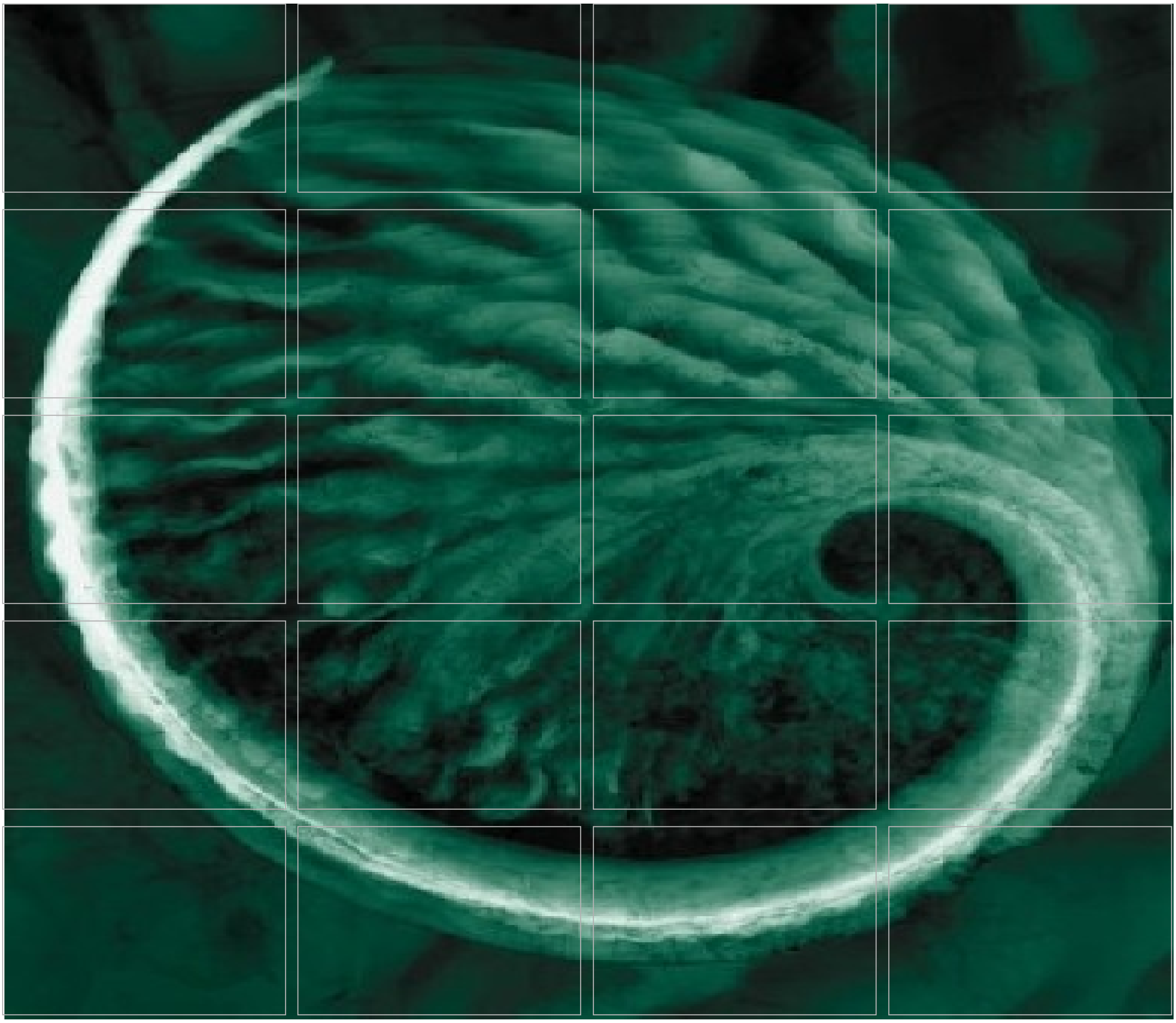

A Review of HSE's Risk Analysis and Protection – Based Analysis Approaches for Land-Use Planning

Final Report

September 2004

Delivering sustainable solutions in a more competitive world

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HSE

A Review of HSE's Risk Analysis and Protection - Based Analysis Approaches for Land-Use Planning

September 2004

Reference 0016072

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For and on behalf of
Environmental Resources Management

Approved by: ____________________

Signed: ____________________

Position: ____________________

Date: ____________________

CONTENTS

EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

The Health and Safety Executive's (HSE's) involvement in land use planning, and the principles on which it bases its advice, is set out in the HSE document "Risk Criteria for Land Use Planning in the vicinity of Major Industrial Hazards" (1). This document was published in 1989 and, therefore, it is over 14 years since the principles in it were determined and agreed.

Consequently, HSE undertook a fundamental review (2) (3) of its involvement in land use planning to determine if its approach was still valid, legally robust and in line with broader governmental and European policy. In addition, this review sought to address the expressed concerns of certain external stakeholders that HSE was being too conservative in some of its approaches in this area.

The Implementation of the Fundamental Review of Land Use Planning (IFRLUP) project was set up to implement the following recommendations of this review:

- the criteria and methodology used for setting planning zones and for "calling in" planning applications should be reviewed and, if necessary, revised and then published;

- HSE's advice to local authorities (LAs) on chemical major hazards and pipelines should be further codified so that consistent, transparent and accurate advice can be given without the demand on HSE resources that detailed individual assessment of planning applications requires; and,

- the codified generic advice should be devolved to LAs so that they can deal with the vast majority of planning applications which are in the vicinity of chemical major hazards and pipelines.

This report forms part of the process by which these aims are being met, constituting a review of the risk analysis and protection based assessment approaches that HSE uses in the course of providing land-use planning (LUP) advice to Local Authorities (LAs).

Certain issues (namely Hazardous Substances Consent and the risk / hazard basis for setting the consultation zones) were remitted to HSE's Policy Group for consideration and have not, therefore, been addressed within this report. It is recommended that these issues are fully explored and the outcomes documented.

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(1) HSE (1989). *Risk criteria for land-use planning in the vicinity of major industrial hazards.* HMSO.

(2) Safety Policy Directorate, HSE. '*Fundamental Review of HSE's Policy on Siting and Land-Use Planning for Major Hazard Installations including Pipelines, Report 6, The Land-Use Planning Policy - Recommendations*'.

(3) HSE, '*The outcome of the fundamental review of HSE's policy on land-use planning for major hazard installations and pipelines*'. HSC paper HSC/misc/02/16.

HSE uses either risk analysis or 'protection-based' analysis for establishing the LUP zone boundaries around a particular site. In general, risk analysis tends to be used for sites handling toxic materials, whilst protection-based analysis tends to be used for sites handling flammable materials.

A formal validation of risk analysis methodology is not possible, since the predictions of the method cannot be compared with an experimental measurement. Therefore the following strategy has been adopted in seeking to review HSE's risk analysis approach:

- each element of the risk analysis (hazard identification, frequency analysis, consequence analysis, etc.) has been examined separately by various means; and,

- the risk analysis results obtained using HSE's approach have been compared with those obtained by other analysts and / or using other models for the same situation.

Details are provided in ***Section 2*** of the report.

The review of HSE's protection-based analysis approach has comprised:

- consideration, in general terms, of the use of protection-based approaches by HSE; and,

- examination of the protection-based analysis approach for a specific type of installation.

The findings are discussed in ***Section 3*** of the report.

In addition, a large number of the assumptions employed HSE when performing either risk analysis or protection-based analysis have been reviewed. The review is presented in ***Section 4*** of the report.

REVIEW OF HSE'S RISK ANALYSIS METHODOLOGY

Overall Conclusions

On the basis of the reviews conducted, it is concluded that HSE's risk analysis methodology is generally fit for purpose. No evidence was found that would indicate that HSE's methodology is either excessively conservative or excessively non-conservative.

It should be noted that:

- at the time of writing, a separate project to perform a detailed evaluation of HSE's consequence analysis methods and models had not been completed; and,

- certain assumptions relating to HSE's approach to Hazardous Substances Consent were excluded from the scope of the review.

Recommendations

The recommendations arising out of the review are that:

1. if in the future HSE seeks to apply QRA to types of plants more complex than those currently analysed using QRA, HSE consider supplementing the 'top down' (1) (see ***Section 1.1.2*** of the report) approach to the identification of hazards with other methods;
2. HSE considers whether events resulting in unintended releases from vents (such as vessel overfill during transfers from road tankers) should be included in risk analyses for sites storing chlorine or other pressurised liquefied gases;
3. in the case of sites storing or using water reactive materials (such as sulphur trioxide), HSE considers whether the risk analysis should include scenarios where water is inadvertently added to the dangerous substance (for example, where water may be used for cleaning of tanks or equipment); and,
4. HSE performs further investigations into the significance of hazards arising from undesired chemical reactions and, if necessary, develops a means of including such hazards in a risk analysis.

REVIEW OF HSE'S PROTECTION-BASED APPROACH

Overall Conclusions

The terminology used in relation to protection-based analysis is not well defined. Similarly, for a given type of installation, the reasons for resorting to a protection-based analysis, and the reasons for the selection of the particular event (or events) chosen to define the LUP zones are generally not well explained or documented.

As further research and development is performed, protection-based analysis may be replaced by risk analysis for some types of site. In particular, adoption of fatality as the harm criterion (in the form of the Total Risk of Death, or TROD) instead of dangerous dose would deal with some of the objections to using risk analysis in particular cases. However, even if risk analysis methods for all types of major hazard installation (MHI) were available, there may continue to be other reasons justifying the use of protection-based analysis. A protection-based analysis could still be appropriate where:

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(1) The 'top down' approach involves identifying potential sources of releases of a dangerous substance by considering failure of the equipment within which the substance is contained.

- the Hazardous Substances Consent documents contain insufficient information for a risk analysis;
- the surrounding population density and demand on land-use are low; and,
- a protection-based analysis would generate similar results (in terms of the sizes of LUP zones and the advice given) to those from a risk analysis.

Recommendations

The review of HSE's protection-based approach resulted in the following recommendations:

5. the terminology used in relation to protection-based analysis (*'worthwhile'* protection, *'unlikely but foreseeable'*, etc.) is better defined;
6. the relationship between the two levels of protection stated in the aim and the three LUP zones defined by the analysis is described;
7. HSE develops internal guidance for Inspectors on selecting events for use in protection-based analyses;
8. where protection-based analysis is used for installations of a given type, the reasons for adopting a protection-based approach, together with the rationale for selecting the event or events used in the analysis, are documented in such a form that the information could be released to interested parties outside HSE as required; and,
9. HSE continues to perform research into risk analysis methods so that some of the reasons for using a protection-based approach can be resolved.

With regard to the specific protection-based approach used for bulk liquefied petroleum gas (LPG) storage, it was noted that the choice of event for the analysis was influenced by the frequency of the Boiling Liquid Expanding Vapour Explosion (BLEVE) (1) event currently assumed by HSE. It is recommended that:

10. the estimate of this frequency is updated and, depending on the outcome of this revision, that the selection of the event used in protection-based analyses of bulk LPG installations is revisited.

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(1) A BLEVE occurs as a result of catastrophic failure of a vessel containing LPG when exposed to intense heat, such as that from a fire.

REVIEW OF ASSUMPTIONS USED

Overall Conclusions

All of the assumptions reviewed were found to be appropriate and / or in keeping with the approach taken by most risk analysis practitioners, with one exception. The assumption questioned is that relating to the amount of LPG in a vessel when it undergoes a BLEVE, for which a recommendation has been made.

Recommendation

It is recommended that:

11. the assumptions relating to the amount of LPG in a vessel when it undergoes a BLEVE are revisited. This is particularly important if the BLEVE event is going to continue to be used for protection-based analysis of bulk LPG storage installations. It is believed that the amounts currently assumed by HSE could represent an underestimate in some cases.

REVIEW OF FINDINGS RELATED TO BULK STORAGE OF LPG

The review findings in relation to the protection-based analysis of bulk LPG (liquefied petroleum gas) installations have been collated in this Section for convenience.

Overall Conclusions

The level of harm arising from many of the major accidents at a bulk LPG establishment would be considerably worse than a 'dangerous dose', justifying the use of a protection-based approach. However, this objection could be dealt with by using a risk-based analysis with fatality as the harm criterion.

Another reason for the adoption of a protection-based approach for bulk LPG storage is that there is considerable uncertainty associated with the likelihood of some of the events that may occur, particularly the probability of ignition of flammable clouds and the frequency of a BLEVE. Further research in these areas is recommended (Recommendations 9 and 10). It may be that, as an interim position, protection-based analysis is retained, but with the use of an event other than the BLEVE, to generate the LUP zones.

The assumption used in the current analysis methodology relating to the amount of LPG in a vessel when it undergoes a BLEVE is questioned. A recommendation has been made (Recommendation 11).

Recommendations

The relevant recommendations are as follows:

9. that HSE continues to perform research into risk analysis methods so that some of the reasons for using a protection-based approach can be resolved;
10. that the estimate of the BLEVE frequency is updated and, depending on the outcome of this revision, that the selection of the event used in protection-based analyses of bulk LPG installations is revisited; and,
11. that the assumptions relating to the amount of LPG in a vessel when it undergoes a BLEVE are revisited. This is particularly important if the BLEVE event is going to continue to be used for protection-based analysis of bulk LPG storage installations. It is believed that the amounts currently assumed by HSE could represent an underestimate in some cases.

1 INTRODUCTION

1.1 BACKGROUND

The Health and Safety Executive's (HSE's) involvement in land use planning, and the principles on which it bases its advice, is set out in the HSE document "Risk Criteria for Land Use Planning in the vicinity of Major Industrial Hazards" (1). This document was published in 1989 and, therefore, it is over 14 years since the principles in it were determined and agreed.

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- the codified generic advice should be devolved to LAs so that they can deal with the vast majority of planning applications which are in the vicinity of chemical major hazards and pipelines.

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Certain issues (namely Hazardous Substances Consent and the risk / hazard basis for setting the consultation zones) were remitted to HSE's Policy Group for consideration and have not, therefore, been addressed within this report. It is recommended that these issues are fully explored and the outcomes documented.

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(1) HSE (1989). *Risk criteria for land-use planning in the vicinity of major industrial hazards.* HMSO.

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(3) HSE, '*The outcome of the fundamental review of HSE's policy on land-use planning for major hazard installations and pipelines*'. HSC paper HSC/misc/02/16.

1.2 *HSE'S ROLE IN PROVIDING LAND-USE PLANNING ADVICE*

Within the UK, the Health and Safety Executive (HSE) is responsible for providing Local Authorities (LAs) with advice concerning the safety implications of developments in the vicinity of major hazard installations (MHIs) and major hazard pipelines (MHPs). In outline, HSE's approach to fulfilling this role consists of:

1. Defining an area around the MHI or MHP within which HSE should be consulted by the LA regarding the safety aspects of certain types of proposed development. This area is bounded by the Consultation Distance (or CD).
2. Within the CD, HSE also defines three concentric zones, termed the Inner Zone (IZ), Middle Zone (MZ) and Outer Zone (OZ) respectively.
3. Defining the types of development about which the HSE wishes to be consulted (e.g. - HSE does not ask to be consulted about relatively small or insignificant applications such as retail developments involving less than 250 square metres of floor space).
4. Considering each application for development that is forwarded by the LA for consultation and determining the advice that HSE should give to the LA. The advice given depends upon the size and nature of the development and which zone it is in (IZ, MZ or OZ).
5. Providing the resulting advice to the LA. This takes the form of a letter giving either an 'HSE advises against' or an 'HSE doesn't advise against' response for the development application in question.

HSE uses either risk analysis or 'protection-based' analysis for establishing the zone boundaries around a particular site. The reasons for selecting one analysis approach over the other are varied and are presented in ***Section 1.4***. In general, risk analysis tends to be used for sites handling toxic materials, whilst protection-based analysis tends to be used for sites handling flammable materials.

When risk analysis is used, the different zones correspond to different levels of risk. The OZ, terminating at the CD, is set at an individual risk of 0.3 chances per million per year (cpm), the MZ at a risk of 1 cpm and the IZ at a risk of 10 cpm. Risk concepts and the term 'individual risk' are explained further in ***Section 1.1***.

For most sites, HSE uses the protection-based approach to determining CDs and zone boundaries. The aim of a protection-based analysis when setting zone boundaries is to:

"achieve a separation between developments and the site which provides a very high degree of protection against the more likely smaller events, whilst also giving very

worthwhile (sometimes almost total) protection against unlikely but foreseeable larger-scale events." (1)

Once the CD and zones are in place, HSE uses a system called Planning Advice for Developments near Hazardous Installations (2) (PADHI) to generate the advice to be given for a particular development proposal. Further information about PADHI can be obtained from HSE's website.

This document presents a review of the risk analysis and protection based assessment approaches that HSE uses in the course of providing land-use planning (LUP) advice to LAs. A description of these approaches as they are applied to MHIs and MHPs is given below.

In the UK MHIs are defined as those sites that are required to have Hazardous Substances Consent (3), obtained from the appropriate Hazardous Substances Authority (usually part of the Local Authority). The Hazardous Substances Consent (or Consent for short) defines the quantities of dangerous substances that the site can hold, and may also define the size of the largest storage vessels, the locations of vessels, the locations of areas used to store transportable containers and the maximum temperatures and pressures within storage and process vessels.

The HSE is consulted concerning applications for Hazardous Substances Consent (applications for permission to create a new MHI or alter the dangerous substances present at an existing MHI). The UK approach to dealing with Consents is the subject of a separate policy review and is not considered within this document.

1.3 RISK ANALYSIS AND ASSESSMENT

As with most scientific and technical disciplines, Risk Analysis has its own terminology, whereby certain words take on a very specific meaning. For example, 'risk' is defined as 'the chance of something adverse happening'. It is important to note that, according to this definition, 'risk' has two components. The first is the 'chance', which may be expressed as a probability (how likely) or a frequency (how often). The second is the 'something adverse', or consequence. The consequence of interest in this context is harm to people. In simple terms:

Risk = Frequency x Consequence

A risk analysis must therefore address both the 'frequency' and 'consequence' components. A risk analysis in which each of the frequency and consequence components is quantified, and which provides a numerical estimate of risk, is termed a Quantitative Risk Analysis (QRA).

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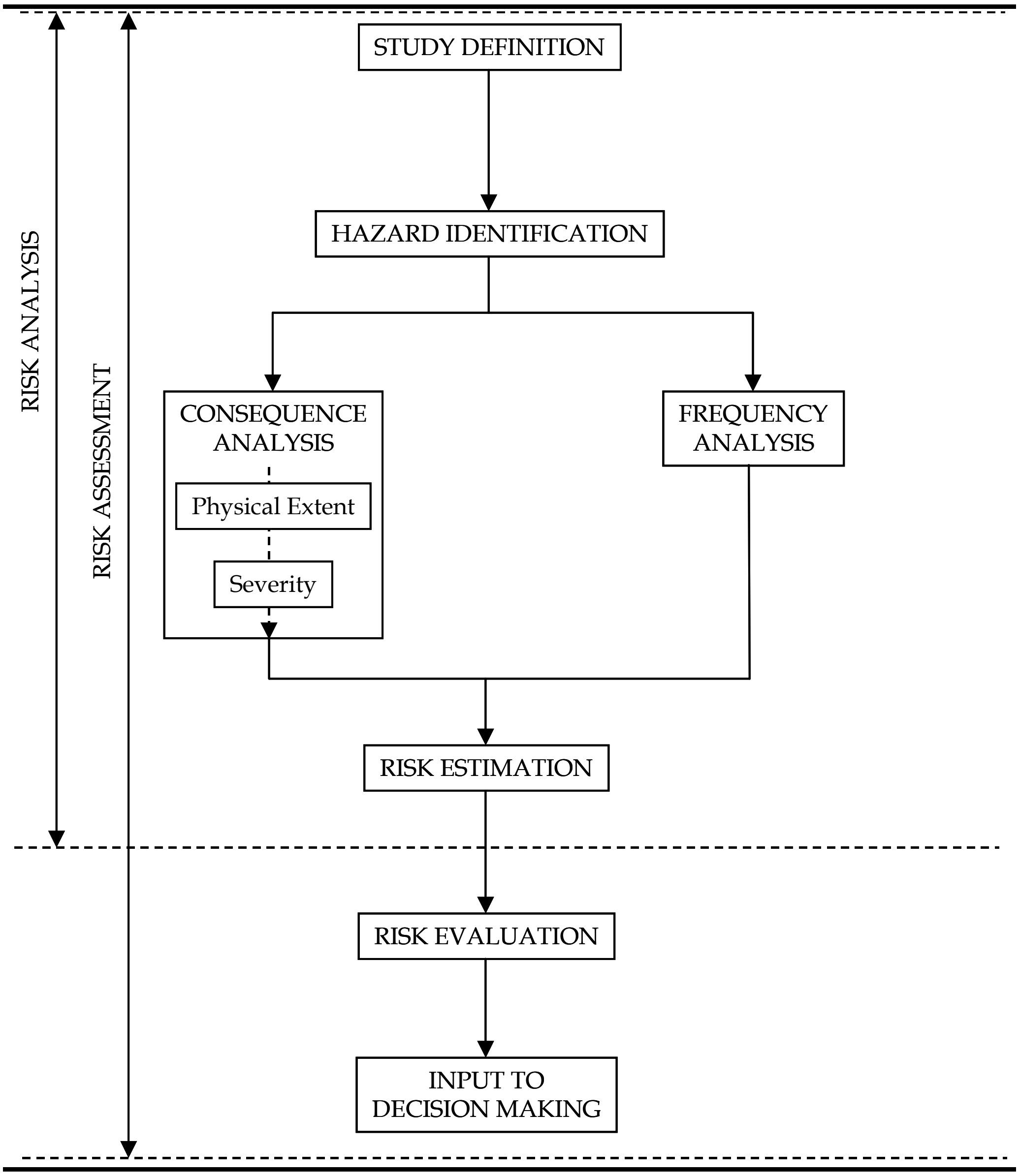
(1) HSE (1989). *Risk criteria for land-use planning in the vicinity of major industrial hazards*. HMSO.

(2) HSE (2003). *PADHI - HSE's Land Use Planning Methodology*. Available at www.hse.gov.uk/landuseplanning/

(3) DETR (2000). *Hazardous substances consent - A guide for industry*. HMSO.

The overall process of a risk analysis an risk assessment is illustrated in ***Figure 1.1***. Each of the elements of the process is described in more detail below.

Figure 1.1 Risk Analysis and Assessment Process



1.3.1 *Study Definition*

The Study Definition step involves defining the scope of the risk analysis and the information that is required from it. This is important, since the way in which the study is defined will have a strong influence on the way in which later steps are conducted. For a risk analysis that is used to generate LUP advice around MHIs and MHPs, there are some important points to note in this regard:

The subject of the risk analysis is MHIs and MHPs. What constitutes a MHI or MHP is defined by legislation. Essentially, whether or not a given installation is a MHI depends on the quantities of dangerous substances that they may use or store (1) (2) (3) (4) (5). Hence not all installations using or storing dangerous substances will be MHIs. In the case of pipelines, MHPs are defined in accordance with the kind of material they convey (whether or not it is a 'dangerous fluid' under the terms of the legislation (6)). What constitutes a dangerous fluid depends on the pipeline operating conditions as well as the nature of the material conveyed. Hence not all pipelines carrying dangerous substances would be classed as MHPs.

The purpose of the risk analysis is to generate estimates of the risks that will be used to inform LUP decisions. Therefore the analysis will focus on the risks to people located in the vicinity of the MHI (or MHP) but not the risks to people at the MHI itself. In other words, the focus is on risks to people beyond the site boundary of the MHI. Risks to people on-site at MHIs are subject to other controls.

