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Development of methods to assess the significance of domino effects from major hazard sites

Prepared by
WS Atkins Safety & Reliability
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Development of methods to assess the significance of domino effects from major hazard sites

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The forthcoming COMAH regulations require the competent authority, responsible for enforcing them, using the information received from operators in notifications and safety reports, to designate groups of establishments where the likelihood or consequences of a major accident may be increased because of the location and proximity of establishments in the group and the dangerous substances present there. The operator of any establishment in a group thus designated shall also pass appropriate information about the establishment to other establishments in the group to enable them to take account of the nature and extent of the overall hazard of a major accident in their major accident prevention policy documents, safety reports and on-site emergency plans.

This project examines the mechanisms by which these 'domino effects' may be realised and reviews the methodologies suitable for identifying and assessing them. Whilst many existing techniques have been developed on an individual basis, little previous work has been attempted to address the subject as a whole. It is concluded that a three stage approach could be used, starting with an examination of maximum hazard ranges, followed as required by an assessment of event frequencies and finally a combined, fully Quantified Risk Assessment, covering all establishments in a group.

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SUMMARY

This report presents the results of a study to investigate and propose means of assessing the potential for a domino interaction between groups of sites in the event of a major accident at one of the sites. The report identifies mechanisms for domino escalation, and investigates methodologies for assessing inter-site escalation and associated damage criteria. Such methodologies will be required by the HSE in order to meet their obligations for assessing safety reports submitted by major hazard sites under the EC COMAH Directive and for giving land use planning advice to local authorities. Article 8 of the COMAH regulations requires that groups of sites with a potential for domino events to be identified so that information is exchanged between sites in order to improve safety on both sites. The information on these escalation events is to used by the sites to inform the public of possible action in the event of an emergency and is to be incorporated in off-site emergency plans.

Factors relevant to domino escalation and various mechanisms for obtaining a domino event have been discussed. This has included consideration of direct and indirect mechanisms, and the effect of mitigation / safety systems.

A review of previous work has been undertaken to identify methodologies which have been used in assessments on groups of major hazard sites. This includes the identification criteria which have been used to assess plant failure when subjected to thermal radiation, blast, missile impact and the indirect effects associated with toxic releases.

Although a number of articles were reviewed which covered domino effects it was found that no one paper provided an overall coherent approach. Therefore, various possible approaches for assessing domino escalation have been considered in this study. It is proposed that a three stage methodology be adopted involving maximum hazard range determination, maximum frequency limitation and finally a risk based approach.

Guideline methodologies based on rapid assessment techniques have been incorporated into the first stage methodology for determining the maximum hazard range. These have mainly covered fire and explosion hazards. Recommended distances for the hazard ranges for missile effects have also been included. The hazard distances associated with toxic releases were dependent on the on the particular toxicological effects and as such it was not possible to generalise without reference to specific examples.

The implications of incorporating domino effects in land use planning procedures were discussed. It was considered that the present land use planning guidelines could be used for assessing the acceptability of a development within the vicinity of two co-located sites with a domino potential provided the two sites were treated as a whole and the overall risks calculated and used in the analysis.

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ABBREVIATIONS AND ACRONYMS

ACMH	-	Advisory Committee on Major Hazards
AIChE	-	American Institute of Chemical Engineers
ALARP	-	As Low As Reasonably Practicable
AQ	-	Airborne Quantity
ARI	-	Approximate Risk Integral
BLEVE	-	Boiling Liquid Expanding Vapour Explosion
CEI	-	Chemical Exposure Index
CIMAH	-	Control of Industrial Major Accident Hazards
COMAH	-	Control of Major Accident Hazards
EC	-	European Communities
ERPG	-	Emergency Response Planning Guideline
FAFR	-	Fatal Accident Frequency Rate
FAR	-	Fatal Accident Rate
F&EI	-	Fire and Explosion Index
HSE	-	Health and Safety Executive
LCCF	-	Loss Control Credit Factors
LC50	-	Lethal Concentration (50% fatality)
LD05	-	5 per cent Lethal Dose
LFL	-	Lower Flammability Limit
LPA	-	Local Planning Authority
LPG	-	Liquefied Petroleum Gas
MHAU	-	Major Hazard Assessment Unit
MPPD	-	Maximum Probable Property Damage
QRA	-	Quantified Risk Assessment
ROSOV	-	Remotely Operated Shut Off Valve
SRI	-	Scaled Risk Integral
STARS	-	Software Toolkit for Advanced Reliability and Safety Analysis
TNT	-	Trinitrotoluene
VCE	-	Vapour Cloud Explosion

1. INTRODUCTION

Article 8 of the European Communities' proposed Council Directive on the control of major hazards involving dangerous substances (COMAH) [1] states

> *Member States shall ensure that the competent authority, using the information received from the operators in compliance with Articles 6 and 9, identifies establishments and groups of establishments or where the likelihood and the possibility or consequences of a major accident may be increased because of the location and the proximity of such establishments, and their inventories of dangerous substances.*
>
> *Member states must ensure that in the case of the establishments thus identified:*
>
> *a) suitable information is exchanged in an appropriate manner to enable these establishments to take account of the nature and extent of the overall hazard of a major accident in their major accident prevention policies, safety management systems, safety reports and internal emergency plans;*
>
> *b) provision is made for co-operation in informing the public and in supplying information to the competent authority for the preparation of external emergency plans.*

Thus the article includes the requirement that consideration is given by the regulatory authority to the so called "Domino Effect". It requires that the Competent Authority identifies those establishments which are so close together that the probability and/or consequence of a major accident are increased. In the UK the "Competent Authority" will be the Health and Safety Executive (HSE). HSE therefore need to consider how this requirement may be met in the context of existing regulations concerned with Land Use Planning, which are also currently under review.

In order to reduce the risk of domino effects, the operators of establishments where there is a potential for this to occur are required to co-operate in devising measures to prevent, prepare for and respond to major accidents.

In order to begin to address these issues, the HSE requested WS Atkins in 1995 to undertake an initial literature search in order to identify previous work in the area of hazardous event escalation, including the identification of incidents where escalation had occurred. However, it was not within the scope of this initial project on hazardous event escalation [2] to provide any detailed information on how domino events should be assessed.

The HSE therefore requested that WS Atkins undertake a more detailed study in order to develop some possible methodologies to assess the significance of domino effects from major hazards, which is the basis of this study. The main objectives of this work are:

- Review previous work on this topic
- Review methodologies for determining the additional risks from domino effects between sites
- Recommendations for criteria for determination of groups of sites with the potential for significant domino interaction
- Examination of MHAU Land Use Planning methodology to determine possible modifications to take account of domino effects

2. DEFINITION AND CLASSIFICATION OF DOMINO EFFECTS

There is no generally accepted definition of what constitutes domino effects, although various authors have provided suggestions. However, if the assessment of "domino effects" is to be part of a legal requirement, then it is important that an unambiguous definition is agreed.

This is an area which requires some discussion, including some examples of what would and wouldn't be classified as a domino event.

2.1 Current Definitions

The following definitions were identified in a review of relevant documents:

Lees (page 65, [3]) defines the domino effect as:

> *A factor to take account of the hazard that can occur if leakage of a hazardous material can lead to the escalation of the incident, e.g. a small leak which fires and damages by flame impingement a larger pipe or vessel with subsequent spillage of a large inventory of hazardous material.*

Bagster and Pitblado [4] give a similar definition for a domino incident:

> *A loss of containment of a plant item which results from a serious incident on a nearby plant unit.*

In the Third Report of the Advisory Committee on Major Hazards [5] the domino effect is defined as:

> *The effects of major accidents on other plants on the site or nearby sites.*

and

> *A loss of containment incident which interferes with the operation of other adjacent plant so that further loss of containment occurs.*

These definitions are all reasonably practical, but may need to be refined/clarified in order to avoid any possible confusion in the application of the forthcoming COMAH Regulations.

2.2 Differentiation between Domino Events and Escalation

In relation to major accidents, it may be argued that the word "domino" implies a subtly different meaning to the word "escalation". Domino implies escalation of an accident to another area or plant and therefore domino is considered to be a subset of escalation, i.e. all domino events are examples of escalation - but not necessarily vice versa.

Escalation could be a small leak, which grows larger, and is then ignited (e.g. Octel [6]). It only becomes a domino event if the fire spreads to other areas or causes a BLEVE which impacts on other areas of plant.

There is a grey area in deciding how far away Plant B has to be from Plant A for an event at A spreading to B to be classed as a domino event. However, for the purposes of this study, it was considered that any event which spreads from one site to another must be classed as a domino event.

2.3 Direct and Indirect Domino Effects

It may be useful to categorise domino effects into the various types that may occur. There are two principal categories which have been identified i.e. *direct* and *indirect*.

DIRECT

Where the domino vector directly causes a loss of containment/fire/explosion at a nearby plant.

INDIRECT

Indirect effects may be brought about by plant/equipment failures due to the initial event or by the impact of the initial event on operators controlling the plant/equipment.

Indirect domino effects may occur where the domino vector impacts on either:

a) *A control system* causing control of a process to be lost - leading to potentially hazardous events.

b) *A mitigation system* preventing action being taken to mitigate the event and stop it spreading to other areas. Fire protection systems, such as fire water mains, sprinkler systems are often knocked out in an incident. Isolation valves may be rendered ineffective or the incident scenario inhibits access to isolation valves thus preventing mitigatory action being implemented.

c) *Other utilities*
A minor event could cause the loss of utilities such as electrical power, water supplies, communications, which may make accidents more likely to spread and make them more difficult to mitigate.

d) *People*
If an event impacts on people controlling an adjacent hazardous operation, then there is a potential for domino effects. Personnel could be either incapacitated and therefore unable to initiate emergency response or may have to be evacuated prior to initiating emergency response actions.

The first three indirect effects emphasise the need for diverse and robust safety systems within a plant. The last indirect effect could point to the need for automatic shutdown controls rather than reliance on human intervention.

2.4 Domino Events Timescales and Hazard Contours

The vectors by which the domino effect is translated from one plant area to another tend either to act immediately (i.e. over a period of seconds) or are gradual (i.e. acting over a period of minutes or more). This is important when it comes to considering the potential for control and mitigation of domino effects. The following broad categorisations can be made:

Immediate	Gradual
Missile	Fire spread
Fireball engulfment	Prolonged thermal radiation
Flash fire	Toxic gas cloud dispersion
Blast overpressure	

The immediate vectors are essentially those where there would be no time for any mitigatory action to be implemented once the initial event had occurred, whilst with the gradual vectors it may be possible to mitigate or even prevent the domino escalation by appropriate actions.

It is also possible to envisage very gradual effects, such as might occur if a corrosive liquid leaks from one plant, eventually causing a catastrophic failure several months later at another plant. For the purpose of this report this vector has been neglected since it has been assumed that this event should be detected and resolved during routine maintenance and inspection thus preventing this type of domino event.

The domino timescales are also important in determining whether, from a risk assessment point of view, the two events are treated as essentially independent and their effects on local populations are quantified separately or whether the effects of the 'super event' need to be analysed [7].

If accidents on two neighbouring sites were treated as independent events then the hazard contours could be underestimated in some cases. For example, if there was a fire on each site which was analysed separately and an overall hazard plot for the two sites produced by merely overlaying the thermal radiation contour plots on each other and ignoring any thermal radiation reinforcement, then the hazard zones would not extend as far as if it was assumed that that the actual thermal radiation from both fires was additive. This can occur for either Fireball-Fireball or BLEVE-Fireball situations. Synergistic effects on hazard contours are considered unlikely for all other combinations of initiating and secondary events, either because of the time delay between the initiating and domino events or because the effects are so different e.g. toxic effects and fire effects.

Another effect of the 'super event' that needs to be considered is the possible increased individual and societal risk within the existing hazard contours. This may occur if there was a insufficient time delay between the initiating event and the domino event to allow rescue and evacuation of personnel to a safe distance before the secondary event occurred. For example an explosion on one site could cause non-fatal injuries on another but people affected may not be rescued or be able to be evacuated before a domino toxic release occurred. However, in any analysis of domino events care must be taken to avoid double counting of fatalities i.e. people killed by fire / explosion should not be counted in determining the consequences of subsequent toxic effects or vice versa.

The situation is complicated further if a third plant is within the existing hazard contour of either or both the initiating or domino site or in the extended hazard contour for the combined plants

The following matrix has been produced to highlight possible effects from combinations of events and is expanded in the subsequent paragraphs.

Initiating Events	Domino (Secondary) Event					
	BLEVE	Cold Catastrophic Failure (Fireball)	Explosion	Jet Fire / Pool Fire	Flash Fire	Toxic Release
BLEVE	Separate	Extended hazard contour	Separate	Separate	Separate	Separate
Cold Cat. Failure (Fireball)	Separate	Extended hazard contour	Separate	Separate	Separate	Separate
Explosion	Possible Increased fatalities	Possible Increased fatalities	Possible Increased fatalities	Possible Increased fatalities	Possible Increased fatalities	Possible Increased fatalities
Jet Fire / Pool Fire	Separate	Separate	Separate	Separate	Separate	Separate
Flash Fire	Separate	Separate	Separate	Separate	Separate	Separate
Toxic release	Possible Increased fatalities	Separate	Possible Increased fatalities	Possible Increased fatalities	Possible Increased fatalities	Possible Increased fatalities

Table 2-1 Domino Event Matrix

BLEVE - BLEVE

Initiation of a BLEVE requires sustained flame impingement, therefore, a secondary event involving a BLEVE is only expected to result from the initiating BLEVE event on an adjacent site causing secondary loss of containment either through missile or thermal radiation effects leading to a jet or pool fire which causes the BLEVE some minutes later. In this case there will be a considerable time period between the thermal radiation effects from the BLEVE fireballs and it would be appropriate to evaluate the effects separately. In reality, if there has been an initial BLEVE it is expected that the emergency services will have evacuated anyone at risk or be in the process of doing so. It has been assumed that onlookers would be prevented from approaching the site and thus they would not be additional casualties of the second BLEVE.

BLEVE - Fireball

A fireball on an adjacent site could be caused by missiles generated by a BLEVE impacting on pressure vessels containing liquefied flammable gases. Thus a cold catastrophic failure of the vessel could result a few seconds after initiation of the BLEVE. It is expected that ignition could result from missile impact and the fireball could occur at approximately the same time as the fireball resulting from the initial BLEVE. Thus if the two fireballs are in close proximity their two thermal radiation fields could reinforce each other.

BLEVE - Explosion

This could result from the same scenario as BLEVE - Fireball except delayed ignition occurs. The two effects are not expected to occur close together. The consequences of any explosion would be the same whether injuries are sustained from the BLEVE on the domino site or not but risks could be overestimated by double counting. Pessimistically therefore the events could be analysed separately.

BLEVE - Jet Fire / Pool Fire

The principal mechanism for initiation of a jet fire or pool fire is expected to be missile damage. Given that pool fires will take time to establish to their maximum extent, by which time the BLEVE fireball is expected to have decayed, then the two can be considered as separate events. Although jet fires are expected to form much quicker than pool fires, their thermal radiation fields are not expected to reinforce that of a BLEVE fireball to any significant extent. As above, the consequences of any jet or pool fire would be the same whether injuries are sustained from the BLEVE on the domino site or not but risks could be overestimated by double counting.

BLEVE - Flash fire

This is expected to arise in a similar manner to the BLEVE - Explosion scenario except that the delayed ignition is not expected to produce damaging overpressures. Due to the time delay, these events are not expected to reinforce each other.

Fireball - All secondary Events

Fireballs are expected to arise principally from cold catastrophic failure of pressure vessels. These will give similar effects to BLEVEs except that the fireballs will be smaller due to the lower degree of superheat and the number of missiles could be greater due to the brittle failure mechanism rather than the ductile failure normally associated with BLEVEs. The possible interactions are thus considered to be similar to those for BLEVE initiating events.

Explosion -All Secondary Events

Explosions could cause injuries on the domino site which would prevent escape before a secondary event occurred. No additive offsite effects would be expected because of the likely time delay between the initial event and a domino event. For Explosion-Explosion scenarios, although the explosion physical effects (i.e. blast waves) are not additive their offsite consequences might be additive. For example, buildings might be initially damaged in the first blast wave and the second blast could then cause them to fall down. However, if the buildings were further away, such that the effects were restricted to broken windows and casualties from flying glass, then the second blast wave is unlikely to lead to synergistic effects

Jet Fire / Pool Fire - All Secondary Events

These are expected to be primarily an onsite escalation mechanism rather than an inter-site domino mechanism. If the pool fire or jet fire is large enough to cause a further fire or explosion on a secondary site the time lag between events is unlikely to bring about any synergistic thermal radiation or other effects.

Flash Fire - All Secondary Events

This is similar to the jet/pool fire situation, although injuries on the secondary site may be more likely, which could affect the ability for escape from the domino event, the time lag between events would be considerable. Some double counting may arise if the events are considered separately.

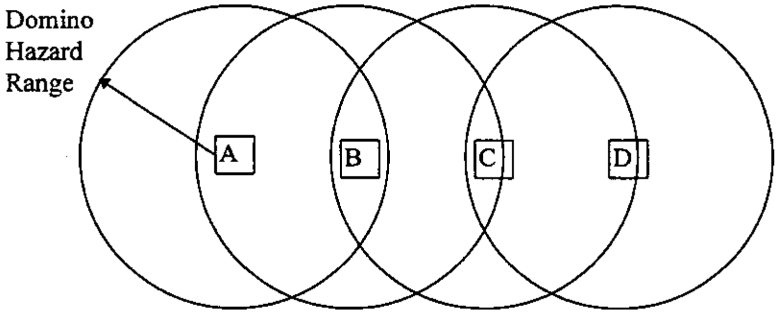
Toxic Releases-All Secondary Events.

Toxic releases could cause operators on an adjacent site to be overcome thus bringing about a secondary event from which they could not escape. Most plants can run for considerable periods without requiring operator intervention and only certain labour intensive processes would be vulnerable. A definite exception to this is Toxic Release-Fireball since no mechanism can be identified.

2.5 Multiple Domino (Chain Reaction) Effects

It should be remembered that domino events can act in a chain, so that a number of plants may become involved. For example, a fire spreading from one tank farm to another, to another etc. Whether or not the risks associated with such multiple domino events are significant depends on the probability of each domino interaction. If the probability of each interaction is close to 100%, then a chain of domino events is likely. However, if the probability of each individual domino effect is around 10% or less, then the risks associated with multiple domino effects are probably not significant. These multiple effects are sometimes termed second, third, etc. order knock-ons.

For example, consider 4 identical plants A, B , C and D, each of which has a site area represented by a square and a domino hazard range which is represented by a simple circle centred on the plant.

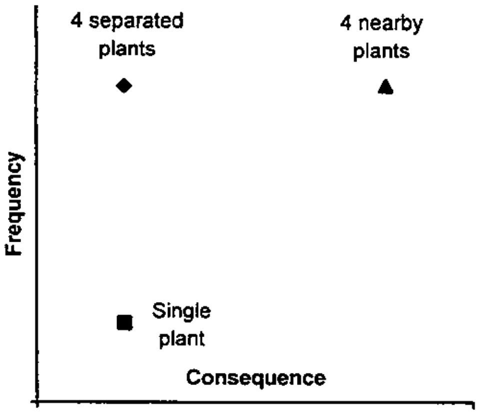


An event at Plant A may have domino effects at B, which in turn may lead to domino effects at plants C and D.

