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HEALTH AND SAFETY EXECUTIVE'S RISK ASSESSMENT TOOL RISKAT

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ABSTRACT

RISKAT is a risk assessment tool developed by the UK Health and Safety Executive (HSE) for quantifying risks to people living in the vicinity of Major Hazards Sites. The paper outlines the approach adopted to conduct quantified risk assessments (QRA). The sensitivity of the risk estimates for both toxic and flammable materials to various uncertainties and the dispersion model used is explored.

The use of the risk estimates by HSE to provide advice to Local Planning Authorities on the development of land near major hazard sites is discussed. Depending on the situation, both the levels of individual and societal risk are considered. The quantitative criteria used for aiding judgement on the significance of the estimated levels of individual risk are defined.

1. INTRODUCTION

In the UK arrangements exist for advice to be given by the Health and Safety Executive (HSE) to Local Planning Authorities on the levels of risk to which occupants of a proposed development in the vicinity of a major hazard plant would be exposed and on whether the proposal should be refused planning permission on safety grounds. In the 1970's and early 1980's this advice was based mainly on professional judgement exercised with the aid of predictions from dispersion calculations for some hypothetical releases of hazardous materials and, in some cases, estimates of the likelihood of those releases occurring ie a hazard based rather than a risk based approach. During this period there were two major public inquiries (see HSE 1978 and HSE 1981) concerning the major accident hazard potential of certain activities (both current and proposed) on Canvey Island at the mouth of the river Thames. HSE evidence to those inquiries was in terms of levels of individual and societal risk (see I.Chem.E. 1985 for definitions) based on assessments conducted by the UKAEA's Safety and Reliability Directorate. Although these assessments were expensive because the procedures used were only partly computerised, they demonstrated the value of the risk based approach for avoiding sterile discussion generated by the possible focus on the worst possible accident scenario.

The need for computerised methods which would greatly accelerate the derivation of risk estimates both in the form of contours of iso-individual risk (Fig 1) and societal risk curves (Fig 2) was underlined at a public inquiry in 1981. At that inquiry HSE was criticised for not using a quantified risk assessment (QRA) approach. Hence, following the inquiry, HSE mounted a project to develop a method for comprehensively assessing and quantifying the risks and acquiring the failure rate data which may be appropriate for major toxic installations. At the outset we decided to use fundamentally similar methods to those developed elsewhere, but to use our own models, assumptions and data.

The study led to some significant methodological advances and HSE considerably improved its understanding of the QRA process and the factors that need to be carefully considered in applying it. The methodology developed by HSE for major toxic hazards was published by Pape and Nussey in 1985. Since then the method has been refined (eg Nussey and Pape (1987) and extended to flammable hazards (Clay et al, 1987). These procedures have become well known as RISKAT (the HSE <u>Risk</u> <u>A</u>ssessment <u>T</u>ool). Further details and examples of the use of RISKAT are given by Hurst et al (1989).

The purpose of this paper is to outline the procedures used, discuss the sensitivity of risk estimates to various sources of uncertainty, outline our plans for addressing these and developing RISKAT, and outline the way in which HSE advice to Local Planning Authorities is formulated on a risk-based approach.

2. CALCULATION OF RISK FROM MAJOR HAZARDS

The procedure which is used by RISKAT to calculate risk for major hazards can be broken down into a number of steps:

- Analysis of the major hazard plant, its control and safety systems, and operational procedures so that a representative number of hypothetical releases with the potential to affect neighbouring populations can be identified.
- For each hypothetical release the chance that such an event will occur in a given time period is determined either from historical failure statistics (so-called generic failure-rate data) or by synthesis from basic component failure rate data using well established techniques such as fault tree analysis.

- For each release case, estimates are made of the rate of release of hazardous material and the duration of the release.
- For toxic, and certain types of flammable release (ie those that do not ignite at source), calculations are made of the atmospheric dispersion of the hazardous material in various weather conditions. For flammable releases the chance of immediate ignition at the source is also considered. Delayed ignition is treated in terms of the predicted concentration levels within a drifting cloud or plume of flammable material and the likelihood of ignition sources being encountered.
- These dispersion, explosion and flame calculations enable the spatial and temporal variations in the effects (toxic gas concentration, thermal radiation, extent of fire zone and overpressure) of the hazards to be mapped out.

For toxic materials the assessment criterion is based on a toxic load, a combination of gas concentration and exposure time (toxic load = $C^n dt$) referred to here as a 'dose' The chance of individuals receiving that, or a greater, 'dose' is calculated. For flammable hazards, harm from thermal radiation, fire and blast overpressure are considered.

In essence RISKAT calculates the chance of a hypothetical individual at a particular location receiving at least a specified criterion dose of the toxic material, a specified dose of thermal radiation, or a specified level of overpressure. In principle these doses may be converted into probabilities of fatality (or some other specified level of injury). One way of doing this is to use 'probit' relationships (Finney 1971) which link dose with probability of death, or some other level of harm so that the level of risk to an individual of receiving at least that dose may be calculated. However, such risk estimates do not take into account the density of the population around a major hazard site or the likelihood of different numbers of people being affected by an incident. These considerations are covered by societal risk which takes the form of a probability in any one year, F, of an event affecting at least a certain number, N, of people.

2.1 Toxic Hazards

The methodology used for toxic hazards has been described fully in Pape and Nussey (1985), Nussey and Pape (1987) and Nussey et al (1990). The procedures are able to give credit for mitigation such as remaining indoors and are based on the calculation of zones defining the region in which people are predicted to have received at least the 'criterion dose'. These zones are calculated for a number of weather conditions (of known probability) and for people indoors or out of doors. Each zone is therefore associated with a particular probability and, under the assumption of a uniform wind rose, the probability of a person at particular locations being engulfed by the hazard zone can be calculated and converted into estimates of individual risk as a function of distance from the release point. The program calculates this variation in individual risk for each failure case and, by summation, the total variation in individual risk as a function of distance from the plant. The total risk figures and the proportions occurring in different weather conditions (under the uniform wind rose assumption) are used with site-specific weather data ie (the probabilities of different wind speed/ weather category combinations in each of a number of equal sectors) to draw iso-risk contours. These show the frequency (10^{-4}, 10^{-5}, 10^{-6}, etc per yr) of a hypothetical individual receiving at least the defined dose (see Fig 1).

An example of the results of such an analysis for a chlorine installation are shown in Table 1. This illustrates the range of possible failure events, their frequency, the rate of chlorine release and the duration of the release. The table shows the resulting individual risk of receiving a specific dose of chlorine as a function of distance from the source of the release. The combined individual risk is calculated assuming a uniform wind rose. Results are then plotted on a site map to show risk contours, taking the local weather pattern into account.

Finally, a separate program can be used with population distribution information, the calculated hazard zones, and the site specific wind/weather probabilities to provide a societal risk calculation. This is obtained by estimating the number, N, of people encompassed by each hazard zone when each zone is aligned in a number (at least twelve) of equally spaced wind directions. Each orientation of the hazard zone has a different probability so that pairs of values of probability and N are obtained from which F, the probability of N or more people being affected, can be derived (see Fig 2).

2.2 Flammable Hazards

For flammable materials current RISKAT procedures focus on hazards associated with liquefied petroleum gas (LPG) installations (Clay et al, 1987, Crossthwaite et al, 1988). The main considerations are: the probability of a boiling liquid expanding vapour explosion (BLEVE) of the main storage vessel occurring with immediate ignition in any one year; and the effects of the resultant fireball. The most likely cause of such an event is when the tank is engulfed by a fire, often referred to as hot tank failure.

