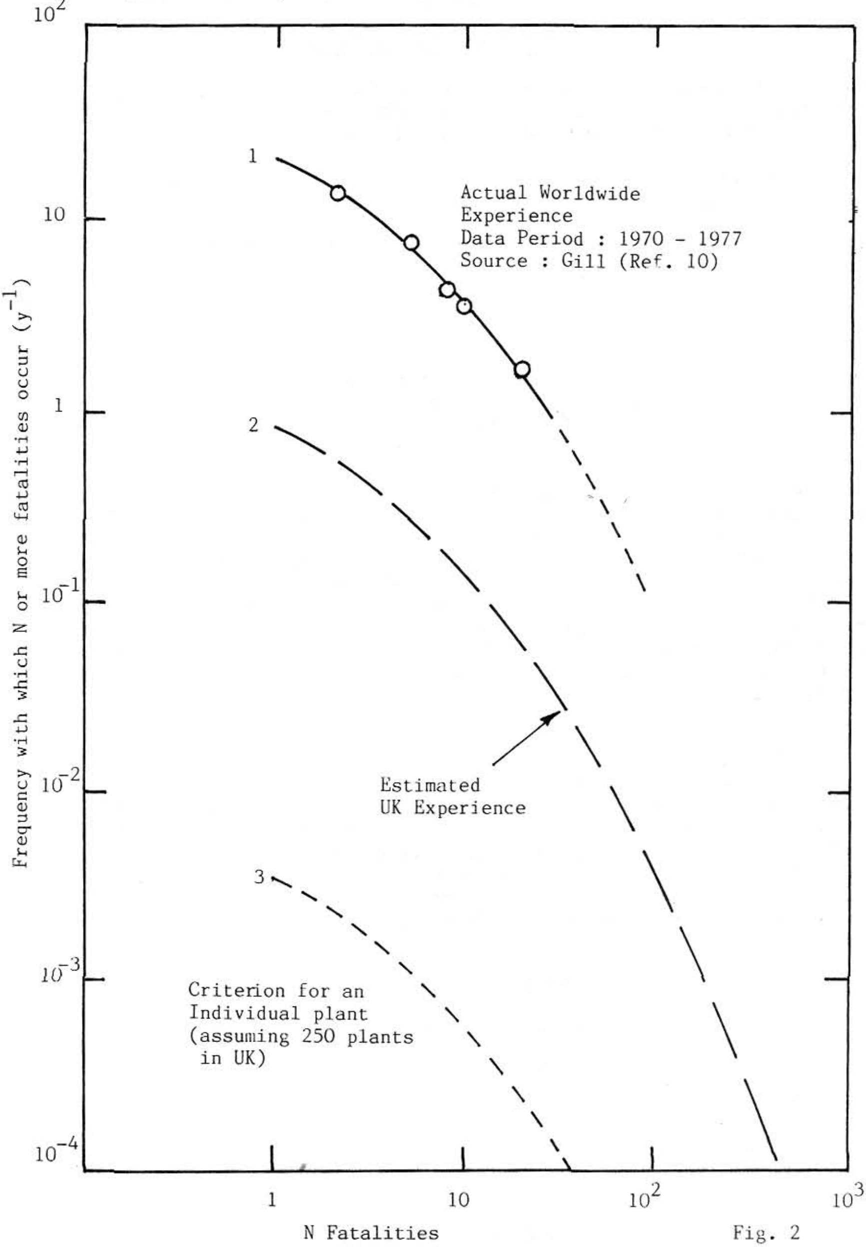

Fig. 2

APPENDIX 1

THE CALCULATION OF RISK

For present purposes risk can be defined as the product of the frequency of an event and the consequence given that the event occurs. In this case the event is the occurrence of a hazard at a chemical plant.

The frequency of the hazard is obtained from the results of quantified safety assessments which may include event tree and or fault tree analyses.

In order to assess the consequence given that the hazard occurs the following information is required:-

(a) An estimate of the nature and magnitude of the hazard.
(b) Data on the toxicity or any other harmful effect due to exposure to the hazard.
(c) A dispersion - consequence model to calculate the pathogenic effects of the hazard on the population in the area surrounding the plant.

For calculational purposes the area surrounding the plant is divided into twelve 30^o sectors. The plume resulting from an accidental release of say a toxic gas is assumed to be confined within one of these 30^o sectors. Each sector is subdivided into a convenient number of radial intervals. The area bounded by two successive radii within a 30^o sector will here be termed a segment. It is convenient to regard the population within a segment as being concentrated at the mid point of that segment so that the total population within any sector may be considered as a series of point populations situated at the appropriate radii ($r_1 \ldots r_R \ldots r_{RMAX}$) along the line bisecting the sector.

