A BASIC APPROACH FOR THE ANALYSIS OF RISKS FROM MAJOR TOXIC HAZARDS

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HSE is required to give advice to Planning Authorities about the siting of major hazards and the control of developments nearby. Risk assessment techniques have been developed for this purpose. In this paper, the steps required for a basic quantitative top-down analysis of risks to the public from a bulk chlorine installation are described in outline. It is indicated that many items of data or assumptions need to be incorporated. Particular attention is paid to the use of local weather characteristics, and the importance of mitigating effects. A computerised procedure developed within HSE is used to present the results in the form of contours of individual risk and graphs of societal risk. The sensitivity of these results to assumptions and judgements and the validity and usefulness of the approach are discussed.

1. INTRODUCTION

Recent years have seen a growing awareness of the potential for large-scale loss-of-containment accidents from major installations. In the UK in 1974 the Flixborough explosion killed 28 workers on-site, and caused widespread damage and some injury off-site (1). This prompted the formation of the UK Advisory Committee on Major Hazards (ACMH). ACMH analysed the situation and made many recommendations, including legislation to control and reduce the risks (2). These recommendations included a need for the analysis of the consequences of loss-of-containment accidents and predictions of their likely frequency so that the risk levels to neighbouring populations could be assessed. They also recommended that research work be conducted to improve and validate the predictive techniques.

The UK Health and Safety Executive (HSE) has been active in this research field. Much work has been done on the dispersion of heavier-than-air gases in the atmosphere, as recommended in the First ACMH report. Work has also been done on the methodological framework for incorporating the results of

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research into a risk analysis, for testing the sensitivity of risk estimates to assumptions and judgements and the associated levels of uncertainty (3, 4). This paper describes and illustrates the basic procedure which is now being used and developed within HSE for risk assessment work. The procedure has been computerised (5) and can be used as a risk assessment tool (RAT) to investigate absolute and relative levels of risk, and to show its sensitivity to uncertainties in input data.

The HSE RAT described here was developed to deal with the effects of bulk toxic gases such as chlorine, and its extension to the assessment of risks from flammable materials such as LPG is being pursued. Within the UK there are about 120 chlorine installations which are notifiable under Regulations pertaining to major hazards (6), plus about 600 LPG installations, 400 natural gas installations and several hundred installations with other materials. The RAT was developed initially for toxics, rather than the more numerous LPG and gas installations, for several reasons:

- the potential hazard range can be several kilometres;
- the interactions of wind directions and weather category likelihoods can be very significant;
- the effect is not instantaneous, so mitigating factors such as escape into buildings must be included;
- details of plants may vary considerably;
- there are considerable uncertainties, so the sensitivities of results to the input data values must be analysed.

The HSE RAT produces estimates of risk levels to individuals in buildings near hazardous installations, and it also calculates the associated societal risk (7) using local population and weather data. Such information is required by HSE to assist in the provision of advice to local authorities regarding the siting of developments (eg new houses) near major hazard installations. This paper illustrates some of the procedures by which such advice is developed.

2. THE BASIS FOR SITING ADVICE

One possible basis for providing advice to local authorities is to use a quantification of the consequences of various potential releases of material, with a qualitative assessment of likelihood, to see what degree of protection is given by distance between the source and a population. This is known as the 'protection concept' and it has been endorsed by ACMH (2,1984). Such an approach is more problematical with toxic gases than with, say LPG, since there are more factors involved in estimating the likelihood of accidental releases and their effects. For toxics, and increasingly for flammables or explosives, effort is desirable to analyse and quantify the likelihoods. This helps to clarify the situation, and it provides a firmer basis for comparisons with other risks in life, so that the task of the planning decision-maker is facilitated.

An alternative approach is to combine the likelihoods of hazardous events with the probabilities that they will result in particular consequential severities being realised so that risk levels to neighbouring populations can be calculated. However it is often argued that quantitative probability assessment in the process industry is useful for comparing the relative risks from different safety strategies, but the absolute results are less trustworthy. Perhaps this is so, but it is helpful in making siting decisions as described above to obtain an impression of the actual risk levels involved. It is then possible to compare the predicted absolute risks, from the plant/people juxtaposition, with other statistical risks in life, to make an informed decision. In this situation, it is vital that the uncertainties in the risk be properly understood. Effort is necessary to test the sensitivity of results to assumptions, both implicit and explicit. The HSE RAT was developed to do this.

The basic approach for the RAT has been outlined by Nussey (3), and the importance of sensitivity of assumptions has been emphasised. A more detailed description of the consequence assessment procedure and development of the RAT is given by Nussey et al (5). The classical approach is used, namely;

Identify the hazard (potential sources of material release);

List release sizes, frequencies and durations;

Estimate concentrations and durations vs distance from source;

Determine doses to people at risk from each item in list;

Determine probabilities that doses will be experienced, taking account of wind and weather dependencies on direction;

Apply toxicology criteria;

Summate risks from all the listed releases;

Test sensitivity to uncertainties in assumptions.

The application of this approach will be illustrated for a hypothetical chlorine installation which is shown in Figure 1. This consists of a basic system for pressurised liquefied gas, comprising a tanker supply-point, two storage vessels (only one of which is shown in Fig 1: the other is on stand-by), and liquid and gas off-takes. The system is instrumented and protected to good industrial standards (8). The installation is located near some hypothetical housing.

3. PROCEDURE FOR QUANTIFYING RISK LEVELS FROM PLANTS PROCESSING ACUTELY TOXIC SUBSTANCES

3.1 Identify Hazards, List Release Sizes and Frequencies

The requirement here is for a basic understanding of the plant, its control and safety systems, operating conditions and practices and managerial arrangements for monitoring, maintaining and improving them. A site visit is therefore an essential requirement. Such an understanding enables a complex process and instrumentation diagram to be reduced to a flow diagram (eg Fig 1) showing the essential information for a top-down approach. This diagram forms the basis of procedures we have found to be useful. In essence the installation is first sub-divided into vessels, pipework, transfer couplings, pumps and user plant. Each of these components could, in principle, produce a continuous spectrum of release sizes, but it is necessary to simplify by reducing the spectrum into discrete sections. For example, a pipe failure could range from complete severance to a weeping pin-hole; this is simplified to two cases, namely guillotine fracture (both ends open) and split (equivalent to a 13 mm diameter circular hole). Each component is separately labelled; for pipe-runs, the label consists of an identifying letter followed by the pipe-diameter (in inches) and a suffix indicating whether the contents are normally liquid (L) or gas (G). *Thus B1L refers to release of liquid* chlorine from the one inch line labelled B in Fig 1. See Figure 2 for an illustration of the analysis process.