One of the important points to note about domino effects, particularly in the case of multiple domino events as described above, is that the close proximity of plants implies that in the event of an accident, not only are the consequences greater, but the likelihood of these increased consequences is also multiplied. For example, consider the 4 plants, i.e. Plants A, B, C and D, each of which is assessed as having a probability of 10^{-4}/y of an accidental fire of 10 megawatts (MW). If the plants are sufficiently close together that domino escalation is considered to be inevitable, then the overall risk would be that of a larger fire of 40 MW with a higher frequency of 4×10^{-4}/y.

This results from:

- the overall frequency of a fire being the sum of the individual plant fire frequencies, i.e. 10^{-4}/y for Plant A + 10^{-4}/y for Plant B + 10^{-4}/y for Plant C + 10^{-4}/y for Plant D, i.e. 4×10^{-4}/y and
- the probability of a fire escalating to involve all plants (i.e. 4 x 10 kW) being calculated from the probability escalation to a second plant (probability = 1) x escalation to a third plant (probability = 1) x escalation to a fourth plant (probability = 1) = 1



2.6 Domino Event Definition

In terms of the COMAH regulations it is proposed that the following definition of domino event should be used:

> *A domino event is defined as a loss of containment incident on a major hazard installation which has resulted either directly or indirectly from a loss of containment incident at an adjacent or nearby major hazard installation. The two events must occur either concurrently or in close sequence and the hazard range from the domino event must extend beyond that of the initiating event.*

Direct mechanisms of causing domino events comprise vectors such as thermal radiation from fires, blast from explosions and missiles resulting from catastrophic fragmentation of pressure vessels. Indirect mechanisms include vectors such as human factors (e.g. delay in launching the on-site emergency plan due to incapacitation of key staff) or loss of either control functions, mitigation systems or utilities.

Contents

3. TECHNICAL APPRECIATION OF DOMINO EFFECTS

3.1 Domino Mechanisms

There are four mechanisms or vectors by which a domino effect may be propagated from one plant to another and these can be summarised as:

- Fire
- Explosion
- Toxic release
- Other hazardous releases

In order to determine whether domino effects from Plant A are likely to occur at Plant B, it is necessary to consider certain factors; these being:

i) The magnitude of the consequence at Plant A

ii) The likelihood that this consequence will cause harm/damage at Plant B

iii) The likely level of harm/damage at Plant B

3.1.1 Fire

There are two major ways in which domino events can occur due to fire:

i) Thermal radiation

ii) Fire spread

3.1.2 Explosion

There are two major ways in which domino events can occur due to explosion:

i) Blast overpressure

ii) Missiles

3.1.3 Toxic Release

There is only one way that domino events can occur due to toxic releases, viz, if the toxic release has some influence on human behaviour, such as causing incapacitation, panic or evacuation. A toxic release may thus lead to:

i) Incorrect human action (errors of commission)

ii) Lack of human action (errors of omission)

3.1.4 Other Hazardous Releases

Other hazardous releases might include releases of corrosive or oxidising material. A release of corrosive material might spread to another area, where it could cause a corrosive attack on other plant items containing hazardous materials, resulting in further releases. As discussed in Section 2.4 this is not included within the scope of this report.

One example of a hazardous oxidising material that could be released is liquid oxygen. This could result in the initiation of spontaneous fires on a adjacent plant due to the oxygen rich atmosphere resulting in an effective decrease in the auto-ignition temperature of many materials.

Releases of cryogenic liquids or even the auto cooling effects of high pressure gas jets could result in low temperature embrittlement of steel and hence failure of vessels or pipework. However, these are much more likely to be confined to the initiating plant area rather than adjacent plants and therefore this vector has not been developed further.

3.2 Factors Relevant to Domino Effects

For any particular type of domino mechanism, such as fire or explosion, there are a number of factors that would influence whether domino escalation was likely to take place.

3.2.1 Fire

Fire can provide a vector for domino escalation, either through fire spread or thermal radiation. Factors affecting each of these have been listed below:

<u>Fire Spread</u>

- Availability of a route for the fire/burning material/gas/liquid to spread along (such as open ground, roads, natural or man made drainage channels, drains etc.)
- Proximity of combustible material
- Fire walls
- Ditches, dikes, slopes, bunds, kerbs to prevent spread of burning liquid (topographic effects)
- Flashover effects
- Active fire prevention may be possible if fire spread is gradual
- Effect of wind spreading fire
- Delay in ignition of flammable releases may cause significant escalation/domino effects
- Ventilation of fire
- Communication between plants

Careful consideration needs to be given as to whether "fire spread" events should be classified as domino events. A fire may spread due to burning liquid flowing from one plant area to another, where it causes further hazardous events, or else a fire could spread via combustion of intervening combustible material. It is not always obvious whether such events are simple accident escalation, or whether they are domino events. The possibility of such events arising as a result of combustion of intervening site vegetation can be minimised by regular application of weedkiller, etc. similarly, the potential for fire spread due to combustion of extraneous stocks of feed, product or waste material can be minimised by good housekeeping.

<u>Thermal Radiation</u>

- Passive fire protection
- Fire walls
- Line of sight effects (blocking by other structures, vessels, walls)
- Active fire protection (water/foam sprays)
- Fire Load (Intensity and duration)
- Flaring / dump tanks to reduce the inventory of the escaping material.

3.2.2 *Explosion*

Explosion can provide vectors for domino escalation in terms of the effects of blast overpressure and missiles. Factors relevant to each of these are listed below:

Blast Overpressure

- Blast walls
- Shielding by structures/vessels
- Blast wave amplification effects
- Vessel supports
- Vessel thickness
- Collapse of material above target
- Orientation of target to blast wave
- Weight of vessel inventory

Missiles

- Minimum mass/velocity required to cause damage
- Missile trajectory
- Missile shape (i.e. drag area, drag coefficient, lift area, lift coefficient, impact area)
- Vessel thickness / material of construction / pre-stressing levels
- Shielding by other structures
- No need to consider missile effects in areas definitely destroyed by blast
- Distribution of missile sizes
- Target size/length
- Number of pipes close together

3.2.3 *Toxic Release*

Factors relevant to consideration of the effects of toxic releases and how these might contribute to domino escalation are listed below:

Dispersion

- Instantaneous, short duration or continuous release
- Wind speed and direction
- Weather conditions

Harmful Effects

- Impact on operators / fire brigade personnel
- Dependent on method of operation of plant
- Ability to shut down plant safely, if a problem occurred
- Rapid safe shutdown mechanism at target plant (i.e. a single button)
- Interruption of hazardous operations, e.g. tanker off-loading
- Affected plant control systems, manual or automatic
- Toxic gas ingress (particularly into control rooms, emergency planning centres)
- Operating / emergency instructions

A toxic release will only cause domino escalation if it impacts on the operators of another plant, or if it prevents operators/fire brigade taking action to mitigate the initial release before it affects other areas.

3.3 Mitigation of Domino Effects

There are many factors that can prevent the occurrence of domino incidents via mitigation of the incident loss of containment accident. The following are examples of safeguards or factors in the control and mitigation of loss of containment accidents.

- Isolation Time
- ROSOVs, Excess Flow Valves
- Available Inventory
- Separation
- Bunds
- Fire Walls
- Blast Walls
- Operator Action
- High Integrity Design
- Fire Detection
- Gas Detectors
- Smoke Detectors

These mitigatory measures can be considered in terms of their effectiveness in blocking the domino escalation mechanisms, such as:

- Thermal Radiation
- Fire Spread
- Explosion Blast
- Missiles
- Hazardous Release

This is illustrated in Table 3-1.

Mitigation Measure	**Domino Mechanisms**				
	Thermal Radiation	**Fire Spread**	**Explosion Blast**	**Missiles**	**Hazardous Release**
Isolation Time	□	□	□	□	□
ROSOVs, Excess Flow Valves	□	□	□	□	□
Available Inventory	□	□	□	□	□
Separation	□	□	□	□	□
Fire Walls	□	□	□	□	□
Blast Walls	□	□	□	□	□
Operator Action	□	□	□	□	□
High Integrity Design	□	□	□	□	□
Fire Detection	□	□	□	□	□
Gas Detectors	□	□	□	□	□
Smoke Detectors	□	□	□	□	□

Table 3-1 Efficacy of Domino Mitigation Measures

3.4 Prevention of Domino Hazards by Initial Plant Design

Once a plant has been built, it is often too late to remove the danger of domino effects, either from or to the surrounding plant. Therefore consideration should be given to domino effects at the planning and design stage of a new plant. There are four aspects to be considered at the initial plant design, these being:

3.4.1 Spacing Between Plants

The physical separation between plants is one of the most important factors that can only be satisfactorily incorporated at the plant design stage.

3.4.2 Segregation Policy

As a general rule, it makes sense to separate vulnerable plants from high hazard plants, particularly if the vulnerable plant also represents a large hazard.

3.4.3 Site Features

Sloping terrain, dikes, embankments, waterways, etc. can be used to help ensure that domino events are less likely.

3.4.4 Robust Safety Systems

Although robust safety systems can be retrofitted during a plant's lifetime, these are best considered and incorporated at the initial plant design stage The effectiveness of these safety systems will depend on the particular accident sequence. Some will be designed to inhibit the development of the initiating incident on Plant A so that it does not develop to a size where it can impact on Plant B or last long enough to cause damage. Others will be included to reduce the effects of the consequences. Robust safety systems include the following:

- Fire rated valves
- Active/passive fire protection
- Automatic shutdown
- Blast walls
- Protection from missiles
- Hazardous materials inventory control

3.5 Review of Past Domino Accidents

A review of data relating to hazardous event escalation has been previously undertaken [2] which has involved examination of incident databases and a wide variety of literature sources. The purpose of the work was to gain a better understanding of the causes of hazardous event escalation and the mitigation measures that ensure minor accidents do not evolve into disasters.

This previous report did not specifically differentiate between escalation which occurred between process plant items on the same plant or site and the domino escalation which occurred between different plants.

Although the information in the report on some of the incidents was limited, as expected, accidents leading to escalation on the same site appeared to be much more common than escalation to an adjacent site.

Examples of the incidents involving the main domino vectors can be drawn from the compiled information.

- Running pool fire resulting in fire spread - Cleveland Ohio 1944
- Explosions leading to explosions - Texas City 1947
- Explosions leading to missile generation and resulting fires- Crescent City 1970, Romeoville 1984

- Spread of flammable material along a water course leading to remote explosion - Hearne Texas 1982
- Unconfined vapour cloud explosion leading to fire - Beek Netherlands 1975
- Explosion leading to toxic release - Baton Rouge 1976
- Uncontrolled reaction in unattended plant following initial explosion - Louisville 1965
- Tank to tank fire spread - Sandwich Massachusetts 1980
- BLEVE leading to BLEVE - Mexico City 1984
- VCE leading to BLEVEs - Feyzin
- Explosion leading to disruption at nearby industrial sites - Flixborough 1974 (leading to loss of cooling water to British Steel blast furnaces)

Although no direct example could be found of a toxic release resulting in escalation, the direct response to a toxic release involving evacuation of staff could produce a similar result to that in the Louisville incident in which the factory was evacuated following a blast in a neoprene plant and a violent decomposition of acetylene / chlorobutadiene occurred approximately 90 minutes afterwards.

Information from this survey has been used by the HSE to produce a spreadsheet format in order to enable further analysis. This has resulted in nearly 140 incidents being searchable under different criteria. Summary information has been presented on breakdown of incidents by year, by country / region and by substance [8].

4. LITERATURE SURVEY / REVIEW OF PREVIOUS WORK

4.1 Introduction

A review of previous information on methodologies for assessing domino effects was undertaken. Databases were searched using keywords which included the following:

- domino
- escalation
- cascade
- siting
- Site Layout
- Knock-on

These were used in conjunction with other keywords such as Chemical Plant, in order to eliminate irrelevant papers.

The titles of papers obtained by the literature survey were reviewed and appropriate papers were identified and obtained. The content of these papers is reviewed in the next section. These papers have been discussed in notional chronological order.

A number of other reports were reviewed which were essentially techniques used for determining plant spacing and layout based on hazard indices.

In addition a number of documents are known to recommend spacing between process plants, plant areas and items of equipment. These are briefly mentioned and illustrated with an example table. However, they were not considered appropriate for domino identification or control.

4.2 Published Articles

ACMH [5] identified the potential for domino effects and highlighted the need to consider their effects. Domino or 'knock-on' events were considered to refer to a loss of containment incident which interfered with the operation of another site. They concluded that the circumstances surrounding such postulated events required examination on an individual basis and that the methodology used in the process industry should be used in such reviews. Such analyses were subsequently used in the Canvey Island investigations.

The Canvey Island Study [9, 10] was one of the first risk assessments of a multi chemical site complex. The Terms of Reference for the Canvey study were:

> *'In the light of the proposal from United Refineries to construct an additional refinery on Canvey Island, to investigate the overall risks to health and safety from any possible major interactions between existing and proposed installations in the area, where significant quantities of dangerous substances are manufactured, stored, handled, processed and transported or used, including the loading and unloading of such substances to and from vessels moored at jetties; to assess the risks; and to report to the commission.'*

In order to meet these objectives, the study considered the potential for escalation of any fire or similar incident at one of the installations due to the effects extending offsite. In addition it also took into account the chance that a small incident might lead to a large one.

Examples of possible interactions covered in the study include:

a) the effect of an explosion in the vehicle filling area at the Shell UK oil refinery associated with one storage area being capable of transmitting a shock wave to the other storage area, and
b) the possibility of tank failure on the Mobil site by impact of a missile from the neighbouring Calor Gas site.

The most significant events with a potential for interaction with adjacent plant were considered to be unconfined vapour cloud explosions from large releases of flammable gases and missiles produced by explosions.

The assessment of domino or knock-on effects was included in an explicit manner, e.g. in the case of assessing pressure vessel failure rate the following approach was taken:

> *The SRD view is that where there are internal and external failures of possible significance in particular cases (e.g. vapour cloud explosions, overpressurisation, fire engulfment, missile impact) the frequency of such events should be analysed separately and added to the spontaneous failure rate of 10^{-5} per vessel year from failure modes such as fatigue.*

In the case of analysis of interactions due to large flammable releases, their methodology was as follows:

> *The dispersion range for each identified release case is evaluated. The effect on the surrounding population of all such releases is considered: in some cases this may be negligible. However, all other plant within the explosion range containing hazardous materials, the release of which would affect population, can also be identified. The consequences of any such subsequent releases will already have been evaluated for intrinsic failures of the particular plants: the frequency of occurrence must be increased to take account of the interaction. This is done by construction of an event tree which describes the required sequence of events leading from the initial release to the knock-on release.*

The report assessed the risk to people in the surrounding area from the existing industrial installations and from proposed developments in the Canvey Area. As such the tolerability of plant siting was assessed in numerical terms. Individual risk and societal risk were evaluated and compared against numerical criteria. Thus the siting of plant was not explicitly studied in terms of assessing the sensitivity of risk to the public with inter-site separation distance, but it was implicitly taken into account in the overall assessment.

The precise definition of domino effects used in the study was unclear since it was stated in the report that:

> *the assessment team assessed the likelihood and possible effects of various kinds of accidents, including a number resulting from interactions between separate activities and installations in the area, though none would produce the so-called domino effect.*

Hence, it might be implied from the above statement that their definition of domino effect was not interaction between 2 plants but it would have to involve 3 or more.

There is a lack of description in the methodology statements regarding the criteria used in assessing the potential for plant-plant interaction effects, although the following threshold value was quoted:

Major damage distance 0.075 atmospheres (1.1 psi).

Highland Council [11] (formerly Highland Regional Council) commissioned Cremer and Warner to undertake studies which would enable them to assess the acceptability of proposed developments in their region. A document was produced entitled 'Guidelines for Layout and Safety Zones in Petrochemical Chemicals' and it is understood from Council staff [12] that this document would still be used in assessing applications regarding the landing of oil and gas, and in petro-chemical developments.

The methodology principally provided a rationale for determining the appropriate layout and necessary safety zones between petrochemical plant and the community, but it did also cover the potential for domino effects between plant items on the same site (intra-site) and those on different sites (inter-site).

The method involves the quantification of both frequencies and consequences, with the criteria being based on the findings and conclusions of ACMH [5].

The fundamental concept of basing a methodology on the notion of 'a maximum credible accident' was not developed due to the difficulty in agreeing the definition of appropriate incidents, but it was replaced by what the authors considered to be a more objective and rational approach.

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The criteria of acceptability adopted in the report were derived from the basic premise that the probabilities and consequences associated with major industrial developments should be commensurate with everyday risks which are accepted by the community. The underlying premise of their criteria was based on an extract from the ACMH first report [13] which stated that:

> *"If, for instance, such tentative conclusions indicated with reasonable confidence that in a particular plant a serious accident was likely to occur more often than once in 10,000 years (or to put it another way - a 1 in 10,000 chance in any year), this might be regarded as just on the borderline of acceptability, bearing in mind the known background of risks faced every day by the general public".*

This led to the use of comparative analysis which was most successfully used for in-plant (intra-site) safety based on FAFR (i.e. Fatal Accident Frequency Rate which is now simply referred to as FARs).

The criteria for assessing the risk to the public was based on:

- a frequency of less than 10^{-4} for serious incidents per annum is treated as the acceptable rate of occurrence of serious hazardous incidents from planned development.
- 'serious' incidents include all events which can cause damaging effects which exceed the defined threshold values. For each of the main categories of incident, i.e. explosion, fire and toxic release, damage thresholds are selected at the 5% of total loss or fatality level.
- for planning purposes, community safeguards are provided in terms of safety distances which ensure that the community risk is acceptable in terms of frequency and extent of potential damage.

The above criteria were summarised as 'the frequency of an event causing 5% chance of fatalities in the community shall be less than once in 10,000 years.'

When assessing the domino effects, only those which had the potential to cause an escalation in the magnitude of the primary event were considered. In these cases, the consequences of the domino events were calculated using the same techniques as for the primary events, however, the contribution of the primary event to increasing the probability of the secondary failures was assessed. Thus domino events were included in the overall analysis, the results of which were judged against the above criteria.

Domino effects are dependent on the probability of damage to other process plants. An important point in the above methodology was that these hazard levels were based on the 'most likely' or 'typical' outcome rather than an extreme worst case.

In assessing the hazard range of unconfined vapour cloud explosions which arise from releases in process areas, the effect of cloud travel was neglected and it was assumed that the epicentre of the explosion is located on the edge of the process area. For releases from storage tanks, which are usually far removed from ignition sources, it was assumed that the cloud travels its full extent before igniting and thus the epicentre was assumed to be located at the mid point of the cloud length.

For instantaneous releases it was assumed that all the released mass was involved in the explosion. This assumption was also made for short duration continuous releases, i.e. if the release duration was less than half the time taken for the gas to reach the LFL. For all other continuous releases, the lesser of the mass between the flammable limits or the total release inventory was used.

A limiting value of 1 psi was taken for community exposure, as this corresponded to serious structural damage in 5% of typical brick buildings. For domino effects on process plant, 5 psi was taken to be the limiting value for pressurised plant and 2 psi for low pressure items.