The main inputs required are:

- Size(s) of vessel(s);
- LPG type (propane or butane);
- Catastrophic vessel failure rate: Cold- tank failure;
- Catastrophic vessel failure rate: Hot-tank failure (BLEVE);
- Limited vessel failure rates (cracks or holes);
- Loss of containment failure rates of associated plant eg vaporisers, pumps and pipework;
- Probability of ignition of plant/ pipework releases; and
- Categorisation of use of land surrounding the storage installation and assignment of ignition probabilities and population density.

Flammable RISKAT calculates the levels of thermal radiation dose $[(kWm^{-2})^{1.33}s]$ and blast overpressure (kPa) which could occur at the centre of cells defined by a Cartesian grid around the installation together with the associated frequencies at which these levels of radiation dose or blast overpressure occur. These data may then be used to derive contours for specified levels of radiation and overpressure ie each contour gives the distance from the source at which a level of radiation or overpressure within a specified range will occur at a particular frequency eg 10^{-5}, 10^{-6}, etc yr^{-1}. In addition these calculated levels of radiation and overpressure can be used with probit equations to derive individual risk of (say) fatality at the various distances, which may again be used to give contours. If the population around the installation is included in the calculation societal risk estimates can be derived.

For plants with up to 200 te of LPG, experience to date using the currently adopted set of failure rate data shows that the BLEVE event is likely to be dominant in determining individual risk levels at distances where some form of planning control is appropriate. Pipework events need not be modelled in detail, because jet entrainment of air at the source, or their size, results in short ranges of dilution to the lower flammable limit. Despite their high frequency, they do not contribute significantly to risk levels at distances in excess of about 50 m. However pipework releases or limited releases from vessels may contribute to hot tank failure if ignited. Cold whole-vessel events are also of minor importance, generally, because the event frequency is typically an order of magnitude lower than that for hot-tank failure and roughly a further order of magnitude reduction in risk levels occurs because of non-ignition and wind direction variability. However, at some 300-400 m the risk from the BLEVE becomes vanishingly small, so that the main risk (albeit small) is from the ignition of drifting clouds resulting from cold-tank failures. For societal risk, the critical factors (in addition to BLEVE event frequency) are the population density and its distribution within about 2 fireball radii from the installation.

The mass in the vessel at the time of rupture is assumed to contribute to the fireball. The variation in this mass is dependent on the operating cycle of the vessel at a particular site which can be accommodated in the procedures.

Because of the importance of the BLEVE event in determining the off-site risk, its frequency may be calculated separately using a quantified fault tree technique. One method, which is being developed for HSE by UKAEA's Safety and Reliability Directorate is called ALIBI (O'Donnel (1988) and takes into account site specific factors eg presence of water sprays, numbers of valves, lengths of pipe etc. The technique and its applications are being refined in the light of experience with its use and, in particular, the results of the Commission of European Communities (CEC) Shared Cost Research programme on Major Technological Hazards 1988 to 1991.

Currently RISKAT runs on an IBM compatible 386 PC with bed plotter and digitiser for map handling and graphical output. At present the procedures assume dispersion over flat terrain of uniform roughness, but work is in hand to include the effects of obstacles which may increase or reduce risk levels depending on whether population are upwind or downwind of any significant feature. HSE is continually enhancing the capacity of RISKAT; some future developments are outlined below.

3. SENSITIVITY OF RISK ESTIMATES TO MODELS PROCEDURES AND DATA

The accuracy of any forecasting procedure is subject to uncertainties generated by assumptions and judgements, and those inherent in the data and models used to conduct the analysis. In the case of major hazards, uncertainty also arises from the possibility of the hazard analysis being incomplete. For example, there may be pathways to failure which are not included in the calculation. In addition the role of human factors in determining risk levels is also important but is often implicit, rather than being explicitly analysed.

The treatment of uncertainty in QRA has been discussed by Nussey (1983) and some organisations are now using Monte Carlo simulation techniques to put confidence bounds on risk estimates. However, the need for large numbers of samples can place considerable demand on the computing requirement needed to complete the calculations. We are currently considering ways of reducing the computing requirement.

3.1 Failure-Rate Data and Human Factors

RISKAT is essentially a 'top down' procedure and considerable reliance is placed on the use of generic failure rate data, tailored as far as possible, to the plant being studied. Generic failure rate data are derived from a variety of plants of different ages, standards of construction, and management. Uncertainty thus arises in the use and adaptation of such data for a wide range of plants. To aid this adaptation process the available data and their sources have recently been input into a database together with the simulated data for vessel failures etc derived from fault tree analysis (FTA) studies. The data base covers vessels, piping and different substances (chlorine, LPG etc). Where the data have been simulated by FTA the uncertainty arises from incompleteness and imprecision implicit in the failure rate data for the basic components.

Failure rate data is often regarded as the greatest area of uncertainty because the spread of values quoted in the literature can cover one or more orders of magnitude. Risk estimates for a particular release are directly sensitive to such uncertainty since risk is essentially (failure probability) x (probability of the undesired event being realised (eg fatality) weighted over all weather conditions). For a plant the variation of risk with distance is the summation of the contributions from all postulated scenarios. However, risk at any distance tends to be dominated by a few scenarios (eg in the far field the whole tank failure events) so that there can be a complicated interplay between variations in the level of uncertainty in the individual event probabilities per year and the impact on the individual risk level at a particular distance.

Because the treatment of uncertainty in the failure rate data cannot be resolved in the short term we have attempted to improve the internal consistency of all our assessments by basing them in general on a 'standard set' of generic failure rate data and focusing on the sensitivity of the risk estimates to potential uncertainties in the consequence assessment as described below. The sensitivity of the risk estimates to the failure rate data is then focussed on those scenarios that contribute most to the risk at the distances of interest.

3.1.1 Human Factors

In general QRAs are conducted on the assumption that the installation is managed at least to average standards, with monitoring by the regulatory authorities to check this. QRA is then carried out on a hardware only basis using generic failure rate data with the 'implicit' assumption that human factors failures are already incorporated in these data. Whether generic failure rate data can be applied in this way to a wide variety of sites needs to be considered. As part of this consideration we are funding research to address questions of the type "To what extent are human errors included in failure rate data and how does the organisational culture and management style affect the risk from a specific plant?"

It may perhaps be argued that the "implicit" approach is conservative (ie over-estimates the risk) because the generic data includes failures from plant which were much worse than average. This may be valid for a QRA of a particular plant where high standards are expected to prevail, but it is not necessarily so where the plant being assessed is an archetype of a class of plants, or where the long-term future may hold the possibility of changes of management. A refinement of this approach is evolving in which the risk figures are modified in a formal way on the basis of a site specific audit to take account of wider issues. This type of modification of risk approach has been reported by Powell and Canter (1985) and Bellamy (1988). It essentially amounts to formalising the methods of using engineering judgement to modify generic failure rates to the conditions found at a particular plant. The use of these methods has the potential to improve the 'transparency' of QRA by making the assumptions in the method explicit and thus enabling a more consistent approach to be adopted. These methods will also allow the cost and benefits of 'software' as well as hardware improvements to be quantified. HSE is funding the development of such techniques and some aspects of this work have been described by Hurst (1991). The aim is to provide an audit system which can measure the quality of safety management at a major hazard site, and to link the results of the audit into QRA procedures via modification of generic values for such items as failure rates. The research is addressing, inter alia:

- the identification of the key indicators or factors which relate to, or measure, the quality of safety management at a plant;

- how these factors can be better audited by companies and regulators;
- how these factors should be weighted and scored for inclusion, in a valid way, into QRA.