1.3.2 *Hazard Identification*

In Risk Analysis terminology a hazard is something with the potential to cause harm. Hence the Hazard Identification step is an exercise that seeks to identify what can go wrong at the MHI or MHP in such a way that people may be harmed. The output of this step is a list of events that need to be passed on to later steps for further analysis.

In a complex chemical plant, for example, there may be any number of things that could go wrong. However, not all of these problems will have the potential to cause harm to people. Some problems may bring the process to a halt, others may affect product quality or output. In general the kind of problems that could harm people are those that give rise to an unintended release of dangerous substance or substances from the equipment (such as vessels, pipes, pumps etc.) within which it is normally contained.

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(1) The Planning (Hazardous Substances) Regulations 1992

(2) The Planning (Hazardous Substances) (Scotland) Regulations 1993

(3) The Planning (Control of Major-Accident Hazards) Regulations 1999

(4) The Planning (Control of Major-Accident Hazards) (Scotland) Regulations 2000

(5) HSE (1999). *A Guide to the Control of Major Accident Hazards Regulations 1999*. HSE Books, L111

(6) The Pipeline Safety Regulations 1996.

In addition, not all of the events found in a hazard identification exercise will have the potential to harm people off-site (particularly small events with a relatively limited range of effect). In the LUP context, the risk analyst is solely concerned with the risk to people beyond the site boundary, hence these smaller events may be 'screened out' of the analysis.

There are a number of techniques available to the risk analyst for performing Hazard Identification studies, such as Hazard and Operability studies (1) (HAZOP) or Failure Modes and Effects Analysis (2) (FMEA). These techniques can determine the detailed potential causes of failures within the system under investigation. However, it is not necessary to have detailed information about the potential causes of failures in order to calculate the levels of risk around an MHI or MHP for the purposes of providing LUP advice. Therefore HSE tends to use what is known as a 'top down' approach to establishing the events with a potential to harm people.

Essentially, the 'top down' approach consists of identifying all of the locations in the MHI or MHP where a release of dangerous substances may occur. The approach also takes into account the fact that releases may be of different sizes, ranging from small 'pinhole' type leaks to catastrophic failures of equipment.

1.3.3 Frequency Analysis

Having identified the events that should be included in the risk analysis, it is necessary to estimate the frequency with which these events could occur. Generally there are three approaches to doing this:

- use historical data on how often these events have occurred in the past;
- use analytical or simulation techniques (such as fault tree analysis) to predict what the frequency will be; and,
- use expert judgement.

Generally HSE uses the first of these methods. In practical terms, this fits well with the 'top-down' approach to hazard identification. The historical data used can be at one of two different levels:

- the incident level (for example, the frequency of fires in warehouses storing dangerous substances); or,
- the equipment level (the frequency of leaks from a particular item of equipment).

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(1) Kletz, T (1992). *HAZOP and HAZAN, Identify and Assessing Process Industry Hazards*. Institution of Chemical Engineers.

(2) Lees F P (2001). *Loss Prevention in the Process Industries*. Second Ed. Butterworth-Heinemann.

The data are derived from records of how often the incident has occurred or how often equipment items (such as pumps, pipes and vessels) found at MHIs have failed in the past. At the equipment level, each type of equipment item has associated with it frequencies with which it may give rise to releases of different sizes.

Typically the frequency analysis is performed by conducting a survey of equipment containing dangerous substances, together with an examination of technical information relating to activities on the site. These activities produce estimates of the numbers of equipment items of each type that are present (how many pumps, how much pipe, how many vessels, etc.). These numbers are then combined with the respective frequencies of releases in order to obtain the total frequency of all releases of hazardous substances at the site.

There are numerous sources of historical data on equipment failure available within the technical literature (1) (2) (3) (4) (5). Different sources can vary widely in their estimates of the frequency of releases from equipment, even when they appear to be dealing with items of a similar type. To arrive at the frequency of releases that it uses in its analyses, HSE has therefore conducted detailed reviews of the sources of information available and has sought to derive frequencies that are appropriate to the kind of equipment it encounters. HSE stores failure frequency information in a document called FRED (Failure Rate and Event Data) (6).

1.3.4 *Consequence Analysis*

In the context of a risk analysis, consequence analysis involves determining the effects of the events of interest in terms of their physical extent and their severity. Determining the physical extent usually involves calculating the maximum distances from the source at which people are affected. The severity of an event is expressed as a level of harm (such as injury or fatality) of interest.

The approach taken by HSE to Consequence Analysis is similar to that used by most risk analysts and comprises a number of sub-steps:

- Source term modelling (i.e., characterising the event in terms of the rate at which the dangerous substance is released, the temperature, pressure, velocity and density of the substance as it is released, and so on);

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(1) Lees F P (2001). *Loss Prevention in the Process Industries*. Second Ed. Butterworth-Heinemann

(2) Exploration and Production Forum (1992). *Hydrocarbon Leak and Ignition Database*. May 1992.

(3) Arulanatham D C and Lees F P (1981). *Some Data on the Reliability of Pressure Equipment in the Chemical Plant Environment*. Int. J. Pres. Ves. & Piping, 9 (1981), 792-800.

(4) Smith T A and Warwick R G (1981). *A Survey of Defects in Pressure Vessels in the UK for the Period 1962-78, and its Relevance to Nuclear Primary Circuits*. UKAEA Safety and Reliability Directorate Report SRD R203.

(5) Davenport T J (1991). *A Further Survey of Pressure Vessel Failures in the UK*. Reliability 91, London, June 1991.

(6) HSL (1999). *Failure Rate and Event Data for Use in Risk Assessment (FRED)*. Issue 1, November 1999, RAS/99/20.

- Dispersion modelling (i.e., calculating how the dangerous substance will move through the surroundings);
- Fire and explosion modelling (i.e., for releases of flammable substances which may be ignited); and,
- Effects modelling (i.e., determining the effect that the release will have on people, or structures such as buildings).

Each sub-step may require detailed calculations to be performed. In most cases these calculations are performed using computer software. In addition to using some commercially available consequence analysis software, HSE has developed its own 'in-house' software for these purposes.

The final sub-step, effects modelling, requires information about:

- the toxicological effects that the dangerous substance has on people at different concentrations; or,
- the effects of heat from fires; or,
- the effects of blast from explosions; or
- other effects such as oxygen enrichment and impact by missiles generated in explosions.

The outcome of a particular release can depend upon a large number of factors, including:

- the dangerous substance involved and the amount present;
- the conditions under which the substance is kept;
- the weather conditions at the time of the event;
- the size of the event (in terms of how quickly the material is released and the quantity released); and,
- the nature of the surroundings (e.g. – whether the substance is spilt on to concrete or water).

Hence, in order to model a given release event, it is necessary to gather a significant amount of information concerning the event. HSE obtains this information from technical documents relating to the MHI or MHP and from other sources (e.g., information on the local weather conditions is obtained from the Meteorological Office).

An important factor in consequence analysis is to determine the level of harm that is of interest. Historically HSE has considered a level of harm called the 'dangerous dose'. A dangerous dose is considered to cause all of the following effects to an exposed population:

- severe distress to almost everyone;
- a substantial proportion requires medical attention;
- some people are seriously injured, requiring prolonged treatment;
- any highly susceptible people might be killed.

The main reasons given (1) for using dangerous dose as a harm criterion instead of fatality are:

- society is concerned about risks of serious injury or other damage as well as death; and,
- there are technical difficulties in calculating the risks of death from a hazard to which individual members of a population may have widely varying vulnerabilities.

HSE has defined dangerous doses for a wide range of toxic substances (2), for thermal radiation from fires and for blast pressure from explosions.

1.3.5 *Risk Estimation*

At this stage the frequency and consequence analysis results are combined in order to generate numerical estimates of risk. Although the calculations required are not that complex (compared to those required for consequence analysis, for example), it is common for a very large number of calculations to be required. Hence most risk analysts employ computer software at this step and HSE is no exception. HSE has developed its own 'in-house' software tools for this purpose. The software most commonly used by HSE is called 'Toxic RISKAT' (3).

The output of risk calculations can be presented in various ways. Currently HSE risk estimates are presented in terms of individual risk. Individual risk is defined as 'the risk of some specified event or agent harming a statistical (or hypothetical) person assumed to have representative characteristics'. The hypothetical person considered in HSE's risk analyses is a hypothetical house resident. This hypothetical person is assumed to be present all of the time and located in a typical dwelling.

The individual risk results produced by HSE are usually displayed as risk contours overlaid on a map. An example is shown in ***Figure 1.2***. Individual risk is expressed in units of 'chances per million per year' or cpm. Hence on the 1 cpm individual risk contour, a hypothetical house resident at that

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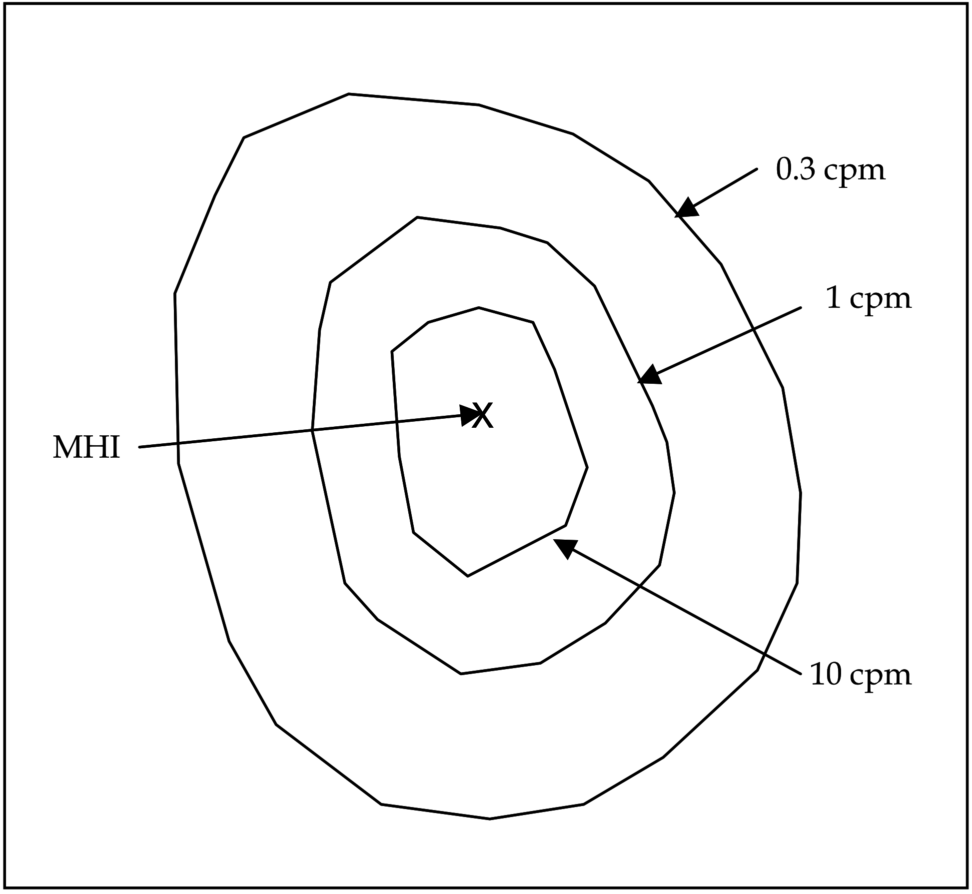
(1) HSE (1989). *Risk criteria for land-use planning in the vicinity of major industrial hazards.* HMSO.

(2) HSE / HID. *Assessment of the Dangerous Toxic Load (DTL) for Specified Level of Toxicity (SLOT) and Significant Likelihood of Death (SLOD).* Available at www.hse.gov.uk/hid/haztox.htm

(3) Pape R P and Nussey C (1985). *A basic approach for the analysis of risks from major toxic hazards.* IChemE Symposium Series No. 93.

location would have 1 chance in a million per year of being exposed to a dangerous dose or worse as a result of a major accident at the MHI.

Figure 1.2 *Example Individual Risk Contours*



1.3.6 Assumptions

Throughout the risk analysis process, it may be necessary to make assumptions about the value of certain parameters, particularly where data are unavailable or the value is known to vary widely (an example is the probability that a given release of flammable material will ignite). Since risk analyses of MHIs and MHPs tend to deal with very rare events, data can be sparse and it is not uncommon for the analyst to resort to the use of assumptions, made on the basis of expert judgment.

When making such assumptions, HSE adopts a 'cautious best estimate approach'. That is, where good data are available, HSE will use that data to quantify the relevant parameter. Where the data are poor or absent, HSE will make assumptions that err on the side of caution (i.e. – that will result in a higher estimate of the risk).

1.3.7 *Risk Evaluation*

Once a numerical estimate of the risk has been obtained, it is usually necessary for the people responsible for managing the risk to make some kind of value judgement regarding the result (e.g. – is the risk acceptable or not?). This is usually done by comparing the risk estimate with risk criteria. HSE has published risk criteria in its document 'Reducing Risks, Protecting People' (1). The risk criteria used for providing LUP advice are described elsewhere (2).

In the case of HSE's role in providing LUP advice, the risk evaluation involves examining the size and nature of a proposed development, and the risk to which the people at the development would be exposed. This step has been codified in the PADHI software. The outcome of this evaluation is communicated to the LA as either 'HSE advises against' or 'HSE doesn't advise against' the development proposal.

1.3.8 *Decision Making*

The decision as to whether a proposed development receives planning permission rests with the LA, taking into account the advice supplied by HSE. The LA has to weigh in the balance all of the factors relating to a proposed development (economic, social, environmental, safety) in reaching its decision. HSE has the option to have an application 'called-in' for determination by the Secretary of State where it believes that the risks are substantial and the LA has not given due weight to its advice in coming to their decision.

The following factors would favour calling in the application:

- Any proposals for significant residential development or development for vulnerable populations in the inner zone;
- Proposals where the risk of death exceeds the tolerability limit for a member of the public of 1 x 10^{-4} per year (1);
- Proposals where there are substantial numbers of people exposed to the risk, giving rise to a high degree of societal concern (3);
- Proposals where the endangered population is particularly sensitive, (e.g., the development is a hospital, school or old people's home);
- Whether there have there been previous call-ins in similar circumstances;

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(1) HSE (2001). *Reducing risks, protecting people*. HSE Books C/100.

(2) HSE (1989). *Risk criteria for land-use planning in the vicinity of major industrial hazards*. HMSO.

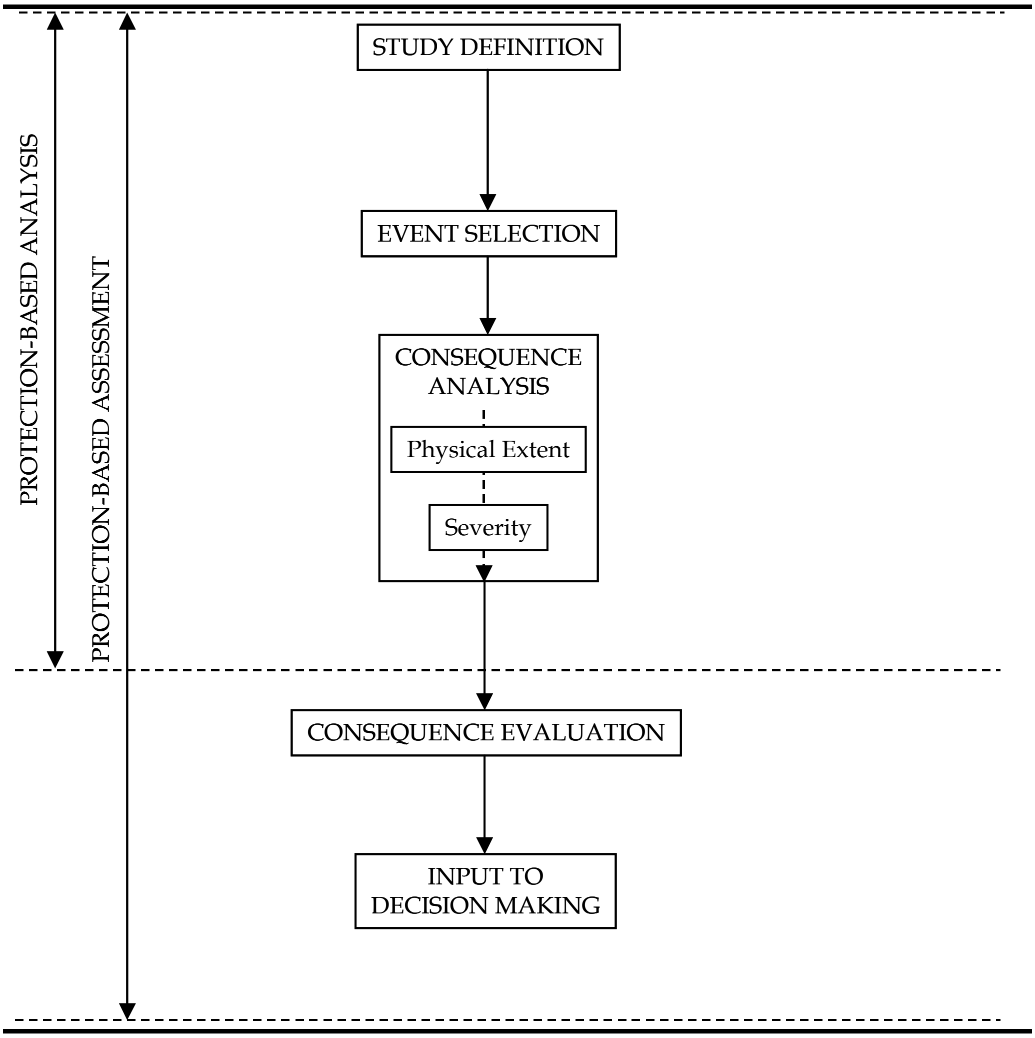
(3) The Methodology and Standards Development Unit (MSDU) of HSE's Hazardous Installations Directorate (HID) has developed a method of assessing the degree of societal risk associated with a proposed development, the Scaled Risk Integral (SRI). In appropriate cases MSDU will apply SRI. Where the SRI is between 500,000 and 750,000, HID considers recommending call-in. If the SRI exceeds 750,000 HID recommends call in.

- Whether there are issues of national concern as opposed to merely of local importance; or,
- Whether there is clear evidence that the case concerned is being used to challenge HSE's risk criteria for land-use planning and failure to meet that challenge would damage HSE's credibility; or where a decision against HSE's advice could, by precedent, set aside parts of the relevant legislation.

1.4 PROTECTION-BASED ANALYSIS

The process of performing a protection-based analysis is a great deal simpler and less time consuming than performing a risk analysis and is illustrated in *Figure 1.3*.

Figure 1.3 ***Protection-Based Analysis and Assessment Process***



Essentially, a protection-based analysis involves:

- selecting the event or events upon which the analysis will be based; and,
- performing a consequence analysis (see ***Section 1.1.4***) of the selected event or events.

For a complex site with a number of discrete inventories of dangerous substances, each inventory would normally be assessed and an appropriate event selected for each. The event selected would depend on the substance for which Consent had been obtained or applied for; and the conditions under which it was kept. A combined set of LUP zones would then be constructed from the zones for each individual event.

It should be noted that the 'Event Selection' step of a protection-based analysis differs somewhat from the 'Hazard Identification' step of a risk analysis. Hazard Identification, as it is performed by HSE, focuses on potential release sources. Event Selection focuses on a specific outcome of a release (or releases). For example, one hazard identified by Hazard Identification might be a release from a storage tank holding flammable liquids. Such a release could have a number of outcomes or events (including a pool fire, a flash fire and a vapour cloud explosion), depending on the circumstances. The corresponding event selected by Event Selection could be a pool fire of a particular size resulting from ignition of a release of flammable liquid.

For some types of installation, experience with risk analysis has shown that there is one event that dominates the risk profile, hence this event has been chosen for the basis of a protection-based assessment.

In other cases, selection of the event or events has involved considering the full range of events that might occur at the installation and 'filtering out' those with a frequency that is so low that the risk associated with them would always drop below the lower limit of HSE's LUP risk criteria. Historically, protection based analysis approaches have been subjected to technical peer-review within HSE prior to adoption.

When the consequence analysis is performed for a protection-based assessment, it usually involves calculating the ranges to three different levels of harm:

- a level significantly higher than dangerous dose (around 50% fatality to the exposed population);
- the dangerous dose; and,
- a level significantly lower than the dangerous dose.

The corresponding three distances are then used as the distances to each of the three zone boundaries (IZ, MZ and OZ respectively). Hence, the zones represent different levels of harm from the selected event(s), rather than different levels of individual risk.

As a general principle, HSE's advice takes account of risk as well as hazard where it is beneficial to do so (1) (a protection-based assessment only takes account of hazard). In practise there are a number of factors which have influenced whether a given installation or type of installation would be subject to a protection-based analysis or a risk analysis, including:

- whether or not the Hazardous Substances Consent for the installation contained sufficient information to support a risk analysis;
- whether there is a high degree of uncertainty regarding the frequency of some of the events that might occur at the site;
- whether the level of harm predicted from events at the installation would be very high (i.e., the risk of dangerous dose or worse would contain a significant proportion of risk of fatality, see ***Section 1.1.4***) – a high level of harm would favour a protection-based approach; and
- the density of population and demand on land use in the area around the site – densely populated surroundings and / or a high demand on land use might support a risk-based approach.

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(1) Office of the Deputy Prime Minister Circular 04/2000. '*Planning Control for Hazardous Substances*'.

When a scientific or engineering model is developed, it is common practice to subject the model to three kinds of scrutiny: verification, scientific assessment and validation.

Verification involves checking that the model actually does what it says it does. As a trivial example, if a user is presented with a piece of software that adds A and B together and multiplies the result by C, it is possible for the user to look at the equations in the computer program and verify that this is what has been encoded.

Another dimension is to check that the right equation has been used in the first place. This is scientific assessment. For example, if a piece of software claims to calculate the volume of a sphere, the user can look up the right equation in a maths textbook and check that this is what has been written into the program.

Validation involves checking the prediction made by the model against some independent source. Hence, for the simple program that adds A and B together and multiplies by C, the user run the software, enter some values of A, B and C and check the output of the software against the answer obtained using a calculator.

It is important to note here that there are different kinds of model. Some models simulate physical processes that behave in some predictable way (deterministic models). In some cases the physical processes may be very complex or poorly understood, which makes construction of the model difficult. An example would be a model designed to predict how a release of toxic gas will disperse under a given set of conditions.

Other models seek to consider processes that are subject to chance (probabilistic models). A simple example would be a model that predicted the probability of being dealt a certain hand in a game of cards.

A deterministic model (such as software to simulate gas dispersion) can be validated by comparing the predictions made by the model with the results obtained in experiments.

Some probabilistic models can also be validated by experiment. For example, to validate the 'hand of cards' model described above, trials could be conducted where the deck was shuffled, a hand of cards dealt, the result recorded and the process repeated a large number of times. The results could then be compared with the predictions of the model.

Risk analysis for LUP uses a combination of both deterministic and probabilistic models. The overall result is probabilistic (remembering that risk is the *chance* of something adverse happening). Clearly such a risk analysis cannot be validated in the same way as the 'hand of cards' model, by conducting a large number of trials. Examination of historical records of major accidents could, in principle, provide some validation, but some of the major accidents postulated in the risk analysis are so rare that they may not appear in the historical record at all. This problem is exacerbated by the fact that some of the deterministic models used within the risk analysis deal with highly complex processes (such as gas dispersion and vapour cloud explosions), which are not completely understood.