Safe limiting values were given for thermal radiation from Pool Fires in terms radiative heat fluxes, i.e. 12.5 kW/m^2 for escalating a fire and 4 kW/m^2 for hazard to people. BLEVEs were discussed but no definitive values were given. The Flash Fire hazard was taken to be the distance to the Lower Flammability Limit. No discussion was reported in terms of toxic releases causing domino effects due to incapacitation of control room staff and operators, however, the hazard to people in general was taken to be the concentration limit which would cause the death of 5% of individuals exposed for a 5 minute period.

The probabilities of domino events were calculated as follows:

$$P_{iD} = P_{jP} \times P_{ij}$$

where P_{iD} = Probability of domino event , i.e. domino failure of equipment (i)
P_{jP} = Probability of initiating event, i.e. primary failure of equipment (j)
P_{ij} = Probability that the domino event will occur given that the primary event has occurred within the potential hazard zone

For the purpose of undertaking assessments in the initial planning stages, an example of a P_{ij} value was given, i.e. 0.1 was assumed to be the probability of a secondary explosion being caused by an initiating explosion.

Domino effects were assessed for all primary events which could impact a plant item and these were added to the primary failure probability

$$P_{iT} = P_{iP} + \Sigma P_{iD}$$

where P_{iT} = Total probability of failure of the equipment
P_{iP} = Probability of primary failure of equipment

In assessing the situation where two plants occupy the same site, i.e. intra-site spacing, then the allowable frequency was shared between the two plants. An equal allocation of the frequency was considered most appropriate as this would give rise to different safety distances around individual plants dependent upon their hazard.

For inter-site spacing, an acceptable frequency of ten times the rate for the community damage was taken and again shared between the plants, i.e. 10^{-3}/year For explosions the damage criterion was taken to be 2 psi overpressure rather than the 1 psi used for community risks. The purpose of inter-plant safety spacing was intended to protect one operator's personnel and plant from other plant risks, which included risks to buildings as well as plant.

Where two adjacent plants have different calculated spacings then it was recommended that the greater should be taken.

Further detail on the Cremer and Warner method described above was given in a published paper by **Cromer et al** [14]. In the flow scheme given for assessing the domino routine, it is inferred that toxic releases are only considered in terms of secondary events, i.e. for toxic releases the distance to the 5 per cent lethal dose (LD05) is compared to the hazard distance of the initiating event. In the example, the frequency of these domino events would only be included if the separation distance between the explosion epicentre and the toxic inventory location plus the toxic hazard distance was greater than the blast hazard distance which could give rise to community risks.

Application of the Cremer and Warner method was described by **Ramsey et al** [15] by reference to specific examples of the siting of hazardous installations and neighbouring facilities. As described previously, their approach to demonstrating the safety of a new facility was based on a risk contour approach. Domino effects were taken into account by modification of the primary failure probabilities if necessary and calculation of the total impact on the local community and neighbouring industrial facilities.

The application of the technique was illustrated by reference to a number of examples.

An explosion overpressure of 0.3 bar (4.4 psi, cf. 5 psi for pressure plant in reference [11]) was considered to cause collapse of conventional buildings and rupture of process pipe connections. Hazard contours for this overpressure were generated for accidents. If the maximum range for any accident did not extend to neighbouring facilities then the current separation distance was deemed to be adequate.

If the hazard contour did extend to the neighbouring facility then frequency arguments were used. No explicit criteria were given in the paper, however see reference [11]. In the article, a frequency for impact on process plant of less than 10^{-7}/year was deemed to be acceptable but a frequency of $50x10^{-7}$/year (i.e. $5x10^{-6}$) was described as 'high' thus requiring explosion protection of equipment or modified layout.

The impact of site office building collapse was assessed in terms of FAR by calculating the frequency of building collapse and assuming 0.5 probability of death to occupants. The predicted FAR was compared to the overall FAR for comparable chemical industry.

An explosion overpressure of 0.1 bar (i.e. 1.4 psi cf. 2 psi in reference [11]) was considered to be capable of causing damage to ambient pressure storage tanks. Again if the frequency of the hazard contour at a specified point was less than 10^{-7} / year then it was deemed to be acceptable.

Envelopment in a burning vapour cloud was assessed in terms of frequency of being enveloped. A frequency of 10^{-7} / year was deemed to be acceptable in the example.

In a general paper on the assessment of hazard and risk **Ramsey** [16] still advocated the use of increased failure frequencies for the inclusion of domino events, i.e. the sum of the primary frequency and the domino failure frequency, rather than a modified event tree approach, i.e. assessing the 'super event'.

Mecklenburgh [17] described a two stage approach to plant layout using intensity criteria and risk criteria. This approach was proposed in order to overcome a lack of reliability data. The first stage was based on selecting all likely loss of containment scenarios, assessing and amalgamating their frequencies and comparing the cumulative value (intensity) with critical intensities or criteria. If the intensity was less than the criteria then the target was considered acceptably safe irrespective of loss of containment. If the layout situations did not satisfy these criteria then the analysis progressed to the second stage. In this case, the concept of the maximum credible accident was applicable and only the ones giving rise to the greatest damage were used.

The approach for the second stage was to take the acceptable risk for the target and determine (possibly subjectively) if the actual risk was consistent with this value. This approach involved assessing the contributions from all credible sources violating the criteria in order to ascertain the risk. Due to the simplifications in the technique then if the critical intensity was exceeded then the risk at the target was the same as the risk of loss of containment.

Criteria were given for blast pressure damage with a detailed table given for damage to different plant items (i.e. Table B.3 in Ref. [17]), thermal radiation (i.e. Section 8.4.4 in Ref. [17]), toxic limits, and flammable clouds, i.e. the LFL limits of releases.

Mecklenburgh indicated that if there was a need to resort to risk criteria, then the overall risk from both plants inclusive of the domino effect had to be evaluated. Individual risks to workers were derived from the FAR for the chemical industry, individuals risk for the public were derived in the usual manner and societal risks were discussed (Section 8.4.5 in Ref. [17]).

Labath and Amendola [18] outlined work undertaken at the Joint Research Centre involving the development of an approach to analyse the domino effect of incident scenarios using the DYLAM code. The aim of the DYLAM code was to drive and control the models and algorithms needed to estimate the consequences of the different types of possible accidents. The DOMINO package was aimed at being able to describe in self contained calculations the random performance of systems such as fire protection systems, and the resulting (steady state and transient) behaviour of the associated physical processes.

The analysis included the evaluation of overpressures and / or heat radiation, and consideration of the possibility of knock-on damage in neighbouring units. The specified threshold limit values which would be used in this last stage were not reported, neither was the overall criteria which would have to be used to assess whether risks associated with the domino effects would tolerable.

A limitation of the DOMINO package was reported to be the difficulty in defining new sequences to those already pre-programmed into the code, to update the existing ones, or to substitute models with updated versions.

Contini et al [19] in a later paper described the more recent work being undertaken at the Joint Research Centre on the development of computer aided methodological approaches to domino effect evaluation. These sought to overcome some of the limitations of the original DOMINO package. The methodology has been implemented in the STARS (Software Toolkit for Advanced Reliability and Safety Analysis) package and enhancements have been made where necessary.

The paper indicated the flexibility of the software in terms of aiming to give the analysts full control of data and models. They indicated that the software, when developed, will provide a flexible framework for undertaking a full and comprehensive analysis of plant taking into account domino effects. Unfortunately, the article only described the overall approach, thus it included very little information on the overall criteria, plant damage criteria etc.; presumably because these could be user defined variables in the final version.

Scilly and Crowther [20] provided a methodology for predicting domino effects from pressure vessel fragmentation. The method predicted the number of missiles, the possible range - frequency distribution of missiles from incidents and the probability of hitting a target.

An estimate of the number of missiles generated was made by comparison of the case specific details with a table of well documented incidents.

Bagster and Pitblado [4] described an approach for the estimation of domino incident frequencies. This was developed on the principle of treating the domino event as an external event in a fault tree context rather than increasing the consequences of a given incident at a frequency appropriate to the domino event to allow for the combined consequences of the initiating and domino effects, i.e. the 'super event'.

The paper described an initial framework model which could be expanded if required. It considered loss of containment scenarios of a catastrophic failure and a leak, which following ignition could give rise to pool fires, explosions, fragments, jet fire or delayed explosion. Location of the centre of the event is tracked and a simple decay law of the effect from the centre of the event could be incorporated to predict the magnitude at a specified distance.

Damage criteria for process plant were proposed, i.e. a fire radiation intensity of 24 kW/m^2 and an explosion overpressure of 36 kPa. These were not be used by the program directly but they affected the range calculated in the consequence estimates. The authors indicated that intensities to cause various effects were discussed in another paper [21].

Purdy et al [22] outlined a method for assessing tank fire escalation - modelling and mitigation. The paper includes a receptor model. The examples given are largely for fires in a tank farm as the separations are up to 2D, i.e. twice the tank diameters.

Crossthwaite and Crowther [23] published an article, which although not specifically covering domino effects had potential use in assessing indirect domino events on an adjacent plant, i.e. through loss of control function by damage to the control room and injuring staff. They discussed an approach to determining the location of on-site buildings close to hazardous chemical processing plant, in which they questioned whether the principle of basing control building design purely on a flammable release was justified. They proposed that it might be preferable to use an alternative philosophy which was based on a consideration of the frequency of occurrence of explosions, rather than just the potential.

They acknowledged that it was not always practical to design the control building to withstand the overpressure which could be generated in a worst case explosion. As a result they proposed a predictive method which identified the hazardous materials, estimated the consequences in terms of overpressure, estimated the frequency, and combined the consequences and frequencies. The overpressure frequency plots showed the frequency of a specified overpressure level occurring at any particular point.

When the location of the control building was superimposed on the overpressure frequency plot the frequency of exceeding the design strength of the building could be estimated. Deriving an acceptable frequency was reported to be difficult and they indicate a number of possible criteria, i.e.

- that the risk to life of the control room operator should not exceed that of an operator in the open.
- that the FAR from a single but dominant process hazard could be in the range 0.5 to 1, or

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- that an individual risk of 1 x 10^{-4} /year may be appropriate as an upper limit for the part of a person's total risk due to overpressure, but it should be subject to ALARP (this value might be reduced by an order of magnitude if there are a large number in the control building).

In order to compute these risk levels it was necessary to make certain assumptions about the probability of fatality for different building strengths, but these were not described in detail.

Latha et al [24] described possible approaches for quantifying the consequences of domino effects resulting from events giving rise to thermal radiation. Factors governing the degree of thermal radiation being received by an object were reviewed and the response of equipment and structures to incident thermal radiation were analysed. A number of correlations were provided.

Pettitt [25] was concerned with assessing the frequency of a major hazard release as a result of a domino event. Four types of event scenario were considered as credible events which could lead to further subsequent failure of process equipment that may contain flammable or toxic material, i.e. (i) jet flame impingement, (ii) pool fire radiation, (iii) vessel fragment impingement, (iv) explosion leading to large overpressures.

Factors which could affect the frequency of domino events were discussed and included: initiating release failure frequency, orientation of vessels / release, ignition, duration and degree of damage, etc. which could affect the probability of different steps in the event scenario.

Duration factors were indicated which represent the probability of failure against the duration of flame impingement for jet fires and pool fires although no explicit derivation was given for these factors.

Lees and Ang published a series of papers [26], one of which indicated that Local Planning Authorities presented with an application for a new hazardous development were faced with a number of pressures in the planning process, i.e.

1. *It is important for the authority to identify all the implications of the development. In relation to hazard and public safety this has included identifying things which have not specifically been the remit of the developer (e.g. possible interaction of the proposed development with other hazards - 'domino effects'; the implications of an additional hazard).*
2. *There is a need to be aware of alternative technical possibilities and solutions in order to consider adequately the proposed plant design. Again the description of alternatives and the reason for choice of proposed project design has not always been seen as the developer's remit.*
3. *The LPA must be seen to take proper account of any public concerns, and concerns may be founded on the basis of worst conceivable accident and not just on the worst credible accident. The LPA must be able to justify fully its approach to assessment and conclusion on risk. There is often particular public pressure on elected members.*

4.3 Hazard Indices

Two possible methods which might be used as a screening method in assessing the potential for interaction are the Dow Index and the Mond index. These are both derived from the basic concept used in the Factory Mutual "Chemical Occupancy Classification" guide [27].

In the **Dow Index** approach [28], an exposure radius can be calculated from the predicted fire and explosion index (F&EI). The F&EI is derived from the product of a material factor and a unit hazard factor. The material factor is a measure of the flammability and reactivity of the substance being processed / stored. Appropriate material factors are taken from reference tables for those process units which are considered to have the greatest contribution to fire and explosion. The unit hazard factor is a penalty factor applied to the material factor and is composed of general process hazard factors and special process hazard factors. These can take into account general factors such reaction types, handling, degree of enclosure, etc., and special considerations such as process conditions, quantities, corrosion, erosion, leakage, use of fired heaters, rotating equipment etc.

The above parameters are compiled on standard proformas using engineering judgement to select values within their pre-defined ranges.

The primary purpose of the F&EI is to serve as a guide to the selection of fire protection methods and identification of the areas of greatest loss potential in a particular process. The method is based on realistic fire and explosion potential of process equipment and their contents.

Other parameters which are calculated using the methodology and which might be of benefit in assessing the potential for domino effects are the damage factor (which is a function of the material factor and the unit hazard factor and which represents the probable relative damage exposure magnitude) and the loss control credit factors, LCCF, (which take account of aspects of Process Control such as emergency power, cooling, explosion control etc.; Material Isolation such as remote control valves, dump lines, blowdown etc.; and Fire Protection such as sprinklers, foam).

The purpose of the LCCF is as a multiplication factor which is applied to the Base Maximum Probable Property Damage, MPPD, in order to reduce it to an Actual MPPD. Although the safety features taken into account in the LCCF will have the tendency of reducing the distance at which critical levels of plant damage occur, the LCCF is not used in the Dow Index method in this manner.

From the point of view of determining the degree of interaction between plant items the LCCF could be applied to the predicted area of exposure. A reduced radius of exposure could thus be obtained from this revised area of exposure.

The Damage Factor is computed as a function of the Material Factor and the Process Unit Hazard Factor. Although it would be possible to use it in a similar manner to the LCCF to reduce the hazard distance for interaction it is considered prudent not to do so.

The Dow Index does include an escalation factor in the estimation of replacement value of damaged plant. However, this value is an inflation index factor rather than a factor to allow for escalation to other plant areas. The main limitations of the Dow Index are that:

i) it does not take into account toxic hazards, i.e. only fire and explosion hazards are considered;
ii) it is unclear whether it includes the potential damage due to missiles arising from fragments of process equipment being ejected in the explosion;
iii) there is only limited discussion in the guide regarding the size of incident on which the index is based, i.e. there is mention that the radius of exposure was computed by considering probable effects of spills of various flammable mixtures to a depth of 3" (8 cm) as well as potential effects of vapour air mixtures and fires. A liquid depth of 3" would be able to sustain a long duration pool fire which would cause considerable plant damage. However, a shallow and broader pool may still have the potential to cause escalation.

The Dow Chemical Exposure Index, CEI, [29] is a separate toxicity index to the Dow Index Fire and Explosion Index and is a measure of the relative acute toxicity risk of chemicals. It is generally used in initial process hazard analysis and in emergency response planning.

The procedure is normally to determine the release scenarios from assessment of the flowsheet and plot plan, the Emergency Response Planning Guidelines ERPG and the airborne quantities AQ.

The AQ is calculated from relationships given in the CEI based on release rate, flash off, pool formation, evaporation. The CEI is then calculated from

$$\text{CEI} = 655.1 \left(\frac{AQ}{ERPG-2}\right)^{1/2}$$

where AQ = airborne quantity (kg/sec), ERPG-2 = value (mg/m^3)

The hazard distance is then determined from

$$\text{HD} = 6551 \left(\frac{AQ}{ERPG}\right)^{1/2}$$

where HD = hazard distance (m)

The particular ERPG which is appropriate for personnel on an adjacent site would have to be selected from one of the three standard categories, expected to be ERPG-2 i.e. serious or irreversible health effects.

The **MOND Index** [30,31,32] was developed from the Dow Fire and Explosion Classification Method, but with some reference back to the original Factory Mutual Method in order to provide a tool which would be useful in determining a logical plant layout and basic spacing distances in accordance with ACMH. The Dow method was modified to enable a wider range of process and storage installations to be studied, to include chemicals with explosive properties, to model hydrogen better, to include special process hazard considerations, to include toxicity and to enable safety features to be taken into account.

As well as ensuring that the individual units on a plant site should be spaced to minimise involvement of other units in an incident where the "domino" effect could occur, another stated objective is to layout a site so as to minimise the effects on adjacent plant sites or other property from internal plant explosion, fire or release of flammable or toxic material.

The technique is based on determining overall hazard ratings for both the adjacent units and a recommended separation distance is then looked up in appropriate tables depending on the type of units involved.

In order to appreciate the relevance of the recommended separation distances it is necessary to understand the basis on which they have been developed. Incidents can broadly be categorised as follows:

1. Minor leakages and events
2. Medium to serious fires and explosions and other effects such as toxic corrosive releases
3. Major and catastrophic events such as large releases of material and explosions of considerable energy

According to the author, Category 1 incidents are difficult to avoid and are thus taken into account in the hazardous area classification zones etc., Category 2 are controlled by hazard study work, operating instructions, maintenance, safety audits and safety cases and Category 3 are considered to occur only at a low probability that is acceptable as a residual risk.

It is argued that plant layout considerations have to be concentrated on Category 2 incidents. Thus, any plant spacings which are quoted have been derived on this basis. It is important to note that in defining the recommended distances it was hoped

> *to ensure that incidents arising from anticipated plant upset conditions (excluding major disasters) will not result in a domino or "knock-on" effect, and produce only a moderate level of damage to adjacent plant sites, with minimal effects outside the works boundary.*
>
> *Clearly in a major in-plant explosion or detonation, the range of distances over which fragments will be distributed to cause secondary fires will be far greater than is economically practical to implement...... Such major disasters would be satisfactorily dealt with by ensuring that their incident frequency was acceptably low.*

The MOND Index provides a means whereby:

- Plant can be split down into units and each unit separately assessed to derive an overall hazard Rating value R.
- Known interaction of toxicity problems with aspects of plant operations can be taken into consideration.
- Credit for safety features can also be given.
- The overall hazard ratings R_a and R_b of both adjacent units are used to define appropriate safety distances between them.

Values are given in look up tables, but it is recognised that these are only general values and that some adjustment might be required for specific features such as varying ground elevations, major ground slopes etc. which could affect dispersion, overflows etc.

The recommended spacings were derived on the basis of what seemed to be appropriate and to represent good and safe practices. The distances have been subject to some revision following experience in applying the method and in the light of additional information [32].

4.4 Plant Design Separation Distances

Various guidelines regarding safe distances can be found in the literature. Care has to be taken with respect to what category of accident is being guarded against. One example is that from Industrial Risk Insurers, IRI [33], and is as follows:

	Process Units - moderate hazard	**Process Units - intermediate hazard**	**Process Units - high hazard**
Process Units - moderate hazard	50	-	-
Process Units - intermediate hazard	100	100	-
Process Units - high hazard	200	200	200
Atmospheric storage tanks	250	300	350
Pressure storage tanks	350	350	350
Refrigerated storage tanks dome roof	350	350	350

Table 4-1 IRI Recommended Separation Distances (feet)

5. REVIEW OF METHODOLOGIES

The methodologies described in the papers and reports reviewed above can be categorised into either steps in the overall assessment process or complete methodologies including assessment criteria.