Individual Risk

Individual risk refers to the risk of death to an individual at any given location outside the site boundary due to accidental releases from the plant. One might think that individuals near to the site boundary are at the most risk. However, in some cases such as releases from high stacks the effect of the hazard at the site boundary is lower than that at distances further from the plant. Thus, it is considered necessary to calculate the individual risk in all the segments assuming that there could be an individual in all segments. The equation for individual risk in any segment is,

$$
\begin{aligned}
I(h, s_S, r_R) &= f(h) \times P(k | h, r_R, w_W) \\
&= f(h) \times P(e | h) \times P(k | e, r_R, w_W) \\
&= f(h) \times \sum_{W=1}^{W=7} P(s_S, w_W) \times P(k | e, r_R, w_W)
\end{aligned}
\qquad (A1.1)
$$

The maximum value of this calculated individual risk is then compared with the criterion for individual risk. The criterion is met if

$$[I(h, s_S, r_R)]_{CALC.\ MAX} \leq [I(h)]_{CRITERION} \qquad (A1.2)$$

Societal Risk

In the present context, societal risk refers to the possibility of a number of people dying as a result of accidents at a chemical plant and is calculated as follows.

The number of deaths in sector s_S given a Pasquill weather category, w_W, when a hazard, h, occurs is given by

$$N(h, s_S, w_W) = \sum_{R=1}^{R=RMAX} Q(s_S, r_R) \times P(k|h, r_R, w_W) \qquad (A1.3)$$

The probability of this number of deaths in a sector is $P[n = N(h, s_S, w_W)]$ and is simply the probability of the wind blowing into a particular sector in Pasquill weather category w_W, i.e. $P(s_S, w_W)$.

Thus, in each sector there are seven values of $N(h, s_S, w_W)$ i.e. one for each weather category.

$N(h, s_S, w_1)$ with probability $P[n = N(h, s_S, w_1)] = P(s_S, w_1)$

⋮

$N(h, s_S, w_7)$ with probability $P[n = N(h, s_S, w_7)] = P(s_S, w_7)$

Since there are 12 sectors there are 84 values of these probabilities each with its associated number of deaths. Each value of $P[n = N(h, s_S, w_W)]$ represents a probability of causing exactly $N(h, s_S, w_W)$ deaths. These numerical values can now be ordered, irrespective of sector, in increasing value of the number of deaths, and plotted as a histogram, on which each value of $P[n = N(h)]$ represents the sum of the probabilities which are associated with exactly N deaths given that hazard, h, occurs. This histogram is already normalised because the weather statistics are given in a form such that

$$\sum_{S=1}^{S=12} \sum_{W=1}^{W=7} P(s_S, w_W) = 1 \qquad (A1.4)$$

The cumulative probability of N or more deaths conditional on the hazard occuring is obtained from summations of the data on the histogram.

$$P[n \geqslant N(h)] = \sum_{n=N}^{n=NMAX} P[n = N(h)] \qquad (A1.5)$$

The above calculations are performed by the dispersion - consequence model and the resulting values of $P[n \geqslant N(h)]$ are plotted against $N(h)$.

Now, if a criterion is specified for the societal risk of death due to accidents at a plant, such as that shown by Curve 3 on Fig. 2, then the criterion is met if, for all values of $N(h)$,

$$f(h) \times P[n \geqslant N(h)] = F[n \geqslant N(h)]_{\text{CALCULATED}}$$

$$\leqslant F[n \geqslant N(h)]_{\text{CRITERION}} \qquad (A1.6)$$

APPENDIX 2

SIMPLIFYING ASSUMPTIONS FOR ILLUSTRATIVE PURPOSES ONLY

Throughout the paper a simple example has been used to illustrate the use of risk acceptance criteria in relation to the calculated risks associated with a major hazards plant. For the purpose of this example the following simplifying assumptions were made.

(i) There is only one weather category and the wind rose for the site is uniform. This implies that

$$P(s_S, w_W) = P(s) = \frac{1}{12} \text{ for all sectors}$$

(ii) The population is uniformly distributed around the plant, and can be considered to be point populations in each sector at a single radius from the plant. Thus,

$$Q(s_S, r_R) = Q(s, r) \text{ for all sectors}$$

(iii) The probability that a person at radius r is killed is 0.1, given that a hazard occurs. Thus in equation A1.1,

$$P(k|e, r_R, w_W) = P(k|e, r) = 0.1$$

and in equation A1.3

$$P(k|h, r_R, w_W) = P(k|h, r) = 0.1$$

With these assumptions the equations in Appendix 1 for individual and societal risk can be simplified as follows.

Individual Risk

Equation A1.1 becomes,

$$I(h, s, r) = f(h) \times P(s) \times P(k|e, r)$$

$$= f(h) \times \frac{1}{12} \times 0.1 \qquad (A2.1)$$

Societal Risk

Equation A1.3 becomes

$$N(h, s) = Q(s, r) \times P(k|h, r)$$

$$= Q(s, r) \times 0.1 \qquad (A2.2)$$

There are 12 values of N(h,s) each having a probability of

$$P[n = N(h,s)] = P(s) = \frac{1}{12}$$

Thus, the histogram is a single point having co-ordinates $P[n = N(h)] = 1$, $N(h)$, and so the cumulative probability, $P[n \geqslant N(h)]$ is also unity. Thus equation A1.6 becomes

$$f(h) \times 1.0 = F[n \geqslant N(h)]_{\text{CALCULATED}}$$

$$\leqslant F[n \geqslant N(h)]_{\text{CRITERION}} \qquad (A2.3)$$

Note that the above assumptions are made purely for illustrative purposes in this paper. In practice the equations given in Appendix 1 should be used to perform the calculations of individual and societal risks.