In view of these difficulties, the following strategy has been adopted in seeking to review HSE's risk analysis approach:

- each element of the risk analysis (hazard identification, frequency analysis, consequence analysis, etc.) has been examined separately by various means; and,
- the risk analysis results obtained using HSE's approach have been compared with those obtained by other analysts and / or using other models for the same situation.

Details are provided in subsequent sections. With regard to the second of these bullet points, two studies have been identified which provide useful information. These are described in ***Section 2.1*** below.

The Study Definition step (see ***Section 1.3.1***) does not require validation in the sense discussed above, since it only involves stating the scope and objectives of the risk analysis.

2.1 *COMPARATIVE STUDIES*

Two studies have been identified which compare HSE's risk analysis approach with those used by others.

The first is known as the ASSURANCE (Assessment of Uncertainties in Risk Analysis of Chemical Establishments) Project (1). This project was co-funded by the EU and ran from May 1998 to April 2001. Seven teams of risk analysts from different countries and organisations performed a risk assessment study of the same facility. The MHI selected as the subject of the analyses stored and distributed ammonia (a dangerous substance that is both toxic and, under the right circumstances, flammable). The study teams were drawn from:

- Det Norske Veritas Ltd. (DNV), UK;
- INERIS, France;

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(1) Risø National Laboratory (2002). *Assessment of Uncertainties in Risk Analysis of Chemical Establishments, the ASSURANCE Project, Final summary report*. Riso-R-1344 (EN).

- HSE, UK;
- NCSR Demokritos, Systems Safety and Risk Assessment, Greece;
- TNO, Department of Industrial Safety, the Netherlands;
- Universita di Bologna, DICMA, Italy; and,
- VTT Automation, Finland.

The EU Joint Research Centre, Ispra, Italy and the Risø National Laboratory, Denmark, co-ordinated the project.

The project consisted of three distinct phases:

- a phase during which the hazards were identified by each participant and a list of events for risk analysis selected;
- a phase during which the participants performed the risk analysis according to their own experience, methodology and models, covering the events that they had selected in the first phase (i.e. – each participant used their own list of events); and,
- a phase during which the participants performed the risk analysis according to their own experience, methodology and models, but using a common list of 11 events (i.e. – each participant used the same list of 11 events).

In addition to comparing the overall risk analysis results produced by each participant, the project report also compares the results obtained at each risk analysis step.

The second study of interest involved work by consultants on behalf of HSE to compare the results obtained using HSE's 'Toxic RISKAT' software with results for the same MHI using a commercially available risk analysis tool (called SAFETI, produced by DNV (1)). This study only compared the final risk estimates produced by the two programs.

The results of these studies are discussed in various Sections below.

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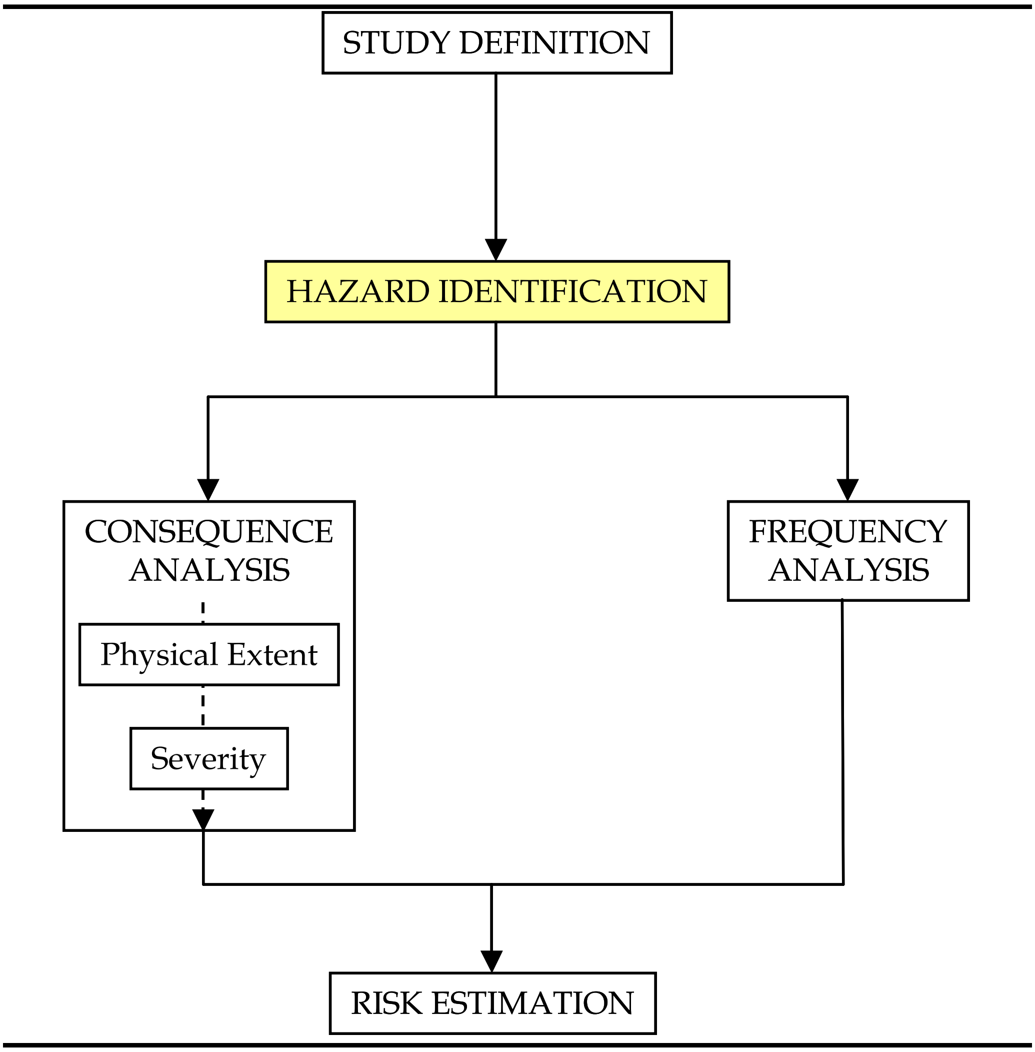
(1) DNV Risk Management Software. Details available at www2.dnv.com/software/

2.2 *HAZARD IDENTIFICATION*

The risk analysis step considered in this Section is highlighted in ***Figure 2.1***.

Figure 2.1 ***Risk Analysis Process - Hazard Identification Step***



HSE's approach to the identification of hazards has been reviewed by:

- considering the results of earlier research that compared QRA approaches with accident experience;
- examining records of accidents at major hazard sites in the UK since 1985 to see whether there is a correspondence between the kind of accidents that HSE would include in its risk analyses or protection-based assessments and the accidents that have actually happened;
- considering the relevant findings of the ASSURANCE project (see ***Section 2.1***).

2.2.1 *Comparison of Accident Experience with QRA Methodology*

HSE commissioned this research by consultants (1) to examine whether the kind of events postulated in QRA studies reflected experience as recorded in accident reports. A survey of QRA methodologies was performed, and the results were compared with information on accidents obtained from three different databases. The 'top-down' approach (see ***Section 1.3.2***) to identifying the events to be included in the QRA was addressed.

It was found that, although the 'top-down' approach generates an extensive list of events (essentially leaks of different sizes from different items of equipment), it may neglect other, more complex failures of the kind that were observed in the accident record. Such complex failures tend to involve a combination of factors such as human errors, abnormal conditions and equipment failures that combine to result in an accident. The research report observed that this is more likely to be an issue when conducting a risk analysis of a complicated plant, where there is greater scope for more complex failures to occur.

The report recommended that, depending on the complexity of the plant being studied and the scope of the analysis, the 'top-down' approach should be supplemented by other hazard identification methods in order to generate a more comprehensive list of events.

At present HSE tends to apply QRA to relatively simple installations (mainly bulk storage of toxic or flammable materials), where there is relatively little potential for events to be missed when using a 'top down' approach. If in the future, HSE should seek to apply QRA to more complex installations (such as a processing unit on a petrochemicals plant), then there might be a need to consider supplementing the 'top-down' approach with other hazard identification methods.

Currently complex facilities like petrochemicals plants or oil refineries are dealt with using protection-based assessments or a hybrid approach using a mixture of protection-based assessments of some parts of the site and risk analysis of specific processing units. In these cases, risk analysis is typically applied to the units handling toxic materials (such as hydrogen fluoride or chlorine).

2.2.2 *Review of Accidents at Major Hazard Sites in the UK*

As part of the European legislative requirements covering major hazard sites, HSE is required to supply details of accidents at such sites to the European Union (EU) Major Accident Hazards Bureau (MAHB) based at Ispra, Italy. The MAHB then records this information in the Major Accident Recording System (MARS). MARS was one of the databases used in the research project

(1) HSE (2000). *A comparison of accident experience with Quantitative Risk Assessment (QRA) methodology*. HSE Books, Contract Research Report 293/2000.

described in ***Section 2.2.1***. A further examination of the MARS data was undertaken for the purposes of this study. All 87 of the UK submissions to the EU since it was first established were obtained. The earliest record was dated October 1985 and the latest May 2003.

Each record was scrutinised in order to determine the type of accident that had occurred and a judgement made as to whether the event fell into one of four categories:

- Category 1: Accidents with an off-site effect or the potential for an off-site effect that would have been identified using HSE's 'top-down' approach in a risk analysis, or that were similar to or less onerous than the events considered in a protection-based assessment of such facilities;

- Category 2: Accidents that would not have been identified because according to the study definition, they would not be 'within scope' (i.e. – either they did not possess the potential to cause harm to people off-site, or they did not involve dangerous substances, or they resulted from terrorist activity);

- Category 3: Accidents with an off-site effect or the potential for an off-site effect that would not have been identified; and,

- Category 4: Accidents where it was not clear how the assessment for the site would have been performed by HSE, either because the approach used depends on site-specific details, or because the methodology is still under development.

The results are summarised in ***Table 2.1***.

Table 2.1 ***Summary of Categorisation of Accidents Reported to the EU***

Category	**Number of Accidents in Category**
1	67
2	7
3	4
4	9
TOTAL	87

Note: See text above for Category definitions

A brief summary of each accident, the effect of the accident, the type of accident (fire, explosion, release etc.) and the category to which it was assigned are shown in ***Annex A***.

Hence, from ***Table 2.1***, it can be seen that only a small proportion of accidents (four out of 87) would either have been omitted from the 'top-down' hazard identification in a risk analysis, or would not have been encompassed by the event(s) considered within a protection-based assessment. This tends to support the findings of the work on the comparison of QRA methods with accident experience as described in ***Section 2.2.1***.

The events that would not have been covered were (see also ***Annex A***):

- two instances of releases of chlorine from vents during transfers from a road tanker;
- addition of water to a sulphur trioxide vessel that was mistakenly believed to be empty, resulting in a chemical reaction and a release of toxic mist; and,
- a chemical reaction in a tank container with a subsequent release of dangerous substances.

The two accidents involving chlorine appeared to be of a similar scale to some of the smaller releases that are covered within HSE's risk analysis approach for such sites. Furthermore, the fact that two such incidents have occurred in the last 15 years suggests that the frequency of events of this type may be significant in comparison with events that are already included within a risk analysis. Therefore it is recommended that HSE consider whether unintended releases from vents should be included in risk analyses for bulk chlorine storage installations and other installations handling bulk pressurised liquefied gases.

In the case of sites storing or using water reactive materials (such as sulphur trioxide) it is recommended that HSE consider whether the risk analysis should include scenarios where water is inadvertently added to the dangerous substance (for example, where water may be used for cleaning of tanks or equipment).

Inclusion of all events involving an unwanted chemical reaction is probably impracticable, particularly for those sites (such as fine chemicals, speciality chemicals and pharmaceuticals) where a large number and variety of different chemicals are handled. It is recommended that the significance of this type of hazard is investigated further and that, if necessary, an efficient way of including it within a risk analysis is developed.

2.2.3 *ASSURANCE Project Findings*

The study found that the participants used several different techniques for identifying hazards. Some participants used a combination of complementary approaches. The participants used broadly similar techniques (known as risk ranking) to whittle down the initial list of events produced by the hazard identification exercise and to select those that should be included in the subsequent steps of the risk analysis.

The overall finding was that the events selected by the participants differed substantially in terms of the details, but that there was good agreement as to which events were considered the most important. Hence it appears that, with regard to the most important events at least, HSE's approach is comparable to those used by other practitioners.

2.2.4 ***Conclusions – Hazard Identification***

The review of research comparing QRA approaches with accident experience as reported in this Section indicates that the approach used by HSE is generally adequate for the relatively simple installations for which HSE currently performs QRAs.

Comparison with accident experience at UK COMAH establishments (1) shows that the majority of incidents detailed in the accident records would have either been identified in a QRA, or would have been similar to or less onerous in magnitude than the event(s) considered in a protection-based analysis. However, there are a four recommendations arising out of this part of the review. The recommendations are:

1. that HSE consider supplementing the 'top down' (see ***Section 1.3.2***) approach to the identification of hazards with other methods, if in the future HSE seeks to apply QRA to types of plants more complex than those currently analysed using QRA;
2. that HSE considers whether events resulting in unintended releases from vents (such as vessel overfill during transfers from road tankers) should be included in risk analyses for sites storing chlorine or other pressurised liquefied gases;
3. that in the case of sites storing or using water reactive materials (such as sulphur trioxide), HSE considers whether the risk analysis should include scenarios where water is inadvertently added to the dangerous substance (for example, where water may be used for cleaning of tanks or equipment); and,
4. that HSE performs further investigations into the significance of hazards arising from undesired chemical reactions and, if necessary, develops a means of including such hazards in a risk analysis.

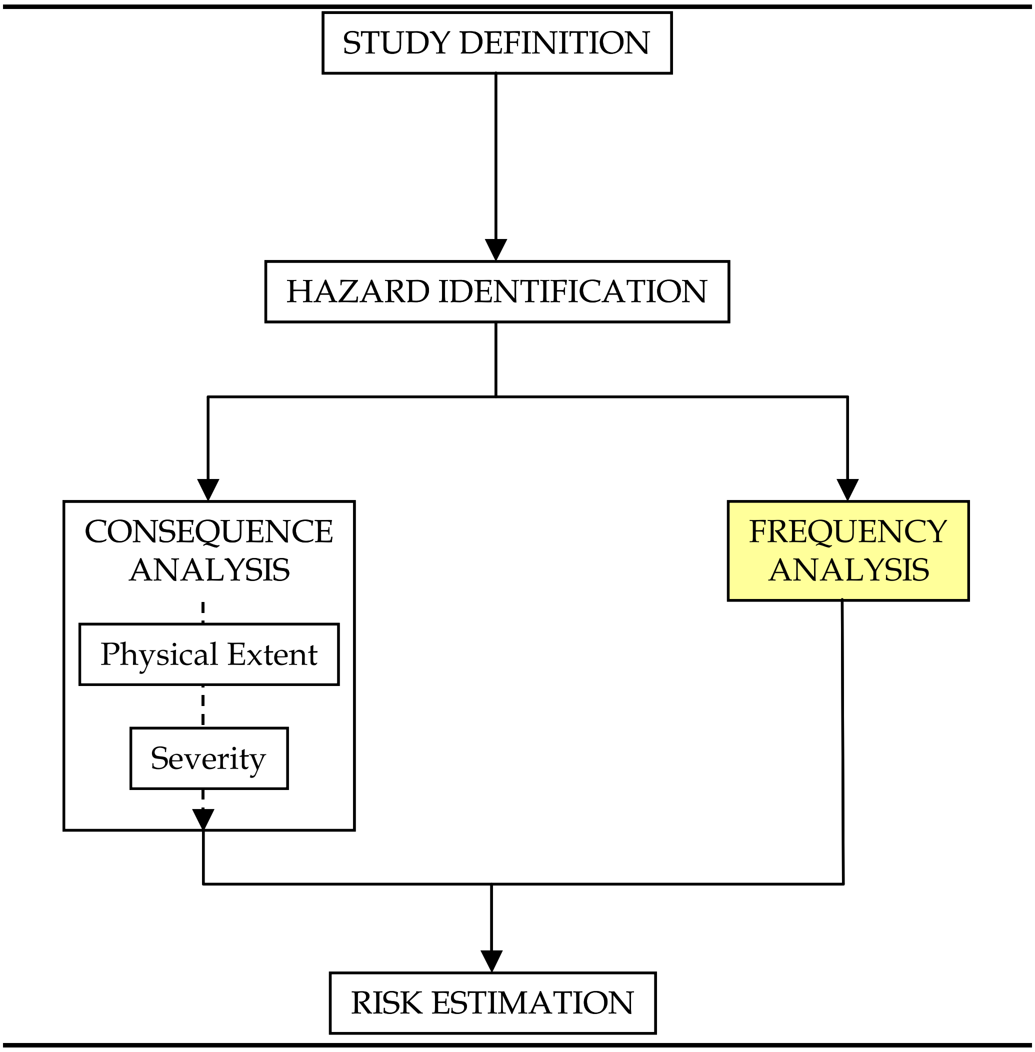
(1) Establishments covered by the Control of Major Accident Hazards Regulations 1999 (COMAH).

The findings of the ASSURANCE Project show that the results obtained using HSE's approach were comparable with those of the other participants, particularly with regard to the most significant events.

2.3 FREQUENCY ANALYSIS

The risk analysis step considered in this Section is highlighted in ***Figure 2.2***.

Figure 2.2 ***Risk Analysis Process - Frequency Analysis***



The review of HSE's approach to frequency analysis has comprised:

- estimation of the historical frequency of accidents at MHIs and comparison with risk analysis predictions;
- a consideration of the results of an independent review, by external consultants, of the frequency data used by HSE in risk analysis; and,
- a consideration of the findings of the ASSURANCE project.

The results are discussed below.

2.3.1 *Comparison with Historical Accident Frequencies*

One approach to checking HSE's risk analysis predictions might be to compare the historical frequency of major accidents with the frequency predicted by QRA studies. In order to conduct such a comparison exercise it would be necessary to determine:

1. how many major accidents have occurred at MHIs over a given period of time (e.g. – the last ten years);
2. how many MHIs there were in operation over the same period; and,
3. the predicted frequency of major accidents at all of the MHIs in operation over this period (e.g. – from QRA studies).

However, in practice such comparisons are difficult to perform. One problem is that not all events recorded as major accidents occur at MHIs. One major accident database, MHIDAS (Major Hazard Incident Data Service) contains information on a large number of major accidents, but in a number of cases it is difficult to determine, from the information in the database, whether the event occurred at a MHI or not. This is because the criterion for deciding whether or not a given incident should be recorded within MHIDAS is the substance that was involved (i.e., whether it is considered a dangerous substance or not), rather than where the accident occurred.

The MARS database (refer to ***Section 2.2.2***) deals solely with accidents at MHIs. Use of MARS data would therefore avoid some of the problems that would be encountered when using data from MHIDAS. Over the period 1985 – 2000, the UK reported 80 accidents via the MARS system. With an estimated 1200 MHI sites in the UK, this equates to a frequency of accidents of around 4 per 1000 site years (or, for a given site, the historical frequency of accidents is around 1 every 230 years). It should be noted that the estimated number of MHI sites in the UK is subject to a degree of uncertainty and therefore the frequencies quoted cannot be considered to be precise values.

However, it should be noted that EU member states are required to report accidents for recording in MARS regardless of whether people are harmed or the environment damaged. The accident frequency calculated therefore relates to the frequency of reported releases rather than the frequency of major accidents.

Furthermore, not all of the accidents recorded in MARS had the potential to cause harm to people off-site and are therefore not relevant to LUP considerations. Removing 6 of the 80 accidents that were not considered relevant to LUP considerations reduces the frequency of accidents to around 1 in every 240 years.

The population of MHIs in the UK is made up of a variety of sites of different types (warehouses, water treatment works, LPG cylinder filling plants, oil refineries, etc.), in different numbers. The accident frequency figure obtained from the MARS data should therefore be regarded as an average frequency across all of the different types of site. It would be expected that some MHIs would have an accident frequency higher than the average, and that others would have an accident frequency lower than the average. Furthermore, HSE has only completed QRAs for a proportion of MHIs in the UK. Many sites have been subjected to protection-based analysis rather than QRA. Hence, it is only possible to compare the predicted frequency for a number of MHIs for which QRA has been performed against the average from the MARS data.

In addition, for some dangerous substances, the release quantities modelled in a QRA for certain small events would be too low to qualify for inclusion in MARS. For chlorine, for example, if a release causes no damage or harm to the people or the environment, then the amount released would have to be at least ½ tonne to qualify for reporting to MARS. However, some of the smaller, short duration events modelled in a QRA (such as pinhole leaks from pipes that are quickly shut off) only involve a few tens of kilograms of material.

Bearing these factors in mind, it is possible to compare the frequency estimate derived from MARS with the total frequency of all releases predicted by QRAs for a range of sites. The results are summarised in ***Table 2.2***. It should be noted that ***Table 2.2*** only covers those sites for which QRA frequency data were readily available; it does not cover every type of site that is covered by MARS.

Table 2.2 Total Release Frequencies as Predicted by HSE LUP QRAs

Installation	**Total Release Frequency for the Site**
Warehouses (fires involving dangerous substances)	Between 1 in 40 and 1 in 1000 years
Ammonia storage (ASSURANCE, HSE team)	1 in 600 years
Chlorine water treatment works (bulk storage) (Note 1)	1 in 2000 years
Large chlorine plant (Note 1)	1 in 600 years
Chlorine water treatment works (drum storage) (Note 1)	1 in 1300 years
Refinery alkylation unit (hydrogen fluoride) (Note 2)	1 in 1500 years
LPG processing plant (Note 3)	1 in 1200 years
LPG distribution depot (Note 3)	1 in 50 years
Bromine container storage (Note 1)	1 in 900 years
Phosgene generation unit (Note 2)	1 in 16,000 years

Notes

1. Excludes release events that would have been too small to report to MARS.
2. All release events would have been large enough to report to MARS.
3. Only includes releases that ignite.

HSE provided estimates of the number of each of the types of site listed in ***Table 2.2***. Data on the numbers of sites are shown in ***Table 2.3***.

Table 2.3 Estimated Number of Sites of Different Types

Installation Type	Estimated Maximum Number	Estimated Minimum Number
Warehouses (storing dangerous substances)	61	54
Ammonia storage (refrigerated)	18	18
Chlorine water treatment works (bulk storage)	30	30
Large chlorine plant	10	5
Chlorine water treatment works (drum storage)	26	26
Refinery alkylation unit (hydrogen fluoride)	7	7
LPG processing plant	29	29
LPG distribution depot	42	42
Bromine container storage	9	9
Phosgene generation unit	4	4

Note: Numbers are for COMAH establishments only, in order to be comparable with MARS data.

These figures were used in conjunction with the frequencies in ***Table 2.2*** to calculate a predicted average frequency per site. The predicted average frequency is in the range 1 in 95 to 1 in 220 years per site (compared with the value obtained from the MARS data of 1 in 240 years per site). Hence the predicted values are somewhat higher than the historical value at the upper end of the range and very close to the historical value at the lower end of the range. Bearing in mind the limited nature of the calculations (not all of the types of site covered by MARS were addressed), the exercise is considered to show reasonably good agreement between the historical and predicted values.

2.3.2 Independent Review of HSE's Frequency Data

As described in ***Section 1.1.3***, the historical frequency data used by HSE are stored in a database known as FRED. It should be noted that these data are very different from the kind of information that is stored in accident databases such as MARS or MHIDAS. FRED contains historical data on the frequency of failure of different kinds of equipment.