Examples of articles which would fall into the category of calculation steps include the algorithm approach of DYLAM by Labath and Amendola [18], the prediction of missile hazards by Scilly and Crowther [20], and the assessment of tank fire escalation by Purdy et al [22].

Complete methods which potentially could be used or adapted to take account of domino effects can be grouped into the following categories:

- Hazard Indices;
- Interaction Frequency Limitation Methodologies;
- Quantified Risk Assessment Methodologies.

These are each discussed in more detail below.

Hazard Indices

The Dow and the Mond Indices provide a similar high level approach to identifying the hazards associated with plants and evaluating the hazard potential after making allowances for the safety features which have been incorporated in the design. Although there are differences in the techniques, both methods have been principally developed for use in formulating a layout of a chemical plant site, i.e. taking intra-site considerations into account.

Although both methods allow a hazard distance to be derived, it is uncertain whether these should be used in their current form for assessment of inter-site domino effects. With the Mond Index it is known that this specifically excludes major (catastrophic) incidents, i.e. the type of incident which COMAH is specifically trying to control. One possible solution would be to use the methods to assess the hazard potential of various plants and process but to re-calibrate the hazard distances to take into account the maximum credible accidents.

Both methods take no account of the probability of occurrence of the initiating incidents.

Interaction Frequency Limitation Methodologies

The methodology used by Highland Council includes a domino assessment approach that is based on limiting the frequency of inter-site domino events. Provided that a suitable set of criteria can be agreed then this methodology avoids having to undertake a full quantified risk assessment to evaluate the risk to the surrounding population.

This is comparable with the second stage in the Mecklenburgh methodology.

Quantified Risk Assessment Methodologies

Quantified risk assessment methodologies, such as that used in the Canvey Island Report, involve a detailed assessment in which the frequencies of incidents are increased to account for domino interactions. Risk contours are then produced for the overall industrial complex and are used to assess whether anyone is exposed to risk levels which exceed individual risk criteria.

This approach is advocated by Mecklenburgh and by Crossthwaite and Crowther as the ultimate step in demonstrating the acceptability or otherwise

Although there is discussion in the literature regarding the use of an event tree approach in which new consequence states are defined and evaluated based on the combined effects of the primary and domino events, most studies to date have incorporated the simpler methodology involving increased frequency of accidents to allow for primary and domino causes. Presumably this approach has been adopted to maintain the Quantified Risk Assessment to a manageable level.

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In the early examples of studies which considered domino events, analysts tended to ignore domino events if they were smaller than the primary event. However, there appears to be a present trend towards taking the geographical location of the domino event into account so that domino events which are smaller than the primary event would be considered if the resultant domino hazard contour extended beyond the primary hazard contour.

6. POSSIBLE APPROACHES FOR ASSESSMENT

The approach proposed here for assessing the potential for domino effects involves a three stage process as shown in Figure 6-1. This staged approach increases in the degree of complexity. The basic philosophy is in line with general approaches to predictive hazard evaluation, as described in standard texts such as Figure 1-2 of the AIChE Guide [34].

In any hazard evaluation it is initially prudent to investigate whether it is possible to demonstrate acceptability on the basis of the consequences being tolerable or non hazardous, followed by a second stage that considers whether the probability or frequency is tolerable. Resort to a third stage involving risk assessment would only be necessary if it was not possible to show that the plant separation was acceptable from a consequences and a frequency viewpoint.

If, in this third stage, it was still not possible to demonstrate risk tolerability, then it would be necessary to investigate and include risk mitigation measures.

This approach is mirrored in the proposed methodology for domino assessment as shown in Figure 6-1, in which

- Stage 1 involves assessment of the maximum hazard ranges for Plants A and B and evaluation whether these hazard zones extend to susceptible critical plant on the other site;
- Stage 2 involves assessment of whether the frequencies of all incidents affecting critical plant exceed some notional threshold value; and
- Stage 3 involves a combined Quantified Risk Assessment of both sites.

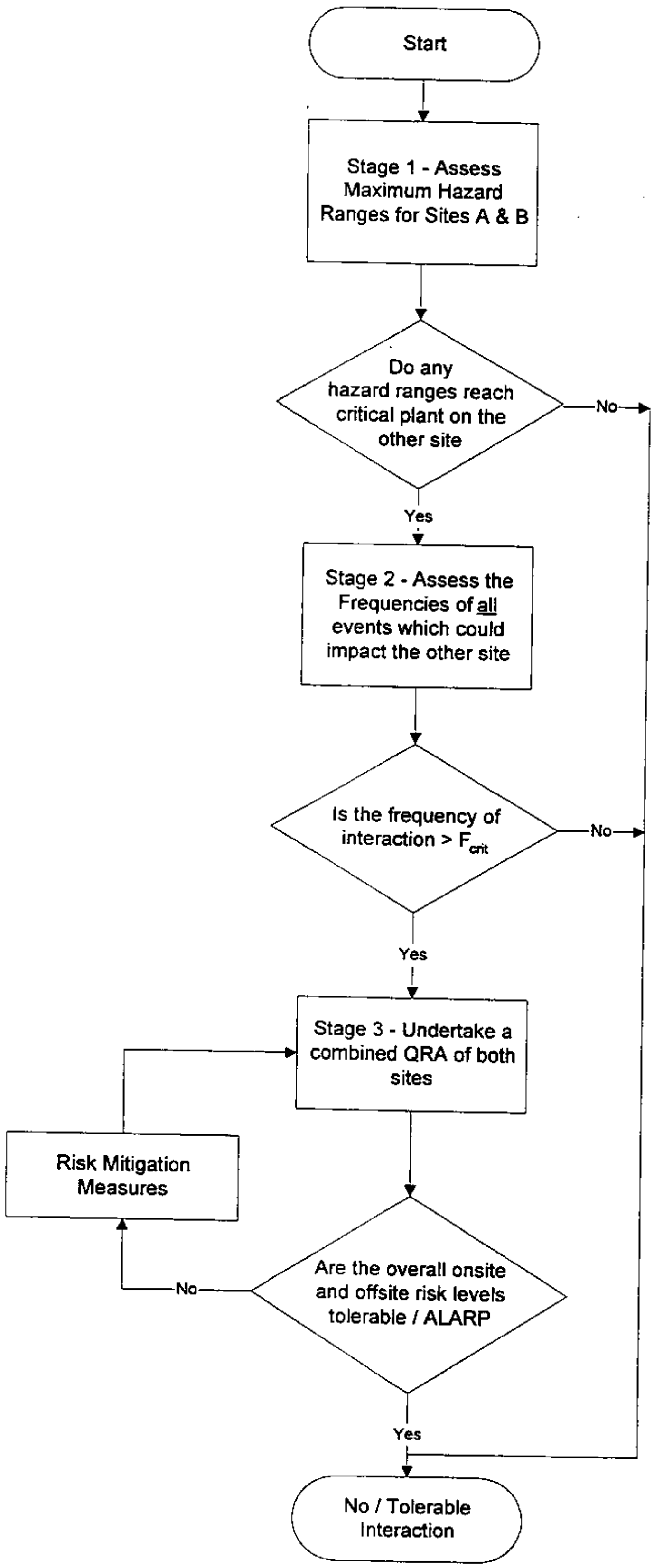

Figure 6-1 Overall Domino Assessment Methodology

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6.1 Damage / Hazard Criteria

A detailed review of the reported amounts of damage arising from the physical effects of fires and explosions has been undertaken in Appendices A1 and A2.

The following values were considered to be the most appropriate for evaluation of thermal radiation effects in an assessment of the potential for domino effects.

Item	Thermal Radiation Flux (kW/m^2)
Pressure Vessels	37.5
Atmospheric Storage Tanks	37.5
Pipework[1]	37.5
Water deluged pipework and vessels[2]	-
Buildings	12.5
Control Buildings	25
People	1000 tdu

Table 6-1 Thermal Radiation Damage Criteria

Item	Overpressure Resulting in Destruction (bar)	Overpressure Resulting in Partial Damage (bar)
Pressure Vessel	0.48	0.38
Fixed Roof Storage Tank	0.21	0.07
Floating Roof Storage Tank	0.45	0.45
Ordinary Plant Buildings	0.07	0.01
Control Buildings	depends on design	depends on design
People - outside	0.14	-
People - indoors	0.16	-
Pipework	0.4	0.24

Table 6-2 Blast Damage Criteria

A review of the methods and available information for assessing the impact damage to plant from missiles has been undertaken in Appendix A3. In preliminary assessments of missile damage, it is recommended that the criteria to be used should be that any missile, regardless of size or shape, should be considered as causing the plant to fail.

In a more detailed analysis, such as if a full Quantified Risk Assessment was being undertaken for the two sites, the criteria summarised in Appendix A3 are recommended for assessing whether impacts on vessels will result in loss of containment.

For assessing the toxic risk to control personnel on an adjacent site, the following criteria were considered to be appropriate. A discussion of the background to the why these values were considered appropriate is given in Appendix B.

[1] Pipework assumed to fail at same radiation level as other process equipment (the higher surface area to volume ratio of pipes hence faster heat up rates of contents is assumed to be offset by the fact that the contents are likely to be flowing.

[2] Assumed that the water deluged vessels will only fail if the deluge system fails and thermal radiation levels are in excess of 37.5 kW/m^2.

	Lethal Concentration	Perceived Hazard Level
Control Staff[3]	Exposure Concentration corresponding to fatality in a few breaths	Exposure concentration causing irritation within a minute

Table 6-3 Toxicity Concentration Criteria

6.2 Stage 1 - Maximum Hazard Distance Approach

6.2.1 Fire / Explosion / Gas Dispersion

The maximum hazard distance approach is based on demonstrating whether the hazards associated with a chemical plant are of sufficient intensity at an adjacent or nearby site as to result in a further loss of containment regardless of the probability of their occurrence. The maximum hazard distances should be based on maximum credible incidents using realistic best estimate assumptions. These hazard distances could be obtained by either:

- re-analysis of the consequences identified in CIMAH / COMAH safety cases to establish the extent of hazards at the required damage threshold levels,
- direct use of consequence information from CIMAH / COMAH safety cases, or
- interpolation / extrapolation of consequence information from CIMAH / COMAH safety cases

If re-analysis of consequences from fires / explosions / gas dispersion for specified damage levels is required then it is assumed that this would be relatively straightforward using currently available models and therefore this aspect of a domino study has not be expanded further in this study.

Maximum hazard distances for a plant that has been categorised as a top tier site under the present CIMAH or future COMAH Regulations should be available from the safety report. The accidents giving rise to the maximum hazard distances should be identifiable from the consequence analysis and, as a minimum, the impact on the surrounding population should have been evaluated. However, the particular hazard contours of interest in the domino analysis might not be reported, i.e. the effect on nearby plant may not have been evaluated. In the case of an explosion the damage contours may have been limited to those for local housing and people in the open and the contours for damage to atmospheric storage plant or pressure vessels which are of interest to domino analysis may not have been predicted.

If a map of the site showing the hazard contours and the location of the sensitive plant is not readily available then a possible gross simplification would be assume that all the equipment at both sites is located on the site boundaries, i.e. at the minimum separation distance. If the separation distances could be demonstrated not to result in any interaction then this would avoid the need for further investigation of the location of incident plant and target plant.

A flowchart of the proposed procedure for using a maximum hazard distance methodology is shown in Figure 6-5.

Pool Fire General Guidelines

General guidelines have been produced in the past which, although they might have uncertainties associated with them, may give a useful indication of potential hazard distances provided they err on the conservative side.

A set of such guidelines is given in the 2nd Canvey Report [10] based on large hydrocarbon pool fires. The approximate hazard ranges are given as:

Range to 12.6 kW / m^2 = 2 pool diameters
Range to 6.5 kW / m^2 = 2.5 pool diameters

[3] Concentrations to be used at point of exposure, i.e. open air concentration for an external control panel and in door concentration for internal control room atmosphere.

Range to 4 kW / m^2 = 3 pool diameters.

It is stated that this approach overestimates the risks from large pool fires because it neglects smoke obscuration, atmospheric transmissivity losses and shielding by objects.

This would tend to suggest that escalation of the fire would not be expected to occur with plant located at 2 pool diameters separation distance, i.e. plant would not be expected to fail due to the direct effects of thermal radiation or as a result of secondary fires.

This is supported by the information in the worked examples in the Institute of Petroleum guide on LPG [35] which includes the following information:

	Example 1 Ground	**Example 1 10m elevation**	**Example 2 25m elevation**	**Example 2 33m elevation**
material	propane	propane	propane	propane
pool fire diameter	20	20	36	36
pool fire elevation	0	0	25	25
wind speed	5	5	4	4
distance to 13 kW/m^2 (m)	31 (1.5D)	41 (2D)	38 (1D)	43 (1.1D)
distance to 32 kW/m^2 (m)	12 (0.6D)	26 (1.3D)	12 (0.3D)	18 (0.5D)

Table 6-4 Information from Institute of Petroleum Guide

It is inferred from the above summary table that the distance to 12.6 kW / m^2 is approximately 2D and that to 37.8 kW / m^2 is approximately 1.5 D.

There is some uncertainty associated with these guidelines since later reported analysis [36] on the spread of tank fires indicates that, for a separation distance of 2 tank diameters, escalation is expected to occur with 50 m diameter naphtha tanks after 11.7 hours in a 4 m/s wind and after greater than 24 hours for a low wind case. Sensitivity studies were undertaken which showed the following escalation times at 2 diameters.

Tank Diameter (m)	30	50	75	100
Escalation Time (hours)	5.5	11.7	>24	>24

Table 6-5 Escalation Times for Tank Fires

This difference is attributed to the escalation mechanism. In the latter case rather than use a simple incident heat flux, a mechanism involving localised vapour generation at the exposed tank surface leading to vapour build up under the tank roof, passing and subsequent ignition.

It is expected that slightly different relationships would result if the more recent two zone emitter models are used instead of the single zone emitter model, as would have been used in the work for the Canvey Studies. The two zone emitter model tends to give lower predicted radiant heat levels as distance from the flame is increased due to the lower contribution of the upper (smoky) portions of the flame when compared against the single zone emitter model.

In view of the above it is considered that a separation of 3D should be used as a guideline for escalation. This would lead to a separation distance of some 300 m for a 100m diameter tank. In most situations in the UK tanks are expected to be smaller than this, hence a smaller separation distance would be required.

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Flash Fire General Guidelines

The 2nd Canvey Report provided guidelines for the dispersion distances of instantaneous releases of propane and butane. Over the range of 10 -1000 te, it was argued that the downwind ranges could be approximated by a generic expression, i.e.

$$R = k\,M^{0.4}$$

where R = downwind range (km)
K = constant
M = mass of release (te)

The following table shows the various constants

Material	Propane		Butane	
Weather Cat / wind speed (m/s)	D5	F2	D5	F2
Downwind range to LFL, R (km)	$0.12\,M^{0.4}$	$0.17\,M^{0.4}$	$0.10\,M^{0.4}$	$0.14\,M^{0.4}$
Downwind range to 0.5LFL, R (km)	$0.14\,M^{0.4}$	$0.21\,M^{0.4}$	$0.12\,M^{0.4}$	$0.16\,M^{0.4}$

Table 6-6 Flash Fire Hazard Ranges

Further correlations were given for rapid assessment of the consequences of LPG [37]; thus for an instantaneous release for dispersion over land the following equations were recommended:

Material	Propane		Butane	
Weather Cat / wind speed (m/s)	D5	F2	D5	F2
Downwind range to LFL, R (km)	$0.1457\,M^{0.294}$	$0.1125\,M^{0.248}$	$0.1531\,M^{0.319}$	$0.1431M^{0.273}$

Table 6-7 Flash Fire Hazard Ranges for Instantaneous Releases

Correlations were also given for the dispersion of continuous releases:

Material	Propane		Butane	
Weather Cat / wind speed (m/s)	D5	F2	D5	F2
Downwind range to LFL, R (m)	$12.1\,m^{0.577}$	$44.2\,m^{0.571}$	$11.23\,m^{0.582}$	$41.\,m^{0.574}$

Table 6-8 Flash Fire Hazard Ranges for Continuous Releases

It is also possible to use the graphical correlations developed by Britter and McQuaid [38]

If the mass of gas released is expressed as a volume release and it is assumed that the release has an initial concentration of 100% and has to disperse to 2% concentration by volume, e.g. a typical value for hydrocarbon gases, then the dispersion hazard can be represented by a single relationship for each wind speed category which shows how downwind dispersion distance varies with release size. The following relationships were derived for continuous releases:

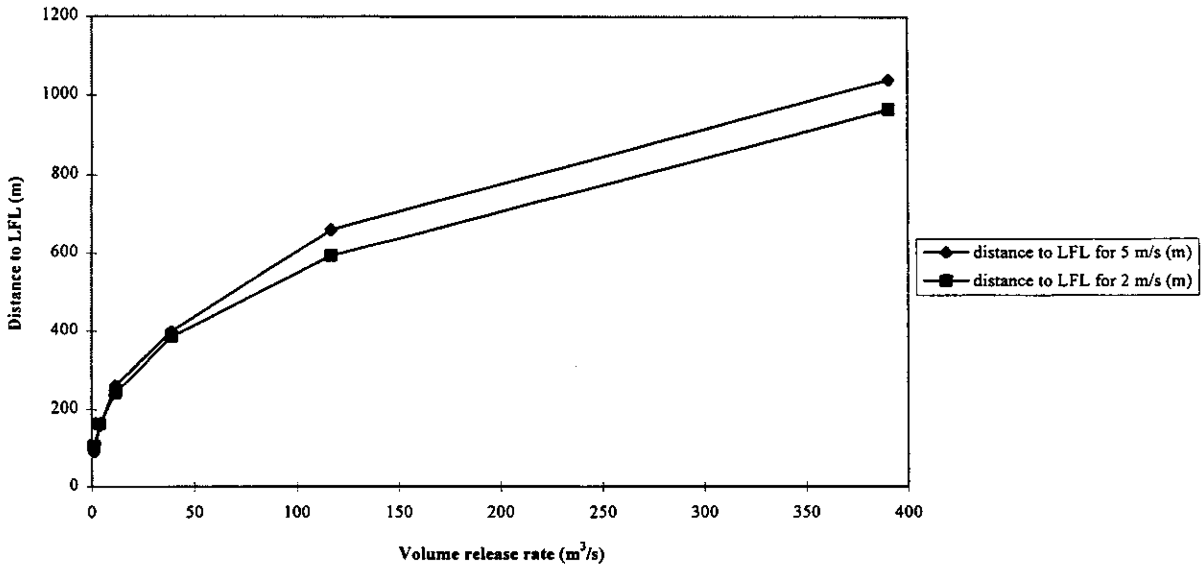

Figure 6-2 Britter and McQuaid Heavy Gas Dispersion (Continuous Releases)

It can be seen that the two curves are very similar and that the curve for 5 m /s wind conditions could be used conservatively for the 2 m/s wind conditions.