Each vessel and pipe run (including fittings) is considered in turn and release rates and durations for each of the postulated major releases are estimated using standard discharge rate calculations and pool formation and evaporation procedures (e.g. 9, 10). This systematic examination of each vessel and pipe run produces a list of vapour generation rates and durations.

In Table 1, each release has been expressed as a vapour production-rate. For chlorine at ambient temerature, it is assumed that releases from pipes or small holes in vessels will vaporise completely. The justification for this is that for unbunded releases the SPILL code (10) predicts that the vapour rate quickly reaches the spill rate. Also, the violent flashing process results in spray formation and air entrainment so that rain-out is limited or non-existent (11). There may, of course, be scale and configuration effects which will complicate the situation. For vessel 'bursts' we have assumed complete vaporisation if the release is directed upwards, or if it is directed into a bund, 50% vaporisation (ie significant rain-out of liquid chlorine at its boiling point). A listing of these assumptions, and others, is given in Appendix 1.

The durations of releases are based on these assumptions with account being taken of the presence of automatic, remotely-operated or manual shut-off valves, or the possibility of patching of vessel leaks.

The frequencies of releases shown in Table 1 are based on generic failure rate data taken from various sources. They are intended to be reasonably typical for a good standard chlorine installation. Ideally, data derived from operating experience of the plant would be used, but of course this is not normally available for large releases. Instead, recourse is made to aggregated data (eg (12) for pressure vessels) with modifying factors applied by judgement to allow for the particular standards of the specific installation (hence the need for site visits and discussion). This is a major source of uncertainty, and the sensitivity of the results to these assumptions should be tested [for examples, see (3)].

It should be noted that currently, for ease of computation, large instantaneous releases are treated as pseudo-continuous. A rule-of-thumb has been developed, that releases over 10 te are assumed to be equivalent to a release of 1½ times the actual quantity with a duration of 10 minutes; smaller releases have a 'duration' of five minutes. The dispersion of such releases is predicted from estimates obtained from the HSE/SRD gas dispersion model CRUNCH (10) which applies for continuous releases. Tests have been applied, using an instantaneous dispersion model (DENZ, (10)) to validate the rule-of-thumb. Work is in hand to build in a procedure for modelling instantaneous releases more rigorously.

It should be noted that the emphasis here is on relatively sudden releases where no prior evacuation is possible. The failure cases of interest are judged accordingly. Also, small releases which would not present an off-site hazard are not included.

3.2 Effects

A computerised procedure is used to calculate the relationship between the probability of individual injury and distance from the source, for each of the specified releases (Table 1). The procedure begins by calculating the dispersion behaviour of the semi-continuous release in various weather conditions. Tests are then applied at various distances to see whether a "significant" dose could result for a person indoors or out of doors in various weather conditions. Here, "significant" implies a dose equal to or exceeding the so-called Dicken Fatal level [(4) and Appendix 1].

The area within which a significant dose could arise is derived for persons indoors and out of doors. This requires assumptions to be made on building penetration by gas, taking due account of the relationship between air-change rate and external weather (See Section 4.2).

A particular feature of the RAT is the allowance for the possibility that a person may be indoors or out of doors, and if he is out of doors he may "escape" indoors before receiving the criterion dose. He may still receive an injurious dose indoors, if the external gas concentration is sufficiently high and prolonged to permit dangerous levels to penetrate into the building (see Figure 3). The probability of an individual suffering a particular consequence at a particular distance is estimated from the widths of a series of isopleths as depicted in Figure 4.

These probabilities take account of the pattern of wind direction and weather category and the probability of the person being out of doors at the time. The weather-weighted consequence probabilities, which take account of the likely occupancy, are then multiplied by the release frequency to determine the level of individual risk. This is done for each scenario so that the total variation in individual risk with distance can be estimated by summing the separate contributions. For the purpose of sensitivity testing described below, a uniform random wind direction is assumed, but the actual pattern must be used to derive risk contours as the probabilities are sensitive to wind (see (5) for a fuller account).

The societal risk is computed by superimposing each area shape/wind direction combination on a map of the neighbourhood with populations marked on it. This indicates the number of people affected by that particular combination. The results for each combination are ranked in ascending order of the number affected so that the frequency (F) of N or more being affected can be obtained by aggregation to produce the F/N curve for the site.

The calculations have been programmed for an Apple IIe microcomputer (5) and contours for multiple-plant sites can be derived. At the contouring stage it is possible to include the contributions to risk levels from explosion or flammable hazards.

4. RESULTS

The results for the 'base-case' are shown in Table 2 and Figure 5. It is seen that the risk very close to the plant is dominated in similar measure by gasket failures, pipe splits, coupling/hose failures, and releases from the vaporiser unit. At 200m, the risk is dominated by pipe splits, coupling/hose failures (on the vapour line) and the vaporiser. At distances beyond 300 m the risk is dominated by major vessel failures, with some contribution from uncontrolled gasket failures and pipe splits.

Beyond 750m the risk is well below 10^{-7}/y. Since this is the risk of receiving doses at the Dicken 'Fatal' level or greater, which may not always be fatal, it seems unnecessary to consider calculated individual risks below this level (following the views of the Royal Society Study Group on Risk Assessment (14)). However, care should be taken not to neglect societal risk at such distances, but it is emphasised that this is the societal risk for casualties, of whom a fraction would be killed.

Table 2 also contains information on the percentage of risk which arises in Category F weather (in parentheses under the risk figures). It is seen that such events tend to dominate the risk beyond 200m, even though F weather only occurs for 17% of the time (at the locality illustrated here), people are assumed to be out of doors for only 1% of the time in such weather, and the building air-change rate is 0.5 air changes per hour.