An important finding from the research so far is that a significant proportion (over two thirds) of vessel and pipework failures could have been prevented either through hazard reviews (HAZOPs etc) or human factors reviews of operational or maintenance activities. Any audit will clearly need to cover the arrangement made for such reviews and implementation of the findings.

Another human factor question is that associated with grossly negligent or perverse human actions which might defeat the best precautions built into a plant. Experience suggests that this is not likely to be a dominant contribution to the overall risk from an installation, provided that a proper degree of vigilance and a safety consciousness is applied. Nevertheless, the possibility remains and must be allowed for by the decision maker in judging the utility of the predicted risk figures. A further issue here is that apparently wilful disregard for safety often results from incompatible pressures placed on individuals. This is a systemic consideration which is amenable to analysis by a 'systems analysis' type of approach to the overall safety at a plant. However the effects may vary dramatically over time and ultimately such considerations must rest with decision makers.

To safeguard against the uncertainty problems outlined above and those that follow below, HSE currently uses an approach which may be described as 'cautious best estimate' Every attempt is made to use realistic best estimate assumptions but where there is clearly difficulty in justifying the assumption, some over-estimate is preferred. In the case of failure rate data this 'cautious best-estimate' approach helps to offset to some extent the uncertainty arising from the possibility of grossly abnormal human behaviour and other unquantified causes of accidents. The degree of caution employed depends on the situation and is currently based on expert judgement. For example in a paper on the Tolerability of Risks from Nuclear Power Stations (HSE, 1988), HSE concluded that the best general indication of the level of risk was to be obtained from an assessment based on plant failures. But when 'unquantifiable' causes of failure are reckoned in, the likely risk level might be up to a factor of 10 higher. This statement gives some indication of the extent to which risk estimates may be sensitive to human factors type considerations.

3.2 Sensitivity Analysis: Toxics

3.2.1 Source Terms

Source terms essentially consider the phenomena associated with releases up to the time that the mixing process with the ambient atmosphere is dominated by ambient turbulence rather than turbulence generated by the momentum of the release itself. In the case of release of liquefied gas (eg ammonia, chlorine) from pressurised containment the transfer processes associated with the discharge of material to the atmosphere are complex, and involve non-equilibrium two-phase 'flashing' flow, rapid expansion of the jet and further flashing of liquid as the jet emerges from the breach, break-up of the liquid into droplets and aerosol with possible liquid 'rain-out', and entrainment of air into the jet as it expands. For the purposes of consequence assessment, it is necessary to distil the complexities of such release phenomena into a source term for the subsequent dispersion calculation. The main factors that must be defined are:

- the rate at which vapour and aerosol is generated;
- the rate of air entrainment into the release and the proportion of the release that is evaporated by mixing with the entrained air;
- the geometry, 'quality', temperature, and density of the release when the mixing processes begin to be dominated by ambient turbulence rather than momentum driven entrainment of air - ie when the jet velocity approaches that of the wind.

The precision with which such quantities need to be defined is determined by the sensitivity of the consequence predictions to variations in them, and the ability of the dispersion codes employed to model such effects as the presence of aerosols in the dispersing clouds or plumes. If the magnitude of the effects due to source term uncertainties is relatively small compared with other steps in the assessment (eg the precision of the data on event frequencies or the toxicity relationship employed to convert the predicted spatial and temporal variation of concentration levels downwind of the release into an effect on people) then simple best-estimate judgements are more than adequate.

An example of the sensitivity of risk estimates to source term assumptions for a small chlorine plant (see Pape and Nussey, 1985) is shown in Table 2. Also shown is the sensitivity to surface roughness - the dispersion codes employed are DENZ (Fryer and Kaiser, 1979) and CRUNCH (Jagger, 1983). The table shows the variation in risk with distance for three different source terms. Taken together the source terms represent changes by factors of about 6, 5, 10 respectively in the aerosol fraction (ie the airborne liquid fraction that remains airborne after initial mixing at the source), the mass of air entrained at the source, and the plume aspect ratio at the source. For these three cases the difference in risk level etc is typically less than 3, from which we conclude that source term effects for the dispersion models currently in use are not very significant for the assessment of consequences for highly toxic two-phase releases which require considerable dilution before they are rendered harmless. (This is not the case for flammable releases in which source term dilution can reduce concentrations below the flammable limit). In consequence, the dispersion distances of interest for toxic releases are relatively large (usually well into the passive, neutrally buoyant, regime) compared with the distance at which source term effects have any impact on the dispersion process. Risk levels are more sensitive to the assumptions made about the proportion of released material that becomes airborne, ie the source strength. Nussey and Pape (1987) showed that ± 30% changes in the source strengths can lead to factors of up to about 2 in risk levels.

An interesting feature of this table is that more dilution at the source does not lead to lower risk in the far field. This is because an increase in air entrainment leads to deeper but less wide clouds/plumes that advect more rapidly, and hence have less time to mix with the ambient air than much wider less deep clouds. Table 2 also shows the effect of a change in surface roughness (z_o). Changing z_o from 0.04 m to 1 m results in a 'cross-over' effect, where risk levels are relatively greater in the near field for the larger z_o, (ie because the clouds are wider)but smaller in the far field - the largest difference being about a factor of 4. The relative magnitude of these effects may be much greater when obstacle features are present. Risk levels may increase significantly for those upwind of the obstacle, while those downwind would receive less exposure. This underlines the need for computationally efficient box models with the capability of predicting the effect of obstacles and terrain on the dispersion process.

3.2.2 Dispersion

Variations in the concentration levels predicted by different dispersion models can vary significantly. For example Fig 3 shows observed and predicted concentrations for a semicontinuous release of chlorine over water. The figure has been adapted from Wheatley et al, (1988). by adding predictions for the SLAB (Ermak and Cham, 1985) model and the Britter and McQuaid, (1988) Workbook (BMW). The maximum difference between the predicted concentrations is about one order of magnitude. Another comparison is shown in Table 3 and is based on large-scale-releases of liquefied ammonia conducted in the Nevada desert in America by the Lawrence Livermore National Laboratory (LLNL)(Goldwire et al, 1985) ie the Desert Tortoise series of trials. The results show that CRUNCH is not conservative for these data and under-predicts the maximum observed concentration levels by a factor of up to about 4. SLAB, on the other hand, is in good agreement with the observations even though the simple aerosol model built into the code was not used. For these trials it was observed that aerosol was present in the cloud for several hundreds of metres. The presence of aerosol would prolong the heavy gas behaviour of the plume since entrained air would be cooled as the aerosol evaporated. On the other hand, any hydrolysis with entrained water vapour would generate heat, and tend to warm up the plume. There are thus compensating thermo-dynamic processes taking place. Such effects are not modelled by CRUNCH. The next generation of box models may need to take the thermodynamic processes of moist air/aerosol vapour mixtures into account. The persistence of aerosol for some time would suggest that the liquid and vapour phase are not in thermodynamic equilibrium. We are funding work to incorporate these effects into a state of the art box model called DRIFT (Webber et al, 1991).

A further comparison of predictions with some data for anydrous hydrofluoric acid releases conducted by LLNL is shown in Fig 4. The trials are described by Blewitt et al (1987). Examination of Fig 4 demonstrates that standard source terms for pressurized releases and the assumption that HF exists as polymers (Clough et al 1987) for large distances (molecular weight, 68) leads to considerable underestimation by CRUNCH of the variation in concentration levels with distance. Agreement of the models and experimental data is significantly improved by regarding the HF as monomer.