A complementary pair of curves was obtained for instantaneous releases:

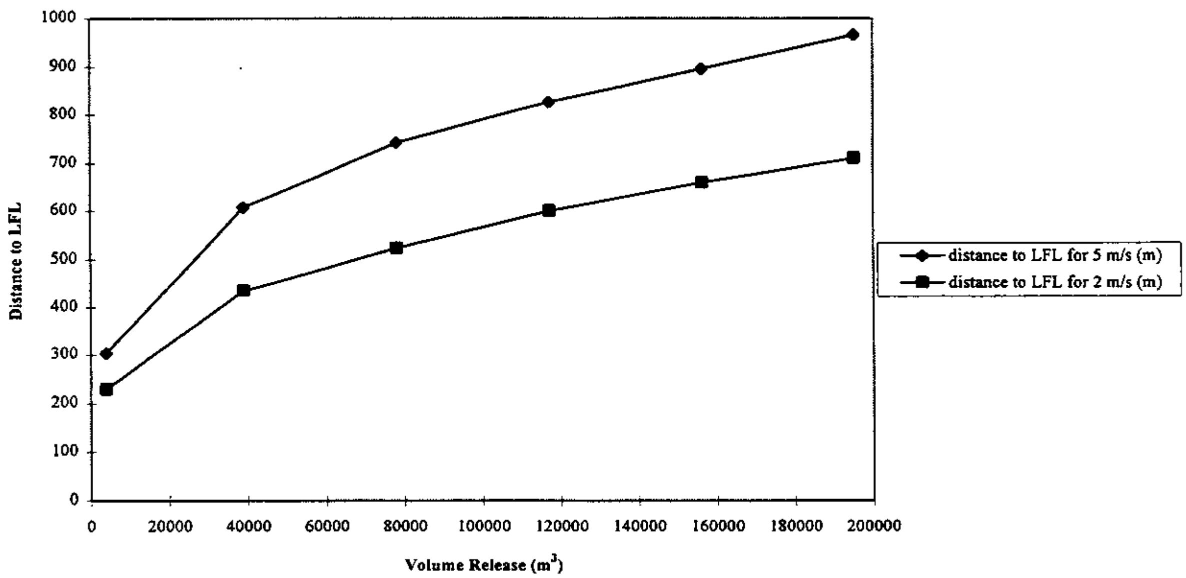

Figure 6-3 Britter and McQuaid Heavy Gas Dispersion (Instantaneous Releases)

An assessment of the release size and the vapour density are required to make an assessment of the hazard distances using the above curves.

Although the Britter and McQuaid workbook is more recent than the other general guidelines detailed above, the study does not explicitly take account of variables such as atmospheric stability, ground roughness etc. There is some discussion on the effect of ground roughness which is argued is probably negligible at the level of the workbook.

The effect of atmospheric stability is considered to be much more important. Britter and McQuaid do not give correlations or relationships for this factor. However, they do indicate that a stable atmosphere will increase the downwind distance by between 0 - 0.5 times the probable effect of that produced in a comparable passive release for both instantaneous and continuous releases.

The above graphical relationships of Britter and McQuaid give comparable dispersion distances to those of Considine and Grint [37] for neutral conditions, i.e. D5. However, when considering stable conditions, i.e. F2, the graphical relationships do not take into account the change in atmospheric stability, and thus give much smaller dispersion distances.

Given the uncertainties in modifying the Britter and McQuaid graphs to take account of atmospheric stability, it is considered that the Considine and Grint equations are more appropriate.

If the release differs significantly from that of a typical heavier than air hydrocarbon such as LPG then it is recommended that the original graphical relationships in the workbook, making the appropriate modifications for atmospheric stability, are used in preference.

Jet Flames General Guidelines

Jet Flames can arise from pressurised releases of gases and liquids. It is considered that in most cases of a jet fire with a large hazard range, the jet fire will only give rise to a transient (short duration) hazard since it will involve a large pressurised release from process or storage plant which will have a limited inventory. If the leak is being fed from a pipeline bringing material to the site, then it is expected that this will be isolatable so as to limit the duration of the release.

Although a number of simple jet flame models are available, e.g. [39], the following model has been chosen as a typical example to show that the magnitude of release which is required to give a significant offsite hazard.

A simple model for a jet fire [37] for a release of liquid ethylene gives:

$$L = 9.1\, m^{0.5}$$

$$W = 0.25\, L$$

Hazard ranges are also given for end on hazard ranges for probability of fatality for human exposure, i.e.

$$r_{50\%} = 1.6\, t^{0.4}\, m^{0.47}$$
$$r_{1\%} = 2.8\, t^{0.38}\, m^{0.47}$$

making the assumptions that the 50% hazard range corresponds to 2250 tdu and 1% corresponds to 1000 tdu, then it is possible to derive a hazard range from the above relationships for 37.5 kW/m^2, the process plant damage threshold, i.e.

$$r = 6m^{0.47}$$

Using the above correlations gives the following hazard range

Release Rate (kg/s)	$L = 9.1m^{0.5}$	$H = 6\, m^{0.47}$	Hazard Range (L+H)
1	9	6	15
10	29	18	47
50	64	38	102
100	91	52	143
200	128	72	201
500	203	111	314
1000	288	154	442

Table 6-9 Jet Flame Hazard ranges

Explosion Assessment General Guidelines

Explosion effects can be estimated using a number of methodologies. However, when considering the use of simple methods the choice essentially appears to be between two models, i.e. the TNT model and the multi-energy method.

The TNT equivalency method is a very direct, empirical relation between a charge weight of TNT and resulting structural damage. The method is reported to work well for average major incident conditions such as a spill of several tons of a hydrocarbon in an environment with local concentrations of obstructions or confinements such as a refinery.

If it is applied in situations where there is little obstruction or confinement then it will overpredict the effects because the basis of the calculation, which assumes that a fast deflagration is possible, will result in significant overpressures outside the cloud boundaries. In the case of an unconfined or uncongested area, this will be very unlikely.

The multi-energy method on the other hand, takes into account current understanding of explosion modelling in terms of the damaging overpressures only being produced by those parts of the cloud which are subject to turbulence from obstructions, confinement etc.

Although it is considered that the multi-energy method gives a better representation if the details of a site are known, it is difficult to apply in a general sense without making gross generalisations about the type and degree of obstructions / confinement. Therefore, for the purpose of a rapid assessment method for domino assessment the TNT equivalence method is the most appropriate.

The TNT equivalent method is being based on the mass of fuel released and so will give a reasonable representation of an incident on the initiating site. Delayed ignition which occurs offsite and which gives rise to significant overpressure can be either argued to be of low probability so that it may be discounted, or it can be argued that it should be treated in the same manner as an on-site vapour cloud explosion.

The latter has been adopted here since it is pessimistic. If the release is a quasi instantaneous release, then as the cloud drifts further away from the site, it will be dispersing and the mass in the cloud which is above the Lower Explosive Limit will be decreasing. As the cloud travels offsite the epicentre of the VCE will be further away but the blast hazard range will be smaller, hence the overall hazard range from the release point could be variable.

Gross assumptions can be made in estimating the overall maximum hazard range such as that the mass involved in the VCE is the original release mass located at half the down wind range for dispersion to the lower flammability limit. Alternatively, the decreasing mass as a function of distance could be predicted and sensitivity calculations undertaken to determine the point which produces the maximum hazard range.

Such an approach could be developed from the rapid assessment equations reported by Considine and Grint as these allow cloud size to be predicted at downwind locations. However, since the Britter and McQuaid approach has been adopted here, then only downwind distance to the LFL is predicted.

Consequently, it is recommended that for VCEs involving instantaneous releases, the release mass should be used in the TNT equivalence model and centred on the edge of the site closest to the domino site. The hazard range from this point for different damage criteria can be predicted using the sub model reported by Considine and Grint, i.e.

$$r = \frac{I^{1/3}}{\left[\frac{Po}{138}\right]^{\frac{1}{1.558}}}$$

where Po is the overpressure, bar (0.05 < Po < 1)
I is the mass of vapour in the cloud (in Tonnes)
r is the distance from the cloud centre (in metres)

It is recommended that an assessment of the potential for an offsite explosion be made by consideration of the number and type of obstacles / confinement between the incident site and the domino site with the dispersion hazard range of the gas cloud. If there is a potential for an offsite explosion then an initial estimate of the blast damage can be obtained by assuming that the initial release mass is involved in the explosion at a location of half the distance to the LFL.

For continuous releases, the epicentre of the VCE can be assumed to be located at half the distance to the LFL. This distance can be derived from curves derived from the Britter and McQuaid graphs. An estimate is required of the flammable plume inventory to be able to predict overpressure from a plume explosion. A previously reported simple relationship is that by Considine and Grint, i.e.

$$I = \frac{m R}{w}$$

where m is the release rate (kg/s)
R is the range to LFL
w is the wind speed.

BLEVE Fireball General Guidelines

As a basic guide to the thermal radiation hazard to process plant from BLEVE fireballs the simple criterion derived by Birk is considered to be appropriate, i.e. at 4R, where R is the fireball radius in metres, the radiant heat flux should be less than 21 kW/m^2 and the blast should be less than 30 mbar. To be consistent, the fireball radius should be calculated using the formula given by Birk, i.e. $R = 3\ m^{0.333}$, where m is the mass of material in kg. This formula is consistent with that reported in Canvey and is in broad agreement with other empirically derived relationships for hydrocarbons as given in AIChE guidelines [40].

The methodology given by Birk shows reasonable agreement with that given by Roberts as reported in the AIChE guidelines. This gives

$$q = 828\ m^{0.771}\ L^{-2}$$

where m is the mass of fuel (kg)
L is the distance from the centre of the fireball (m)
q is the radiant heat received by a detector at distance L (kW/m^2)

The above equation can be rearranged to give

$$L = 6.43\ m^{0.3855}$$ for a radiant heat flux of 20 kW/m^2.

Thus, thermal radiation levels will be less than the criteria given in Table 6-1 for damage to pressure vessels and atmospheric storage tanks. The blast levels at this distance will also be less than the criteria for damage to process equipment and for destruction of ordinary plant buildings. There will still be a residual hazard from missile effects as some of the missiles could travel further, and this is discussed in Section 6.2.2.

Toxic Hazards General Guidelines

It is not possible to generalise about the hazard from toxic releases as it will be dependent on the particular chemical, the release location and the susceptibility of operators to exposure to the chemical.

In general, it is considered that the Consultation Distance will provide a reasonable estimate of the probable range within which domino effects could be significant for toxic events.

6.2.2 Missile Effects

Unlike assessment of the maximum hazard range for fires, explosions and gas dispersion discussed in the previous section, the maximum hazard distance for missiles is less likely to be included in CIMAH / COMAH reports as it may have been neglected on probability grounds. In addition the models for assessing missile travel are not as well developed as those for the more common hazards.

Consequently, methods for deriving the possible maximum range for missiles have been discussed in Appendix C. These have been discussed in detail in the appendix where the dependency of the hazard range on the characteristics of the vessel and its contents, the vessel failure mechanism and, in some circumstances, on the orientation of the vessel has been identified.

Possible approaches which were considered were theoretical, probabilistic and deterministic. Theoretical approaches were considered to be overly pessimistic whereas deterministic approaches were possibly optimistic. Therefore, a probabilistic approach is considered to be the most appropriate.

Where sufficient information was available to be able use or derive a probability range equation for missiles based on accident or test data, then it was considered that probabilistic methods based on a 99 percentile value were the most appropriate.

As LPG is one of the most common materials resulting in sites being classed as major accident hazard installations then on the basis of the information identified in the review, it was possible to derive appropriate guidelines, i.e.

Failure Scenario	**Missile Hazard Range (m)**
BLEVE of LPG[4] bullet (domino site vessel within 30 degrees of bullet axis)	1150
BLEVE of LPG bullet (domino site vessel beyond 30 degrees of bullet axis)	770
BLEVE of LPG Sphere	812
Brittle Failure of LPG Sphere	130 - 400[5]

Table 6-10 Missile Hazard Ranges for LPG Vessels

6.2.3 Fire Spread via Drains

An evaluation of the hazard from domino effects from flammable liquids being inadvertently discharged into the drainage systems from sites may be an important consideration. However, this is considered to be so site specific that it is totally inappropriate to try and generalise about possible maximum hazard ranges.

BS 5908:1990 Code of Practice for Fire Precautions in Chemical Plant [41] indicates that the disposal of industrial effluent is subject to stringent control under statutory regulations and local bylaws. Although the water authorities do not permit the entry of flammable or harmful substances into the drainage system of any public authority or natural water course under their control, this only extends to site drainage in so far as is practicable. There is also a requirement for adequate drainage for stormwater and for the special provision of pumps, run off areas etc. in order to cope with the disposal of water used in fire fighting operations. Nevertheless, in some circumstances, there is still considered to be a potential for hazardous liquids / gases to enter the water authority drains leading offsite and thus affect some other site which is connected to the same drainage network.

This particular hazard can only be evaluated by an in-depth consideration of the site drainage arrangements to evaluate whether a site has the potential to act as a domino initiating site in this regard, whether there is any other hazardous installation connected to the same drainage network, and if so, whether this site has any major

[4] based on Propane
[5] dependent on pressure at time of failure (range covers 6.6 to 19 bar for propane)

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inventory plant which could be affected by either a fire or explosion in the drain or backflow of hazardous material up the drain.

6.2.4 Summary of Maximum Hazard Distance Approach

The preceding sections have discussed how the maximum distance at which domino events could occur can be calculated for various different types of hazard. This distance can be used to provide a rapid indication of whether a particular major hazard site was likely to impact on other nearby sites. If there is insufficient data or resources to calculate the maximum hazard distance then the table below may be used to provide an initial estimate, which should be sufficient for preliminary screening purposes. In many cases, the consultation distance is a reasonable first estimate, if no other information is available.

Major Hazard	Quantity (tonnes)	Distance (metres)	Comments
Explosive Hazards			
Explosives (Class 1 explosives at licensed sites)	0.1 1 10 100	66 300 950 2080	Based on 2 times the Outside Safety Distance for Class 2 protected works.
Other explosive substances (R2 and R3)	< 50 > 50	1000 1500	
Flammable Hazards			
Ethylene oxide	5 - 25 > 25	500 1000	Based on example consultation distances [42, 26].
LPG and other extremely flammable gases and liquids	Cylinders 6- 10 11 - 15 16 - 25 26 - 40 41 - 80 81 - 120 121 - 300 > 300	100 150 175 250 300 400 500 600 1000	Based on LPG consultation distances [26].
Flammable and highly flammable liquids	< 10000 > 10000	250 500	
Oxidising substances	> 1	100	
Toxic Hazards			
Chlorine	Cylinders only Drums only Small users (2x35 te) Medium users (2x50 te) Others	150 500 750 1000 1500	Based on example consultation distances [**Error! Bookmark not defined.**].
Other toxic and very toxic gases (e.g. NH_3, SO_2, HF)	< 100% Q > 100% Q	1000 1500	Where Q = top-tier CIMAH threshold quantity.
Toxic liquids	> 1	100	

Figure 6-4 Typical Maximum Domino Hazard Ranges

Clearly, this table could be refined much further as more experience is gained in assessing potential domino interactions. However, it should be adequate to provide a conservative preliminary first pass assessment of large numbers of sites to identify those which require more detailed consideration. More detailed assessments can then be concentrated on those sites where the potential for interaction is most significant.