A procedure for carrying out a formal uncertainty analysis was described by Nussey (3) and has subsequently been implemented on the HSE computer. Here, we show the results of variations in some of the key factors using the RAT, to illustrate its application.

Results for sensitivity tests are shown in Table 3 and Figures 5, 6 and discussed below:

4.1 Outdoor Risk

Cases ID1 and ID2 test the sensitivity to the proportion of time spent out of doors. In ID1 the proportion is zero while in ID2 the proportion is 100%. The effect of ID1 is very small while the extreme case of ID2 increases the risk by up to a factor 2 at intermediate distances. This is consistent with the view that people out of doors would usually have a chance to escape indoors, except when very close to the source of a large release. For such releases, the dose for those indoors near the source would probably be excessive anyway. (It is of course possible that the likelihood of escape indoors has been overstated in the model, but experience of accidents suggests that people do often have a good chance of escaping indoors).

4.2 Air Change Rate

Work by the Building Research Establishment (15) shows that air-change rates can cover a wide range, depending on whether windows etc are open or closed. Also, the rates are sensitive to windspeed. This could be important here, since most of the risk accrues to people indoors. Case ACH1 increases air-change rates by a factor 4 in D weather, and factor 2 in F weather. The effect is most pronounced at intermediate distances, where the risk is doubled or trebled. Case ACH2 uses an air-change rate of 0.5 in D/2.4 weather, and the rate is halved in F weather. This reduces the risk, particularly at intermediate distances, by a factor of up to 4.

4.3 Evacuation Time

For case EVAC, the time taken to leave a building was increased to 60 minutes from the start of the release. This increases the risk, at intermediate distances, by a factor up to 2½. This suggests that emergency action to get people out of doors as soon as the cloud has passed could be quite beneficial. (For a fuller discussion, see Purdy and Davies (16)).

4.4 Toxicology Criterion

The base case used the Dicken 'Fatal' criterion to define the threshold of a significant dose. We have not attempted to use a Probit approach (17), so the risks derived here relate to the probability of receiving a dose of Dicken 'Fatal' or greater.

Case TOX1 tests the effect of a change in slope of the toxicology (concentration vs time) relationship, with the position of the curve determined by 100 ppm/10 min as in the Dicken 'Fatal' curve. The slope in TOX1 is similar to that used by other workers in Probit approaches (17). Also C_1 is changed to 500 ppm and C_2 to 300 ppm (see Fig. 4). These changes have little effect on the predicted risks. Case TOX2 uses a Toxicology criterion which may correspond to LC_{50} for healthy people (18). This produces a dramatic reduction in predicted risk levels, with the distance to 10^{-7}/y being reduced from 750 to 300m.

Case TOX3 uses the Dicken 'Distress' criterion. As expected, the risk of receiving such a dose is substantially greater than the 'Fatal' case, particularly at distances beyond 200m.

4.5 Gasket Size

Case GASK tests the effects of a reduction in gasket thickness, by reducing the release-rates of chlorine from gasket failure to 1/4 of the base-case. This has a moderate effect at short ranges where small events are most significant.

4.6 Vessel Failure-Rate

Case VES includes vessel failure-rates increased tenfold for all vessel failure cases. This has substantial impact on the risks in the far field. The range to 10^{-7}/y is doubled.

4.7 Large Plant

Case BIG is included to illustrate the effects of increasing plant size and complexity. The number of vessels is increased to 5, length of liquid pipeline to 200m, with 120 loading operations/y, 1 extra vaporiser and 2 pumps (body failure rate 10^{-4}/y). Gaskets and valves are increased tenfold. As expected, this produces risks which are greater than those from the 'base-case', by factors which are more or less pro-rata with the change in numbers of components. (Of course, this is probably rather simplistic: large plants would have larger diameter piping, larger vessels etc, so that release sizes would be greater. However, larger components may be better able to withstand impact etc, so that their failure frequencies may be lower).

5. DISCUSSION OF SENSITIVITY TESTS

The results are fairly insensitive (± 50% or less) to the following:

Proportion of time out of doors (ID2 is a totally unrealistic case for housing, although it may have relevance in the assessment of sports stadia, open-air markets etc).

Slope of C vs t in toxicology criterion, and concentrations causing rapid incapacitation;

Gasket size (only sensitive in near field).

The results are moderately sensitive (± factor 3x) to the time to evacuation and the air-change rates.

The increased risk for the 'big-plant' is more or less pro-rata with size and throughput, and risks in the far-field vary pro-rata with vessel failure frequencies.

The use of a different toxicology criterion can have a very significant effect, as expected. The difference between the criteria in TOX1 and TOX2 is large (eg 67 ppm/30 min for TOX1 and 400 ppm/30 min for TOX2). This difference does not represent uncertainty about a particular criterion, but a more fundamental difference in approach. (See also (4) for a fuller discussion).

The predictions are also sensitive to the dispersion model behaviour, which can differ significantly between teams using other models than those in (10). Attempts have therefore been made to validate the whole consequence assessment procedure used by HSE (4).

In this and other work, we have found that the individual risk results (based on HSE's dispersion codes) are fairly robust towards changes in the various assumptions. The sensitivity towards most assumptions taken one-at-a-time is pro-rata or less. A greater sensitivity is only associated with air change rate and time to evacuation. Nevertheless, we feel that it is important to aim for best-estimate values in all assumptions, to avoid multiplying conservatisms or optimisms. We have taken care to include mitigating factors where possible, but not to overdo this. For example, escape by running or walking out of the cloud is not included, since it would require prolonged 'rational' behaviour in conditions of extreme distress, and it would enhance the respiration rate while exposed to high concentrations.

6. RISK CONTOURS AND SOCIETAL RISK

6.1 Risk Contours

To derive risk contours, it is necessary to modify the increments of risk calculated as above, to take account of the directional dependencies of weather stability and wind speed probabilities on wind direction. The results are shown in Figure 7.

It should be noted that the contours do not stretch out down the 'prevailing' wind direction (ie to NE) but they stretch out down the direction into which the wind mainly blows in 'F' weather (ie to W).