An independent peer review of the contents of FRED was undertaken by external consultants in July 2001 (1). The scope of the work included a check of the data in FRED (and other HSE documents which were proposing some additions to FRED) against various sources in the technical literature to ensure that the release frequencies used were valid. A second task was to compare the contents of FRED with proprietary data sources held by the consultant.

The check of that data in FRED concluded that, in general, the data are of good quality and are a reasonable representation of release frequencies for the types of equipment considered. However, the consultants did raise some comments on the data relating to certain items. As a result HSE undertook to make a number of corrections and clarify some of the supporting text in the subsequent version of FRED. It is understood that this has now been completed.

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(1) AEA Technology (2001). *Review of Failure Rate and Event Data (FRED) for use in Risk Assessment.* AEA/RSMS/RD02032001/01/Issue 1.

The comparison of FRED's data with the consultant's data proved problematic. In many cases the consultant's data consisted of records of zero failures in a known period of operation. Calculating failure frequencies from such data is subject to large uncertainties. In addition, as a result of differences in the way the data were recorded, it was difficult to be sure that 'like with like' comparisons were being made. In general the consultant's release frequency for a given item tended to be higher than HSE's. However, this difference was considered to be at least partly due to the way the consultant's 'zero failures' data had been processed to allow a direct comparison with HSE's data.

2.3.3 ASSURANCE Project Findings

Background information on the ASSURANCE Project is given in ***Section 2.1***.

The project report observed that there was some variation in the approaches to frequency analysis used by the different teams of analysts:

- two teams (one of which was HSE) only used historical data;
- four teams supplemented the use of historical data with the application of analytical / simulation techniques for certain events; and,
- one team did not produce numerical estimates of frequencies at all but used a different approach entirely, involving a determination of how many safeguards would have to fail for the event to occur.

The different approaches taken to the frequency analysis step tended to reflect the different approaches taken at the hazard identification step. That is, teams that had used a detailed approach to event identification tended to use the more detailed approaches to frequency analysis.

With regard to the frequency values generated by the participants, it was found that, although there was reasonable agreement about which events were the most frequent, and good agreement about which events were the least frequent, the actual frequency estimates for any given event varied significantly.

For some events agreement between the different teams was poor, with the highest value of the event frequency provided by any team being 10,000 times greater than the lowest value. In this case HSE's estimate was towards the upper end of the range, but was not the highest. For the events where the best agreement was obtained, the highest value of the event frequency provided by any team was ten times greater than the lowest value. In this case HSE's value was the highest.

Further investigation revealed that one of the main causes of the differences observed was the different assumptions that had been made by the various teams concerning site-specific details. For example, for one event involving failure of a pipe, estimates of the length of the pipe varied between 5 m and 1500 m (HSE's estimate being at the upper end of this range). Since the failure frequency of pipe is directly related to the length of pipe that is present, this had a marked effect on the predicted frequency for this scenario. Having identified this problem, a case study was conducted to try and eliminate some of the variation due to the assumptions used. The teams re-calculated the frequencies of a set of events using the same assumptions. In most cases this resulted in much better agreement between the teams. For the revised frequencies, for the events where the worst agreement was obtained, the highest value of the event frequency provided by any team was around 100 times greater than the lowest value.

The frequency values generated by HSE were lowest for two events, joint lowest for two others, joint highest for 1 event and somewhere in the middle of the range for the rest.

2.3.4 Conclusions – Frequency Analysis

A comparison of the predicted frequency of accidents at a range of sites with the historical accident frequency obtained from the MARS data shows reasonable agreement, considering the limited nature of the calculations performed.

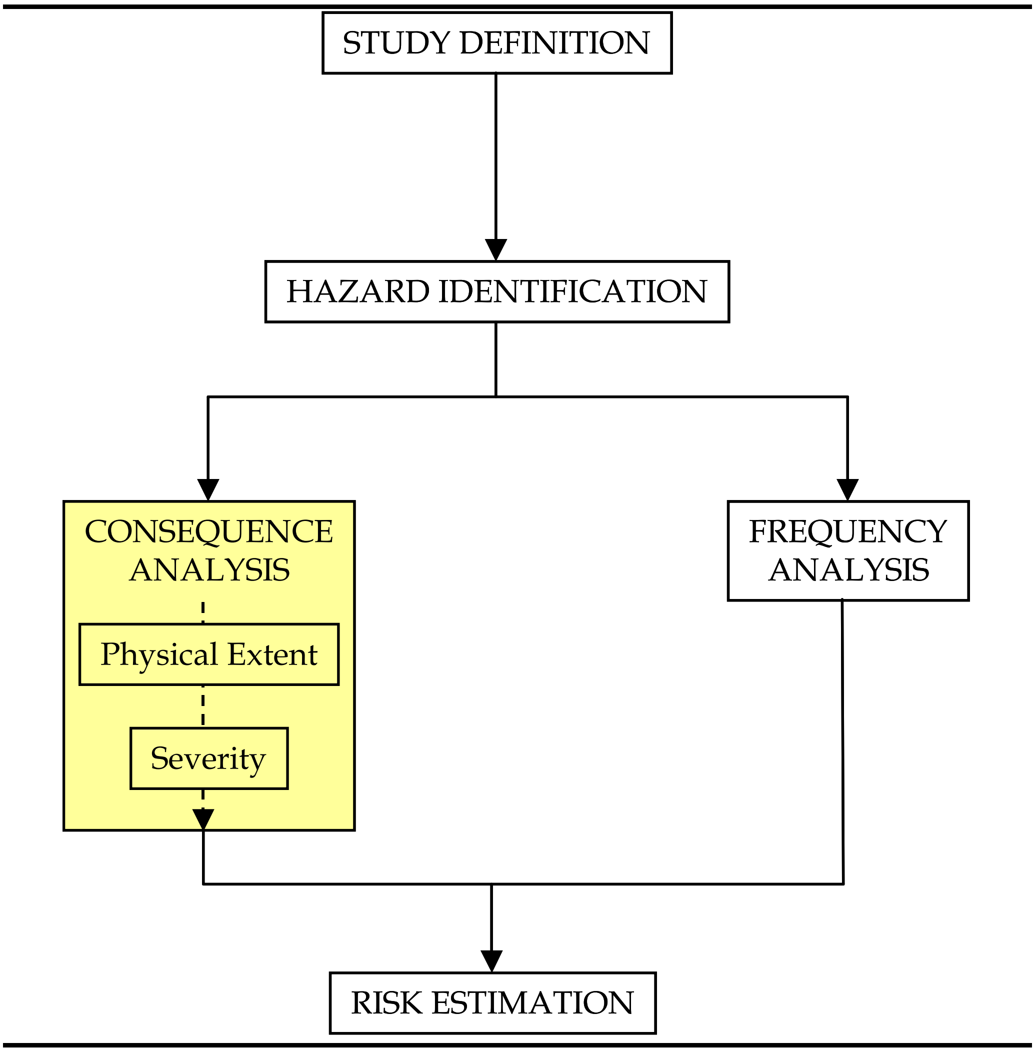
An independent peer review of HSE's failure frequency data determined that the data were generally of good quality and were a reasonable representation of the failure frequencies of the types of equipment considered.

The frequency analysis aspects of the ASSURANCE Project indicated that overall the agreement between the various participants was poor, but was improved somewhat when all participants used the same set of assumptions. HSE's results were not consistently the highest (most conservative) nor consistently the lowest (least conservative).

2.4 CONSEQUENCE ANALYSIS

Figure 2.3 highlights the risk analysis step considered in this Section.

Figure 2.3 *Risk Analysis Process - Consequence Analysis*



The review of HSE's consequence analysis methods has included:

- a separate model evaluation exercise;
- a comparison of data gathered from accident reports with consequence analysis model results;
- consideration of the findings of the ASSURANCE project (see ***Section 2.1***); and,
- comparison of the toxic doses and thermal radiation intensities used by HSE with those used by other practitioners.

The studies undertaken and the findings are discussed below.

2.4.1 *Model and Methodology Evaluation Exercise*

As a separate task under the IFRLUP project, a review of the models and methodologies used by HSE has been undertaken. The purpose of the review was to:

- obtain a robust picture of the relative strengths and weaknesses of the methods and models;
- enable prioritisation of the methods and models for development; and,
- provide evidence based data to inform the debate with stakeholders on CD setting.

The main criteria used to assess the methods and models were as follows:

- fitness for current purpose;
- risk to HSE (i.e. – could the method / model be defended when subject to external scrutiny); and,
- wider influences (e.g. - developments within the EU and among commercially available packages).

Consideration was also given to:

- extent of use (i.e. – how often is the tool used?);
- likelihood of success (i.e. – can the tool be improved and, if so, what would be required?); and,
- sensitivity to site-specific details (i.e. – information gathered at a one-off site visit).

The outcome of this evaluation exercise is to be reported separately (1).

2.4.2 *Comparison with Accident Data*

Across the world there have been a number of major accidents in the last twenty to thirty years. These accidents are the type of events modelled in QRA studies. However, comparison of what happened in these accidents with the outputs of consequence analysis models is often difficult. This is because, as mentioned in ***Section 1.1.4***, consequence analysis models require input data about the event that may not be available or known. For this reason, comparisons between accident data and model results can only be very broad.

A number of accidents have been chosen for the purposes of the comparison exercise:

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(1) Work not complete at the time of writing

- Bhopal, India, 1984 (1);
- Nantes, France, 1987 (2) ;
- Potchefstroom, South Africa, 1973 (3);
- Blair, Nebraska, 1970 (4);
- Chicago, USA, 1974 (5);
- Mexico City, 1984 (2);
- Pipeline Accidents, USA and Canada, 1965-1996 (6) (7);
- Flixborough, UK, 1974 (8); and,
- Toulouse, France, 2001 (9).

Bhopal, India, 1984

The disaster at Bhopal occurred in the early hours of 3rd December 1984. At the time The Union Carbide plant at Bhopal was storing approximately 41 tonnes of methyl isocyanate (a toxic and flammable substance that reacts readily with water). Of the original 41 tonnes of material, 25 tonnes were released into the atmosphere over a period of two hours. Some of the material had reacted with water, generating enough heat to vaporise the rest. The weather conditions (stable, with light winds) were amongst the worst possible for dispersion, meaning that the vapour did not disperse as readily as it might have otherwise. After about two hours the cloud reached the 10,000 people residing at the Railway Colony, about 2 km away. After only a few minutes exposure, 150 people were dead, 200 were paralysed, 600 were unconscious and 5000 were severely affected. It has been estimated that in total 170,000 people required hospital treatment and there were over 4,000 fatalities.

With the release and atmospheric conditions described, HSE's methods would predict that the cloud within which people outdoors would be exposed to levels of vapour above the HSE 'dangerous dose' would be over 10 km long and 850 m wide, encompassing an area of around 1,000 hectares. The cloud

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(1) Lees F P (2001). *Loss Prevention in the Process Industries*. 2nd Edition, reprinted with corrections. Cutterworth-Heinemann.

(2) Carter D and Hirst I L (2003). *Comparison with Accident Experience*. HSE internal discussion document.

(3) Lonsdale H (1975). *Ammonia Tank Failure - South Africa*. Ammonia Plant Safety **17**, 126-131.

(4) MacArthur J G (1972). *Ammonia Storage Tank Repair*. Ammonia Plant Safety **14**, 1-5.

(5) Hoyle W C (1982). *Bulk Terminals: Silicon Tetrachloride Incident*. In Bennett G F, Feates F S and WIlder I (1982). *Hazardous Materials Spills Handbook*. McGraw-Hill.

(6) Kinsman P and Lewis J (2000). *Report on a study of international pipeline accidents*. HSE Books CRR 294/2000.

(7) Kinsman P and Lewis J (2002). *Report on a second study of pipeline accidents using the Health and Safety Executive's risk assessment programs MISHAP and PIPERS*. HSE Books RR 036.

(8) Lees F P (2001). *Loss Prevention in the Process Industries. 2nd Edition*, reprinted with corrections. Cutterworth-Heinemann.

(9) Barthelemy F et al. (2001). *Accident on the 21st of September 2001 at a factory belonging to the Grande Paroisse Company in Toulouse*. Available in English translation at the HSE web site http://www.hse.gov.uk/spd/toulouse.pdf

for people indoors would be somewhat smaller, since most buildings provide protection against exposure to a toxic gas cloud.

The number of people exposed depends on the density of the population in the area affected by the cloud. For housing in the developing world, the population density can be up to a few hundred persons per hectare (compared to around 60 per hectare for typical UK housing). Combining a population density of this order with the cloud area of 1,000 hectares would give an estimate of the number exposed of around 200,000 people. This compares well with the reported number of 170,000 people requiring hospitalisation. Hence, in this case, HSE's model gives reasonably good agreement with accident experience, in terms of the numbers of casualties arising from the event.

A site in the UK holding 41 tonnes of methyl isocyanate would be allocated a consultation distance of around 3 km by HSE. The size of the inner and middle zones (see ***Section 1***) would depend on the specifics of how the site was designed and operated.

Nantes, France, 1987

Some dangerous substances can break down in a fire to generate toxic gases or vapours. Such materials include certain synthetic fertilisers. It was this kind of substance which was involved in the fire at a warehouse in Nantes, France, on 21st January 1987. At the time the warehouse held 1,450 tonnes of 'NPK' (nitrogen, phosphate and potassium) fertiliser and around 750 tonnes of ammonium nitrate fertilisers. About 100 tonnes of fertiliser were consumed in the fire.

The smoke and toxic gases (nitrogen oxides) generated in the accident formed a visible plume that was reported as measuring 250 m high, 5 km wide and 15 km in length. Approximately 25,000 people were evacuated and 29 injured. However, there is no further information on where the injured people were at the time of the accident, nor the nature of their injuries (e.g. - burns from the fire or the effects of inhaling toxic gases).

HSE models of fires in fertiliser stores do not estimate the extent of the visible plume, hence a detailed comparison with the observations made during the accident is not possible. However, HSE's models do show toxic plumes from such events extending several kilometres in length, which is broadly in agreement with the observations above.

The 'NPK' fertiliser involved in the Nantes incident would not be considered a dangerous substance under Consent legislation. HSE consultation distances around ammonium nitrate stores in the UK are typically in the region of 500 – 1,000 m.

Potchefstroom, South Africa, 1973

Ammonia is a toxic substance that can also burn in the right circumstances. It is a gas under normal conditions but, like chlorine, it is often stored as a liquid under pressure. The fertiliser plant at Potchefstroom, South Africa, stored ammonia in this way, in four 50 tonne vessels. On the afternoon of 13th July 1973 one of these vessels failed suddenly, releasing an estimated 38 tonnes of material. The ammonia vaporised rapidly and the resulting gas cloud was carried by a light breeze towards a nearby township. The visible portion of the cloud was estimated as extending 450 m from the vessel and was about 300 m wide. A total of 18 people were killed and 65 required medical treatment.

Analysis of the consequences of the accident using HSE's models predicts a range to 50% fatalities outdoors of around 470 m, with a range to 1% fatalities outdoors of approximately 600 m. The models also predict that neither the 1% fatality nor 50% fatality levels would be reached for people indoors. These findings compare reasonably well with the details of the accident, where those who died were either outdoors at the time or were inside a building but moved outside in an attempt to escape. Personnel located in buildings during the accident, or who escaped into buildings, survived.

Blair, Nebraska, 1970

In addition to being stored as a liquid under pressure, ammonia can also be stored as a liquid by refrigerating it to a temperature just below its normal boiling point of –33.4°C. The Gulf facility at Blair, Nebraska stored refrigerated liquid ammonia in a single tank with a design capacity of 35,000 tons. The accident occurred on November 16th 1970, when the tank was taking delivery of ammonia from several barges and was overfilled. As a result ammonia spilled from the tank overflow and generated a sizeable gas cloud. It was estimated that the cloud extended, at times, to over 2,700 m from the tank and covered an area of up to 360 hectares. Fortunately, although some livestock were killed, there were no human fatalities or injuries.

Using HSE's tools to predict the pool formation, boiling and gas dispersion gives a range to 1% fatalities outdoors of 1130 m (using the peak rate of generation of vapour from the pool). This is somewhat less than the maximum visible cloud observed. One explanation for the difference may be that, on arrival, the local emergency services directed a stream of water on to the relief valve from which the ammonia was being released. Although this may have washed out some of the ammonia vapour from the atmosphere or dissolved some of the ammonia as it was released, it may also have had the effect of increasing the evaporation rate of the remaining ammonia liquid. It is not possible to model this kind of effect with the tools currently available.

Chicago, Illinois, 1974

Silicon tetrachloride is a liquid that reacts readily with water (even water that is only present as vapour in air) to give toxic fumes of hydrogen chloride. It was stored in a 3,300 m^3 storage tank at the Bulk Terminals installation at Calumet Harbor, Chicago. On April 26th 1974 a release of silicon tetrachloride

occurred, originating from the piping associated with the storage tank. As the liquid came into contact with moisture on the ground and in the air, it generated hydrogen chloride vapours, forming a cloud that measured from 8 km to 16 km long at times. About 2 ½ hours after the start of the event, the cloud measured about 400m wide, 300 m to 450 m high and around 1600 m in length. Approximately 16,000 people were evacuated and it was over a week before the incident was brought fully under control.
HSE's models were used to estimate the cloud dimensions at the point 2 ½ hours into the incident. As mentioned previously, HSE's models do not predict the extent of the visible cloud, but at a range of 1600 m, the models predict a concentration of hydrogen chloride (the product of silicon tetrachloride's reaction with the air) of around 10 parts per million. The range to 1% fatalities outdoors at ground level was estimated to be approximately 150 m. This would lead to a prediction of a small number of injuries or fatalities as a result of the event, which is reasonably consistent with the observations made during the accident, particularly when it is considered that no fatalities resulted.

Mexico City, 1984

Just as it is possible to liquefy some toxic gases by applying pressure to them (like chlorine and ammonia, as described above), it is also common practice to store some flammable substances in a similar way. One such material is Liquefied Petroleum Gas (LPG), the same material that is found in 'camping gas' cylinders.

The PEMEX LPG distribution plant in Mexico City received LPG by pipeline and stored it in six large spherical vessels and forty-eight smaller cylindrical vessels. The disaster that occurred on 19th November 1984 began as a leak from the incoming pipeline. This leak generated a large cloud of flammable gas, which was subsequently ignited when it came into contact with a flare at the facility. The resulting fire was fed by the contents of the pipeline and ultimately led to the almost total destruction of the plant. Many of the storage vessels exploded (by a mechanism known as a Boiling Liquid Expanding Vapour Explosion, or BLEVE). Fragments of the sphere vessels were projected more than 800 m, and one cylindrical tank flew some 1200 m into a nearby housing area. Damage and casualties resulting from the large, intense fires (fireballs) produced by the exploding vessels were severe.

When the plant was being built the distance to the nearest housing was around 300 m. However, demand for housing generated by large numbers of people migrating to the area resulted in housing encroaching to within 130 m from the site at the closest point. It has been estimated that each dwelling in this settlement contained at least five people. The residential area was heavily damaged out to a distance of 300 m. About 650 people were killed, 1,000 were reported missing, 4,250 were injured and 60,000 were evacuated. Around 10,000 people were made homeless.

For a fireball following explosion (BLEVE) of a vessel equal in size to the largest sphere at Mexico City, HSE's model predicts that all people caught within about 300 m of the vessel would be killed. At about 500 m, it is predicted that about half of the people exposed would be killed. Fatalities among people outdoors would be expected out to a range of around 850 m. The total predicted number of fatalities is around 1,000 for such an event (based on the limited population data available), which is in reasonable agreement with the number of fatalities recorded.

The HSE consultation distance for such an installation in the UK would be set at about 850 m. The inner zone and middle zone boundaries would be at around 500 m and 650 m respectively.

Pipeline Accidents

Major hazard pipelines can carry a range of different dangerous substances, including high-pressure natural gas, pressurised liquefied gases like LPG (see Mexico City, above) and substances that are liquid under normal conditions, like crude oil.

If the pipeline fails, then different kinds of fires can result (including fireballs, jet fires, crater fires etc.), depending on the properties of the material in the pipeline, the mode of failure, when the escaping material is ignited (if it is ignited) and the nature of the surroundings.

HSE possesses two pipeline risk models – MISHAP and PIPERS. MISHAP is used by HSE for generating LUP zones around high-pressure natural gas pipelines. There are around 20,000 km of such pipelines in the UK.

The PIPERS model is still under development and is not used for land-use planning assessments, but is currently capable of analysing risks from pipelines carrying other kinds of materials (liquids and pressurised liquefied gases) in addition to high-pressure natural gas. PIPERS contains some of the same consequence analysis models as MISHAP, but has additional models that are capable of analysing other fire phenomena.

The studies comparing accident data with HSE's pipeline consequence analysis models were undertaken by external consultants. The work was performed in two phases.

The first phase, completed in 2000 (1), compared the consequence analysis model predictions obtained from the then current versions of MISHAP (MISHAP98) and PIPERS with data on nine different accidents involving high-pressure natural gas pipelines. The results indicated that one of the models common to both MISHAP98 and PIPERS, the fireball model, tended to over-estimate the effects of fireball events somewhat in most cases (in terms of

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(1) Kinsman P and Lewis J (2000). *Report on a study of international pipeline accidents*. HSE Books CRR 294/2000.

the predicted burn area). However, another of the models common to both tools, the jet fire model, tended to under-predict the effects of jet fire events.

At the completion of the first phase, it was recommended that the jet fire model be improved. In order to assist with this goal, it was also recommended that data on a larger number of pipeline accidents be examined.

The second phase (1) was conducted with these recommendations in mind. This work considered information on 17 accidents involving high-pressure natural gas, 10 accidents involving 'conventional' liquids (i.e. – not pressurised liquefied gases) and 13 accidents associated with pressurised liquefied gas pipelines.

In line with the recommendation of the first phase, MISHAP98 was modified to include a different jet fire model, the new version being designated MISHAP01. It was found that the new jet fire model gave much closer agreement with the available accident data on high-pressure natural gas pipeline failures than the previous model, in the majority of cases (60%). It was also found that the new model could be adapted to simulate some of the more unusual fire phenomena observed (accounting for another 20% of cases). In an important minority (around 20%) of cases the type of fire produced was not adequately modelled and development of a new model specifically for this kind of event was recommended. The conservative nature of the fireball model was confirmed.

The comparison of PIPERS predictions with information on releases from 'conventional' liquid pipelines indicated a number of shortcomings that, it was recommended, would need to be addressed as the model was developed. These included:

- a failure to take account of the real behaviour of liquids when they are released – such releases are strongly affected by the lie of the surrounding land;
- a failure to take account of the possibility of explosions and some types of fire event (flash fires); and,
- a failure to take account of events where the liquid is released in the form of a spray.

In the case of pipelines carrying pressurised liquefied gases, the most serious shortcoming identified in PIPERS was the lack of an explosion model. In two of the accidents involving this type of material, explosions were the main cause of damage and casualties.

HSE's pipeline risk assessment methods are to be considered in more detail in the model evaluation exercise described in ***Section 2.4.1***.

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(1) Kinsman P and Lewis J (2002). *Report on a second study of pipeline accidents using the Health and Safety Executive's risk assessment programs MISHAP and PIPERS.* HSE Books RR 036.

Flixborough, UK, 1974

The Flixborough accident happened on 1st June 1974. A temporary by-pass pipe ruptured, releasing a large quantity of the flammable substance cyclohexane. This formed a large cloud, which subsequently ignited, giving an explosion. The explosion caused extensive damage to the site and started numerous fires. A total of 28 people were killed, 108 were seriously injured and 1,500 houses were damaged, with broken windows reported up to 3 km away.