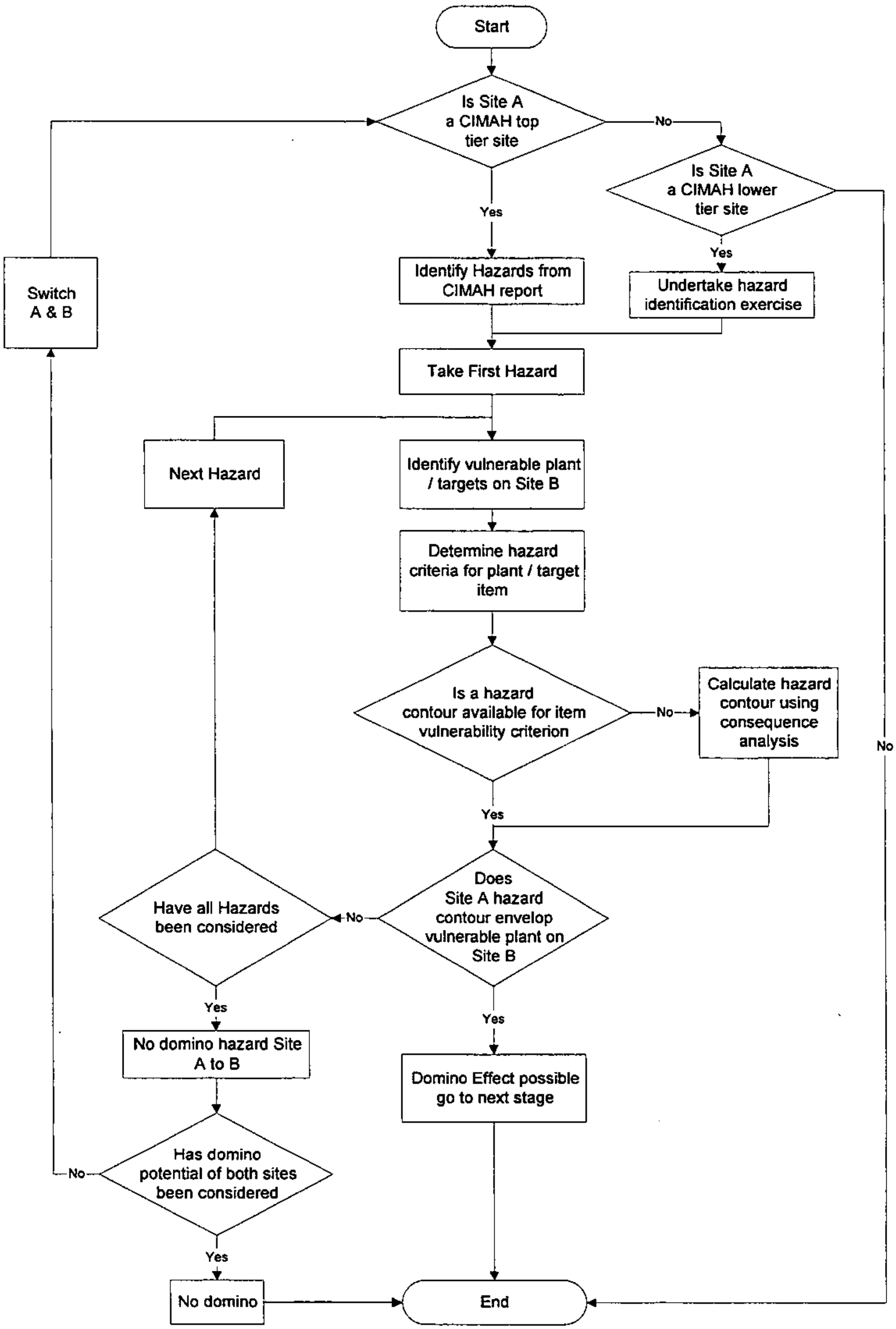

Figure 6-5 Maximum Hazard Distance Methodology Flowchart

Contents

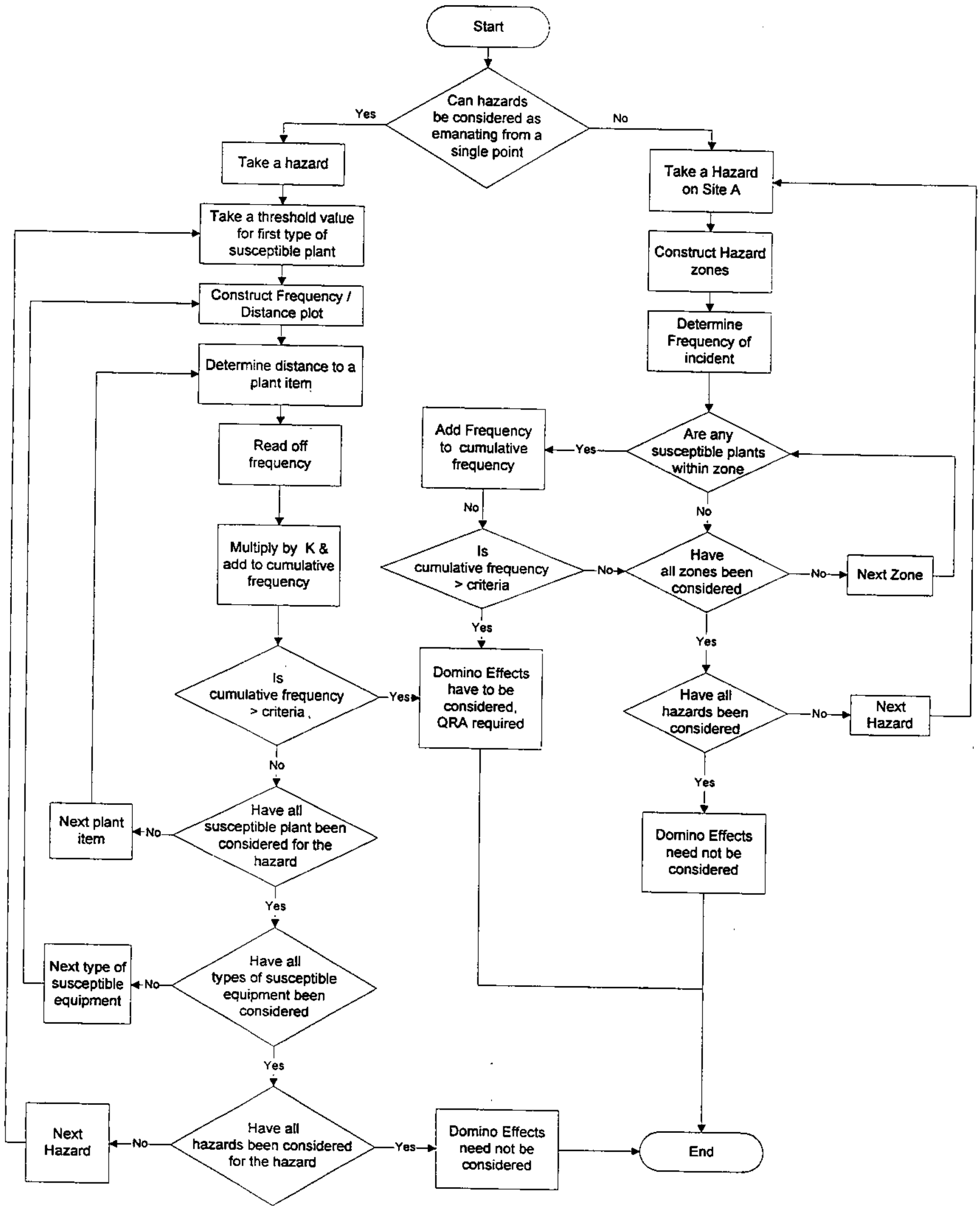

Figure 6-6 Frequency Limitation Methodology Flowchart

6.3 Stage 2 - Frequency Limitation Approach

6.3.1 Introduction

A Frequency Limitation methodology is based on the premise of being able to show that the frequency of interaction between two sites is less than some specified criterion. The development of a possible criterion is outlined in Section 6.3.2. A flowchart for the methodology is given in Figure 6-6. This essentially has two paths depending on whether the hazard can be considered as effectively emanating from a single point or multiple points.

The former case is considered to lead to a simpler analysis procedure and can be explained by means of a simple example as described in Section 6.3.3. Multiple point hazards are discussed in Sections 6.3.4 and 6.3.5. A methodology for combining hazard levels which cause partial damage to plant that may lead to a domino effect and total failure of critical plant which is assumed always to result in a domino event is discussed in Section 6.3.6. Means of incorporating toxic effects and missiles are discussed in Sections 6.3.7 and 6.3.8.

6.3.2 Frequency Criteria

A number of ways of deriving an appropriate criterion for use with a frequency limitation approach for assessing domino interaction of sites were considered. These included the following means:

- an apportionment of site risk levels,
- previously used criteria,
- limitation of risk to neighbouring plant operator risk levels,

Apportionment of site risk levels

Apportionment of site risk levels would imply that given that there are overall limits to the risk levels which members of the general public or operators can be exposed, then if there is more than one source of risk, such as two chemical plants, then each plant can only utilise a fraction of the overall limit.

Thus if there are two plants and the maximum individual risk limit is defined as X probability of death / year then the permissible contribution for one of the plants would be X/2 probability of death / year, assuming that the risk is allocated evenly between the two plants.

It could be argued that the contribution from domino events should not be a significant fraction of this value. Typically, in past risk assessment philosophies less than 10% has been seen as not being a significant fraction of limit, which would result in a criterion for domino events on the chemical plant of X/20 probability of death / year.

In order to be able to derive a frequency criterion for domino interaction using this approach requires either:

- an assumption that the site risk to the general public is insignificant, i.e. less than 5×10^{-7} / year (viz, 10^{-6} / year / 2) in which case the domino risk criterion becomes 5×10^{-8} / year which would be conservative for most plants since they are likely to be operating in the ALARP region, or
- knowledge of the whereabouts of the plant risk values in the ALARP region.

However to be able to determine the current ALARP levels for the plant requires a full quantified risk assessment. If a QRA has to be undertaken to determine an appropriate frequency criteria then it negates the advantage of undertaking a frequency limitation approach.

Having established the overall plant risk level and derived a risk limit by dividing by an order of magnitude, a corresponding frequency of domino events could be calculated from this risk limit. However, this would require a detailed analysis of the domino accident scenarios to determine the probability of being killed as a result of each accident. Therefore, a means of deriving a domino frequency criteria from apportionment of risk was not developed further.

Previously Used Criteria

An example of a previously used criteria is the value developed by Highland Council. In the Highland Council methodology, a criterion for safeguarding the public was based on a 5% fatality hazard level which should not be experienced at a frequency of more than 10^{-4} / year. The supplementary criterion that was derived for inter-site domino effects involved limiting the frequency of site operator exposure at a 5% fatality level to less than 10^{-3} / year i.e. a factor of 10 greater frequency than for public. This domino criteria was split equally between the two sites.

The Highland Council criteria were considered to be less stringent than the current HSE general risk criteria and therefore a more restrictive set of criteria have been proposed here for the purposes of domino assessment.

A frequency criterion based on the underlying dangerous dose principle of the HSE planning guidelines is thus proposed. The HSE have published land use planning guidelines which are based on frequencies of receiving a dangerous dose or worse of toxic gas, heat or explosion overpressure. The present guidelines [46] indicate that, for typical housing developments around a major hazard plant, the HSE would generally advise refusal of planning consent if risk levels were above an upper limit of 10^{-5} / year of receiving a dangerous dose, and they would generally allow development to proceed if risk levels were below a lower limit of 10^{-6} / year. The decision would also take into consideration factors such as the size of the development, and whether it forms a precedent for further growth.

Thus applying a reduction factor which is similar to that used by Highland Council to the lower limit of 10^{-6} / year of receiving a dangerous dose then an appropriate criterion of 10^{-5} / year for interaction between two sites would be recommended.

If this factor was also to be also applied to the upper limit of 10^{-5} / year of receiving a dangerous dose then this would be in line with the draft HSE policy [47] that members of the public should not be subjected to a level of risk from all hazardous installations in the vicinity in excess of 100 chances per million per annum of receiving a dangerous dose. In this respect a worker on one hazardous installation should be treated as if he were a member of the general public as far as being exposed to hazards from the other site.

However, for the purposes of this study, the lower limit of 10^{-5} / year was selected for use as a domino frequency limit criteria since the aim of the criteria was to provide a preliminary indication whether the degree of interaction was acceptable or whether a more detailed analysis was required.

Allowing for the fact that not all domino events are expected to result in offsite hazards and if they do the wind could convey toxic or flammable releases in other directions than towards the population at risk then the actual risk of the general public of receiving a dangerous dose is expected to be thus lower and approaching a frequency of 10^{-6}/year.

If the above limitation on the frequency of operators receiving a dangerous dose from the initiating incident was applied to operators in the open who are directly exposed to the hazard then the corresponding risk of fatality would be much lower than 10^{-5} /year. The definition of a dangerous dose implies only unusually vulnerable people who are exposed might be killed and the worker population is expected to be on average healthier and therefore less susceptible to hazards than the population in general. Thus this risk is expected to be below the level classed as insignificant risks, i.e. 10^{-6} /year.

Limitation of Risk to Neighbouring Plant Operator Risk Levels

Damage to the process plant on Plant B can be seen as resulting in a risk to both offsite general public and the Plant B operators, thus the specified frequency limit will also result in limitation of the risk to the general public and the operators.

In addition to the general public exposure, plant operators would also be exposed to domino hazards. Given the operators' proximity to the damaged equipment, they are expected to be more at risk than the general public. Thus if they were not killed or injured by the initial incident that was hazarding the process plant then they are more likely to experience hazard levels well in excess of the dangerous dose levels. This will increase their probability of being killed as a result of the domino incident. However, given that they are expected to be only on site for 2000 hours / year there is a 'time at risk' factor of approximately 0.25 which can be invoked. Thus, given the domino frequency of 10^{-5} / year and the time at risk factor, the individual risk is expected to be $2.5x10^{-6}$ / year. Given that the individual risk for chemical industry operators in general of approximately $2.4x10^{-5}$ / year (FAR = 1.2) then the risk of fatality from domino events from the neighbouring plant is expected to be only a fraction of his own plant risks. This can also be compared to the level of individual risk to workers in manufacturing industry in general of $2.3x10^{-5}$ / year [43].

Recommended Frequency Criteria

A frequency limitation criterion of 10^{-5} / year for interaction between two sites is recommended.

6.3.3 Single Point Hazard Methodology

Complications to this simple frequency criterion arise where there is more than one possible outcome to an event. In particular this applies to Vapour Cloud Explosions (VCE). If Plant A contains a single process block which can give rise to a number of volatile hydrocarbon liquids (VCE_1 - VCE_n) and gases that result in various sizes of explosive vapour clouds (M_1 - M_n) at different frequencies (F_1 - F_n), then these can be listed in a following manner prior to evaluation.

Release No.	Release Frequency	Release Size
VCE_1	F_1	M_1
VCE_2	F_2	M_2
VCE_3	F_3	M_3
.	.	.
VCE_N	F_N	M_N

If it can be shown that the frequency of the most likely initial release and any subsequent ignition to give a VCE is less than the 10^{-5} frequency criterion then the analysis is complete (this can be assumed as a single point event in the frequency limitation flowchart Figure 6-6. However if this is not the case then further analysis may be required. This may be done as part of the full QRA (see section 6.4). Details of a possible methodology is given in the following paragraphs.

If all the explosions are assumed to be centred on the single process area on the plant and the effects are assumed to be omni-directional, then the frequency of experiencing an overpressure of P_1 at a distance D from the plant can be calculated by evaluating the effects of each of the explosions in turn to determine if an overpressure greater than P_1 can be produced at D and if so then its frequency is added to the cumulative frequency. In this way it is possible to construct a cumulative frequency plot as shown in Figure 6-7.

If Plant B only contains atmospheric storage vessels which will fail at an overpressure of P_1 thus causing a domino event, and the closest of these is located x metres from Plant A process area, then it is possible to use the cumulative frequency plot to show whether the separation distance of x metres would result in an interaction frequency greater than the criterion for acceptability.

When using a frequency limitation criteria methodology care is required to avoid excessive conservatism by double counting potential domino events. In the above example with the blast hazard arising from a single location, then it would be only the nearest process plant in each vulnerability category which is required to be considered. Although plant which is further away will also have a frequency of being damaged, the domino event will have already been initiated by the closer plant in all cases under the above assumptions.

As well as assessing the potential for assessing the domino potential of existing sites, it could also be used to calculate a minimum safe separation distance if new process equipment such as storage tanks were to be installed on a site.

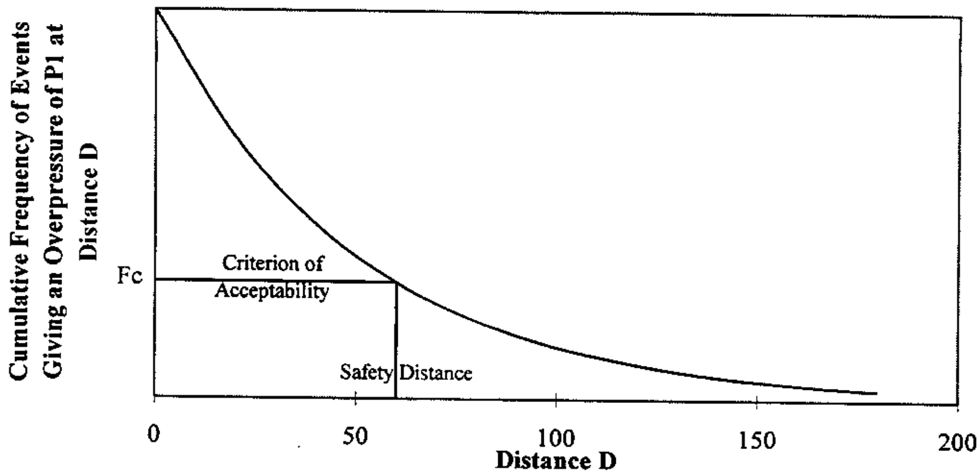

Figure 6-7 Cumulative Frequency Plot

If there were also pressure vessels on Plant B that failed at an overpressure of P_2 then a similar calculation routine would have to be followed to derive another cumulative frequency plot. If the nearest pressure vessel was at a distance of y metres then the interaction frequency for pressure vessels, F_{PV}, would have to be read off this new plot for a distance y. As before, if the nearest storage tank was at a distance of x metres then the interaction frequency for storage tanks, F_{ST}, would be read of the plot for overpressure P_1. However, in this case the combined interaction frequencies for atmospheric storage tanks and pressure vessels (i.e. $F_{ST} + F_{PV}$) would have to be shown to be less than the criterion of acceptability Fc.

It could be argued that there is a dependency between failure of atmospheric and pressure vessel items, but this link is not as easily quantified using this approach. Neglecting this dependency will lead to some conservatism in the prediction of a safe separation distance, due to the potential for double counting. This could possibly introduce a factor of up to 2 into the assessment of frequency as some of the explosions producing a pressure P_1 which affects atmospheric storage tanks may also produce a pressure P_2 which affects pressure vessels.

Plants which could give rise to multiple hazards, e.g. blast, thermal radiation, toxic hazards, are not expected to have a high degree of dependency between the various hazards and therefore it is recommended that these be treated as independent hazards. In deriving a criterion of acceptability for a particular hazard then not only has an overall plant - plant criterion to be allocated between the various independent hazards but also between the hazards posed by Plant A on B as well as those from Plant B on A.

6.3.4 Multiple Point Hazard Methodologies

A variation of the single point method can accommodate factors such as multiple point ignition sources if it can be shown that a two dimensional cumulative frequency plot is still applicable, as indicated in the following example.

Consider the case of not all vapour clouds finding an ignition source in the process area but some being subject to delayed ignition. In the following example, vapour cloud explosions 4, 5 and 6 are subject to delayed ignition which is assumed to occur at a point 50m in the direction of the vulnerable plant. This has an implicit assumption that either the wind is always advecting the clouds towards Plant B or that those travelling in other directions fail to find an ignition source.

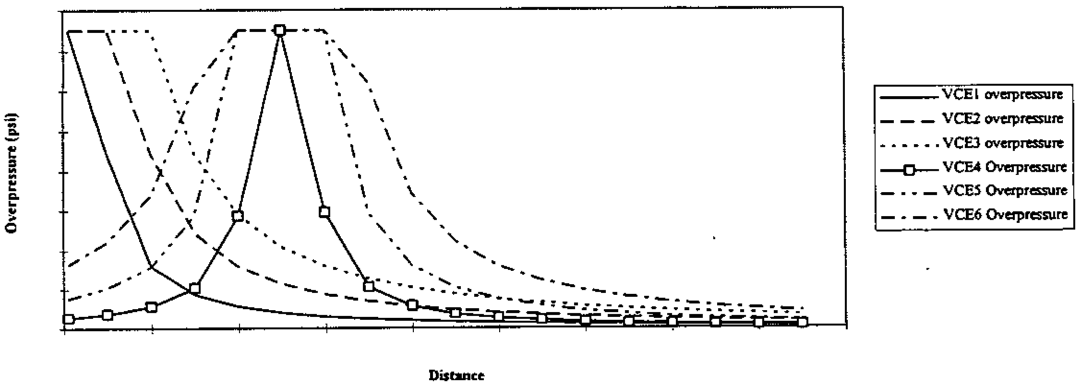

Figure 6-8 Blast Levels from Various Sizes and Locations of VCEs

Taking the frequencies of each of the VCEs into account a cumulative frequency plot can be constructed for various overpressures (in the example arbitrary levels of 1, 2, 5 and 9 psi are shown). Thus the appropriate curve could be used to determine the frequency at which blast levels sufficient to cause damage to the item is expected to occur.

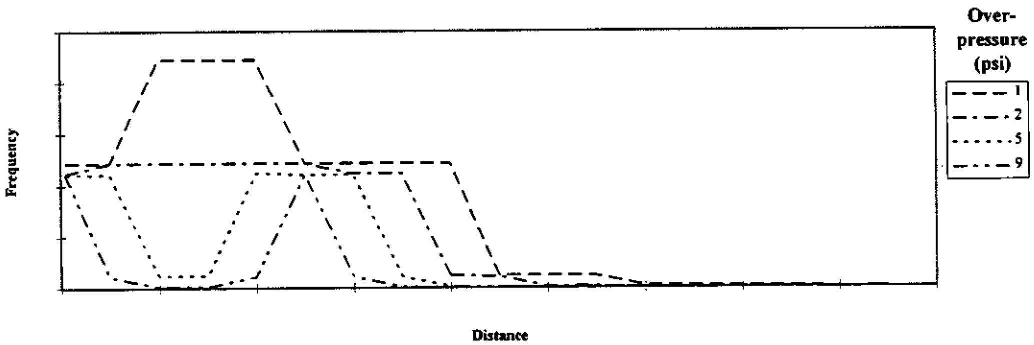

Figure 6-9 Cumulative Frequency Plot For Various Levels of Overpressure Resulting from VCEs

If however the explosions could occur at a number of locations which can not be considered as being on a straight line between the two sites then it will be necessary either:

i. to produce a matrix approach which considers the domino potential for each vessel in turn from all likely initiating VCE events, or
ii. to resort to a three dimensional representation showing the x y location and the frequency at that point of exceeding a specified damage level.