The above comparison of the performance of CRUNCH and SLAB indicates that SLAB is the more robust since it represents the experimental data quite well, whereas CRUNCH has a greater tendency to underpredict the observed concentrations. One might hypothesize therefore that risk levels estimated by use of CRUNCH and DENZ are significantly underestimated. To test this hypothesis SLAB was incorporated into a version of RISKAT and the predicted risk levels compared with those obtained using DENZ and CRUNCH (Nussey et al, 1990). First variations in risk levels (based on DENZ and SLAB) for an instantaneous two-phase release of a 50/50 mass ratio mixture of HF and butane were compared with that of pure HF monomer. Although the concentration levels of HF are lower in the mixture, the overall cloud size and time to pass a particular location increase. As a result of these competing effects, the predicted risk figures for the dispersing mixture are greater than those for the pure HF release by

a factor of 2. Moreover the risk predictions obtained using DENZ are about twice those obtained using SLAB, even though the predicted maximum concentration level at particular distances for DENZ are about 2 or 3 times smaller than those for SLAB. The reason for this unexpected result is that DENZ predicts wider clouds and larger passage times than SLAB does and this results in the predicted hazard zones being wider than those for SLAB, even though the centre line concentration is less. This underlines the need when validating dispersion models to consider cloud and plume dimensions and passage times, ie a comprehensive consideration of temporal and spatial variations in concentration.

Second, risk estimates for a small chlorine plant were compared (Pape and Nussey, 1985). The variations in risk obtained are shown in Figure 5. The risk estimates in the near field based on DENZ and CRUNCH are about twice those based on SLAB. Similar agreement is obtained for a combination of HF releases. The calculations were repeated using a 'state of the art' box model GASTAR developed by Britter (1991); in this case the risk levels predicted by the use of GASTAR are up to twice those for DENZ and CRUNCH. These calculations provide further evidence of the compensating effects between concentration levels, cloud dimensions and passage times. These differences in predicted risk levels are small when compared with those implicit in failure rate data (factor of 10 or more, see Nussey, 1983) and toxicity (see below), and demonstrate that further refinements in source term and dispersion modelling for risk assessment purposes over 'flat ground' need to be very carefully targeted.

3.2.3 Severity of Injury Criteria

The risk calculations within RISKAT are based on an estimate of the probability of receiving at least a specified dose of toxic gas, thermal radiation, or a specified level of overpressure at a particular distance from the major hazard plant. The actual dose received will depend on the actions of the individual (eg an infirm person may not be able to quickly retreat indoors). Also the effect of the specified dose will depend on who receives it. Thus when we make statements about the chance of being able to escape from a toxic cloud by retreating indoors, or the likely effect the specified dose would have on an individual, we need to do so in terms of predefined individual characteristics. Most of our assessments assume that the individual is average in the attributes which determine what dose will be received. In all cases allowance for special sensitivity to the exposure (eg an old people's home) is also considered at a later stage in the assessment procedure or in the use of special risk criteria. For an average individual we can make judgements about how such a person may respond to specified doses, or the dose that is likely to be dangerous or fatal, etc.

Toxicity Considerations

The toxicity of the main substances processed at major hazard sites has received much attention over the past 6 years. In general, this reassessment of the toxicity of acutely toxic gases such as chlorine and ammonia has tended to make much less conservative recommendations than hitherto.

The main uncertainties arise from the possible physiological differences between animals and man, and the subsequent extrapolation of animal data obtained for essentially homogeneous populations under controlled conditions to a highly un-homogeneous human population that is in a state of panic and exposed to fluctuating rather than steady concentrations. Another consideration is the likely state of human activity in the presence of an acutely toxic gas. Increased activity can have two main effects: first, larger volumes (up to 12 or more times greater) of contaminated air are inhaled (Henderson and Haggard, 1943); and second there is an increased demand for oxygen. Some evidence of such an exacerbating effect due to human activity in the presence of chlorine has been analysed (Withers and Lees, 1985) (Nussey et al, 1984). Withers and Lees (1985) make suggestions for allowing for increased sensitivity and activity.

The effect of variations in inhalation rates on the risk of receiving a toxic load that would result in at least a 50% chance of death is shown in Table 4. The table shows that the predicted risks of receiving at least an LC_{50} dose diverge with increasing distance from the plant; the differences at 750 m being very significant (factor of about 30). This analysis shows that when calculating fatality risks, careful consideration would need to be given to the choice of vulnerability model. Because of the considerable uncertainty regarding vulnerability models for acutely toxic gases, HSE has adopted a pragmatic approach, and for each material a specified 'dose' criterion or toxic load of

$C^n dt$ = constant is used, in which the value of n and the constant define the criterion adopted. This is used for all assessments and enables the advice to be consistently based.

The HSE approach to defining toxicity criteria for land use planning purposes has been described (Turner and Fairhurst, 1989 and Davies and Hymes, 1985). These sets of authors stress that for land use planning purposes, criteria based solely on lethality are not sufficiently comprehensive. For land use planning purposes HSE attempts to derive toxicity criteria that would result in: severe distress to almost everyone exposed; a substantial fraction requiring medical attention; some of those seriously injured requiring prolonged treatment; highly susceptible people possibly being killed. These fairly broad criteria avoid creating a spurious impression of accuracy, which is often implied by the derivation and use of probit relationships to predict consequences of loss-of-containment accidents. In reality the effects of a stated dose will depend on the recipient. A dose that would cause distress to a fit young man would probably kill an old person or one suffering from lung disease.

Toxic load relationships currently in use for ammonia, chlorine and anhydrous hydrofluoric acid are, respectively:

$NH_3 : C^2 t = 3.76 \times 10^8$ (ppm² min)

$Cl_2 : C^2 t = 1.08 \times 10^5$ (ppm² min)

$HF: Ct = 1.2 \times 10^4$ (ppm.min)

Despite the uncertainties in human dose-effect relationships, the evidence presented in Table 4 (when contrasted with the estimates in Table 1) suggests that the HSE approach does make some allowance for the likely human activity/response to a toxic gas emergency, and it has proved acceptable to local planning authorities. The way in which risks based on these dose criteria are assessed is described in Section 4.

3.3 Sensitivity Analysis: Flammables

Fig 6 shows the contributions to individual risk levels for the LPG storage (200 te bullet) facility considered by Crossthwaite et al (1988). It is clear that the variation in risk levels is dominated by the Boiling Liquid Expanding Vapour Cloud Explosion (BLEVE) event for which there are three input parameters: event frequency, fireball mass, and rupture pressure (which influences the surface emissive power of the fireball). Variations in risk levels to the latter two parameters is shown in Table 5. At a distance of 200 m from the vessel the risk varies by a factor of 7 between fill fractions of 80% and 40%, while the corresponding variation for differences in burst pressure of 1.4 MPa and 0.32 MPa is less than 2. It is axiomatic that the results are mainly sensitive to the assumed BLEVE frequency and the mass of LPG in the tank at time of failure. This demonstrates the importance of safety features (eg remotely operated shut off valves or mounding) incorporated to reduce the likelihood of a BLEVE.