To analyse this kind of event HSE uses the 'Multi-Energy Model' (MEM). The creators of the model gave a comparison of MEM's predictions with the records of the damage caused by the Flixborough explosion when it was first published (1). They obtained good agreement with the data available. However, this was on the basis of changing the model inputs until good agreement was obtained, rather than working from first principles.

Staff at HSE's Health and Safety Laboratory (HSL) performed further studies (2) comparing MEM with the Flixborough explosion, attempting to work from first principles. On the basis of some realistic assumptions about the size of the cloud involved in the explosion (obtained from drawings of the site where the explosion is known to have occurred) and the initial strength of the blast, reasonable agreement with the historical data was obtained.

In summary, HSE's model would predict an overpressure sufficient to demolish a typical building at 125 m, and to cause lesser structural damage out to 500 m and beyond. HSE consultation zones would be set at 125m, 315 m and 540 m.

Toulouse, France, 2001

In addition to generating toxic fumes in the event of being involved in a fire (see the description of the Nantes incident, above), ammonium nitrate can also explode under certain conditions. An event of this type occurred at the AZF Plant in Toulouse on 21st September 2001.

The explosion happened in a warehouse holding (it is thought) approximately 300 tonnes of ammonium nitrate fertiliser. The origin of the fertiliser is not totally clear, much was reject from the production process but it also included other material, most likely this material had been returned from customers and/or had an experimental coating. The explosion left a crater 50 m in diameter and 7.5 m deep. It resulted in severe damage to buildings within 1 km and minor damage to buildings out to 3 km. Approximately 11,000 dwellings were severely damaged and 50,000 were left without windows. Three hospitals, more than 60 schools, a university campus and a football

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(1) van den Berg, A C (1985). *The Multi Energy Method a Framework for Vapour Cloud Explosion Blast Prediction*. Journal of Hazardous Materials 12 (1985) 1-10.

(2) Thyer A M (1997). *Updates to VCE Modelling for Flammable RISKAT: Part 2, Comparison of VCE Models with the Flixborough VCE*. HSL Report RAS/97/09.

stadium were declared unusable. A total of 31 people died and up to 4,500 were injured.

HSE's model for an explosion involving ammonium nitrate predicts serious damage to typical buildings out to a distance of 600 m. HSE consultation distances for such installations in the UK are in the range 500 m to 1,000 m.

Overpressure contours calculated from damage observations showed reasonable agreement with HSE's predictions for a 300 te stack of ammonium nitrate. It should also be noted that HSE's model for such assessment is risk-based and predicts that explosions of uncontaminated ammonium nitrate occur with a relatively low frequency, the risks being dominated by the toxic effects from nitrogen oxides produced by the decomposition of the material.

2.4.3 ASSURANCE Project Findings

Background information on the ASSURANCE Project is given in ***Section 2.1***.

One of the activities undertaken during the project was to compare the consequence analysis results obtained by each team for a set of 11 accident events. Each event involved a release of ammonia of some kind (pipe ruptures, vessel failures, etc.). The teams were asked to predict the distance to a given concentration of ammonia (6200 parts per million, ppm) for each event. Some of these release events were instantaneous, whereas others were continuous.

An instantaneous release, as the name suggests, involves suddenly releasing all of the hazardous material present in a piece of equipment. A continuous release involves release of the material over a relatively long period (several minutes or more). To use a simple example, a bursting car tyre would release the air it contained instantaneously. A punctured, leaking car tyre would release the air it contained continuously, for a few minutes or more.

The 11 events were modelled in two different weather conditions – neutral (so-called 'D5') and stable ('F2') (1). Neutral weather conditions would correspond to an overcast sky with moderate wind. Stable weather conditions correspond to a clear sky with very little wind and are usually only observed at night.

There were significant variations in the distances predicted by the teams. For the event where the worst agreement was observed, the smallest distance predicted was 185 m and the largest 3,100 m. For the events where the best agreement was achieved, the largest distance predicted by any team was around 2-3 times higher than the lowest.

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(1) Weather conditions are often described in terms of a stability category (A to G) combined with a wind speed in metres per second.

In general, it was found that HSE's prediction of the concentration of ammonia at a given distance from the source tended to be:

- in the upper half of the range of predictions for continuous releases in neutral (D5) weather conditions;
- in the lower half of the range of predictions for instantaneous releases in neutral (D5) weather conditions; and,
- in the lower half of the range of predictions at distances closer to the point of release, and in the upper half of the range at distances further from the release point, for both instantaneous and continuous releases in stable (F2) weather.

It should be noted that the observations only relate to the dispersion of ammonia.

Hence, for the substance and events modelled, HSE's consequence analysis results were neither consistently the most conservative (i.e. – HSE did not consistently predict greater distances than all of the other participants) nor consistently the least conservative (i.e. – HSE did not consistently predicted smaller distances than all of the other participants).

It was found that the extent of variation in the results was related to how well the event was understood by all participants, in scientific terms. That is, for some of the events the behaviour of the release is known to be very complex (e.g., the behaviour of liquid ammonia when spilt on to the sea), but the models available do not cater adequately for this complexity. Furthermore, there is little experimental data relating to such events that would allow the development and validation of new models. The variation in the predictions made by the teams was greatest for these events.

Other factors that were thought to have contributed to the variations observed included:

- differences in assumptions or modelling approaches;
- differences in estimates of the rate at which the dangerous substance was released to atmosphere (due to differences in assumptions); and,
- differences in modelling techniques.

2.4.4 *Comparison of Toxic Doses and Thermal Radiation Intensities*

The toxic dose or thermal radiation intensity (flux) used as the cut-off for the consequence analysis (the harm criterion) can have a very significant effect on the level of risk predicted at a given location.

For example, assume that the harm criterion of interest was 1% fatality, and that for the toxic gas of interest there were two different values of the dose and gas concentration (A and B) that could cause 1% fatality available in the literature. Furthermore, assume that concentration A is greater than concentration B. If two QRAs were performed, one using end-point A and the other using end-point B, the risk contours obtained using A would be smaller than those obtained using B.

In HSE's QRAs the dangerous dose is currently used as the harm criterion, as described in ***Section 1.1.4***. The dangerous dose corresponds roughly to a level of 1% fatality in a typical (1), exposed population. HSE arrives at the dangerous dose value for a given substance using a procedure that has been published in the technical literature (2). In simple terms this involves a review of the toxicological information for the substance. Only data sets that have been produced using a scientifically rigorous approach are considered further. The derivation of a dangerous dose value is based on the data for the most sensitive animal species and strain that has been tested.

Concentrations and doses giving rise to 1% fatality can also be derived using so-called 'probit' equations. A probit equation enables the user to estimate the likelihood of fatality as a function of substance, exposure duration and substance concentration. A wide range of such equations is available in the technical literature as listed in ***Table 2.4***. Such equations are used routinely for QRA studies in other EU countries (such as The Netherlands).

However, HSE has serious objections to many of the probit equations found in the literature (although not to probit analysis as such). The objections principally relate to the way in which some workers, when deriving probit equations, have 'pooled' experimental data from a variety of sources. Commonly the experiments in the 'pooled' set were performed in different laboratories, under different conditions and upon different animal species and strains. Such an approach is considered by HSE to be technically flawed.

HSE also applies the dangerous dose concept to exposure to thermal radiation. The dangerous dose for thermal radiation is 1000 thermal dose units (tdu, where 1 tdu = 1 $(kW/m^2)^{4/3}$. s). Probit equations for thermal radiation are also available (see References [1] and [2] in ***Table 2.4***).

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(1) A typical population is one representative of the UK average in terms of numbers of children, numbers of adults, numbers of elderly persons, numbers of ill or infirm persons etc.

(2) Fairhurst S and Turner R M, 1993. *Toxicological assessments in relation to major hazards*. J. Haz. Mat. 33, 215-227.

Table 2.4 ***Probit Equation References Consulted***

Ref. No.	Reference
1	Committee for the Prevention of Disasters, 1999. 'Guidelines for quantitative risk assessment'. Report CPR18E (The Purple Book), Voorburg, The Netherlands.
2	Eisenberg N A, Lynch C J and Breeding R J, 1975. 'Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills'. Report CG-D-136-75. Enviro Control Inc., Rockville, MD.
3	Withers, R M J 1986. 'The lethal toxicity of ammonia – a report to the MHAP'. IChemE NW Branch Papers, 1986 No. 1, Manchester.
4	ten Berge W F, Zwart A and Appelman L M 1986. 'Concentration-time mortality response relationship of irritant and systemically acting vapours and gases', J. Haz. Mat. **13**, 301-309.
5	HSE, 1978. 'Canvey – an Investigation of Potential Hazards from Operations in the Canvey Island / Thurrock Area', HMSO.
6	HSC Advisory Committee on Dangerous Substances, 1992. 'Major Hazards Aspects of the Transport of Dangerous Goods', HMSO.
7	Silver S D & McGrath F P, 1948. 'A comparison of acute toxicities of ethylene imine and ammonia to mice', J. Ind. Hyg. Toxicol., **30**, 7-9.
8	Withers R M J and Lees F P, 1985. 'The assessment of major hazards. The lethal toxicity of chlorine. Part 2, Model of toxicity to man'. J. Haz. Mat. **12**, 283-302.
9	ten Berge W F and Vis van Heemst M, 1983. 'Validity and accuracy of commonly used toxicity models in risk analysis'. 4th Int. Symp. Loss Prevention, Harrogate.
10	Zwart A and Woutersen R A, 1988. 'Acute inhalation toxicity of chlorine in rats and mice: time-concentration mortality relationships and effects on respiration'. J. Haz. Mat. **19**, 195-208.
11	Vis van Heemst M, 1990. 'Estimating chlorine toxicity under emergency conditions'. Chlorine Safety Seminar, Brussels, November 14-15.
12	Schlagbauer M and Henschler D, 1967. 'The toxicity of chlorine and bromine with single or repeated inhalation'. Int. Arch. Gewerbepathol. Gewerbehyg., **23**, 91-98.
13	Mudan K, 1989. 'The use of toxicity data in quantitative risk assessment of HF alkylation units'. AIChE Summer National Meeting, August.
14	Perry W W and Articola W J, 1980. 'Study to Modify the Vulnerability Model of the Risk Management System', CG-D-22-80, US Coast Guard, Washington DC.
15	Wohlslagel J, Dipasquale L C and Vernot E H, 1976. 'Toxicity of solid rocket motor exhaust: Effects of HCl, HF and alumina on rodents'. J. Combust. Toxicol., **3**, 61-70.
16	Bitron M D and Aharonson E F, 1978. 'Delayed mortality of mice following acute doses of CH_2O, SO_2, Cl_2 and Br_2'. J. Am. Ind. Hyg. Ass. **39(2)**, 129-138.
17	HSE, 2002. 'Assessment of the Dangerous Toxic Load (DTL) for Specified Level of Toxicity (SLOT) and Significant Likelihood of Death (SLOD)'. Downloaded from http://www.hse.gov.uk/hid/haztox.htm on 5/8/2002.

Toxic Gases

A range of probit equations (References [1-16] from ***Table 2.4***) have been used to calculate the concentrations required to give 1% fatality for a number of toxic substances, for both 10 minute and 30 minute exposures. The results have been compared with the concentrations predicted using the HSE dangerous dose relationship (Reference [17]). The concentration values obtained are displayed in ***Table 2.5***.

Table 2.5 Concentrations Required to give 1% Fatality

		Concentration for 1% Lethality (ppm v/v)	
Material	**Reference**	**10min Exposure**	**30min Exposure**
Ammonia	[1]	3864	2231
	[2]	2670	1791
	[3]	10647	6147
	[4]	24288	14099
	[5]	3174	2129
	[6]	3437	1985
	[7]	6006	3467
	[17] (HSE)	**6148**	**3550**
Bromine	[1]	83	48
	[17] (HSE)	**158**	**91**
Chlorine	[1]	96	65
	[2]	30	20
	[8]	122	71
	[4]	146	107
	[9]	118	79
	[10]	1020	355
	[6]	61	41
	[11]	264	136
	[12]	95	55
	[17] (HSE)	**104**	**60**
Hydrogen Fluoride	[1]	387	186
	[13]	3688	1229
	[14]	501	167
	[4]	592	336
	[15]	1214	405
	[17] (HSE)	**1200**	**400**
Phosgene	[1]	17.2	5.7
	[17] (HSE)	**30**	**10**
Sulphur Dioxide	[1]	1216	769
	[14]	621	207
	[16]	1231	935
	[16]	1056	610
	[17] (HSE)	**682**	**394**

Note: HSE results in **bold**.

The results for ammonia, chlorine, hydrogen fluoride and sulphur dioxide are also displayed graphically in ***Figures* 2.1, 2.2, 2.3** and **2.4** respectively. The HSE results correspond to Reference [17] from ***Table* 2.4** (denoted R[17] on the graphs).

Figure 2.4 Concentrations Required for 1% Fatality - Ammonia

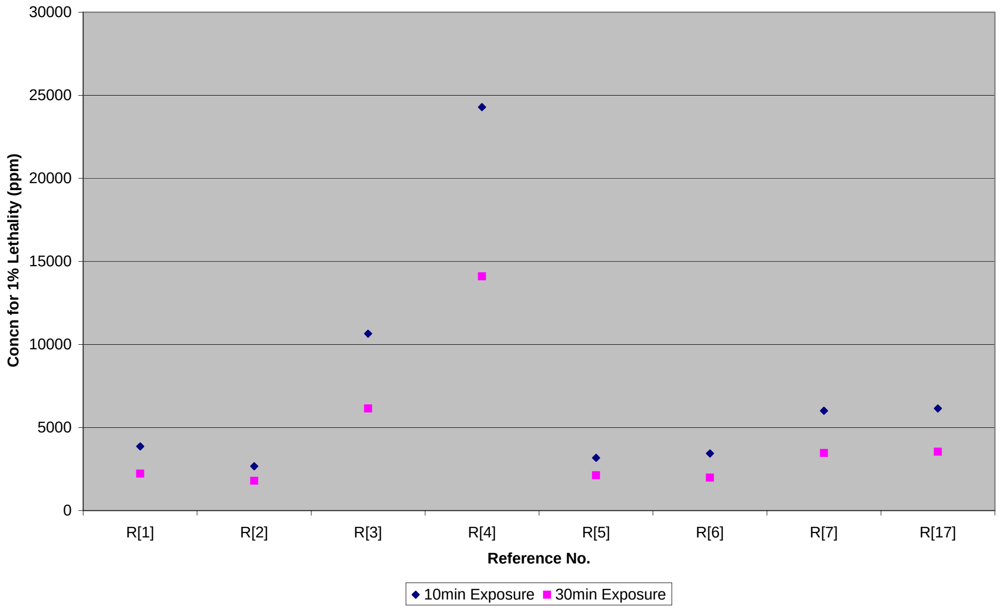


Figure 2.5 Concentrations Required for 1% Fatality - Chlorine

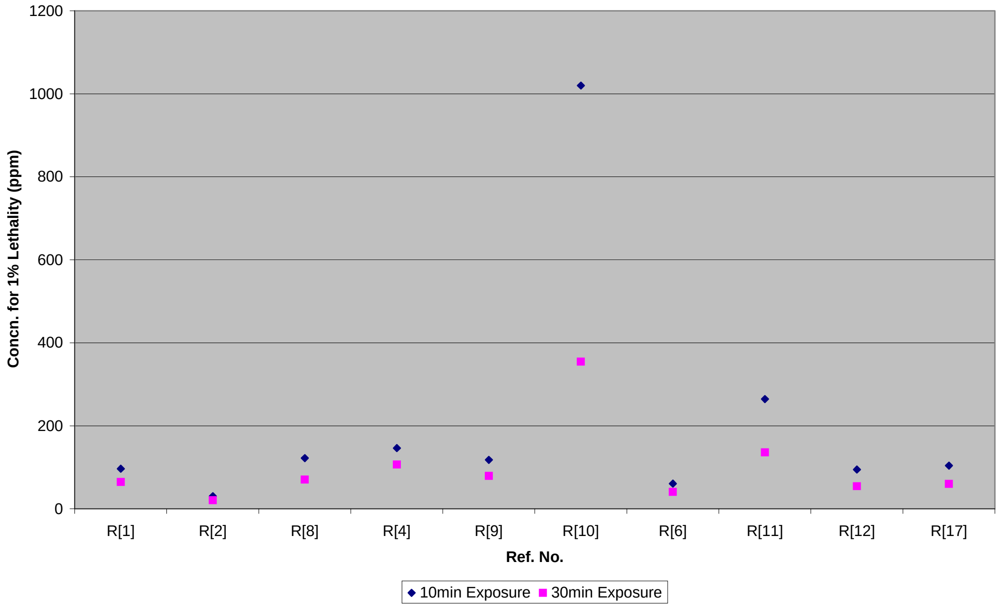


Figure 2.6 Concentrations Required for 1% Fatality – Hydrogen Fluoride

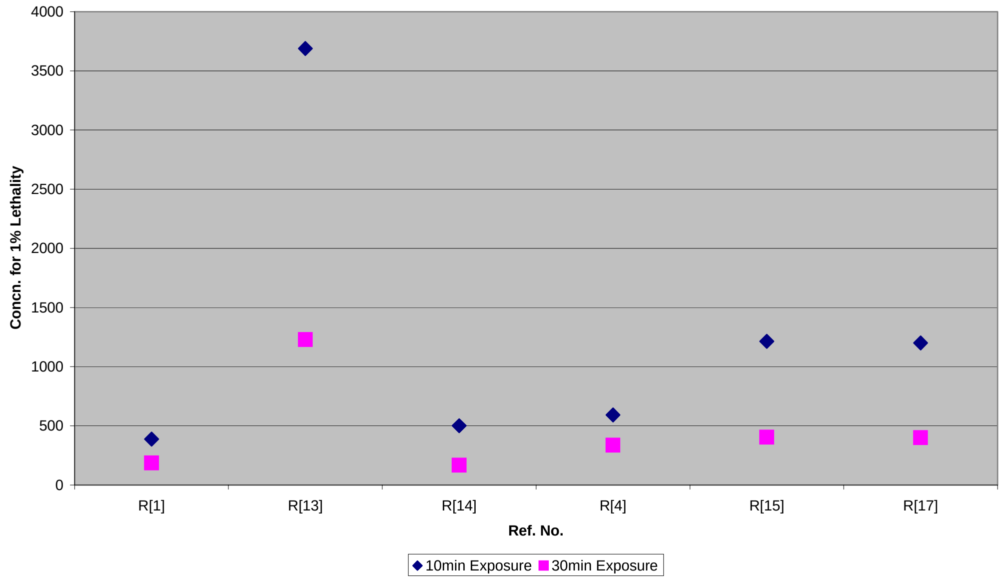
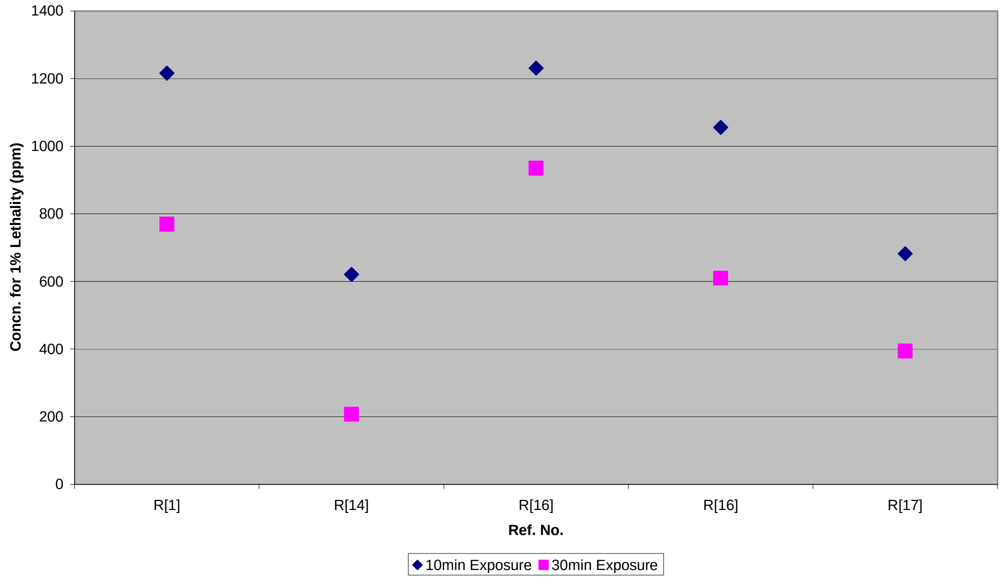


Figure 2.7 Concentrations Required for 1% Fatality - Sulphur Dioxide



In the case of ammonia, the majority of the results are below around 6000 ppm for a 10 minute exposure or 4000 ppm for a 30 minute exposure. There are two sets of results that appear at odds with the others – those given by references [3] and [4]. Excluding these results, the HSE values are at the upper end of the range of predicted values.

For bromine, the HSE results are higher than those obtained using the probit equation in reference [1] by around a factor of 2.

The majority of the chlorine results lie in a band below around 300 ppm for a 10 minute exposure or around 150 ppm for a 30 minute exposure. There is one exception to this, the results for reference [10] being significantly higher than the rest. If this result is excluded, the HSE values are close to those for a number of the remaining references (namely [8], [9] and [12]) and roughly in the middle of the rest.

In the case of hydrogen fluoride, the results for reference [13] are significantly higher than the other results. Excluding reference [13], the HSE values are at the high end of the range observed.

For phosgene, the HSE values are greater than those obtained using the probit equation in reference [1].

There is considerably more 'scatter' in the results for sulphur dioxide. The HSE values are roughly in the middle of the range of results obtained.

Overall, the HSE results could not be described as overly conservative in comparison with values obtained using the probit equations found in the literature (remembering that a higher concentration would lead to a lower risk estimate).

Thermal Radiation

The intensities of thermal radiation (i.e. – the thermal fluxes) required to give 1% fatality for a 10 second and 30 second exposure have been calculated using three probit equations (from References [1] and [2] in ***Table 2.4***). The results are compared to those obtained using the HSE dangerous dose in ***Table 2.6***.

Table 2.6 ***Thermal Fluxes Required to give 1% Fatality***

	Flux for 1% Fatality (kW/m^2)	
Reference	**10s Exposure**	**30s Exposure**
1 (Note 1)	16.5	7.3
1 (Note 2)	21.2	9.3
2	30.6	13.4
17 (HSE)	31.6	13.9

Notes

1. Equation is for unprotected (unclothed) persons
2. Equation is for protected (clothed) persons

The HSE results are similar to those using the probit equation in reference [2], but are significantly greater than the values obtained using either of the probit equations in reference [1]. The HSE values are therefore similar to or greater than (i.e., less conservative than) those obtained from the probit equations.

2.4.5 *Choice of Harm Criterion*

Currently HSE uses the 'dangerous dose' harm criterion, as explained in ***Section 1.3.4***. However, some practical problems have been encountered in the use of dangerous dose, which have led HSE to consider the use of fatality as the harm criterion.

The problems stem from the fact that, when the risks are calculated using dangerous dose, the result is the risk of dangerous dose *or worse* at locations around the installation of interest. This can be explained by reference to ***Figure 2.8*** and ***Figure 2.9***. It should be noted that these figures are purely illustrative.

Figure 2.8 shows how the individual risk of dangerous dose or worse varies as the distance increases, away from an installation handling a toxic gas such as chlorine. The further away from the installation, the lower the risk becomes. The figure also shows the proportion of the individual risk of dangerous dose or worse that is actually risk of death at three selected points. Hence, close to the installation, at point A, the risk of dangerous dose or worse is actually entirely risk of death. At point B (on the IZ boundary) approximately half of the risk of dangerous dose or worse is risk of death. At the point C, on the MZ boundary, the fraction has fallen to about one third.