The first option would be more practical if there was only a small number of critical vessels on the target site, such that each is considered in turn, and the effects of each explosion evaluated at the appropriate separation distance to determine whether the vessel fails as a result of the blast overpressure. The cumulative frequency of initiating explosions which can hazard the vessel is then determined and values are summed for all critical vessels to determine whether the interaction frequency criterion is exceeded.

In the second option, the cumulative frequency plot equivalent to Figure 6-7 would thus become a frequency contour plot, as shown below. In this case three explosion centres are represented, and the contours indicate the different frequencies that areas would experience a specified overpressure or other hazard level.

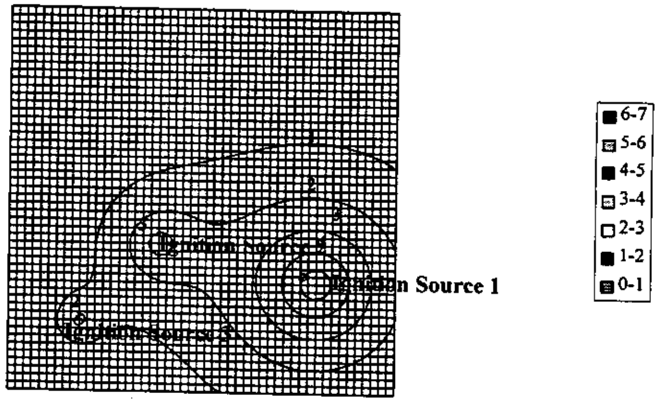

Figure 6-10 3D Cumulative Frequency Plot

6.3.5 Multiple Hazard Sites Methodology

For complex sites, it is quite probable that the hazards on a site will not be restricted to one type, e.g. blast from VCEs, rather there is likely to be a mixture of hazards which could occur at various locations under various accident scenarios. In addition there are likely to be various types of critical process plant which if damaged could cause a domino effect. Thus a whole range of cumulative frequency plots may need to be developed and overlaid on a site plot for hazards such as thermal radiation and blast. The number of hazard levels which would have to be considered would depend on the variation in damage susceptibility of the Plant B process plant (e.g. non deluged and deluge protected plant when assessing thermal radiation hazards).

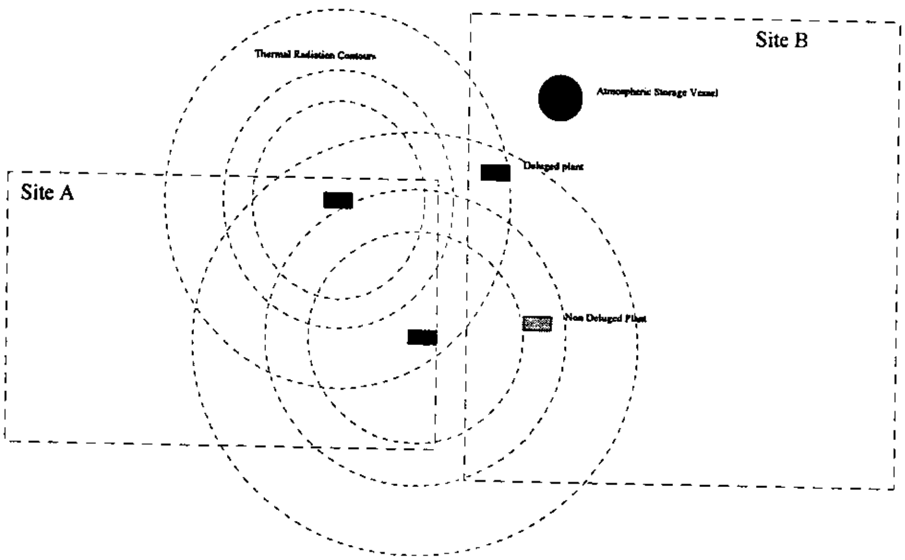

Figure 6-11 Plot Plan of Sites

For the example given in Figure 6-11, in which the thermal radiation hazards arise from a single location and the blast hazards also emanate from another single location, the frequency of critical events occurring as result of overpressure could be read off a plot such as Figure 6-12 and as a result of thermal radiation from Figure 6-13.

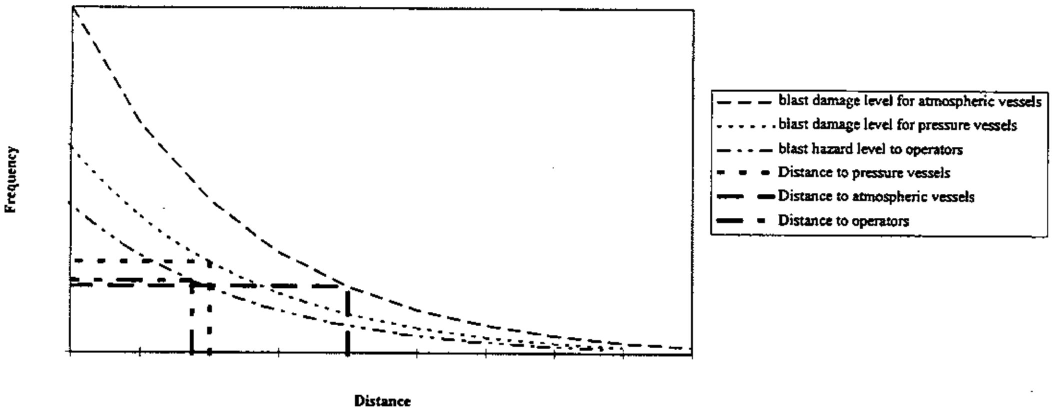

Figure 6-12 Cumulative Frequency Plot for Blast Impact on Plant B

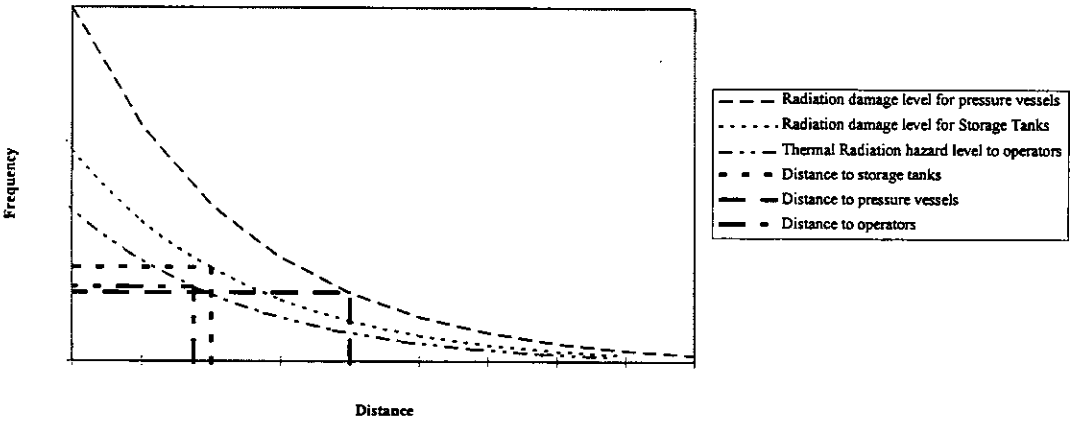

Figure 6-13 Cumulative Frequency Plot for Thermal Radiation Impact on Plant B

In certain circumstances it can be foreseen that some vulnerability categories might completely bound others and if both were included in calculating an interaction frequency then it could lead to a higher frequency being predicted than is appropriate. This would not be a problem where overestimating frequencies would still give a negative result but it may be important if results are close to the frequency criterion. For example, at a site with a water deluged protected process plant item and a non deluge protected item side by side, each would have a frequency at which hazards could arise which would seriously damage them (the deluge protected item having a lower value). However, in all cases when the deluge protected vessel fails, the non protected vessel would have already failed and have been deemed to cause a domino event and hence it is necessary to consider conditional probabilities of domino events.

6.3.6 Conditional Probability of Domino Event Occurrences

For complex plants where there a large number of potential hazards, in order to calculate the frequency of domino events that can arise from the various hazards and on plant which can suffer complete or partial failure which may or may not result in a domino event then it has been necessary to develop an approach which allows these factors to be included without double counting. Thus the conditional probability of a domino event (represented by a factor K) has been introduced.

If the same notation is used as in the HRC methodology, as described in Section 4.2, i.e.

$$P_{iD} = P_{jP} \times P_{ij}$$

where P_{iD} = Probability of domino event , i.e. domino failure of equipment (i)
P_{jP} = Probability of initiating event, i.e. primary failure of equipment (j)
P_{ij} = Probability that the domino event will occur given that the primary event has occurred within the potential hazard zone

then the following modifications can be made.

Let the factor P_{ij} represent the probability that a domino event will occur on equipment (i) if it is considered in isolation given that the primary event has occurred. Also let K_{ij} represent the conditional probability that a domino event occurs on equipment (i) without it previously occurring with equipment closer to the source of the initiating event. This conditional probability is used in Figure 6-6 and can be derived as follows:

If there are N items of process equipment (e.g. pressure vessels) that could be affected by the primary failure of equipment j, then it is necessary to avoid double counting, i.e. taking into account the domino effect occurring on a plant item when it has already occurred on closer plant items. This double counting would arise if the probabilities P_{ij} to P_{Nj} were simply added to give the overall probability of a domino event because the cross products would have been ignored and a value greater than 1 could be obtained.

In order to avoid having to calculate explicitly the cross products it is possible to convert to probability of the success state (i.e. the probability of a domino not arising as a result of primary failure of equipment j on item i can be expressed as $1-P_{ij}$). If terms for each of the N equipment items are developed and are multiplied together then the probability of a domino not arising as a result of primary failure of equipment j on items 1 to N becomes.

$$\prod_{i=1}^{N} (1-P_{ij})$$

The probability of a domino event is thus

$$1 - \prod_{i=1}^{N} (1-P_{ij})$$

This expression gives the overall probability of a domino occurring from a particular event such as an explosion. If it is required to identify the contribution that a particular plant item has on the domino potential given that it could be one of a number of items then it is necessary to develop this expression further. The need for this is illustrated in the following example.

If it is assumed that the nearest plant item would be first to be affected by failure of equipment item j then the conditional probability of it giving rise to a domino is

$$K_{1j} = 1 - (1-P_{1j})$$

and the conditional probability of the second plant item is the combined probability of the first and second plant items minus the probability of the first plant item, i.e.

$$K_{2j} = [1 - (1-P_{1j})(1-P_{2j})] - [1 - (1-P_{1j})]$$

This can be represented by a general expression for equipment item (i) when it is the m[th] item of equipment from the source of the initiating event (j), i.e.

$$K_{mj} = [1 - \prod_{i=1}^{m} (1-P_{ij})] - [1 - \prod_{i=1}^{m-1} (1-P_{ij})]$$

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which can be simplified to the following expression

$$K_{mj} = \prod_{i=1}^{m-1}(1-P_{ij}) - \prod_{i=1}^{m}(1-P_{ij})$$

In the above expression, the plant items being considered should commence with the nearest.

If, as in the examples given in Sections 6.3.3 to 6.3.5, the hazard level is such that a domino event will always result when a vulnerable plant is affected, i.e. P_{ij} for all plant items is taken as 1, then K_{1j} for the nearest plant will be equal to 1 and all subsequent values of K_{ij} will be 0, hence, only the closest item needs to be considered in the analysis.

In order to allow for the vulnerability of the plant items to hazards from another site the concept of P factors has been introduced. The frequency of the primary event impinging on the plant item can be multiplied by the P factor to give the frequency of the domino event. Thus the P factor can take into account the fact that plant might not initially fail catastrophically but that only a small leak might occur which has the potential to escalate to a large accident and to incorporate the effect of safeguards which, if working correctly, will inhibit domino effects but which will still have a probability of failure on demand, e.g. water deluge systems.

The following P values are considered to be appropriate:

Domino Hazard to Item	P factor
Thermal radiation on Pressure Vessels	1
Thermal radiation on Storage Tanks	1
Thermal radiation on Control Room	0.1
Thermal radiation on Pressure Vessels (water deluged)[6]	0.01
Thermal radiation on Storage Tanks (water deluged)	0.01
Blast on Pressure Vessels (catastrophic)	1
Blast on Storage Tanks (catastrophic)	1
Blast on Pipework (catastrophic)	.5
Blast on Pressure Vessels (Leakage)	0.1
Blast on Storage Tanks (Leakage)	0.1
Blast on Pipework (Leakage)	0.05
Blast on Control Room (catastrophic)	1
Blast on Control Room (Partial Damage)	0.5
Lethal Concentration at Control Station (highly automated plant)	See Appendix B
Lethal Concentration at Control Station (unautomated / manual plant)	See Appendix B
Perceived Toxic Hazard at Control Station (highly automated plant)	See Appendix B
Perceived Toxic Hazard at Control Station (unautomated plant)	See Appendix B
Missile Impact	1 (See Appendix C)

Table 6-11 P Factor Values

[6] A more precise value of probability of failure of water deluge could be calculated if the site specific details are known

6.3.7 Approach to Assessing Toxic Hazards

Toxic hazards will have a potential to cause domino events, albeit of an indirect nature, through loss of control of process plant on site B. Consideration was given to how this should be included and how many concentration hazard levels would be necessary to simulate the number of ways in which an operator might react.

If a single hazard level was used, for example based on a dangerous dose level, then it would be extremely conservative to assume that the plant was always left in a dangerous state when the operators evacuated the control room. If a higher toxic hazard level was used which resulted in a probability closer to 1.0 that the plant was left in an unsafe state, then the hazard zones would be smaller.

Thus it was considered that a methodology based on a single toxic hazard would not be appropriate and a two level approach would be necessary. A two zone approach has therefore been proposed, as indicated in Table 6-11, based on doses corresponding to an actual immediate (acute) hazard and to a perceived hazard. An approach which describes how these hazard levels can be derived is described in Appendix B. A methodology for deriving an appropriate P factor, which takes into account aspects such as control room characteristics, operator training and the degree of automation, is also described in Appendix B.

6.3.8 Approach to Missile Effects

Although the probability of domino events due to missile effects has often been omitted in previous studies on the basis that there was considered to be a low frequency for missile generating incidents combined with a low probability of hitting a specified target, it is considered that a methodology should be included in this study for completeness.

The discussion regarding the initiating event has been limited to catastrophic failure of pressure vessels as these are considered to be the most relevant to major hazard installations. It is recognised however, that missiles could also be generated by disintegration of large high speed rotating equipment

The probability of a domino effect being initiated by a fragmenting pressure vessel is a function of the following:

i) the frequency of pressure vessels on the incident site (Plant A) failing catastrophically with the ejection of fragments which act as missiles,
ii) the number of missiles produced,
iii) the probability of one of the resultant missiles reaching the critical vessels or components on the target site (Plant B), and
iv) the probability that the missiles have sufficient kinetic energy and impact characteristics to cause failure of the critical plant.

An outline methodology is given in Appendix C for assessing the probability of impact on target vessels by missiles generated from catastrophic failure of pressure vessels. Due to differences in the way in which accidents can develop a number of failure scenarios have been considered. The methodologies for various pressure vessel shape / orientation / failure mechanisms have been discussed in the context of LPG. Missile range - probability distributions are available for LPG as it is one of the most commonly encountered hazardous materials.

6.4 Stage 3 - Full Quantified Risk Assessment

It is envisaged that a full quantified risk assessment would be undertaken as the ultimate stage in demonstrating whether domino interaction between sites is tolerable. This step would not be required for the purposes of COMAH which only requires that '*Member States identifies establishments and groups of establishments or where the likelihood and the possibility or consequences of a major accident may be increased because of the location and the proximity of such establishments, and their inventories of dangerous substances.*' However details are given below on what a full QRA may involve. Some details such as Multiple Point Hazard Methodologies are discussed in section 6.3 above.

Selection of the overall risk criteria to be used in the study would depend on whether a probit type approach to model people's different susceptibility to the hazard or the concept of dangerous doses was used.

Risk to operators and to the general public would have to be assessed using consequence analysis in conjunction with appropriate harm criteria to determine the likelihood of injury or fatality given exposure to the hazards associated with any particular accident sequence. Risks would be computed taking into account the frequency of being exposed to the hazard. These risk levels would then be compared with standard individual risk criteria [44] in order to determine whether they were tolerable.

The domino initiating events arising from Plant A incidents would have to be identified using the plant damage criteria as discussed in Section 6.1 and standard consequence analysis.

If a risk assessment is undertaken using the concept of a dangerous dose, as is used in the HSE land use planning guidelines, then risk contours can be plotted in terms of chances per million of receiving a dangerous dose. Similar contours for the risk of fatality may be derived using probit expressions.

The specification of dangerous doses in terms of thermal radiation is given in a report containing the HSE draft methodology [47] for people in the open (fireball, jet fire, pool fire, flash fire) and for people indoors (fireball, jet fire, pool fire, flash fire). Normal and vulnerable populations are differentiated. This document also specifies dangerous dose levels of blast for normal and vulnerable populations in buildings as well as the blast level corresponding to fatality for people in buildings.

Reference is also given in the document to a discussion document [45] on how to determine appropriate dangerous toxic doses.

Whereas a full quantified risk assessment using a probit approach can evaluate the risk in terms of both individual and societal risk, a risk assessment based on the concept of dangerous doses currently has limitations due to not explicitly taking account of societal risk. The HSE guidelines [46], which are currently in force and which describe how the technique is utilised, indicate that it is only possible to evaluate the risk on a quasi individual risk basis.

Further guidance [47], which outlines how it may be possible to derive some 'pseudo' societal risk estimates in the form of an Approximate Risk Integral and a Scaled Risk Integral, is still only a draft document and it is understood that these guidelines may not be implemented in their present form.

Regardless of whether a probit approach or a dangerous dose approach is adopted for evaluating the risk, there are possible limitations in the underlying methodology.

If the overall domino methodology used in a quantified risk assessment was similar to that used in the HSE Canvey study, then the frequency of major accident scenarios on Plant B would be increased to allow for them being initiated by domino events from Plant A.

One inherent drawback of this method is the possible double counting of some of the risks to operators and to the public, and omission of others under certain accident sequences. As the domino event will be treated as essentially independent of the initiating event, then the risks to the operators and the public from the domino event will also be analysed and included in the risk estimate, regardless of whether they have been killed or injured in the initiating event.

This double counting will be propagated through both the individual risk and societal risk estimates. This is immaterial from a domino identification viewpoint and it will give an overestimate of the risk, however, it could have ramifications in the accuracy of cost benefit evaluation of mitigation measures, if the overall risks are not tolerable.

Omission of some risks can be attributed to not analysing the 'super event' where the combined effects of the initiating and domino events reinforce each other and injure people or damage equipment which would otherwise be unaffected by the two events in isolation.

This aspect of the methodology was discussed in Section 2.4 where it was considered that for the majority of domino events likely to be encountered, the increased frequency due to double counting would not introduce great inaccuracies.

7. IMPLICATIONS OF DOMINO ASSESSMENT ON HSE LAND USE PLANNING METHODOLOGY

7.1 Introduction

The current and future draft HSE land-use planning philosophies [46, 47] and their basic underlying principles have been reviewed to determine what, if any, modifications need to be made to take account of domino effects.