3.3.1 Combined Toxic and Flammable Hazards

The dangerous dose concept used by RISKAT may create difficulties in comparing different types of harm eg radiation effects with toxic effects, since it is necessary to choose, in each case, doses that produce equivalent levels of harm. Provided this choice is exercised judiciously, the separate risk contributions for different types of hazard can be aggregated into a total risk and treated as a single entity. At present the selection of equivalent levels of harm is rendered difficult by the sparsity of data and the problems associated with relating dose to harm. For example, some differences may arise in the long term effects of the agents. The scarring from a burn may never heal, or have a disfiguring effect, while the damage from a non-lethal dose of toxic gas might be temporary. The choice of a 'dangerous' dose for the different hazards needs to reflect these types of consideration. Another, and probably more important consideration, is the choice of failure rate data since this also influences the contribution to risk from the toxic and flammable hazards. For example at present the BLEVE frequency adopted (now under review) is, in general about five times that of whole tank failure for a tank storing liquefied chlorine under pressure. It is likely therefore that individual risk in the near field will be dominated by the fireball event and outside the fireball hazard range by toxic effects. This may not be the case for societal risk (see below) since this depends on the population distribution.

3.3.2 Societal Risk

Societal risk is calculated as described in Section 2.1. There is a complicated interplay between the size, shape and 'frequency' of the calculated hazard zones, and the spatial variations in population density. Because of this the remarks made in Section 3.2.1 on toxic source terms may not hold for societal risk. For example if the population is dense relatively close to the plant source terms that lead to much wider plumes may significantly increase societal risk levels.

4. FORMULATION OF HSE ADVICE ON LAND-USE PLANNING

The Health and Safety Commission's general approach to risk regulation, industry wide, is set out in the HSE's Tolerability of Risk paper (HSE, 1988). Having assessed, or where appropriate estimated a risk, it is necessary to determine:

a. whether it is so great or the outcome so unacceptable that it must be refused altogether;

b. whether the risk is, or can be made, so small that no further precaution is necessary;

c. if a risk falls between these states, that it has been reduced to a level which is "as low as reasonably practicable".

This approach is consistent with that recommended by the Royal Society Study Group (1983) on Risk Assessment. It

has applied for many years in the control of exposure to radiation arising from normal operations, and to exposure to certain dangerous substances (control limit, plus further reasonably practicable reduction). It is indeed the approach applied, in many cases in a very rough and ready way, in relation to any situation where HSE Inspectors are called upon to make a judgement. In short it is a process which is essentially economic and political though informed technically.

When giving advice to Local Planning Authorities (who make the decisions by weighing the levels of risk against all other relevant factors eg availability of land, benefits to the community from the activity etc). HSE usually begins with a simple statement of whether or not the risk seems sufficient to justify a refusal of planning permission. If a Planning Authority requires more detailed information (eg for a case which is otherwise strongly favoured locally), HSE will explain the level of risk, either in correspondence or at a meeting. If a Planning Authority refuses an application on the basis of HSE's advice, and the applicant then appeals, HSE would support the Local Planning Authority by giving details of its advice to the Appeal Inquiry. HSE might also appear at an Inquiry at the request of the Department of the Environment (or Welsh Office or Scottish Office) where there are major issues involved and assistance is required on safety assessment.

For formulation of advice on planning applications for new development in the vicinity of an existing major hazard HSE has published a Discussion Document (HSE, 1989) describing the risk criteria used. The risk at issue is the risk to the people who would use the development, eg house residents in housing, or shoppers in retail buildings, or users of leisure facilities, etc. HSE believes that the criteria for such developments should consider both Individual and Societal Risk. For Individual Risk, HSE suggests that a level below 10^{-6}/yr frequency of receiving at least the specified dangerous dose, as calculated via RISKAT, would not be 'significant' for housing for the general public. A somewhat lower level, 3×10^{-7}/yr, is suggested for especially vulnerable developments such as housing for the elderly, to compensate for the increased likelihood that the specified dose would be fatal to them. This sets the level below which the risks would be 'negligible'. At a somewhat higher level, 10^{-5}/yr or above, it is suggested that substantial housing developments eg 10 or more family units, would always be 'significant'. Thus HSE will normally advise against such cases.

The zone between 10^{-5}/yr and 10^{-6} or 3×10^{-7}/yr is left as a 'grey area' within which judgement can be applied. Major factors here would be the size of the development and the amount of difference it makes to the nature of the land use in the vicinity. For example, 10 houses in an area which is already largely built-up, might seem to make little difference but in an area of green fields around a Major Hazard they might seem highly significant. HSE will normally advise that a development of 30 or more houses at risks above 10^{-6}/yr is significant but developments between 10 and 30 houses in the 'grey area' are for specific judgements. For judging the significance of societal risk levels, HSE has not proposed numerical criteria since there are difficulties in judging the significance of an increment to an existing Societal Risk. HSE deals with several thousand development cases near major hazards each year of which several hundred require detailed consideration. This may amount to 10,000 cases in 30 years. Each case on its own may not contribute much to the total national societal risk, but together they could add up to a significant worsening of the national situation. The difficulties would be to partition any criterion for 'significant' addition to the total national societal risk among 10,000 potential cases, and also to define how a two-dimensional parameter (F/N graph) may be compared with a criterion parameter if the actual F/N curve and criterion F/N curves cross (Pape, 1988).

For those types of development that give rise to trivial levels of individual risk, but potentially substantial societal risk (eg supermarket ie a transient population) the following procedure is used:

a. Calculate the individual risk to a hypothetical resident in the development location;

b. Judge the significance of the proposal in comparison with a number of houses (some factors for helping in this judgement are given below);

c. Apply the rules for individual risk for housing as outlined above.

Thus, for example, a shop catering for 200 customers at any one time between 8 am and 8 pm say, might be judged equivalent to 20 houses. It would probably be advised against if it fell within the 3 x 10^{-6}/yr individual risk contour for housing, subject of course to secondary factors such as the nature of surrounding land uses (see HSE, 1989). The factors referred to in b. above include:

a. Fraction of time a development is occupied, and variations in occupancy (eg peak periods, etc);

b. Fraction of their time in which any one person is present;

c. Relative vulnerability of typical occupants;

d. Ease of emergency action;

e. Degree of protection given by the building.

These factors may be applied in qualitative judgements, or some quantitative assessment may be done to help with those judgements. We also assume that Society would wish a special level of care for certain types of population, such as children, the elderly, etc; who may be more vulnerable than the average. For these groups, and for extremely large developments, the 'grey area' might be extended down to the 3 x 10^{-7}/yr contour of individual risk for housing.

The factors outlined above relate mainly to objective determinants of the levels of individual and societal risk. HSE is aware that the 'acceptability' of risk to the public and their representatives also depends on subjective or perception factors. This may make it difficult or impossible to produce universal criteria for all hazards (Cohen, 1988). These subjective factors may be grouped into various categories:

i. The nature of the hazard (eg immediate or delayed injury), other effects than injury to man (eg property damage, evacuation, environment damage, etc) and the offsetting economic benefits of the activity;

ii. The nature, purpose and limitations of the risk assessment;

iii. Economic and political factors (local or national);

iv. Public attitudes and confidence in the regulatory system.

There may be very significant differences between types of hazard such that any attempt to read across from what appears 'acceptable' for one, to what appears 'acceptable' for another would require great care and possibly substantial modifications. Thus the criteria outlined above for the formulation of advice on land use planning in the vicinity of existing Major Hazards should be regarded as limited to that purpose. However, the factors discussed are also relevant to the siting of new major hazard installations though the weighting of the factors may be quite different to that implied above as the land available for new installations is restricted. Again considerable judgement is needed in the decision making process, but the exercising of that judgement is considerably aided by adopting a risk based approach.

5. CONCLUSIONS

The RISKAT procedures described here have been used and developed by HSE over the past six years. During that time our understanding of the limitations and advantages of quantified risk assessment has improved. Although considerable care and professional judgement are needed in applying the methods it is our view that the quality of our advice to local planning authorities has increased considerably. Experience suggests that increased refinement and confidence in the results justifies a less-cautious approach in the advice, thus minimising the amount of land which is affected.