6.2 Societal Risk

To simplify computation, societal risk is calculated for an indoor population and an outdoor population without mitigation. For the situation considered here, where allowance is made for people out of doors being able to retreat indoors, we only give the indoor risk. These risk levels are unlikely to lead to substantial underestimates of risk for housing since the greater part of the risk arises from releases in stable weather conditions when people could be expected to be indoors. However, consideration is given to outdoor risk levels whenever this is appropriate.

The results for the hypothetical site are shown in Figure 8, as an F/N curve. This shows that an accident leading to 10 or more 'Dicken Fatal' exposures has a likelihood of 6 $\times 10^{-6}$/y. The exact implications of such exposures for the likelihood of fatality are not known but it can be expected that all those who survive would require hospitalisation. Moreover in many cases the criterion dose level will have been exceeded.

To put risk into perspective, it may be compared with world and UK historical experience. Fig 8 contains an F/N curve from available World date on chlorine fatalities, including transport accidents (derived from (19)). Also shown is data from (19) for injuries in the UK. The comparison suggests the following points:

The present 'base-case' results for N = 100 is 10^{-5} times the World fatalities frequency for N = 10. This is a useful comparison, since the present toxicology criterion would only kill a fraction of those exposed (assuming that the population does not contain a high proportion of very susceptible people). Thus this situation comprises 10^{-5} of the total World risk.

The UK frequency for industrial major accidents is typically about 3% of the total World frequency, for a given N. The implication of this for chlorine in the UK is shown in Fig 8 as the 'UK fatalities: predicted' line. The present base-case situation appears to represent about 3 x 10^{-4} of the total UK risk from chlorine, using the basis for comparison outlined above. Now, compare this fraction with the possible existence of perhaps 100 similar situations in the UK, plus transport risks, bearing in mind that the present estimate is for off-site risks to people living beyond 200m from the plant. (Accident experience suggests that most serious injuries occurred to people within the works or close to it). Also, note that the 'base-case' plant is simple and has a high standard of protection built in. Thus the fraction would be expected to be well below 10^{-2}, and a value in the range 10^{-3} -10^{-4} seems consistent with World fatal accident experience.

Care is necessary in making comparisons of this type since the risk estimates are determined by many assumption and model predictions. Comparisons should cover the whole procedure rather than any part of it in isolation (eg see (6)). Bearing this in mind, work on validation and refinement of the procedures is continuing with the aim of providing risk predictions that are best estimates.

7. APPLICATIONS

The basic approach described above is not very demanding on resources for a team which is familiar with methodology and which has available an agreed list of assumptions. A two-person team might spend a day collecting information from a simple site. For an assessment which includes existing local buildings etc., it would be necessary to check that the local map was up-to-date. The team would then spend another day or two analysing the information, performing the calculations and doing sensitivity tests. The team's report should take pains to list the information, assumptions and uncertainities, as well as the best-estimate results.

This approach has been used to analyse four plants and our experience suggests that it would provide at best an estimate of absolute risk levels to within half an order of magnitude. A major problem is the uncertainty in failure-rate data and the difficulties in improving on the uncertainty. In addition, the consequence analysis is inevitably somewhat uncertain but the possibility of improvements here is perhaps more promising. Such uncertainties should be made clear to the decision-maker and a view on how the results of the assessment compare with historical experience, should be expressed. In doing this it is necessary to make appropriate judgements as to how the given situation compares with these situations which have been involved in accidents, and also how the present situation compares with the average which forms a basis for deducing the historial accident frequency.

The application of the results for advice on siting of new developments near existing hazardous installations has yet to be fully explored. At present, it is suggested that the results for individual risk can be used to show whether the level would be well above or well below the Royal Society's 'trivial' mark (ie 10^{-6} - 10^{-7}/y). If the level were well above 'trivial' for a significant number of people there are clear reasons for advising against the development on individual safety grounds. If the risk were well below it would still be necessary to consider societal risk (eg consider a major shopping development where occupancy by individual shoppers is very small, so individual risk is very low, but any accident might involve large numbers of people who are not easily amenable to evacuation/emergency action). For individual risk near the 'trivial' mark, careful consideration should be paid to societal risk and other planning factors. In making these judgements, attention must be paid to the implications of uncertainty in the results, and to the possibility of conservative or optimistic bias.

The case of the siting of a new installation near an existing population is more problematical. If there were many people likely to be exposed to additional risks well above the 'trivial' mark, it would be difficult to justify the proposal. However, if there were only a few individuals exposed to significant risk, and the societal risk were low, the proposal might well be justifiable. Also, in this situation the opportunity may exist to seek a reduction in risk by alterations to the installation design or site layout without too much expense. Such decisions can be aided by the use of the RAT and would enable the benefits of various options to be compared rationally.

The approach used here was developed in the context of HSE's provision of advice to Planning Authorities, but it may also be useful in a Safety Case under the new Control of Industrial Major Accident Hazard Regulations (20), to indicate the level of safety achieved with existing situations. The analysis of failure cases is no substitute for a rigorous Hazop or analytical approach, but the consequence assessment procedure may be used to show the implications of such an analysis. Also, the overall approach may provide a useful support for qualitative assertions about risks to the public.

CONCLUSIONS

The HSE Risk Assessment Tool (RAT) has been developed to calculate the effects of accidental releases of toxic gases in terms of individual and societal risks, for use in the formulation of advice on risks to the public for Planning Authorities. The approach takes due account of weather patterns and the mitigating effects of being indoors. The RAT is versatile, and particularly useful for testing sensitivity to input assumptions. In particular, it show the effects of different siting options, and it may be useful in illustrating the effects of emergency plan strategies.

A procedure for analysing a plant to produce release cases has been described. When these cases are analysed using the RAT, the results are fairly robust against variations in individual cases.

The use of the RAT has been illustrated for a hypothetical chlorine plant, using best-estimate assumptions.

The sensitivity of the results, in terms of the variation in individual risk levels with separation distance, has been tested for different input assumptions.

The results are fairly insensitive to: likelihood of being out of doors; slope of toxicology C v t curve. The results are more sensitive to: building air-change rate; absolute position of toxicology C v t curve; dispersion model; and failure-rate data.