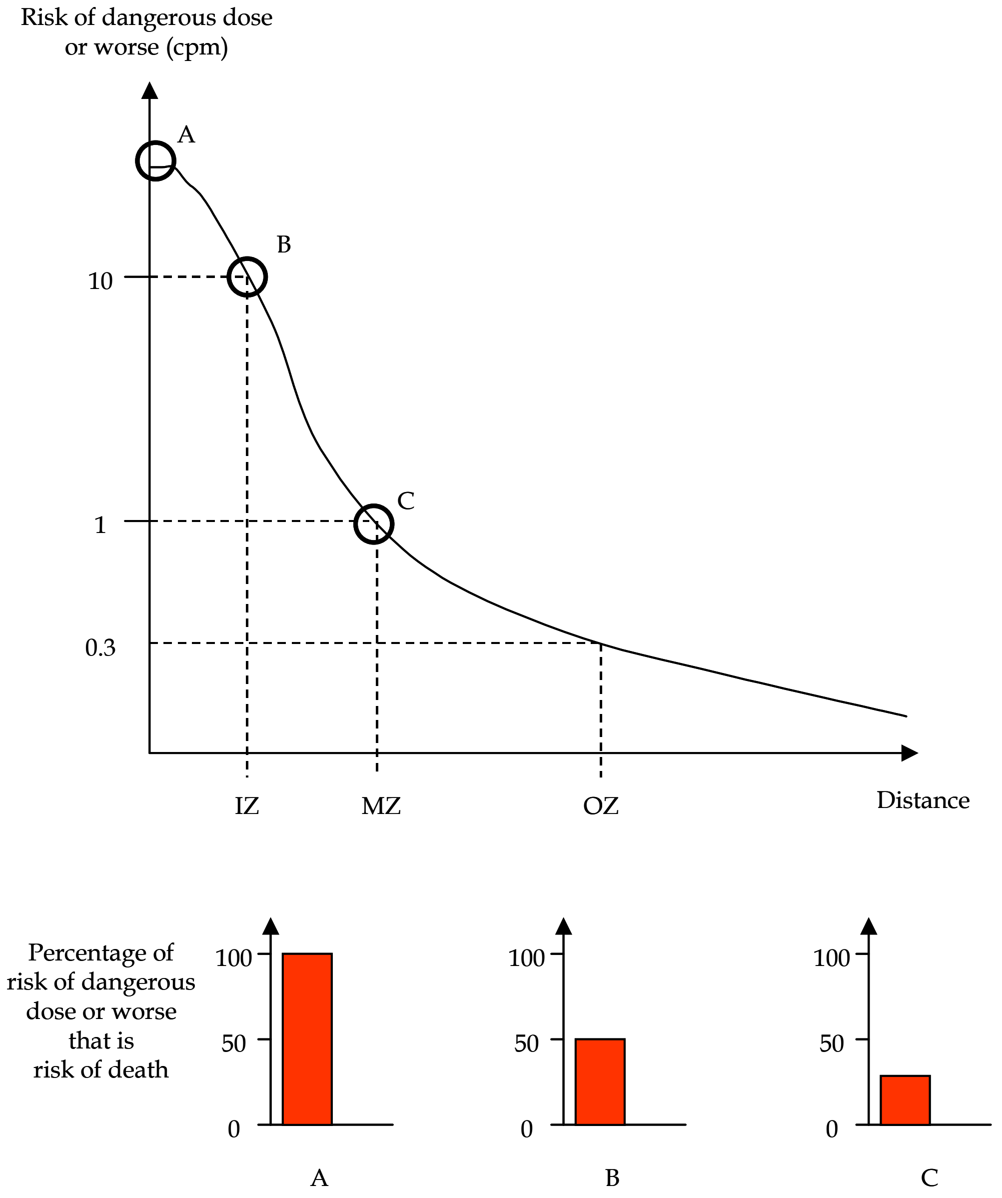
Figure 2.9 shows similar information for an installation handling flammable materials. Again, at the point closest to the installation (point D), the risk of dangerous dose or worse is entirely risk of death. At point E (on the IZ boundary) approximately 80% of the risk of dangerous dose or worse is risk of death. At the point F on the MZ boundary the fraction has fallen to about one half.

Comparing ***Figure 2.8*** and ***Figure 2.9***, it can be seen that, although the same term, 'risk of dangerous dose or worse', is used to described the risk from the two installations, the composition of the risk, in terms of the proportion of risk of fatality, is quite different for the two types of installation at most locations. For the toxic gas installation, a 1 cpm risk of dangerous dose or worse contains less risk of fatality than 1 cpm risk of dangerous dose or worse at the flammables installation (this is one reason why HSE has tended to use protection-based assessments when considering flammable risks).

This means that, for example, if the two installations were in proximity to one another, it would not be meaningful to add the two sets of risk results together to produce a 'total' risk of dangerous dose or worse. Also, for two identical development proposals at nominally the same risk of dangerous dose or worse at the two installations, it would be necessary to consider whether or not the same advice should result.

Detailed investigations (1) have shown that the pattern of the amount of risk of death in a given risk of dangerous dose or worse is very similar for a range of toxic substances, including chlorine, ammonia, hydrogen fluoride and sulphur dioxide. However, relative to these toxic gases, a different pattern is observed with flammable materials and with certain other materials (such as pesticides stored in warehouses).

Figure 2.8 ***Variation in Risk of Dangerous Dose or Worse - Toxics***



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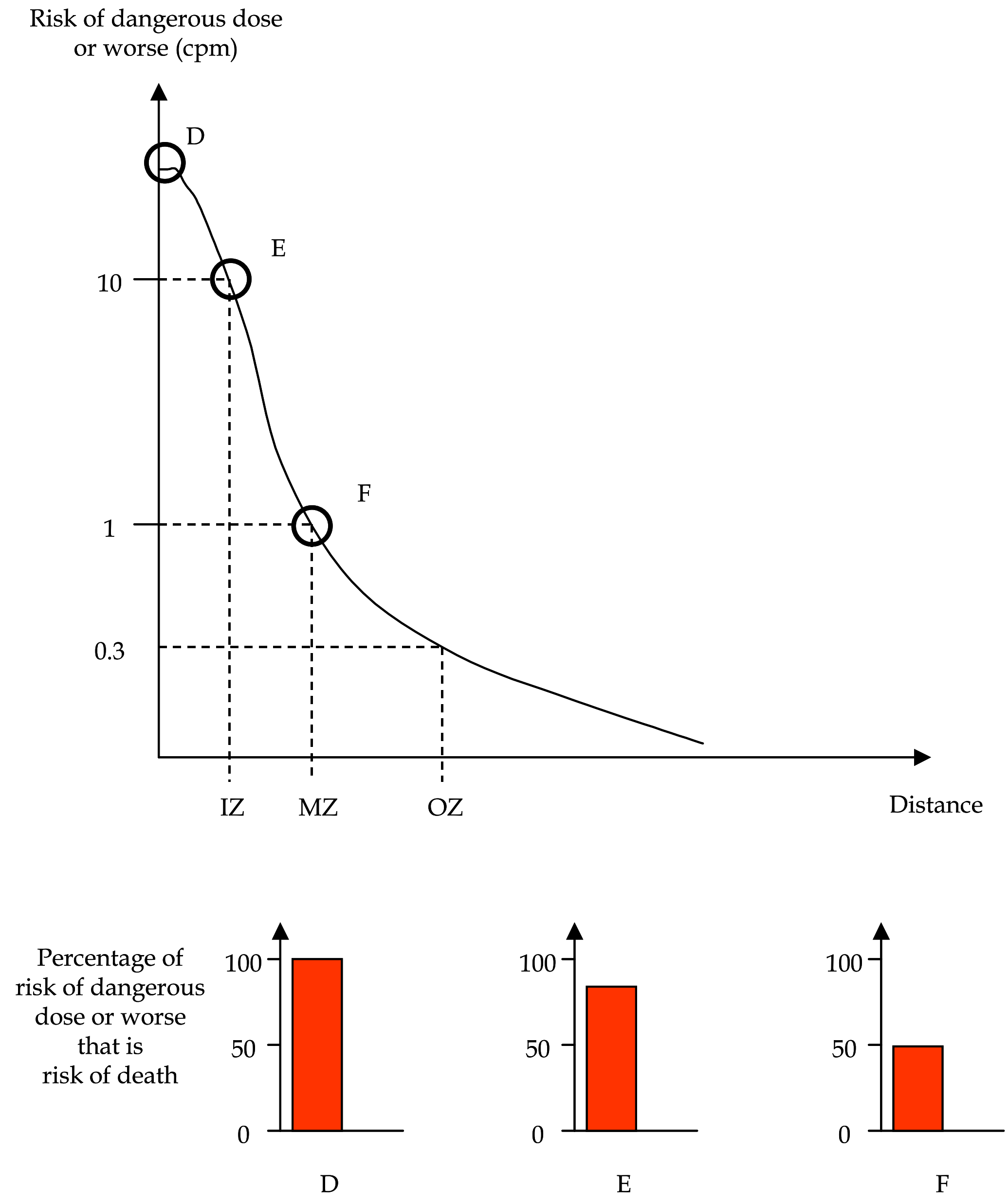
(1) Franks A P, Harper P J and Bilo M (1996). *The relationship between risk of death and risk of dangerous dose for toxic substances*. Journal of Hazardous Materials 51 (1996), 11-34.

Figure 2.9 Variation in Risk of Dangerous Dose or Worse - Flammables



HSE has considered using a measure of the risk of fatality in order to avoid some of the problems encountered with dangerous dose. There are different technical approaches available for calculating the toxic dose, thermal radiation or blast pressure required to give a defined proportion of fatalities among a typical exposed population. In the case of toxic substances, HSE's approach (1) involves a detailed review and screening of the available scientific literature for experiments using a particular substance, following which the data relating to the most sensitive animal species and strain are used to derive the required doses.

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(1) Fairhurst S and Turner R M, (1993). *Toxicological assessments in relation to major hazards*. J. Haz. Mat. 33 (1993), 215-227.

HSE's method for calculating the risk of fatality (called Total Risk of Death or TROD) combines three dose levels to give an overall profile. The three dose levels combined are those for 50% lethality (LD_{50}), 10% lethality (LD_{10}) and 1% lethality (LD_{01}). Hence, at the consequence analysis stage, it is necessary to calculate the physical extent that relates to each of the three doses of interest.

The use of fatality (TROD) as the harm criterion is still under consideration by HSE and has not yet been formally adopted.

2.4.6 Conclusions – Consequence Analysis

At the time of writing, a separate Model Evaluation Exercise was not complete.

A comparison of predictions made using HSE's consequence models with accident outcomes generally gave reasonable agreement, bearing in mind the degree of uncertainty in the definition of the conditions under which most of the accidents occurred. Where disagreement has been observed, it has been possible to identify reasons as to why this may be the case.

The consequence analyses performed under the ASSURANCE Project showed poor agreement between the results obtained by the various participants. HSE's results were not consistently the most conservative or consistently the least conservative.

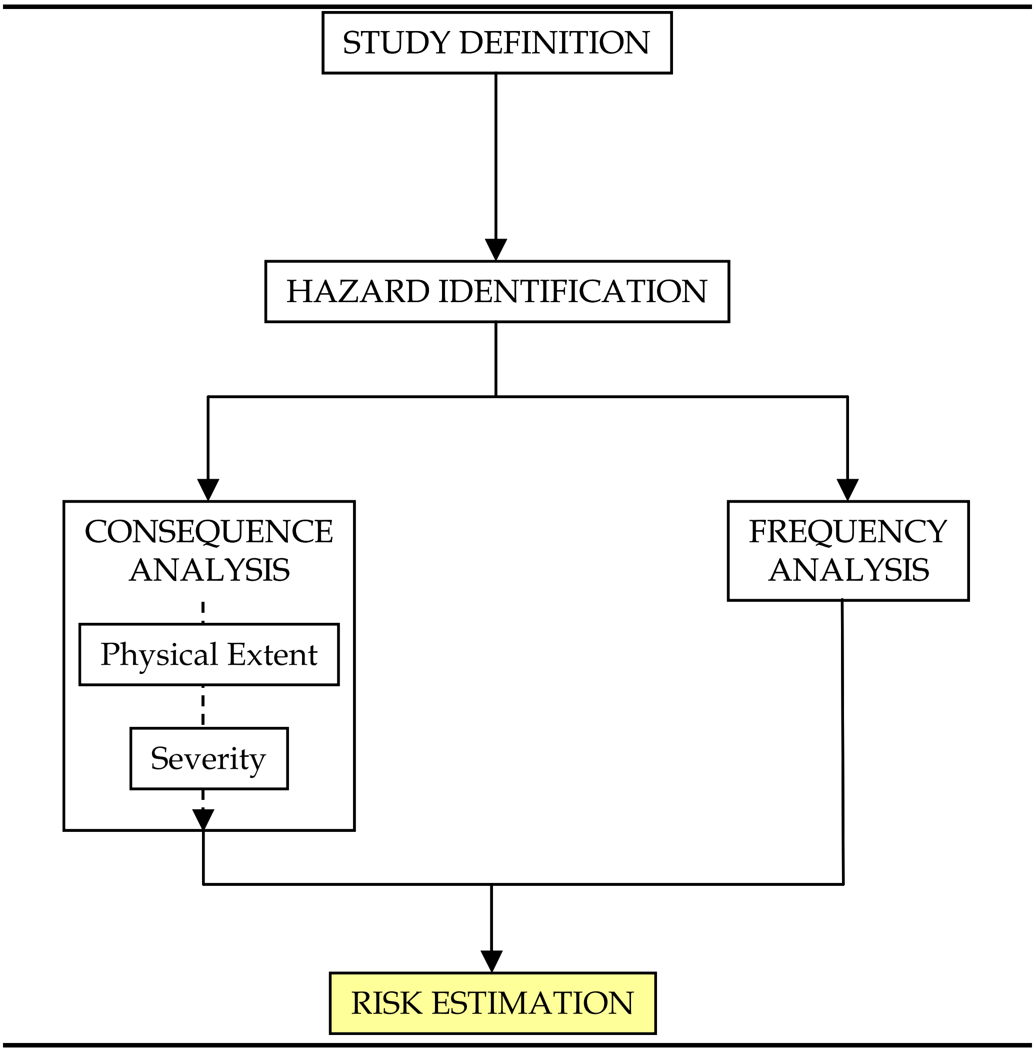
The HSE dangerous dose equates to a level of approximately 1% fatality among the exposed population. HSE dangerous doses were compared with the results of other methods of predicting the dose required to cause 1% fatality for toxic substances and thermal radiation. In general it was found that use of the dangerous dose would generate risk results that were similar to, or lower than, the risk results that would be obtained by using the doses predicted by other methods.

Use of dangerous dose presents some technical difficulties that could be avoided by use of fatality as the harm criterion. HSE is considering adoption of fatality as the harm criterion, using a measure of risk of fatality called the Total Risk of Death (TROD).

2.5 RISK ESTIMATION

The risk analysis step discussed in this Section is highlighted in ***Figure 2.10***.

Figure 2.10 Risk Analysis Process - Risk Estimation



The review of HSE's approach to estimating risk (by combining the results of the consequence and frequency analyses) has involved consideration of the two comparative studies described in ***Section 2.1***, namely:

- the ASSURANCE Project; and,
- a comparison of HSE's RISKAT software with the commercially available SAFETI package.

The outcome of these comparisons is discussed below.

2.5.1 ASSURANCE Project Findings

Each of the teams that performed a calculation of risk (one team did not) generated a set of individual risk contours (see ***Section 1.1.5*** for an explanation). It was found that the estimated individual risk at any given location varied widely between the teams, as reflected by significant differences in the sizes of the contours produced. At some locations the highest estimate of individual risk produced by any team was around 100,000 times greater than the lowest value. The degree of variation increased with distance from the site.

It was observed that the results fell into two groups – one set of teams predicting significantly larger individual risk contours than the other. The HSE results were in the middle of the group of smaller contours.

The differences in the individual risk results can, to a large extent, be accounted for by the differences in the frequency and consequence analysis results as discussed in ***Sections 2.3.2 and 2.4.3***.

2.5.2 Comparison of RISKAT with SAFETI

This study was commissioned by HSE to compare the individual risk results obtained using RISKAT with those obtained using SAFETI (1). SAFETI is a commercially available software package used for risk calculations, whereas RISKAT is produced by and used exclusively by HSE.

As far as possible, both models were configured to consider identical cases. Several realistic sets of input data were used, representing:

- a water treatment works storing and using chlorine;
- a storage facility for bromine containers;
- a phosgene generation plant;
- a storage facility for pressurised, liquefied ammonia; and,
- a storage installation for sulphur dioxide.

All of the dangerous substances involved are toxic.

The study examined both the individual risk contours produced (see ***Section 1.1.5***) and how much each event contributed to the overall 'total' individual risk.

It was found that:

- In the case of the chlorine installation, the initial results indicated that the individual risk contours generated by SAFETI tended to be larger than those produced by RISKAT, in some cases significantly so. That is, at a given distance from the site, SAFETI predicted higher risks than RISKAT. However, following some refinement of the SAFETI inputs (2), closer agreement was obtained. In general there was

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(1) DNV Risk Management Software. Details available at www2.dnv.com/software/

(2) The inputs adjusted were associated with definition of the rate of release of material. HSE's models take account of frictional losses for releases from pipework, SAFETI can be configured to perform calculations in a similar way.

reasonable correspondence between the predictions of which events contributed most to the overall risk.

- For the bromine site, RISKAT tended to predict higher risks than SAFETI at greater distances from the site, but this position was reversed closer to the site. Refinement of the SAFETI input did not lead to any improvement in the results. However, there was reasonably good agreement between the two models concerning the prediction of which scenarios were the most important risk contributors.

- The SAFETI individual risk contours for the phosgene plant were larger than those produced using RISKAT. There was little agreement between the two models regarding the prediction of which scenarios were the most important risk contributors.

- For both the ammonia and sulphur dioxide facilities, the individual risk contours obtained using SAFETI were significantly smaller than those produced using RISKAT. There was reasonably good agreement between the two models concerning the prediction of which scenarios were the most important risk contributors.

The study did not undertake an investigation into the reasons for the differences observed. However, since the frequency data used in both models were identical, it is thought that the differences observed are chiefly due to the different consequence analysis models used within the two packages.

2.5.3 Conclusions – Risk Estimation

The estimates of individual risk generated within the ASSURANCE Project varied widely from participant to participant, as reflected by significant differences in the size of contours produced. The results fell into two groups, with one set of participants predicting significantly larger individual risk contours than the other. The HSE results were in the middle of the group of smaller contours.

Results obtained using HSE's software, RISKAT, were compared with those calculated using the proprietary SAFETI package. Although reasonable agreement was obtained for chlorine, the level of agreement was poor for the other substances assessed. Neither model was consistently more conservative than the other.

3 *REVIEW OF HSE'S PROTECTION-BASED APPROACH*

3.1 *INTRODUCTION*

A large number of MHIs in the UK have been subjected to protection-based analysis. The majority of these sites store or handle flammable materials such as Liquefied Petroleum Gas (LPG). The size of the resulting LUP zones tends to be significantly smaller (in terms of extent and the area covered) than the risk-based LUP zones for MHIs handling toxic substances.

The review of HSE's protection-based analysis approach has comprised:

- consideration, in general terms, of the use of protection-based approaches by HSE; and,
- examination of the protection-based analysis approach for a specific type of installation.

The findings are discussed below.

3.2 *GENERAL POINTS*

3.2.1 *Aims and Terminology*

As stated in ***Section 1***, the aim of a protection-based analysis when setting zone boundaries is to:

"achieve a separation between developments and the site which provides a very high degree of protection against the more likely smaller events, whilst also giving very worthwhile (sometimes almost total) protection against unlikely but foreseeable larger-scale events." (1)

A review of HSE's protection-based approach is made more difficult by the fact that the terms used in this statement have not been defined. Hence it is not clear what is meant by *'a very high degree of protection'*, or how this differs from *'worthwhile (sometimes almost total) protection'*. Similarly, the terms *'more likely'* and *'unlikely but foreseeable'* are not defined, although they appear to relate to the frequency of the event (or events) considered in the analysis.

In addition, it is not clear how the two levels of protection (*'very high'* and *'worthwhile'*) relate to the three zones (inner zone, middle zone and outer zone; or IZ, MZ and OZ respectively) used for giving LUP advice.

The original LUP risk criteria document (1) outlined some of the objections to a protection-based approach, namely:

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(1) HSE (1989). *Risk criteria for land-use planning in the vicinity of major industrial hazards*. HMSO.

- *"the possibility that the protection provided is beyond that which is 'reasonable', if a low probability of serious injury is combined with a very low likelihood of the critical event, thus resulting in excessive restrictions on land use";*
- *"the somewhat arbitrary nature of the worst event, and potential inconsistency between installations in deciding which major event to use as a basis";* and,
- *"the difficulty of comparing the degree of protection with that which seems to be necessary or desirable for other hazards in life".*

Since protection-based analyses have not altered greatly since the risk criteria document was published, it is concluded that these criticisms remain valid. Moving to a risk-based approach, coupled with use of appropriate risk criteria, deals with these objections. However, use of risk analysis is not without its own difficulties, as has been indicated in ***Section 2***. Hence there remain reasons why, in certain cases, HSE may continue to use a protection-based analysis.

3.2.2 Reasons for Using a Protection-Based Approach

The reasons for resorting to a protection-based analysis are listed in ***Section 1.4.*** These reasons have been reviewed and are considered to be appropriate, given the current limitations of risk analysis techniques. However, it is not always clear, from the information and documents reviewed to date, which of these reasons or which combination of reasons has been used to justify a protection-based approach in a given case.

In addition, as risk analysis methodologies and techniques develop, it is possible that some of the reasons for adopting a protection-based approach will be dealt with, enabling use of a risk-based analysis. This is summarised in ***Table 3.1***.

Table 3.1 Dealing with Reasons for Using a Protection-Based Approach

Reason for Using a Protection- Based Approach	**Means of Resolution**
The Hazardous Substances Consent for the installation does not contain sufficient information to support a risk analysis.	This is an issue that is largely beyond HSE's control, since it is not the enforcing authority for the Consent regulations. Hence this is likely to continue to be a reason for using a protection-based approach.
There is a high degree of uncertainty regarding the frequency of some of the events that might occur at the site.	For some types of site at least, the levels of uncertainty may be reduced by gaining a better understanding of the event frequency through further research.
The level of harm predicted from events at the installation would be very high (i.e., the risk of dangerous dose or worse would contain a significant proportion of risk of fatality).	This could be resolved by using an approach based on risk of fatality instead of risk of dangerous dose or worse.
The density of population and demand on land use in the area around the site are low.	In pragmatic terms, in such a situation there would be little justification for undertaking a risk analysis, with the additional resources this would entail. Hence this is likely to continue to be a reason for using a protection-based approach.

3.2.3 *Selection of Event*

The selection of the event (or events) to be used in a protection-based analysis is a critical step, since it will determine the size of the LUP zones generated. However, there is no written policy or guidance for Inspectors on how to select a suitable event when performing a protection-based analysis on an installation of a type that has not been considered before. In such cases the approach is developed on an ad-hoc basis and subjected to internal peer review. Where the protection-based approach for a certain type of installation (such as bulk LPG storage) is already established, the event to be used is well documented.