We are committed, as an organisation, to reducing the limitations and uncertainties in the methods. For example, through our intramural and extramural research programmes we have demonstrated that the modelling uncertainties for ground level releases dispersing over flat ground are now relatively small compared with those in the event probability data and the toxicity data used to convert predictions into actual consequences. Because of such uncertainty HSE uses a consistent set of failure data for each assessment and has adopted a pragmatic approach to toxicity. The 'dangerous' dose concept is used for acutely toxic materials and is the basis of all assessments so that estimated risk levels can be compared with one another and with criteria (HSE, 1989) developed for land use planning purposes.

For superheated liquefied toxic gases which may exhibit aerosol formation and hydrolysis, we have presented some evidence for chlorine, ammonia and anhydrous hydrofluoric acid suggesting that there may be compensating thermodynamic processes occurring which enable some existing box models to predict observed field trial data reasonably well. Moreover, because of trade-offs between concentration levels and cloud/ plume dimensions and passage times, models that do not predict observed maximum concentration levels well can lead to similar or even greater predicted levels of risk than those that do. There is therefore a need for all of these factors (ie the full spatial and temporal variations in concentration) to be considered when validating dispersion models and not just the variation of C_{max} with distance. In the light of these observations, it is our view that the main need of risk assessors is for computationally efficient box models which can predict the effects of obstacles and terrain features. HSE is collaborating with a number of European organisations to this end through the EC shared cost research programmes.

At a more general level, a major difficulty with any QRA is to convey to lay people and decision-makers a proper impression of the predicted levels of risk and the associated uncertainties. QRA practitioners therefore have a major role to play in explaining the complexities of the QRA process and de-mystifying the subject generally, ie improving QRA's transparency so that it is more readily understood. We are conscious of these needs and are working towards satisfying them in ways described in this paper.

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TABLE 1

Toxicity parameters n = 2.000 A = 0.108 x 10^6 [C^2t = A]

Mitigating factors Occupancy probs 1.000 overall, .100 outdoors
Evacuation time = 30.0 min, Lag = 10.0 min

Wind and weather categories	D 2.4	D 4.3	D 6.7	F 2.4
Probabilities	.1400	.1900	.5100	.1600
Air changes per hr	2.00	2.00	3.00	2.00

Type of gas Chlorine

Release Data				Individual Risk levels (x 10^6) at distances (metres): (assuming uniform wind rose)					
"Puff" release quantity (tonnes)	Plume release rate (kg/sec)	Release duration (mins)	Probability (x 10^6)	100.	200.	300.	500.	750.	1000.
Vessel Holes 50mm liquid(l) & vapour(v) space									
l .0	44.5	6.7	2.00	.47	.37	.30	.20	.11	.06
v .0	2.5	30.0	3.00	.43	.23	.09	.03	.00	.00
Vessel Holes 25mm liquid(l) & vapour(v) space									
l .0	11.1	30.0	2.00	.40	.28	.22	.12	.05	.02
v .0	1.0	30.0	3.00	.33	.07	.03	.00	.00	.00
Vessel Holes 13mm liquid space									
.0	3.0	30.0	4.00	.44	.33	.18	.04	.02	.00
Vessel Hole 6mm liquid space									
.0	.6	30.0	1.60	.14	.02	.00	.00	.00	.00
Vessel Hole 13mm vapour space									
.0	.3	30.0	6.00	.19	.04	.01	.00	.00	.00
Vessel Hole 6mm vapour space									
.0	.1	30.0	2.40	.00	.00	.00	.00	.00	.00
Tanker Hose Coupling Failure Excess flow valve (XSFV) and remotely operated shut-off valve (ROSOV) operate									
.0	6.0	1.0	88.60	9.30	3.30	.10	.00	.00	.00
XSFV Operates, ROSOV fails									
.0	6.0	1.0	13.20	1.39	.49	.02	.00	.00	.00

Table 1 (continued)

Release Data				Individual Risk levels (x 10^6) at distances (metres): (assuming uniform wind rose)					
"Puff" release quantity (tonnes)	Plume release rate (kg/sec)	Release duration (mins)	Probability (x 10^6)	100.	200.	300.	500.	750.	1000.
ROSOV operates XSFV fails									
.0	4.6	20.0	2.74	.44	.27	.16	.04	.01	.00
Both ROSOV and XSFV fail									
.0	6.0	20.0	.41	.07	.05	.03	.00	.00	.00
Liquid line to vaporiser - Guillotine Failure									
.0	1.9	5.0	58.20	5.49	.76	.00	.00	.00	.00
25mm Split									
.0	1.9	20.0	1.80	.23	.09	.03	.00	.00	.00
4mm Hole									
.0	1.1	20.0	300.00	31.25	5.93	1.77	.00	.00	.00
Vapour line to Reactor - Guillotine Failure									
.0	1.4	5.0	38.80	2.58	.01	.00	.00	.00	.00
.0	1.4	20.0	1.20	.14	.03	.01	.00	.00	.00
Liquid line to vaporiser-4mm hole									
.0	.06	20.0	600.00	.00	.00	.00	.00	.00	.00
Liquid line to vaporiser - flange leak									
.0	.4	20.0	20.00	.56	.11	.00	.00	.00	.00
Vapour line to reactor - 4mm hole									
.0	.06	20.0	400.00	.00	.00	.00	.00	.00	.00
13mm Flange leak									
.0	.6	20.0	30.00	1.55	.28	.10	.00	.00	.00
Catastrophic Vessel Failure Over Bund									
18.0	.0	.0	2.00	.63	.46	.38	.25	.13	.07
Into Bund									
9.0	.0	.0	2.00	.55	.40	.30	.14	.06	.03
TOTALS				56.61	13.52	3.74	.85	.39	.18

TABLE 2:

Variation in individual risk:
Sensitivity to source terms and surface roughness (z_o)
for small chlorine plane

				Individual risk (x10^6) at distances (m) of:				
Aerosol fraction	dil	AR	z_o	100	200	300	500	1000
0.2	10	1.0	0.4	61.8	12.1	3.5	0.57	0.07
0.86	24.3	1.0	0.4	66.5	15.0	5.4	0.62	0.06
0.14	*	0.1	0.4	36.0	4.7	1.6	0.22	0.03
0.2	10	1.0	0.04	55.5	17.7	6.5	1.3	0.13
0.2	10	1.0	1.0	70.4	8.7	1.5	0.43	0.04

dil = dilution ratio, mass basis
AR = aspect ratio
* Just sufficient air entrained to evaporate liquid fraction

TABLE 3:

Desert Tortoise ammonia spills:
Comparison of the maximum observed concentration (%)
with the codes CRUNCH and SLAB

Test	Down Wind distance (m)	Maximum Observed	CRUNCH	SLAB
3+	100	9.0	4.2	6.6
	800	1.6	0.57	1.8
	2800	0.22	0.12	0.21
4*	100	6.5	4.9	7.6
	800	2.0	1.8	3.0
	2800	0.53	0.13	0.68

\+ 133 kgs^{-1} for 166 s; $U_{10} = 9.2\ ms^{-1}$, Pasquill D,RH 14.8%
* 108 kgs^{-1} for 381 s; $U_{10} = 5.6\ ms^{-1}$, Pasquill E,RH 21.3%

TABLE 4:

Sensitivity of risk levels (x $10^6\ yr^{-1}$) to toxicity criterion: failure scenarios; small chlorine plant