REFERENCES

1. Various articles in the Chemical Engineer, No 404, June 1984

2. Advisory Committee on Major Hazards: First Report 1976, Second Report 1979, Third Report 1984, Publ. HMSO

3. Nussey C, 1983: 4th Euredata Conference, Venice, 23-25 March 1983

4. Nussey C, Mercer A, Fitzpatrick R D, 1985: Proceedings of the Third Symposium on Heavy Gas Dispersion and Risk Assessment, Bonn, 12-13 November 1984

5. Nussey C, Clay G, Corlett T C: to be published

6. Notification of Installations Handling Hazardous Substances Regulations 1982: SI 1982/1357

7. Holden P, 1983: Symposium on 'Safety Criteria - Requirement, Establishment and Application', Safety and Reliability Society, 29 September 1983

8. Chemical Industries Association, "Guidelines for Bulk Handling of Chlorine at Customer Installations" (NB Revision in hand at present)

9. Canvey: a Second Report, by HSE and UKAEA SRD, Publ. HMSO, 1981

10. Program DENZ: See Fryer L S, Kaiser G D, Report SRD R 152(1979); Program CRUNCH: See Jagger S F, Report SRD R 229(1982); Program SPILL: See Prince A J, Report SRD R 210(1981); Program PIPE 2 by Heat Transfer and Fluid Flow Service, Harwell

11. Fletcher B, 1982: in 'The Assessment of Major Hazards', I Chem E Symposium Series No. 71

12. Smith T A, Warwick R G, 1981: Report SRD R 201

13. Dicken A N A, 1974, Chlorine Bicentenial Symposium, The Electrochemical Society, San Francisco

14. 'Risk Assessment - a Study Group Report', Publ. The Royal Society, 1983

15. Guillaume M, Pracek J, Warren P R, Webb P C, 1978: Building Research Establishment Report PD 43/78

16. Purdy G, Davies P C, 1985: I Chem E: Multistream '85 - Subject Group Symposium, London 16-18 April

17. Lees F P, 'Loss Prevention in the Process Industries', Publ. Butterworths, 1980.

18. ten Berge W F, van Heemst M V, 1983: 4th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, I Chem E, 12-16 September.

19. Lewis R C, Hymes I, UKAEA SRD - private communication.

20. Control of Industrial Major Accident Hazards Regulations 1984: SI 1984 No. 1902.

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 Only 1 live at once. Typical stock : 20 te	Burst	50*	10	1	Over bund. pseudo-plume
	Burst	25*	10	1	Into bund. pseudo-plume
	50mm hole, liq.	25*	10	1.6	pseudo-plume
	50mm hole, gas	6.4	20	2.4	2 x flash
	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 holes) 3mm thick, 1/4 of circumference	AIL	2.4	20	17	17 joints, live 2% of time, failure 10 x normal rate
	BIL	2	5(C)	220	47 joints;(3 below RSOV so "uncontrollable")
		2	20(U)	15	
	CIG	0.13	20	60	12 joints
	DIG	0.13	20	9	9 joints;Live as AIL
	EIG	0.13	20	1.3	26 joints
Transfer Coupling/hose	FCI	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).

TABLE 2 : RESULTS, BASE-CASE

RATE (Kg/s)	DURATION (min)	FREQUENCY (x 10^6/y)	50	100	200	300	500	750	1000	1500
50	10	1	.29 (23)	.23 (24)	.17 (26)	.13 (29)	.08 (39)	.04 (57)	.01 (94)	0
22	10	5	1.29 (24)	.99 (25)	.68 (30)	.46 (38)	.18 (62)	.06 (95)	.02 (92)	0
6.4	20	2	.5 (26)	.35 (30)	.18 (42)	.08 (59)	.02 (94)	0	0	0
5	30	4	.82 (27)	.56 (31)	.28 (44)	.11 (63)	.03 (93)	0	0	0
1.25	20	156	23.8 (34)	9 (52)	1.46 (93)	.04 (8)	0	0	0	0
4	5	232	44.6 (29)	22.4 (42)	4.33 (89)	.13 (22)	0	0	0	0
5	20	7	1.44 (27)	.98 (31)	.43 (48)	.17 (69)	.04 (94)	0 0	0 0	0 0
0.2	20	141	3.04 (94)	.04 (8)	0	0	0	0	0	0
2.4	20	17	3.09 (30)	1.73 (40)	0.42 (72)	0.14 (93)	0	0	0	0
2	5	220	33.05 (36)	7.36 (86)	.15 (19)	.04 (23)	0	0	0	0
1	5	150	13.64 (49)	1.36 (82)	.03 (20)	0	0	0	0	0
9	20	1	.33 (26)	.24 (29)	.14 (36)	.07 (48)	.01 (94)	.0	0	0
1.4	30	20	3.38 (33)	1.55 (46)	.26 (94)	.08 (92)	0	0	0	0
2	20	15	2.63 (31)	1.37 (43)	.23 (94)	.09 (93)	0	0	0	0
TOTALS			131.5 (35)	48.1 (51)	8.8 (76)	1.6 (53)	.4 (66)	.1 (80)	0	0

Note: Values in parentheses show contributions to risk levels in stable weather.

APPENDIX

Assumptions used in Illustrative Example for Chlorine

Note: The assumptions included here are for purposes of illustration only; they are not necessarily endorsed by HSE.

1. TOXICOLOGY

1.1 Significant exposure: $C^{1.67} t > 20{,}000$ (C = concentration, ppm; t = time, minutes) (ie Equivalent to Dicken 'Fatal' dose (13)).

1.2 For a person initially out of doors, the probability of escape indoors before receiving a significant dose is:

Concentration out of doors (ppm)	Probability of Escape Indoors
> 1000 (C1)	0
(ie C_2) 570-1000(C1)	0.2
140* - 570	0.8
< 140*	1

*For 5 min release. 140 ppm for 5 min is threshold for significant dose. For other durations, use $C = (20{,}000/t)^{1/1.67}$

2. WEATHER

2.1

Pasquill Category/ Windspeed (m/s)	Probability
D/2.4	0.30
D/4.3	0.24
D/6.7	0.29
F/2.4	0.17

2.2 For risk contours, wind direction/weather category correlation were made using data from the Meteorological Station at Squire's Gate, NW England (NB. This does not give the same distribution as 2.1).