3.2.4 *Combination of Results*

A further difficulty with the protection-based approach arises when it is necessary to combine the results of protection-based and risk-based analyses. This may be necessary at, for example, large establishments such as oil refineries where the current approach is to perform protection-based analysis of some parts of the establishment and risk-based analysis of other parts. Although, in principle, the results of several risk-based analyses of different parts of the establishment could be added to give a total risk in the vicinity of the establishment, the results of protection-based and risk-based analyses cannot be added. This is because the level of risk associated with the three protection-based zones is not known.

A hypothetical example showing two overlapping sets of zones is shown in ***Figure 3.1***, where the zones associated with MHI 1 have been generated using a risk analysis, and those for MHI 2 have been created using a protection-based analysis.

From ***Figure 3.1***, it can be seen that:

- in region A (red), the two MZs overlap;
- in regions B and C (orange) the OZ of one installation overlaps with the MZ of the other; and,
- in regions D and E (green), the two OZs overlap.

At present, the approach taken is to treat these regions as the more onerous of the two overlapping zones. Hence regions B and C would be treated as MZ, for example. This results in the 'merged' zones shown in ***Figure 3.2***.

However, this treatment of the overlapping zones does not take into account the fact that the addition of the overlapping risks results in expansion of the various zones (see ***Figure 3.3***).

Figure 3.1 *Example of Overlapping LUP Zones*

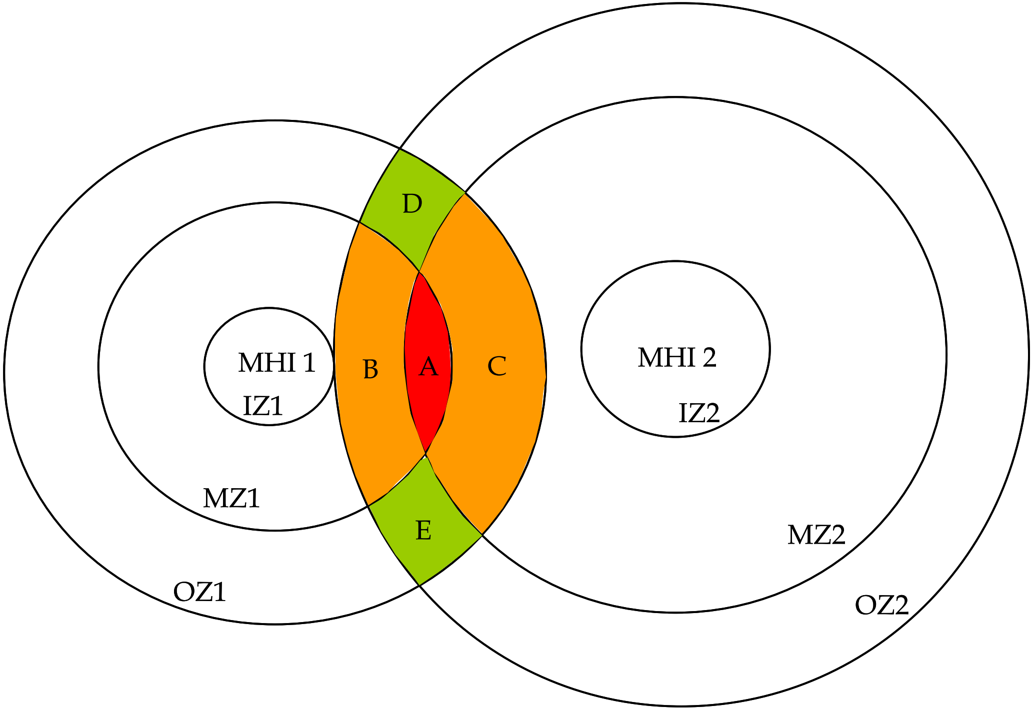


Figure 3.2 Example of Merged LUP Zones

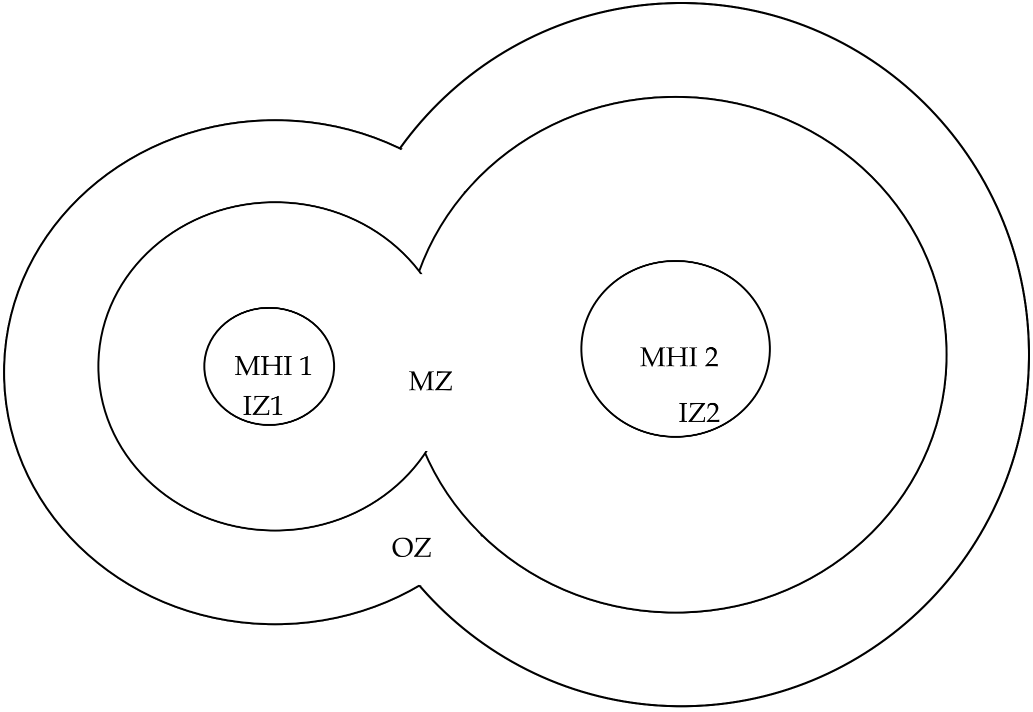
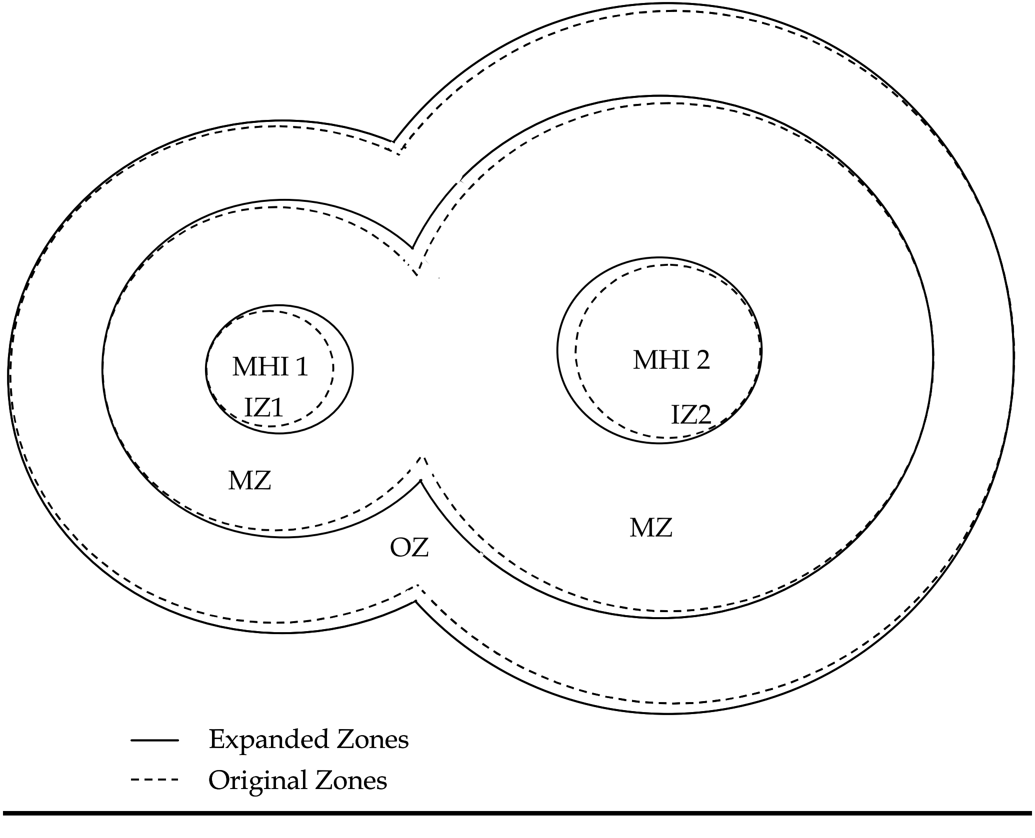


Figure 3.3 Additive Nature of Risks in Overlapping Zones



3.2.5 *General Points - Recommendations*

In view of the points raised above, it is recommended that:

- the terminology used in relation to protection-based analysis (*'worthwhile'* protection, *'unlikely but foreseeable'*, etc.) is better defined;
- a description of the relationship between the two levels of protection stated in the aim and the three LUP zones defined by the analysis is provided;
- HSE develops internal guidance for Inspectors on selecting events for use in protection-based analyses;
- where protection-based analysis is used for installations of a given type, that the reasons for adopting a protection-based approach, together with the rationale for selecting the event or events used in the analysis, are documented in such a form that the information could be released to interested parties outside HSE as required; and,
- that HSE continues to perform research into risk analysis methods so that some of the reasons for having to resort to a protection-based approach can be resolved.

One of the reasons favouring the use of a protection-based analysis is that the level of harm from events at the MHI would be very high (i.e., the proportion of risk of fatality in the risk of dangerous dose or worse would be significant). As mentioned in ***Section 1.3.4***, HSE is already considering the use of a measure of risk of fatality instead of risk of dangerous dose or worse. Use of fatality as the harm criterion would deal with this reason for the use of protection-based analyses.

Finally, although use of risk analysis in place of a protection-based analysis deals with many of the difficulties associated with the latter, the resources (in terms of staff time and effort) required in performing a risk analysis are often significantly greater. Hence, where it can be shown that a protection-based approach would generate similar results to a risk analysis (in terms of the sizes of zones and the LUP advice given), then the protection-based approach could be retained.

3.3 *APPROACH FOR BULK LPG STORAGE*

A review of the protection-based analysis approach for bulk storage of LPG as a pressurised, liquefied gas was conducted. Sites of this type comprise a significant number of those to which the protection-based approach is applied.

It is understood that the specific reasons for adopting a protection-based analysis for bulk LPG storage are:

- that the level of harm arising from many of the major accident hazards posed by such MHIs can be significantly more onerous than a dangerous dose; in other words, the proportion of fatality risk within the 'risk of dangerous dose or worse' is high (see ***Section 1.3.4***); and,
- that there is considerable uncertainty associated with the likelihood of some of the events that may occur, particularly the probability of ignition of flammable clouds and the frequency of a Boiling Liquid Expanding Vapour Explosion (BLEVE).

For the majority of bulk LPG facilities, the event considered within the analysis is a BLEVE. A BLEVE involves catastrophic failure of a vessel containing a pressurised liquefied gas, as a result of being exposed to fire. Rupture of the vessel results in an intense fireball as the vessel contents are burned, together with generation of a blast wave and projection of fragments of the vessel. Of these, the effects of the fireball tend to be the most significant from a major hazard point of view (1).

Adopting fatality as the harm criterion instead of dangerous dose, could deal with the first of the reasons listed above. However, the issues relating to the likelihood of major accident events at bulk LPG sites are more difficult to resolve.

Calculation of the probability of ignition of a flammable cloud is not straightforward. It depends upon the size of the cloud, the number of ignition sources that the cloud may come into contact with, their strength and how often they are likely to be active. Ignition probabilities are therefore both event- and site-specific. HSE research on ignition probability is ongoing (2).

It should be noted that determination of ignition probability is an issue that is relevant to all MHIs storing or handling flammable substances, although it is particularly problematic at those MHIs where a flammable cloud may be generated.

The selection of BLEVE as the event used within the analysis is influenced by the frequency that HSE assumes for such an event. Currently HSE considers the BLEVE frequency to be 1 in 100,000 years per vessel (3). At this frequency the BLEVE event tends to dominate the risk profile for the MHI, although there may be other events that have the potential to affect people at a greater distance from the site.

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(1) This is because, although the range associated with the projection of missiles may be greater than that for harmful thermal radiation, there is a relatively low probability of being struck by a missile. In addition, the blast effects tend to have a shorter range than the thermal radiation effects.

(2) Spencer H and Rew P J (1997). *Ignition probability of flammable gases*. HSE Books, Contract Research Report CRR 146/1997.

(3) Crossthwaite P J, Fitzpatrick R D and Hurst N W (1988). *Risk Assessment for the Siting of Developments Near Liquefied Petroleum Gas Installations*. IChemE Symposium Series No. 110, Preventing Major Chemical and Related Process Accidents, 373-400.

According to reviews performed on behalf of HSE (1) (2), estimates of BLEVE frequency vary widely. It was found that frequency estimates divided into two groups:

- those based on historical data (i.e., using data on the number of BLEVE accidents that have occurred in the past); and,
- those based on analytical approaches (i.e., using mathematical techniques to predict the frequency).

The reviewers found that results obtained using historical data tended to be significantly higher than those calculated using analytical techniques. The average value of the historically based results was around 2 in 100,000 years per vessel. The average of the results obtained using analytical techniques was approximately 6 in 10,000,000 years per vessel. The reasons for this discrepancy are not clear. HSE's value, which is historically based, is towards the upper end of the range of values encountered. This reflects HSE's cautious best-estimate approach (see ***Section 1.3.6***), where, in the face of uncertainty, HSE tends to take a conservative view.

In one of the reports reviewed (3) the result obtained using an analytical approach was 9 in 10,000,000 years per vessel. The frequency was also estimated using historical data, which gave a figure of 1 in 100,000 years per vessel. The authors of this report described the difference as 'not unexpected', commenting that, since the accidents in the historical record had taken place some time (ten years or more) prior to their study, the lessons learned would have been applied to modern installations, resulting in a lower frequency. This may be one of several reasons for the discrepancy between the two approaches observed more generally.

If the analytically based BLEVE frequency estimates were indeed more representative of modern installations (or were better than estimates using historical data for some other reason), then the BLEVE event would not necessarily dominate the risk profile and may not be the best choice of event for use in a protection-based analysis.

In view of the discrepancies described above, and the fact that HSE's estimate of BLEVE frequency was obtained over 15 years ago, it is recommended that the estimate is updated to reflect more recent experience, and that the reasons for the differences between historical and analytical estimates are explored further.

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(1) Hankin R (1991). *A Literature Review of Generic Failure Rates and a Comparison with the Failure Rates used in RISKAT.* HSL Report IR/L/HA/91/4.

(2) Simpson G J (1993). *Review of Failure Rate Data Used in Risk Assessment*. MSc Dissertation, Heriot-Watt University.

(3) Selway M (1988). *The Predicted BLEVE Frequency of a Selected 2000 m^3 Butane Sphere on a Refinery Site*. UKAEA Safety and Reliability Directorate Report SRD/HSE/R492.

However, it should be noted that it is considered unlikely that a move to a risk-based analysis for bulk LPG would result from implementation of this recommendation in the near future. This is because:

- even if some of the uncertainties surrounding BLEVE frequency could be removed, calculation of ignition probabilities would remain problematic; and,
- although HSE has a software tool (called ALIBI – Assessment of LPG Installations leading to BLEVE Incidents) for performing analytically based calculations of BLEVE frequency, the software has only been validated for a certain type of LPG installation. Expanding the scope of the model to deal with all of the types of installation encountered would require a considerable amount of research.

Instead, as an interim measure, it is recommended that, depending on the result of the updated calculation of BLEVE frequency, the choice of event for use in a protection-based analysis for bulk LPG installation is revisited.

An alternative candidate for the event of choice in a protection-based analysis is the 'cold' catastrophic failure (i.e., a catastrophic failure that does not result from exposure to fire) of a vessel, generating a large flammable cloud. Such a cloud could drift for a considerable distance prior to being ignited and cause injuries or fatalities among those caught within it (an event of this type, involving a burning cloud of flammable vapour, is called a flash fire). The maximum distance at which people could be harmed could exceed that for a BLEVE.

4 REVIEW OF ASSUMPTIONS USED

Table 4.1 displays those significant, commonly used assumptions employed by HSE when performing analyses. The table gives a statement of the assumption, some background explanation, indicates where the assumption is applied (i.e. – in what kind of analysis) and comments on the use and validity of the assumption.

With regard to ***Table 4.1***, it should be noted that:

- the abbreviation LPG stands for Liquefied Petroleum Gas. LPG is an extremely flammable material. At normal temperatures and pressures it is a gas, but it is kept as a liquid, either by subjecting the material to pressure, or by refrigeration. It is the same material that is found in 'camping gas' cylinders.

- a particular major hazard event of interest for LPG is the Boiling Liquid Expanding Vapour Explosion (BLEVE). A BLEVE involves catastrophic failure of a vessel containing a pressurised liquefied gas, as a result of being exposed to fire. Rupture of the vessel results in an intense fireball as the vessel contents are burned, together with generation of a blast wave and projection of fragments of the vessel.

It was found that all of the assumptions reviewed were appropriate and / or in keeping with the approach used by most risk analysis practitioners, with one exception. As described in ***Table 4.1***, it is recommended that the assumptions relating to the amount of LPG in a vessel when it undergoes a BLEVE are revisited.

It should be noted that there is a set of assumptions used by HSE in relation to consideration of applications for Hazardous Substances Consent, namely:

- the amount of dangerous substances present at a site is the full amount to which they are entitled under their Consent, and that this quantity is present all of the time;

- the analysis is based upon the equipment items specified in the Consent (tanks, vessels and transportable containers) and may not take account of other equipment, such as long pieces of piping, that may be present; and,

- when the site has Consent to store materials within a generic category (such as 'Toxic' or 'Very Toxic') then, unless there are conditions applied to the Consent to prevent it, the substance considered in the analysis is the worst case material in that category, whether the site actually has it or not.

These assumptions have not been addressed in ***Table 4.1***, since HSE's approach to dealing with Hazardous Substances Consent is the subject of a separate policy review.

Table 4.1 Assumptions Used in HSE Analyses

Assumption	**Explanation**	**Application**	**Comment**
All of those people outdoors caught within a flash fire will be casualties.	A flash fire results when a cloud of flammable vapour is ignited. Flames spread through the cloud from the point of ignition.	Risk analysis of certain installations and pipelines handling flammable substances.	Currently the assumption used by HSE is that all of the people within the flammable cloud receive a 'dangerous dose' or worse, when performing analyses for the purposes of giving LUP advice around existing MHIs. When performing analyses in order to give advice on proposals for new MHIs, HSE assumes that people outdoors in a flash fire will be killed. For people indoors, the fraction of people killed is estimated to be between 0.2 and 0.5, depending on the circumstances. These assumptions are not greatly different from those used by other risk analysis practitioners (61).
The extent of a flash fire is determined by the region in which the concentration of flammable vapour is half of the Lower Flammability Limit (LFL) or more.	The LFL is defined as the concentration below which a flammable gas or vapour is too lean to burn. The predicted size of a gas cloud as defined by the locations at which the LFL is reached is significantly smaller than the predicted size of a gas cloud as defined by the locations at which half of the LFL is reached. The gas concentration within the cloud is determined using a consequence analysis model.	Risk analysis of certain installations and pipelines handling flammable substances.	Historically HSE used the extent of the cloud to half of the LFL to define LUP zone boundaries. However, in more recent times, HSE have adopted a position of using the cloud extent to LFL, but in association with: a) consideration of events of a greater magnitude than those previously included in the analysis (e.g., consideration of flammable liquid pool fires that have spread beyond a bund, as opposed to a flammable liquid pool fire that is contained by the bund); and, b) on the basis of research conducted by the Health and Safety Laboratory, ensuring that the consequence analysis model used is correctly configured for this kind of analysis. It should be noted that, if a consequence model is used incorrectly in this context, then the extent of the cloud to LFL could be under-predicted.
When calculating the effects of a BLEVE, it is assumed that vertical, cylindrical vessels are 80-90% full when the event occurs. Horizontal, cylindrical vessels are assumed to be 50% full.	The magnitude of the fire produced by a BLEVE depends on how much material is in the vessel when the event occurs. Some time may elapse between the onset of exposure to heat from a fire and failure of the vessel. During this time some of the vessel contents may be lost through the vessel's pressure relief valve.	Protection based analysis of installations where such vessels are present.	The assumed fill levels are based on a consideration of the fill level that would have to be reached before unwetted tank shell came into contact with impinging flame from a pool fire engulfing the vessel. Jet flame impingement does not appear to have been considered. A jet flame could be in contact with unwetted vessel shell at higher levels than calculated for a pool fire. It is recommended that these assumptions are revisited.

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(61) Lees F P (2001). *Loss Prevention in the Process Industries*. Second Ed. Butterworth-Heinemann.

Assumption	Explanation	Application	Comment
The level of heat to which a building can be exposed before it catches fire is based on data for wood.	Intense fires of the type observed in major accidents can generate so much heat that they can cause wood, fabric, plastic etc. to ignite even when they are some distance away from the fire.	Historical basis of LUP advice for siting of buildings in the vicinity of MHIs and MHPs.	Some types of building do not contain much wood in their construction (being composed mainly of concrete, steel and masonry). Office buildings, for example, may have PVC window frames and glass doors. Other than wood and fabric, there are virtually no data available in the technical literature relating to other materials, such as plastics. Hence HSE has continued to use the figures based on wood data for all types of building, regardless of how it is constructed. The figures used are generally in keeping with values quoted by other sources.
Protection-based LUP consultation zones for thermal radiation hazards are calculated assuming that the receptor is outdoors.	Protection-based assessments of the thermal radiation effects from major hazard fires assume that the people exposed are initially outdoors. This assumption appears inconsistent with HSE’s general approach of considering hypothetical house residents who are indoors most of the time.	Protection-based assessments of thermal radiation hazards.	Over the exposure times of interest (20-30 seconds), the thermal flux levels required to generate a dangerous dose are similar to the levels that could cause piloted ignition of a building. In the event of a building catching fire, the occupants are likely to attempt to escape outdoors, hence the use of an outdoor receptor is appropriate. In addition, some types of vulnerable / sensitive involve outdoor populations. Overall the approach is considered to be defensible.
Accidental releases are generally modelled as being directed horizontally.	In reality a release from a piece of equipment (such as a pipe or vessel) could occur in any one of a number of directions, including straight up in the air. Assuming that releases are projected horizontally is conservative, since it usually results in higher concentrations of dangerous substance at ground level.	Virtually all analyses involving a release of gas or pressurised liquefied gas from containment.	Although the assumption of horizontal releases is conservative, it is in keeping with what is done by most other risk analysis practitioners. HSE does model vertical releases for events involving pipelines.
Use of 'dangerous dose' rather than fatality as the harm criterion.	HSE's analyses currently use a dangerous dose as the level of harm of interest (see ***Section 1.3.4***). Exposure to a dangerous dose corresponds to a low probability of fatality (1%)..	All analyses.	The use of dangerous dose has been criticised by some as being overly conservative and inconsistent with the approach taken by the majority of risk analysis practitioners. It also presents technical difficulties when it is necessary to combine the results of analyses of dangerous substances of different types (e.g. - toxic and flammable). HSE is considering the use of a risk of fatality based approach (see ***Section 1.3.4***).