Toxicity relationship (LC_{50})		Individual risk levels at downwind distance (m) of 50	100	200	300	500	750	1000
$C^2t = 3675100$	a	65.1	13	0.72	0.2	0.05	0.01	
$C^2t = 4.13 \times 10^8$	b	49.0	6.3	1.0	0.2	0.03	0.0	
$C^2t = 1875000$	c	76.1	18.7	1.17	0.42	0.04	0.01	
$C^2t = 1325000$	d	83.0	24.7	1.51	0.54	0.11	0.01	
$C^2t = 281820$	e	111.8	46.4	8.3	1.4	0.4	0.11	0.02
$C^2t = 53000$	f	132.1	74	20.1	6.5	0.98	0.34	0.15

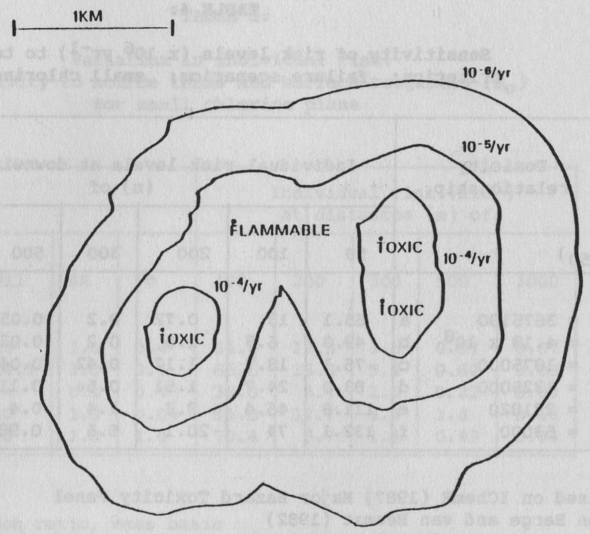
a Based on IChemE (1987) Major Hazard Toxicity Panel
b Ten Berge and van Heemst (1982)
c Withers & Lees (1985): Regular population; standard activity
d Withers & Lees (1985): Average population; standard activity
e Withers & Lees (1985): Average population; walking at 4 miles h^{-1}
f Withers & Lees (1985): Average population; state of panic
C ppm; t, min

TABLE 5+:

Individual risk due to BLEVE (x $10^6\ yr^{-1}$)

Distance	Different fill levels			Different burst pressure	
m	80%	40%	5*Fractions	1.4 MPa	0.32 MPa
0	10	10	10	10	10
50	10	10	10	10	10
100	10	10	10	10	10
150	10	3.74	7.17	7	6.79
200	2.77	0.39	1.49	2.02	1.44
250	0.49	0.03	0.21	.65	.18
300	0.07	0	0.03	.24	.01

\+ Adapted from Crossthwaite et al, 1988
* The 5 fractions were 80%, 70%, 60%, 50%, 40%, full, each with a probability of 0.2.



*Location of hazardous plant

Fig. 1 - Risk contours example for a complex site

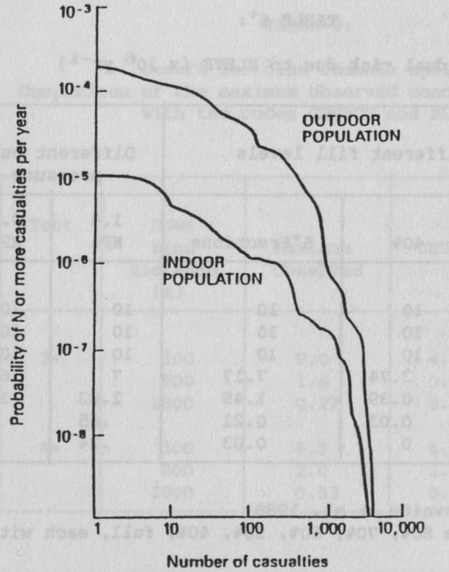


Fig. 2 - Comparison of societal risks for outdoor & indoor populations

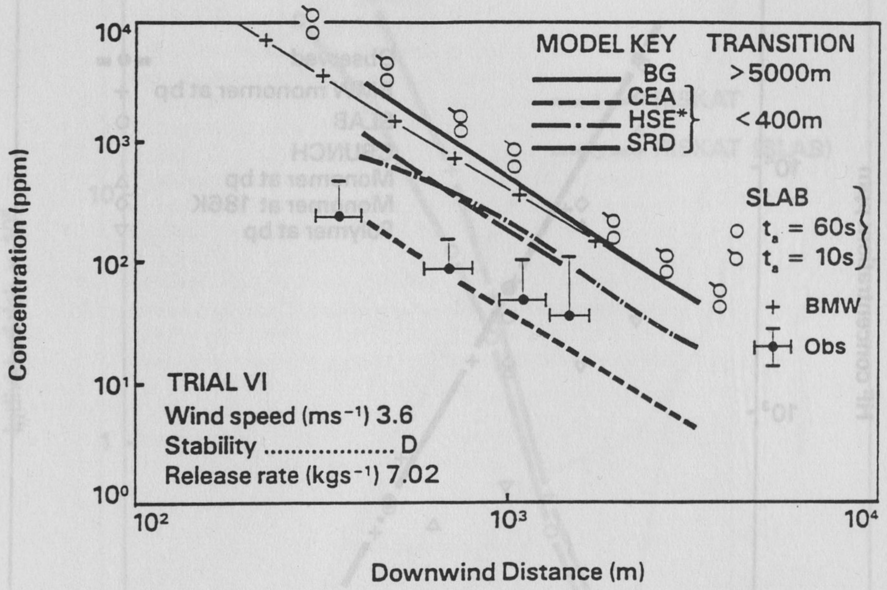
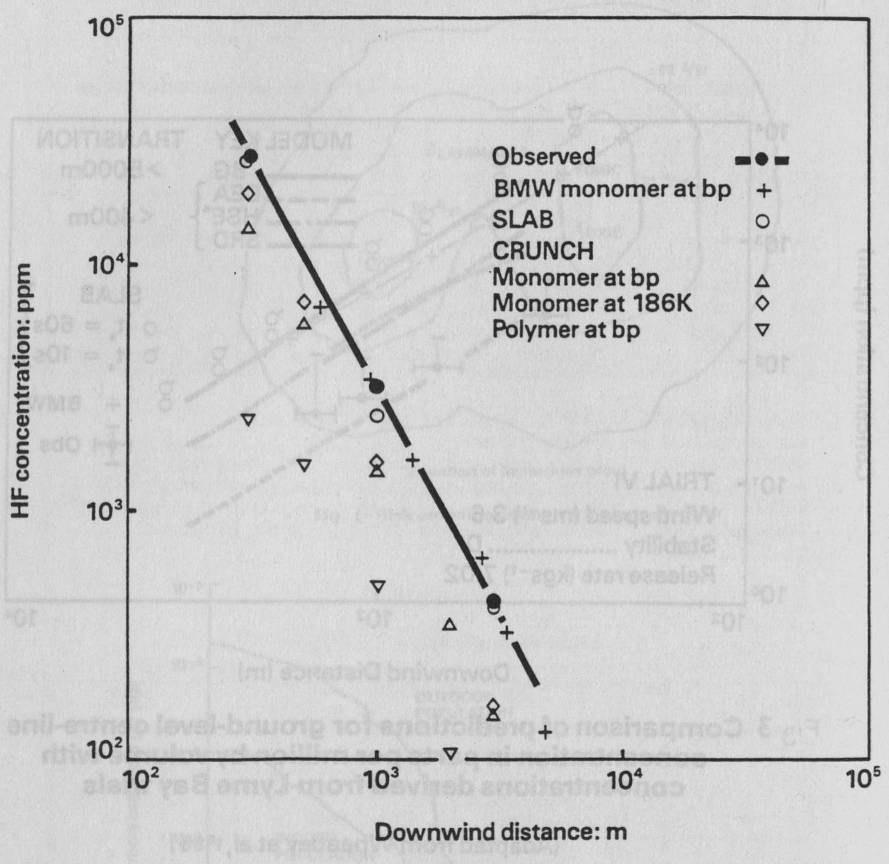