3. FAILURE

Failure-rates are based on aggregated data from various sources, modified by judgement. Rates used are for sudden failures, ie leaks which develop into major failures before preventive action can be taken.

3.1 Vessels: Near-instantaneous release of whole contents: 2×10^{-6}/y
Lesser events: Based on partition of total 6×10^{-5}/y:

Equivalent Hole Diameter (mm)	Frequency x 10^6/y
50	4
25	8
13	10
6	40

60% of "lesser events" in gas-space, 40% in liquid space.
NB. "Vessel failure" includes events up to and including the first flange on any nozzle or penetration.

3.2 Pipework: for guillotine fracture:

Pipe Internal Diameter (mm)	Frequency (x 10^6/m.y)
25	0.3

Lesser events (equivalent 13mm diameter hole): 10 times 'guillotine' rates

3.3 Gaskets: 3×10^{-6}/y for 0.6 mm thick gaskets
5×10^{-6}/y for 3 mm thick gaskets

Failure = loss of one section, between two adjacent bolts. (NB. Check whether gasket i.d. is equal to pipeline i.d.). Actual frequency may well depend on inspection and replacement procedures.

3.4 Valve leaks: assumed to be included in 3.2 and 3.3.

4. DURATIONS OF RELEASES

4.1 Vessels lesser events: 30 min or time taken to release all available contents whichever is less (NB. for leaks in gas space, available contents = 2 x flash-fraction for 50 and 25 mm holes, and 1 x flash-fraction for smaller holes).

4.2 Pipework: if automatic (detector-operated) shut off: 1 min.

Remote manual shut-off: 5 mins.

Local manual shut-off: 20 mins.

Fractional dead time of automatic or remote manual system is 0.01. Such a failure would place a demand on the manual back up system leading to 20 min release.

5. OTHER PLANT ITEMS

5.1 Tanker transfer coupling/hose 3 x 10^{-6}/operation. Failure-rate of tanker excess flow valve 0.01/demand.

5.2 Tanker vessels: same rates as vessels in 3.1 above. Make allowance for fractional time on site.

6. RELEASE-RATES

6.1 For vessel bursts, 100% of release vaporises for bursts over bund; 50% vaporises for bursts directed into bund.

6.2 For pipeline release, 100% vaporises.

6.3 For 2-phase (flashing) flow from pipeline guillotine fraction release-rate = 4 kg/s when driven by chlorine vapour pressure, for 25 mm id pipe (NB. Recently the computer code PIPE 2 (10) has been applied to calculate 2-phase flow taking account of pipe geometry, break-points, padding-pressure etc).

6.4 Release-rate = 9 kg/s for release driven by padding pressure through *tanker coupling failure (ie assumes single-phase liquid flow through 25 mm* orifice).

6.5 Release-rate from 13 mm hole in pipework is 4 kg/s, by single-phase flow.

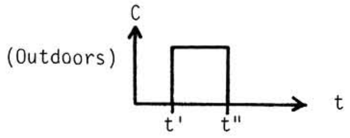
7. DILUTION

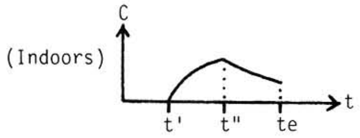
An initial dilution by a factor of 10 (on a mass basis) is assumed at source for releases from pressurised containment. (Results are relatively insensitive to this factor at the separation distances of interest).

8. DISPERSION

8.1 During the time of passage of a plume, <u>at a particular location</u> a uniform concentration for the duration of the release. Concentration variations within the plume are assumed to be Gaussian, but hazard ranges cannot extend beyond the edge of the plume predicted by CRUNCH, during the heavy gas dispersion phase.

8.2 This leads to gas penetration of buildings thus:





t^1 = time of arrival of plume (h)
t^{11} = time of departure of plume (h)
C = concentration at time t (ppm)

$C_{In}\ (t'\rightarrow t") = C_{out}\ (1-e^{-k\lambda(t-t)})$
when $t = t"$, $C_{In} = \text{Max}$
$C_{In}\ (t"\rightarrow te) = \text{Max.}\cdot e^{-k\lambda(t-t")}$

t_e = time when house is evacuated

λ = air-change rate (h^{-1})

k = efficiency-of-mixing factor

8.3 For base-case, $k\lambda$ varies with weather thus:

Weather (Category/Windspeed)	D/2.4	D/4.3	D/6.7	F/2.4
$k.\lambda$	0.7	1.0	1.5	0.5

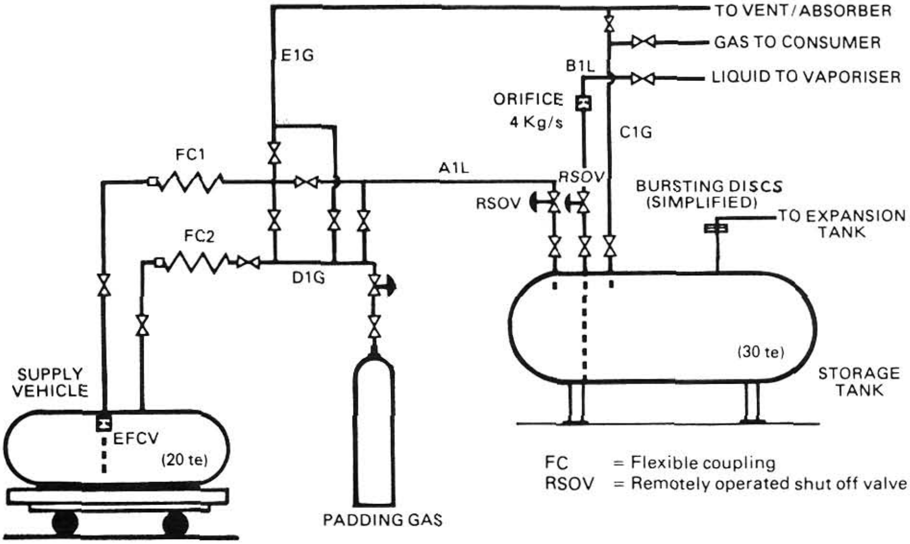
(These values are derived by judgement taking account of data produced by the Building Research Establishment etc (15) and they make some allowance for the possibility of a few windows being open).