Assumption	Explanation	Application	Comment
When establishing the CD for an installation handling flammable materials using a protection based assessment, the thermal radiation level used is lower than the dangerous dose level.	The dangerous dose for thermal radiation (heat from a fire) is 1000 thermal dose units (tdu). The thermal dose and harm that results are a function of both the intensity of the heat to which a person is exposed and the time for which they are exposed. For a protection based assessment of an installation handling flammable substances, the CD is set at the distance to 500 tdu.	Protection based analysis of installations where flammable substances are present.	The lower dose level is used to ensure adequate protection of sensitive and vulnerable populations. Populations of this type would include the elderly (e.g. - a care home) or children (e.g. - a school). For a given degree and extent of burn injury, elderly people are more likely to suffer fatality than younger people. Children have reduced tolerance to the mechanism of burns. Additionally, children can be particularly traumatised by the disfigurement that can be associated with burn injuries.
The individual at risk is always considered to be downwind of the release source.	A 'real' individual would not always be located at the same point. This assumption is part of HSE's approach of considering hypothetical house residents in their analyses. These hypothetical individuals are assumed to be located in a typical domestic dwelling and be present all of the time.	All analyses.	Although the hypothetical individual is assumed to be at a fixed location downwind of the source, the methodology for toxic substances does allow for people who are initially outdoors escaping indoors. The protection based analyses for flammable substances also allow for people trying to run away from an event and find shelter, where this is considered practicable. This approach is less conservative than that taken by some risk analysts, who do not consider the possibility of escape at all.
When a protection-based analysis is performed for an installation storing flammable, pressurised liquefied gas (like LPG) the calculations do not take into account any water spray systems that may be fitted to the storage vessels.	Water sprays on LPG vessels are intended to cool them in the event that they are exposed to heat from a fire.	Protection based analysis of installations where flammable substances are present.	Although water sprays might delay a BLEVE of the vessel, they are unlikely to prevent such an event, particularly when an intense flame is in direct contact with the vessel.
Consequence analysis models for dispersion of gases do not take into account the topography of the land around the release point.	The dispersion of gases that are denser than air can be strongly influenced by slopes and other topographical features. Currently HSE's dispersion models consider the surrounding terrain to be flat and featureless.	Consequence analysis - dispersion modelling of dense gas releases.	The 'flat terrain' assumption inherent in the use of these dispersion models is in keeping with the approach taken by the majority of risk analysts. Dispersion models capable of considering topography (the shape of the surrounding ground) are available as research and development tools, but are not yet in a suitable format for integration into a risk analysis.

Assumption	Explanation	Application	Comment
The average number of people in a typical dwelling is 2.5.	This figure becomes relevant when societal risk is calculated, it has no bearing on individual risk.	Societal risk calculations	HSE has commissioned work to establish realistic, site-specific population data for the areas around MHIs and MHPs. Should HSE adopt a position of considering societal risk more explicitly in LUP applications, this data would be used instead of the '2.5 people per house' assumption.
When determining the harm criteria to be employed for a particular toxic substance, HSE uses toxicological data for the most vulnerable species and strain reported, unless there is a good technical reason to do otherwise.	Data on the response of people to exposure to toxic gases is extremely sparse, even for common substances or substances that have been used as 'war gases', such as chlorine. HSE therefore has to resort to the use of data obtained from experiments on animals.	Consequence analysis - modelling the effect of releases of toxic substances	In view of the considerable uncertainty attached to establishing harm criteria for toxic substances, a conservative approach is considered appropriate.
HSE's risk analyses calculate individual risk to hypothetical householders (i.e - people indoors most of the time). However, HSE can be called upon to give LUP advice on developments involving large outdoor populations (such as open air markets or sports stadia)..	People located indoors receive some protection from exposure to a toxic gas cloud.	LUP advice for outdoor populations in the vicinity of MHIs handling toxic substances.	HSE has taken account of the lack of protection afforded to outdoor populations when considering the sensitivity level that should be applied to the proposed development. This is embodied within the PADHI (Planning Advice for Developments near Hazardous Installations, see ***Section 1***) system.
In HSE's analysis of pipeline risks, the size of the fireball that can result when a high-pressure gas pipeline ruptures is the maximum theoretically possible.	When a pipeline ruptures, a great deal of gas is released very quickly. This gives a cloud that is 'fuel rich' and burns as a fireball if ignited.	Risk analysis of pipelines.	HSE's pipeline risk analysis models are to be covered by the model evaluation exercise (see ***Section 2.4.1***).

Assumption	Explanation	Application	Comment
Releases from high-pressure gas pipelines are assumed to be vertical jets.	Rupture of a high-pressure gas pipeline is a violent event that results in disruption of the ground cover and formation of a crater around the point of failure. It is assumed that the gas is projected vertically upwards from this crater.	Risk analysis of pipelines.	There is evidence from accident reports, experiments and computer modelling work that the release of gas may be in directions other than vertical. HSE's pipeline risk analysis models are to be covered by the model evaluation exercise (see ***Section 2.4.1***).
The probability that a release of flammable material will be ignited.	Potential ignition sources for accidental releases are many and varied. On-site sources may include welding activity or equipment containing flames, such as boilers or furnaces. Off-site sources may include vehicles, traffic lights, smoking and domestic appliances.	Risk analysis of MHPs and MHIs handling flammable substances.	Currently ignition probabilities are established using expert judgement informed by research on the numbers of potential ignition sources present in different typical types of land use (residential, industrial, rural etc.). However, HSE has invested in further research in this area with a view to putting these values on a more rigorous basis in the future. It is partly because of the uncertainty associated with establishing ignition probabilities that many analyses of MHIs handling flammable materials are currently protection based.
Risk analysis studies for toxic substances like chlorine model failure of the vessel in two ways – release of the entire vessel contents upwards into the air; and release of the entire contents downwards, so that half is retained in the vessel bund. The vessel is assumed to be completely full when it fails.	The distance to which the cloud generated by a vessel failure remains hazardous depends on the quantity released to atmosphere. The larger the quantity, the greater the distance at which the cloud is still hazardous.	Risk analysis of installations handling toxic, pressurised liquefied gases (such as chlorine).	This assumption considers two different ways in which a chlorine storage vessel could fail catastrophically, representing the two extremes of a spectrum of possible failures. The assumption of 100% fill of the vessel is related to the Hazardous Substances Consent that the site would hold for storing the material. A site would be entitled to store this much material for as long and as often as they liked. Note that the kind of vessel failure event considered here is very different from a BLEVE.

5 SUMMARY AND CONCLUSIONS

5.1 REVIEW OF HSE'S RISK ANALYSIS METHODOLOGY

5.1.1 *Overall Conclusions*

A rigorous scientific validation of a risk analysis is not possible for the reasons explained in ***Section 2***. The approach taken has therefore been to review each element of HSE's risk analysis methodology in several different ways. The findings of the reviews are summarised in ***Table 5.1***.

On the basis of the reviews conducted, it is concluded that HSE's risk analysis methodology is generally fit for purpose. No evidence was found that would indicate that HSE's methodology is either excessively conservative or excessively non-conservative.

It should be noted that:

- at the time of writing, a separate project to perform a detailed evaluation of HSE's consequence analysis methods and models had not been completed; and,
- certain assumptions relating to HSE's approach to Hazardous Substances Consent were excluded from the scope of the review.

5.1.2 *Recommendations*

There are a few recommendations arising out of the reviews. The recommendations are that:

1. if in the future HSE seeks to apply QRA to types of plants more complex than those currently analysed using QRA, HSE consider supplementing the 'top down' (see ***Section 1.3.2***) approach to the identification of hazards with other methods;
2. HSE consider whether events resulting in unintended releases from vents (such as vessel overfill during transfers from road tankers) should be included in risk analyses for sites storing chlorine or other pressurised liquefied gases;
3. in the case of sites storing or using water reactive materials (such as sulphur trioxide), HSE consider whether the risk analysis should include scenarios where water is inadvertently added to the dangerous substance (for example, where water may be used for cleaning of tanks or equipment); and,

4. HSE perform further investigations into the significance of hazards arising from undesired chemical reactions and, if necessary, develop a means of including such hazards in a risk analysis.

Table 5.1 *Summary of Review Findings – Risk Analysis*

Risk Analysis Element	Review Approaches	Review Findings
Hazard Identification	Research comparing QRA approaches with accident experience	The approach used by HSE is generally adequate for the relatively simple installations for which HSE currently performs QRAs.
	Comparison with accident experience at UK COMAH establishments	The majority of incidents detailed in the accident records would have either been identified in a QRA, or would have been similar or less onerous in magnitude to the event(s) considered in a protection-based analysis. A few incidents were described which would not have been addressed by a QRA of the installation on which they occurred.
	Findings of the ASSURANCE project	The results obtained using HSE's approach were neither consistently pessimistic nor consistently optimistic in comparison with those of the other participants, particularly with respect to the most significant events.
Frequency Analysis	Comparison with frequency of incidents at UK COMAH establishments	Only a limited comparison was possible, since QRA studies have not been performed for all COMAH establishments in the UK. The historical frequency of accidents (representing an average over all establishments) was within the range of predicted accident frequencies for several different establishments.
	Independent peer review of HSE's failure frequency data.	The peer review found that the data used were generally of good quality and were a reasonable representation of the failure frequencies of the types of equipment considered.
	Findings of the ASSURANCE project	Agreement between the various participants was poor, but was improved somewhat when all participants used the same set of assumptions. HSE's results were not consistently the highest (most conservative) nor consistently the lowest (least conservative).
Consequence Analysis	Model Evaluation Exercise	Not yet completed
	Comparison of consequence modelling predictions with accident outcomes	In general reasonable agreement was obtained between the predictions of HSE's models and the outcomes of accidents as given in historical accounts, bearing in mind that there is significant uncertainty in the definition of the conditions under which most of the accidents occurred. Where there is disagreement it has been possible to identify reasons as to why this may be the case.
	Findings of the ASSURANCE project	There was poor agreement between the results obtained between the different participants. HSE's results were not consistently the most conservative or consistently the least conservative.
	Comparison of the HSE dangerous dose with other means of predicting the dose required to cause 1% fatality in the exposed population	HSE's dangerous doses for a range of toxic substances and for thermal radiation would generally result in risk estimates similar to, or lower than, those that would be obtained using other approaches.

Risk Analysis Element	Review Approaches	Review Findings
Risk Estimation	Findings of the ASSURANCE project	The estimates of individual risk at any given location varied widely between the participants, as reflected by significant differences in the sizes of the contours produced. The results fell into two groups – one set of teams predicting significantly larger individual risk contours than the other. The HSE results were in the middle of the group of smaller contours.
	Comparison of results obtained using HSE's RISKAT software with those obtained using SAFETI	Although reasonable agreement (in terms of the size of the individual risk contours produced) was obtained for chlorine, the level of agreement was poor for the other substances assessed. Neither model was consistently more conservative than the other.

5.2 REVIEW OF HSE'S PROTECTION BASED APPROACH

5.2.1 *Overall Conclusions*

The findings of the review are summarised in ***Table 5.2***.

The terminology used in relation to protection-based analysis is not well defined. Similarly, for a given type of installation, the reasons for resorting to a protection-based analysis, and the reasons for the selection of the particular event (or events) chosen to define the LUP zones are generally not well explained or documented.

As further research and development is performed, protection-based analysis may be replaced by risk analysis for some types of installation. In particular, adoption of fatality as the harm criterion (in the form of TROD) instead of dangerous dose would deal with some of the objections to using risk analysis in particular cases. However, even if risk analysis methods for all types of MHI were available, there may continue to be other reasons justifying the use of protection-based analysis. A protection-based analysis could still be appropriate where:

- the Hazardous Substances Consent documents contain insufficient information for a risk analysis;
- the surrounding population density and demand on land-use are low; and,
- a protection-based analysis would generate similar results (in terms of the sizes of LUP zones and the advice given) to those from a risk analysis.

5.2.2 *Recommendations*

The review of HSE's protection-based approach resulted in the following recommendations:

5. the terminology used in relation to protection-based analysis (*'worthwhile'* protection, *'unlikely but foreseeable'*, etc.) is better defined;
6. the relationship between the two levels of protection stated in the aim and the three LUP zones defined by the analysis is described;
7. HSE develops internal guidance for Inspectors on selecting events for use in protection-based analyses;
8. where protection-based analysis is used for installations of a given type, the reasons for adopting a protection-based approach, together with the rationale for selecting the event or events used in the analysis, are documented in such a form that the information could be released to interested parties outside HSE as required; and,

9. HSE continues to perform research into risk analysis methods so that some of the reasons for using a protection-based approach can be resolved.

With regard to the specific protection-based approach used for bulk LPG storage, it was noted that the choice of event for the analysis was influenced by the frequency of the BLEVE event currently assumed by HSE. It is recommended that:

10. the estimate of this frequency is updated and, depending on the outcome of this revision, that the selection of the event used in protection-based analyses of bulk LPG installations is revisited.

Table 5.2 Summary of Review Findings - Protection-Based Analysis

Review Area	Specific Subjects	Review Findings
General Considerations	Aims and Terminology	The terminology used is not well defined. It is not clear how the stated aims (which refer to two levels of protection) relate to the three zones used for LUP. The objections to use of protection-based analysis as stated in the original Risk Criteria Document remain valid (62).
	Reasons for Using a Protection-Based Approach	The general reasons stated for using a protection-based analysis are considered to be appropriate, considering the current limitations of risk analysis techniques. However, it is not always clear specifically which reasons have been used to justify use of protection-based analysis in a given case. Some (but not all) of the reasons for using a protection-based approach may be eliminated as research into risk-based analysis methods progresses.
	Selection of Event	Event selection is a critical step. However, there is no guidance for Inspectors on how to select a suitable event when performing a protection-based analysis of an installation of a type that has not been considered before. The justification for the selection of events for a given type of site is not always documented.
	Combination of Protection-Based Analysis Results	The current approach of 'merging' overlapping protection-based zones does not take into account the potential for increased levels of risk in the regions where the zones overlap. This problem could be avoided by use of risk analysis instead of protection-based analysis.
Analysis Approach for Bulk LPG Storage	Level of Harm	The level of harm arising from many of the major accidents at a bulk LPG establishment would be considerably worse than a 'dangerous dose', justifying the use of a protection-based approach. However, this objection could be dealt with by using a risk-based analysis with fatality as the harm criterion.

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(62) HSE (1989). *Risk criteria for land-use planning in the vicinity of major industrial hazards*. HMSO.

Review Area	Specific Subjects	Review Findings
	Uncertainty in Risk Analysis	Another reason for the adoption of a protection-based approach is that there is considerable uncertainty associated with the likelihood of some of the events that may occur, particularly the probability of ignition of flammable clouds and the frequency of a BLEVE (see below). Further research in these areas is recommended. It may be that, as an interim position, protection-based analysis is retained, but with the use of an event other than the BLEVE, to generate the LUP zones.
	BLEVE Frequency	The BLEVE frequency is not used within the analysis, but influences the selection of BLEVE as the event to be modelled. Estimates of BLEVE frequency in the technical literature vary widely, with a significant discrepancy between estimates based on historical data and those calculated using analytical techniques. The reasons for this discrepancy are not clear. Further research is recommended.

5.3 REVIEW OF ASSUMPTIONS USED

5.3.1 Overall Conclusions

The review of assumptions is summarised in ***Table 5.3***. All were found to be appropriate and / or in keeping with the approach taken by most risk analysis practitioners, with one exception. The assumption questioned is that relating to the amount of LPG in a vessel when it undergoes a BLEVE, for which a recommendation has been made (see ***Section 5.3.2***).

Table 5.3 Summary of Review Findings - Assumptions

Assumption	**Review Comment**
All of those people outdoors caught within a flash fire will be casualties.	The assumption used is not greatly different from those used by other risk analysis practitioners (63).
The extent of a flash fire is determined by the region in which the concentration of flammable vapour is half of the Lower Flammability Limit (LFL) or more.	The assumption used is defensible.
When calculating the effects of a BLEVE, it is assumed that vertical, cylindrical vessels are 80-90% full when the event occurs. Horizontal, cylindrical vessels are assumed to be 50% full.	The assumed fill levels are based on a consideration of the fill level that would have to be reached before the unwetted tank shell came into contact with impinging flames from a pool fire engulfing the vessel. Jet flame impingement does not appear to have been considered. A jet flame could be in contact with the unwetted vessel shell at higher levels than calculated for a pool fire. It is recommended that these assumptions are revisited.
The level of heat to which a building can be exposed before it catches fire is based on data for wood.	The figures used are generally in keeping with values quoted by other sources.
Accidental releases are generally modelled as being directed horizontally.	The assumption is in keeping with what is done by most other risk analysis practitioners. HSE does model vertical releases for events involving pipelines.
Use of 'dangerous dose' rather than fatality as the harm criterion.	The use of dangerous dose has been criticised by some as being overly conservative and inconsistent with the approach taken by the majority of risk analysis practitioners. HSE is considering the use of a risk of fatality based approach (see ***Section 1.3.4***).
When establishing the CD for an installation handling flammable materials using a protection based assessment, the thermal radiation level used is lower than the dangerous dose level.	The assumption used is defensible.
The individual at risk is always considered to be downwind of the release source.	Taken in the context of the overall methodology, the approach is less conservative than that taken by some risk analysts, but the assumption is defensible.
When a protection-based analysis is performed for an installation storing flammable, pressurised liquefied gas (like LPG) the calculations do not take into account any water spray systems that may be fitted to the storage vessels.	The assumptions used are defensible.
Consequence analysis models for dispersion of gases do not take into account the topography of the land around the release point.	The approach used is in keeping with that currently used by the majority of risk analysts.

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(63) Lees F P (2001). *Loss Prevention in the Process Industries*. Second Ed. Butterworth-Heinemann.

Assumption	Review Comment
The average number of people in a typical dwelling is 2.5.	HSE has commissioned work to establish realistic, site-specific population data for the areas around MHIs and MHPs. Should HSE adopt a position of considering societal risk more explicitly in LUP applications, this data would be used instead of the '2.5 people per house' assumption.
When determining the harm criteria to be employed for a particular toxic substance, HSE uses toxicological data for the most vulnerable species and strain reported, unless there is a good technical reason to do otherwise.	In view of the considerable uncertainty attached to establishing harm criteria for toxic substances, a conservative approach is considered appropriate.
HSE's risk analyses calculate individual risk to hypothetical householders (i.e - people indoors most of the time). However, HSE can be called upon to give LUP advice on developments involving large outdoor populations (such as open air markets or sports stadia).	The assumptions used are defensible.
In HSE's analysis of pipeline risks, the size of the fireball that can result when a high-pressure gas pipeline ruptures is the maximum theoretically possible.	HSE's pipeline risk analysis models are to be covered by the model evaluation exercise (see ***Section 2.4.1***).
Releases from high-pressure gas pipelines are assumed to be vertical jets.	There is evidence from accident reports, experiments and computer modelling work that the release of gas may be in directions other than vertical. HSE's pipeline risk analysis models are to be covered by the model evaluation exercise (see ***Section 2.4.1***).
The probability that a release of flammable material will be ignited.	HSE has invested in further research in this area with a view to putting these values on a more rigorous basis in the future. It is partly because of the uncertainty associated with establishing ignition probabilities that many analyses of MHIs handling flammable materials are currently protection based.
Risk analysis studies for toxic substances like chlorine model failure of the vessel in two ways – release of the entire vessel contents upwards into the air; and release of the entire contents downwards, so that half is retained in the vessel bund. The vessel is assumed to be completely full when it fails.	The assumptions used are defensible.

5.3.2 *Recommendation*

It is recommended that:

11. the assumptions relating to the amount of LPG in a vessel when it undergoes a BLEVE are revisited. This is particularly important if the BLEVE event is going to continue to be used for protection-based analysis of bulk LPG storage installations. It is believed that the amounts currently assumed by HSE could represent an underestimate in some cases.

5.4 *REVIEW FINDINGS RELATING TO BULK LPG STORAGE*

The review findings in relation to the protection-based analysis of bulk LPG installations have been collated in this Section for convenience.

5.4.1 *Overall Conclusions*

The level of harm arising from many of the major accidents at a bulk LPG establishment would be considerably worse than a 'dangerous dose', justifying the use of a protection-based approach. However, this objection could be dealt with by using a risk-based analysis with fatality as the harm criterion.

Another reason for the adoption of a protection-based approach for bulk LPG storage is that there is considerable uncertainty associated with the likelihood of some of the events that may occur, particularly the probability of ignition of flammable clouds and the frequency of a BLEVE. Further research in these areas is recommended (Recommendations 9 and 10). It may be that, as an interim position, protection-based analysis is retained, but with the use of an event other than the BLEVE, to generate the LUP zones.

The assumption used in the current analysis methodology relating to the amount of LPG in a vessel when it undergoes a BLEVE is questioned. A recommendation has been made (Recommendation 11).

5.4.2 *Recommendations*

The relevant recommendations are as follows:

9. that HSE continues to perform research into risk analysis methods so that some of the reasons for using a protection-based approach can be resolved;
10. that the estimate of the BLEVE frequency is updated and, depending on the outcome of this revision, that the selection of the event used in protection-based analyses of bulk LPG installations is revisited; and,

11. that the assumptions relating to the amount of LPG in a vessel when it undergoes a BLEVE are revisited. This is particularly important if the BLEVE event is going to continue to be used for protection-based analysis of bulk LPG storage installations. It is believed that the amounts currently assumed by HSE could represent an underestimate in some cases.

Annex A

Details of Incidents Reported to MARS

A1 ACCIDENT DETAILS

This Annex presents details of the accidents reported by HSE to the European Union's (EU's) Major Accident Reporting System (MARS) database, as described in ***Section 2.2.1*** of the main report. The details are provided in ***Table A1.1***.

Table A1.1 Accidents Reported to the EU MARS Database

Date	Description	Effect	Accident Type	Site Type	Category	Comment
26/10/1985	Failure of water seal on gas holder causing loss of natural gas. No ignition.	None	Release	Gas holder	1	Seal fires addressed (in protection based assessment)
13/02/1986	During unloading of a road tanker to storage, a vent valve on the transfer line was open when it should have been closed, allowing liquid chlorine into the main vent. The chlorine vapourised and escaped to atmosphere.	6 people hospitalised and 2 given first aid (all on-site)	Release	Bulk chlorine storage (chemical manufacturing)	3	Assessment only considers releases from parts of plant where dangerous substances normally present.
19/05/1986	A drain/wash line was left open when it should have been closed, allowing toluene to escape from an extraction column into the effluent discharge system and eventually into a tidal estuary.	Environmental damage	Release	Pharmaceuticals	2	Not relevant to LUP considerations.
15/05/1986	Release of ethylene oxide during dismantling of a valve for maintenance.	1 person hospitalised (on-site)	Release	Ethylene Oxide Storage (Petrochemicals Site)	1	Potential magnitude of event less than that for the representative event for this type of installation
15/03/1986	Explosion in a deodorisation unit, thought to be due to exothermic decomposition, followed by fire in the process building.	1 fatality (on site).	Explosion, Fire	Pharmaceuticals	4	HSE's methodology is based on what is allowed within the site Consent and would probably include failure of reactors etc. Whether deodorisation was covered would depend on what was defined in the Consent.
26/10/1986	Self-sustaining decomposition of mixed fertiliser following heating in a drying unit, with release of toxic nitrogen oxides and (possibly) chlorine	1 fatality and 6 injuries (on site). 12 people injured outside the establishment, with an estimated 10,000 affected.	Release	Chemicals manufacturing	4	HSE's written QRA methodology addresses storage of ammonium nitrate in warehouses. Whether or not drying operations would be covered would depend on what was defined by Consent.