Fig.3 Comparison of predictions for ground-level centre-line concentration in parts per million by volume with concentrations derived from Lyme Bay trials

(Adapted from Wheatley et al, 1988)

*N.B. Both HSE and SRD use CRUNCH but there are minor differences (see Wheatley et al)

+ BMW see reference Britter, McQuaid Workbook



LLNL HF Test 1

Fig 4 Comparisons with BMW, CRUNCH and SLAB

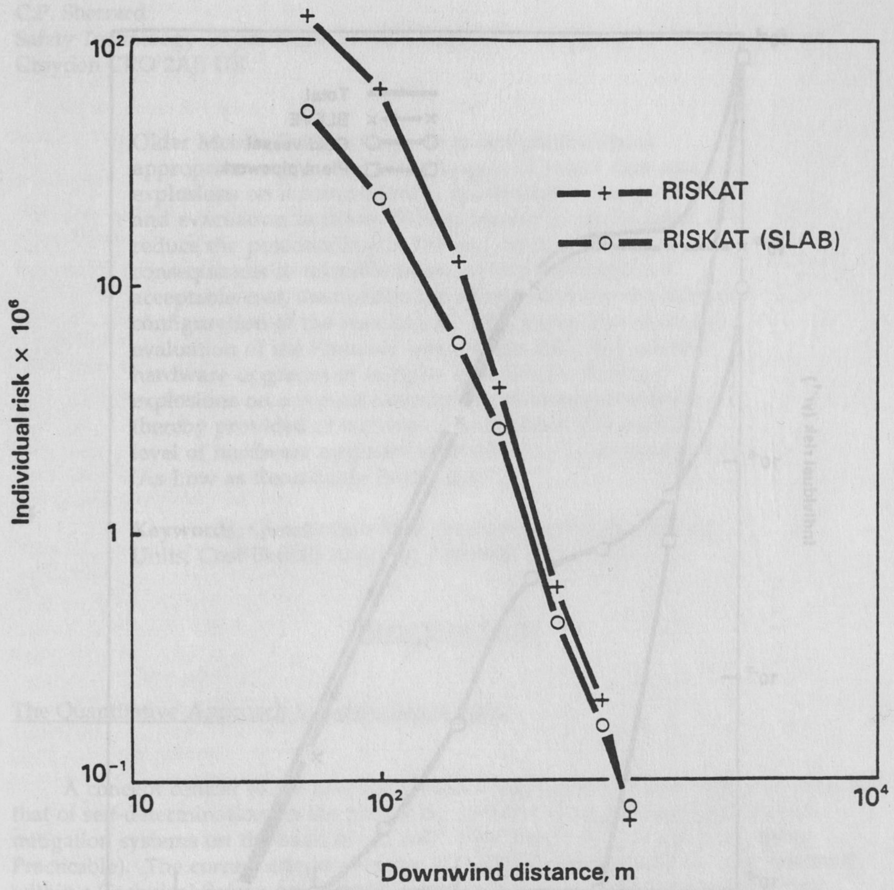


Fig. 5 Individual risk for a small chlorine plant

Predictions from standard RISKAT and RISKAT (SLAB)

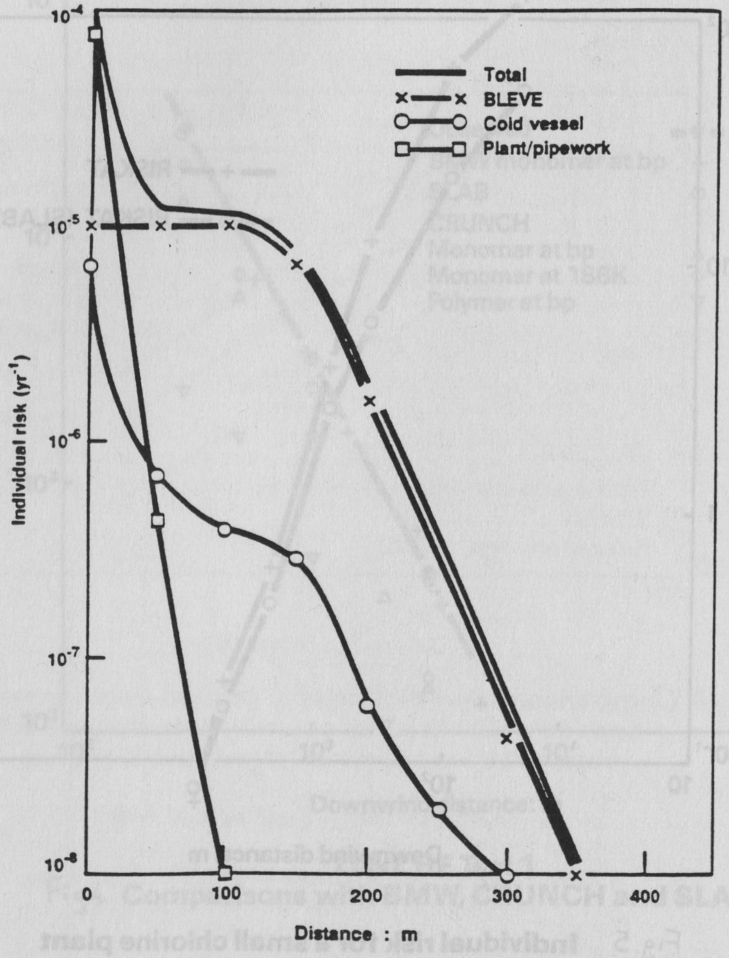


Fig.6 - Variation of individual risk with distance.

AN APPROACH TO THE QUANTITATIVE EVALUATION OF SAFETY ON EXISTING MOBILE DRILLING UNITS

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Older Mobile Drilling Units were designed without appropriate cognisance of the impact of major fires and explosions on accommodation, muster areas, escape routes and evacuation facilities. Whilst measures can be taken to reduce the potential loss of life and other undesirable consequences to tolerable levels within the bounds of acceptable cost, the options are often limited by the inherent configuration of the installation. This paper illustrates the evaluation of the Potential Loss of Life (PLL) for selected hardware upgrades to mitigate quantifiable fires and explosions on a typical installation. A demonstration is thereby provided of techniques to establish the requisite level of hardware upgrades on the basis of aiming for a risk 'As Low as Reasonably Practicable'.

Keywords; Quantitative Risk Assessment, Mobile Drilling Units, Cost-Benefit Analysis, Potential Loss of Life.

INTRODUCTION

The Quantitative Approach to Safety Assessment

A concept central to the new UK offshore legislation in place from mid-1992, is that of self-determination on the part of rig owners, of accident prevention and mitigation systems on the basis of 'ALARP' (risk levels As Low As Reasonably Practicable). The correct adoption of the ALARP principle should be demonstrated within a Technical Safety Assessment, which will be the major constituent of the Safety Case. Where major items of hardware and equipment are proposed, the Health and Safety Executive (HSE) will expect to see a cost-benefit analysis in the Safety Case particularly where

(a) Benefits in terms of the reduction in risk and Potential Loss of Life (PLL) are quantifiable,

and

(b) The level of proposed hardware and equipment does not meet the risk targets pre-determined by the rig owner or operator and agreed by the HSE.