9. BEHAVIOUR

9.1 Evacuation occurs 30 min after arrival of cloud (or later if cloud persists for more than 30 min).

9.2 Probability of being initially out of doors is 0.1 in 'D' weather, 0.01 in 'F'.

9.3 Escape indoors is sufficiently rapid that the total dose is the same as that for a person initially indoors.



Pipe Labelling Scheme
First letter is for identification
Number refers to pipe dia. in inches
Final letter indicates liquid (L) or gas (G)

Fig.1 - Chlorine installation (Basic plant, not showing all valves, instrumentation etc)

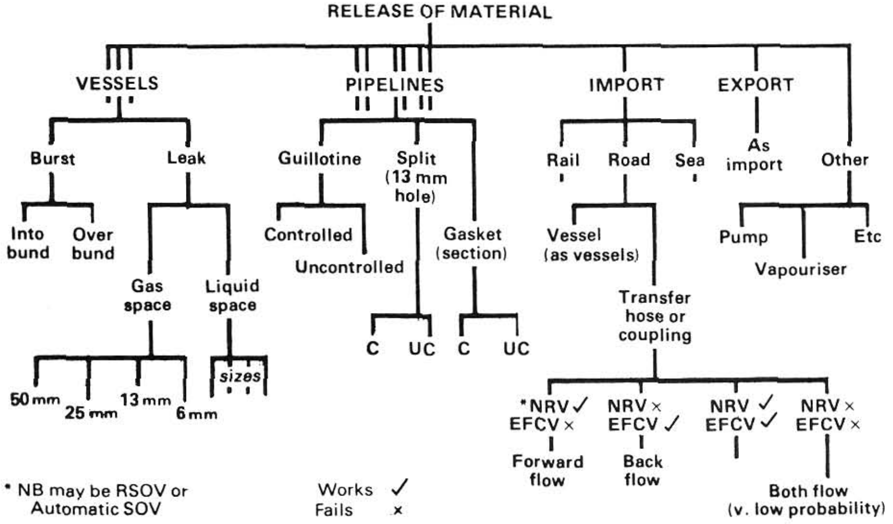


Figure 2: Analysis of Release Cases

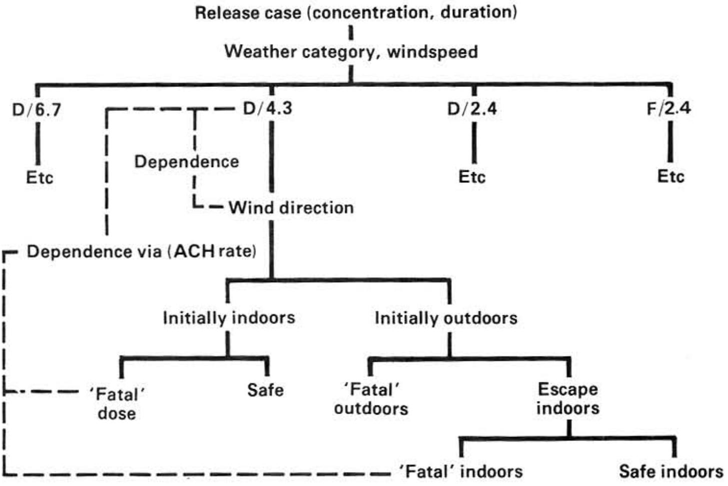
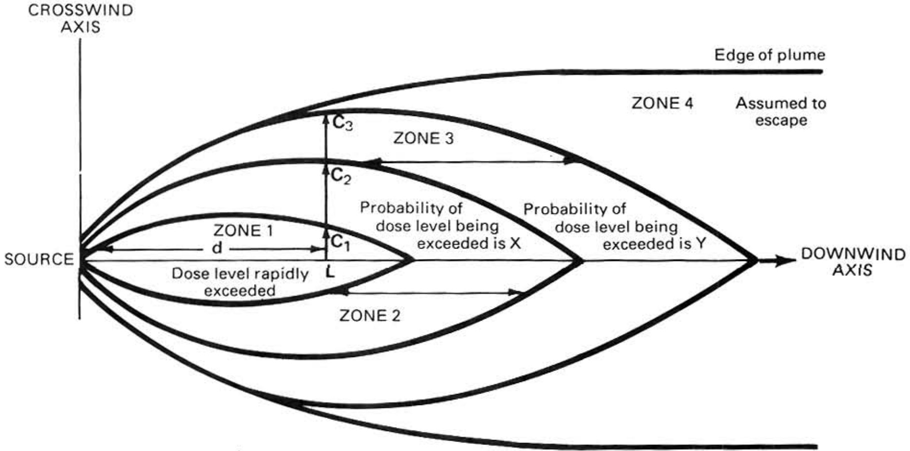


Fig.3 - Analysis of consequences



$$Pco = \sum^{n} \frac{po(i)\ pw(i)}{\pi d} \left\{ LC_1 + X(LC_2 - LC\ ) + Y(LC_3 - LC_2) \right\}$$

where:

Pco = probability of dose level being exceeded if out of doors at a particular downwind distance, d

Po(i) = probability of being out of doors in weather category i

Pw(i) = probability of weather category i occurring regardless of wind direction

n = number of weather categories

LC_1, LC_2 and LC_3 are isopleth half width for user chosen concentration levels C_1, C_2 and C_3

Fig.4 - Derivation of outdoor consequence probability for a uniform wind-rose

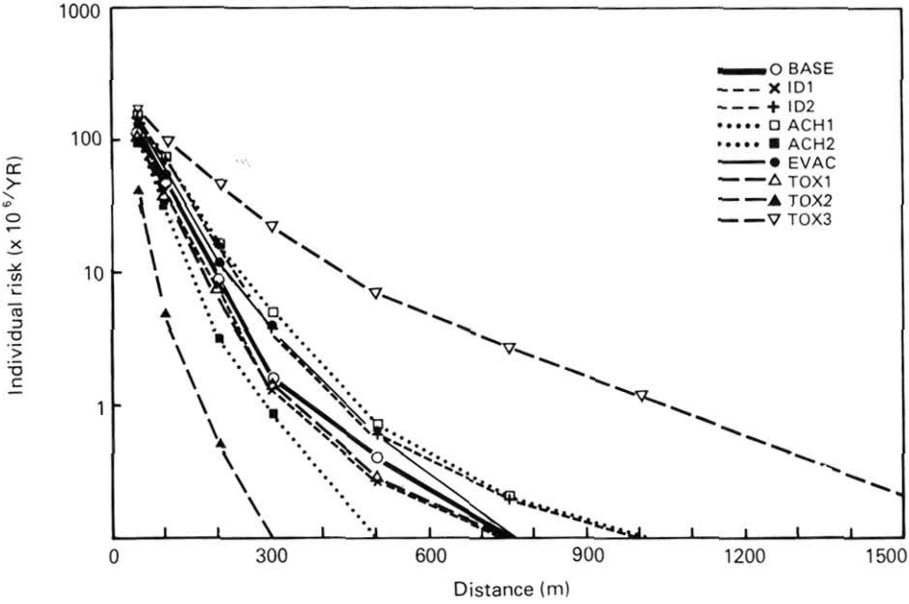


Fig.5 - Results:- sensitivity tests

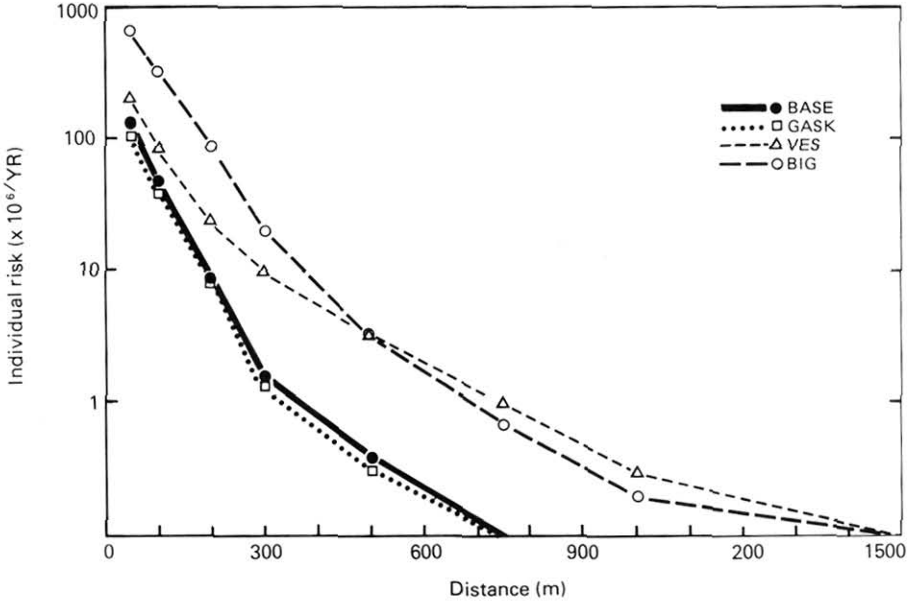


Fig.6 - Results:- sensitivity tests

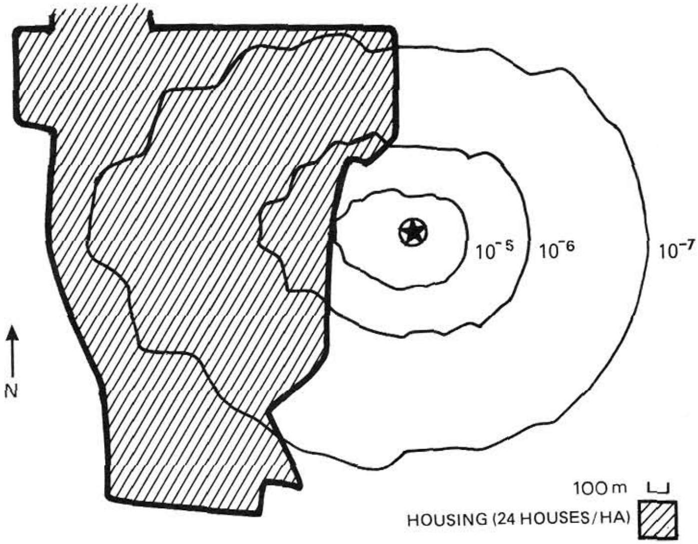


Fig.7 - Individual risk (per year)

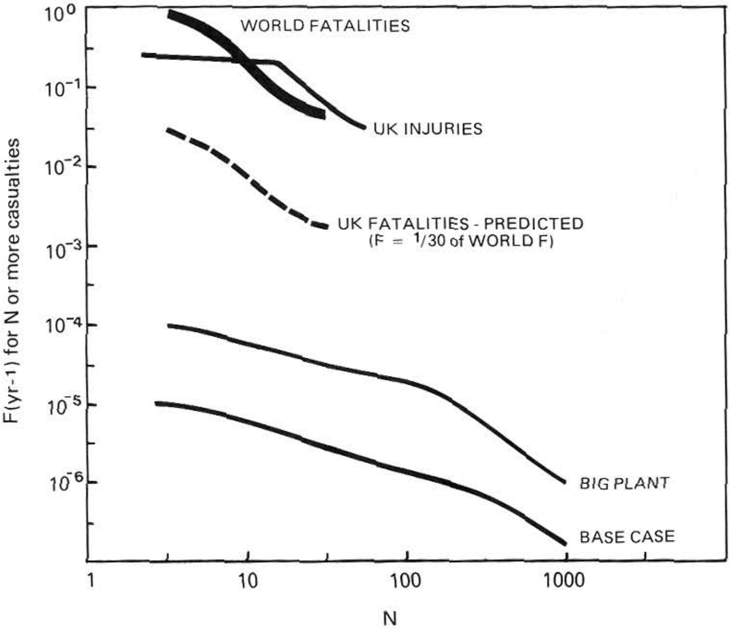


Fig.8 - Societal risk