The following sections review and summarise the essential elements of the land use planning methodology and then discuss the implications arising from the need for domino event identification and control.

The basis of the HSE's advice to planning authorities was originally formed on the protection concept promulgated by the ACMH. ACMH suggested that policies for separation of the public from hazardous installations should aim to give 'almost complete protection for lesser and more probable accidents' and 'worthwhile protection for major but less probable accidents'. This was illustrated in the ACMH 3rd Report using an example for Chlorine as follows:

> *'HSE recommends separation distance limit such that the consequences of major plant failures would be unlikely to seriously injure more than a small fraction of the population downwind, in typical prevailing weather conditions. In unfavourable weather, or with larger releases from tank failure, people at greater distances could be injured, but the risk to an individual from such a scenario is very low.'*

When describing their original approach for giving guidance to local planning authorities, the HSE thus initially had a protection concept which was based on ensuring a separation between the development and the hazard which provided a high degree of protection against more likely smaller events whilst giving worthwhile (sometimes almost total) protection against foreseeable larger scale events. However, this was later superseded due to criticism regarding i) the protection sometimes being more than is reasonable, ii) the arbitrary nature of selecting the worst events and iii) the difficulty in making comparisons with other hazards.

The HSE, thus, adopted their current risk based approach [46] which took into account the likelihood of the accidents as well as the consequences.

7.2 Existing Land Use Planning Methodology

In dealing with the uncertainties in their risk based assessment methodology, the HSE tried to adopt a cautious best estimate approach in which every attempt was made to use realistic best estimate assumptions.

Rather than use a probit type approach in the assessment of individual risk, HSE introduced the concept of a dangerous dose. The dangerous dose concept sought to address the public's perception regarding concern not just about death but also serious injury and impact on the community, and society's concern about harm to particularly vulnerable members of a community. Dangerous doses for blast, thermal radiation and toxic exposure giving broadly equivalent levels of harm have been reported [43, 47]. The individual risk may then be expressed as chances per million of receiving a dangerous dose or worse.

Whilst being instrumental in the development of various risk criteria and thus fully aware of its limitations, the HSE chose not to consider societal risk explicitly, but rather to weight individual risk criteria depending on the size of the proposed developments in order to take account of society's aversion to larger scale disasters.

The three band approach used by the HSE for the different types of development is summarised in Table 7-1.

Category	Inner Zone ($>10^{-5}$ cpm)	Middle Zone (10^{-6} to 10^{-5} cpm)	Outer Zone ($3x10^{-7}$ to 10^{-6} cpm)
Category D Highly vulnerable or very large facilities	Refuse	Consult	Consult
Category A Housing, hotel or holiday accommodation	Refuse	Consult	Don't Advise Against
Category C Retail, community, leisure, etc.	Consult	Consult	Don't Advise Against
Category B Some workplaces, parking areas	Don't Advise Against	Don't Advise Against	Don't Advise Against

Table 7-1 Existing Land Use Planning Regulations

The HSE stipulate that the criteria quoted in Table 7-1 only relate to proposed new developments near existing hazards, and they do not relate to existing buildings near a major hazard or to an increase in the level of hazard generated by a site. They point out that under these circumstances a different appraisal of what seems reasonable or justifiable is required, although, this is not defined in the current land use planning methodology [46].

If it has been demonstrated that there is potential interaction between two sites under accident situations using the maximum hazard distance approach followed by the frequency limitation approach then a risk based approach is required to justify whether the interaction is tolerable in terms of risk to the surrounding population. As discussed in Section 6.4 the land use planning methodology could be used in this stage.

When evaluating the risks from each site, consequence assessment will have to be undertaken to determine the distances to dangerous dose levels for fires, explosions and toxic releases. These will have to evaluated for each accident scenario that could have an off-site impact. In addition, the frequency of each of the above accident scenarios including domino escalation needs to be determined.

Each of the accident scenarios will thus have a dangerous dose hazard with an associated frequency. These need to be amalgamated to produce a map showing frequency contours around the sites within which the frequency of obtaining a dangerous dose is exceeded.

Thus evaluation of the overall amalgamated risks from both sites in terms of frequency of dangerous dose could be undertaken. Thus if the risks associated with existing land use were shown to be in the 'Allow' regions then the domino interaction between the two sites would be deemed to be acceptable as far as offsite hazard was concerned.

Although the decision matrix in Table 7-1 has been principally devised for assessing developments around an existing major hazard installation, it could be used for assessing the risk to workers on the adjacent domino installation. In this case the workers on the domino site could be considered as being similar to workers in the development category entitled "some work places, parking areas, etc."

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7.3 Draft Future Land Use Planning Methodology

A possible alternative to using the above criteria could be to incorporate the underlying philosophy of the proposed future regulations [47], however, it is understood that these currently are only draft regulations and they might not be implemented in their present form.

Whereas the existing regulations could only be used to consider a planning application in the vicinity of existing hazardous installations, the proposed future regulations are more flexible and address a range of possible considerations.

Three situations have been identified in which domino effects may have to be considered, i.e.

- two existing adjacent hazardous installations with existing housing / industrial or retail facilities require to be assessed as the potential for domino effects has previously not been recognised or addressed,
- a new land use application is received in the vicinity of two existing adjacent hazardous installations which have a potential domino effect,
- an application for a new hazardous installation is received which to be sited in the vicinity of an existing hazardous installations and the spacing between the two installations is such that domino effects could occur and impact on the surrounding population.

As stated above, the criteria summarised in Table 7-1 are only applicable to the second of these land use situations.

The third situation has been addressed in the draft regulations [47]. This has been summarised as follows:

HSE advice will be to refuse applications related to new hazardous installations, or alterations to an existing hazardous installations which would increase the risks from major hazards at that installation, if

- *any member of the public be subjected to a level of risk from all hazardous installations in the vicinity in excess of 100 chances per million per annum,*
- *any group of three or more normally occupied dwellings be located within the 10 chances per million per annum individual risk contour for the new hazardous installation (or the installation as modified)*
- *any highly vulnerable population (i.e. sensitivity level 4) be located within the 1 chances per million per annum individual risk contour for the new hazardous installation (or the installation as modified).*

The frequency contours which require to be plotted appear to be those corresponding to

100 changes per million of exceeding a dangerous dose,
10 changes per million of exceeding a dangerous dose,
1 changes per million of exceeding a dangerous dose,
0.3 changes per million of exceeding a dangerous dose.

Societal Risk criteria should be applied when the decision is not clear cut. Two concepts are introduced, namely the Approximate Risk Integral (where ARI = frequency of all major events x max. no of fatalities) and the Scaled Risk Integral.

The Scaled Risk Integral is calculated using the following

$$SRI = \frac{P\ R\ T}{A}$$

where P is the population factor and is calculated by $P = \frac{(n + n^2)}{2}$

n is the number of people on site

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R is the average estimated level of individual risk per million per annum (cpm)
T is the proportion of the time the development is occupied
A is the area of the development in hectares

a lower comparison value has been proposed set at 2,500 based on a limiting case of 30 dwellings at 1 cpm on an area of 1.2 hectares which has a precise SRI of 2,375. The value of n is proposed to be adjusted by a 'c' factor whereby it is suggested that c has values of 0.25 for a working population and 4 for a sensitive population.

Use of the above criteria require a quantified risk assessment to be undertaken before a decision can be made as to whether the development is acceptable. This would require extensive analysis of the probability of accidents in order to derive the contours. In order to avoid having to do this in all circumstances HSE has been developing alternative approaches for common situations.

7.4 Effect of Domino Interaction on Existing Land Use Planning

It was considered that when evaluating the acceptability of new developments in the vicinity of two existing hazardous installations which have been shown to have a potential for domino interaction that the domino effect in itself would not be sufficient justification to change the existing criteria. This was considered to still be appropriate providing that the combined effects of both installations can be shown to result in acceptable risk levels for the development.

It is assumed that the two installations excluding the domino would satisfy the land use planning criteria and that it is only the additional effect of domino events which require consideration. If domino events were sufficient to take the development into the 'consult' region then the HSE would have to consider the implications using an appropriate means of evaluating societal risk.

The criteria could also be used for existing land use facilities located in the hazard zones from existing hazardous installations which have a newly recognised domino potential. Use of the existing criteria would be conservative, since the proposed draft guidelines indicate that the criteria might possibly be relaxed when considering the impact on land use facilities of new hazardous installations in the vicinity of an existing installation.

8. CONCLUSIONS AND RECOMMENDATIONS

Factors relevant to domino escalation have been discussed and various mechanisms which could lead to domino effects have been identified. This has included direct and indirect mechanisms, and the effect of mitigation / safety systems. Although a large number of factors have been identified as being relevant and could be included, some have not been developed further in this study. It has been necessary to make simplifications in some areas in order to enable a general assessment technique to be developed.

A review of previous work has been undertaken to identify methodologies which have been used in past assessments on groups of major hazard sites, and to identify criteria which have been used in evaluation of plant failure when subjected to thermal radiation, blast and missile impact. The review also investigated whether any study had previously considered the potential for a domino event being caused indirectly from toxic effects.

Although a number of articles were reviewed which covered domino effects it was found that no one paper provided an overall coherent approach. Some publications provided elements in an overall methodology whereas others, such as those being developed in Italy, provide a general framework but did not give details of assessment methodologies, damage assessment criteria or overall risk criteria. Possible approaches for assessing domino escalation have been considered, such as that developed for Highland Regional Council. The potential use of Hazard Index techniques was also evaluated.

It was proposed that a three stage methodology be adopted involving:

(i) maximum hazard range determination (hazard based approach);
(ii) maximum frequency limitation; and finally,
(iii) a risk based approach.

It is expected the first of these steps would be of most interest to the HSE as this will provide an alternative to the general arbitrary guideline of a 500 m separation distance. The final stage is not a requirement of COMAH but the methodologies proposed may assist HSE in considering how to deal with this aspect in detailed consideration of Land Use Planning Applications.

8.1 Initial Assessment - Hazard Based Approach

The hazard based approach is intended to be a simple preliminary screening tool for use by regulatory authorities such as the HSE, who need to determine whether there are potential domino interactions between a large number of sites. The hazard based approach simply determines whether there are any other major hazard sites within the maximum hazard range.

Damage criteria were developed based on typical approaches used in risk assessment techniques in general. It is known that these are gross simplifications, i.e. assumptions of vessel failure at a specified overpressure neglecting impulse characteristics, or at a specified thermal radiation incident flux without considering exposure time or vessel contents. However, development and application of more precise methods was considered to be more justified in any follow up analysis after a rapid assessment of domino potential has been undertaken.

The information on probability of loss of containment from vessels and tanks resulting from them being impacted by fragments of failed pressure vessels has been reviewed. From this review it was possible make generalisations regarding the probability of loss of containment on impact taking into account factors such as contact area, kinetic energy, type of vessel, etc. However, in order to use this type of approach, information is required concerning the mass of a fragment, its flight trajectory and its kinetic energy on impact. It is possible to undertake such an assessment as methods exist for considering the flight trajectory of missiles taking into account the lift and drag on an object. However, this still requires a detailed assessment of the characteristics of the missile and this would generally involve gross assumptions about its launch angle, mass and shape, which tends to undermine the value of the analysis.

As there has been no previous attempt to match the information on missile masses, shapes and ranges observed from actual incidents with theoretical predictions in order to make judgements about the likely launch angles, then the analysis method was restricted to frequency range (probabilistic) distributions.

A summary of the proposed damage criteria to be used in domino assessments is given in Section 6.1.

Guideline methodologies based on rapid assessment techniques have been incorporated into the first stage methodology for determining the maximum hazard range. These have mainly covered fire and explosion hazards. Recommended distances for the hazard distances for missile effects have also been included. However, as these were based on probabilistic relationships, it was necessary to select an arbitrary cut off point, i.e. a 1 in 100 residual probability was taken. A summary of the maximum hazard distances and the rapid assessment techniques is given in Sections 6.2.1 and 6.2.2.

It was considered that the principal hazards resulting in domino effects between different sites were explosions and missiles from BLEVEs as these have the greatest maximum hazard distances. Although flammable gas clouds are more likely to result in an explosion if they find an ignition source on site compared to offsite, the probability of an offsite explosion could not be discounted when developing a generalised approach. Techniques exist such as the multi-energy method which enable the degree of congestion / confinement to be taken into account. However, without a detailed assessment of the site and its environs this could not be used without making even more gross assumptions than just applying the TNT equivalent model. The TNT equivalent model was therefore adopted.

The hazard distances associated with toxic releases were dependent on the particular toxicological effects and as such it is difficult to generalise without reference to specific examples. However, the consultation distance is considered to represent a reasonable estimate of the distance within which toxic effects are likely to be significant.

The table in Section 6.2.4 summarises the maximum distances within which various types of hazard could reasonably be expected to lead to potential domino effects.

8.2 Frequency Assessment

If, after evaluating the maximum hazard range in Stage (i), it was considered that although the two hazardous installations were within the maximum hazard range produced by a potential domino initiating event but that the frequency of accidents which could produce this hazard was very low, then it was recommended that a frequency limitation approach be adopted, i.e. Stage (ii). A methodology was developed taking into account differing damage thresholds, i.e. catastrophic failure or leakage. Catastrophic failure was always assumed to result in a domino event whereas partial damage (leakage) was considered to only have a chance of escalating into a catastrophic failure, hence a domino event.

A means of predicting the overall frequency of interaction was developed along with a criterion for assessing acceptability. The basis of deriving this criterion took into account the risks to the operators on the domino affected site and the general public in the neighbourhood.

8.3 Risk Assessment

Finally if the potential for domino effects between two or more sites could not be demonstrated to be acceptable on a maximum hazard distance or a frequency basis then it was recommended that the analysis be progressed to a quantified risk assessment approach. This would of course involve assessing the overall risk of fatality to workers at the hazardous installations from all accidents. In order for this to be consistent with land use planning methodologies it was argued that the dangerous dose concept be utilised rather than a probit analysis type approach. The overall risks from all sites in the vicinity would have to be evaluated and compared to the criteria for the different types of establishments as detailed in the land use planning guidelines.

The implications of incorporating domino effects in land use planning procedures were discussed. It was considered that the present land use planning guidelines could be used for assessing the acceptability of a development within the vicinity of two co-located sites with a domino potential provided the two sites were treated as a whole and the overall risks calculated and used in the analysis.

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APPENDIX A

REVIEW OF HAZARD LIMITS

A1. REVIEW OF THERMAL RADIATION LIMITS

A1.1 Introduction

In order to identify suitable criteria for assessing the threshold levels at which damage would result from thermal radiation being absorbed on an item of process plant or people, two broad categories of data were noted. These can largely be grouped in terms of whether the exposure duration is considered as well as the intensity.

When considering process plant, most studies in the past have considered only the intensity and neglected exposure duration. In the case of process plant that is subjected to a steady thermal radiation intensity, the temperature of the material exposed will increase until a steady state temperature is reached. Simplicity, this occurs when the amount of re-radiated heat is equal to the incident radiation intensity. In order to define an allowable radiation intensity, some criteria are generally used which are derived from avoidance of unacceptable effects which would occur at higher temperatures, e.g. loss of structural properties of material of construction, decomposition and generation of flammable vapours in the case of wood etc.

The above methodology is not appropriate for assessing the effects on humans as the damage to tissue is a function of the total radiation dose received. However, thermal radiation intensities are still quoted for human exposure but these are based on inherent assumptions regarding the exposure duration. This approach is sometimes still used as it simplifies the risk analyses since it avoids having to make assumptions regarding the rate of escape and the need to calculate the exposure time taking into account the size and intensity of the thermal radiation field.

A1.2 Generic Exposure Limits for Process Plant and Humans

The following limits for thermal radiation intensity for both the effects on process plant and on humans were identified:-

Thermal Radiation Intensity (kW/m^2)	Limit
15.6	Intensity on structures where operators are unlikely and where shelter is available
9.5	Intensity at design flare release at locations to which people have access and where exposure would be limited to a few seconds for escape
6.3	Intensity in areas where emergency actions lasting up to a minute may be required without shielding but with protective clothing
4.7	Intensity in areas where emergency actions lasting up to several minutes may be required without shielding but with protective clothing
1.6	Intensity at design flare release at locations where people are continuously exposed.

Table A1 Design Guidance API 510:1990 [1]

Thermal Radiation Intensity (kW/m^2)	Limit
38	Intensity on storage tanks
12.5	Intensity on wood or plastics
5	Intensity on people performing emergency operations

Table A2 Design Guidance Kletz: 1980 [2]

Thermal Radiation Intensity (kW/m^2)	Limit
37.5	Intensity at which damage is caused to process equipment
25	Intensity at which non piloted ignition of wood occurs
12.5	Intensity at which piloted ignition of wood occurs
4.5	Intensity sufficient to cause pain to personnel unable to reach cover in 20 seconds, through blistering of skin (first degree burns) unlikely
1.6	Intensity insufficient to cause discomfort for long exposures

Table A3 Design Guidance BS 5908:1990 [3]

Thermal Radiation Intensity (kW/m^2)	Limit
14	Intensity which normal buildings should be designed to withstand
10 - 12	Intensity at which vegetation ignites
6	Intensity tolerable to escaping personnel
3	Intensity tolerable in infrequent emergency situations lasting up to 30 mins
1.5	Intensity safe for stationary personnel and members of the public

Table A4 Design and Assessment Guidance Mecklenburgh [4]

Thermal Radiation Intensity (kW/m^2)	Limit
30	Spontaneous ignition of wood
15	Piloted ignition of wood
12	Plastic melts
37.5	Equipment damage[i]
9	Equipment damage[ii]

Table A5 Assessment Guidance Dinenno (1982) [5]

Receiver	Tolerable Temperature (^{o}C)	Emissivity	Tolerable Intensity (kW/m^2)
Water Drench	90	1	38
Equipment	550	1	30
Special Buildings	500	1	25
Normal Buildings	390	1	14
Escape routes (30 secs)	65	0.1	6
Emergency work (30 mins)	40	0.1	3
Safe	25	0.1	1.5

Table A6 Tolerable Ignition Temperatures as Reported in Mecklenburgh [4]

Target	Thermal Flux (kW/m^2)	Effects
Human Body	4.7	Threshold of Pain. Average period pain for to be experienced 14.5s
Buildings	12.6	Resins in wood, building felt produced flammable vapours which could be ignited by pilot ignition
Storage Tanks	37.8	Hazardous for a tank adjacent to a tank fire to receive this flux

Table A7 Damage from Various Levels of Thermal Radiation [6]

The information in Table A7 was used by Crocker et al [7] in preference to other extensive considerations[8,9,10].

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[i] Source Ref. Gelderblom (1980) (see ref. [5] for details)

[ii] Source Ref. Tan (1967) based on design of flare system (see ref. [5] for details)

Radiation Intensity Level (kW/m^2)	Observed Effect
37.5	Sufficient to cause damage to process plant
25	Minimum energy required to ignite wood at indefinitely long exposures (non piloted)
12.5	Minimum energy required for piloted ignition of wood, melting of plastic tubing
9.5	Pain threshold reached after 8s; second degree burns after 20 secs
4	Sufficient to cause pain to personnel if unable to reach cover within 20 secs; however blistering of the skin (second degree burns) is likely; 0% lethality
1.6	Will cause no discomfort for long exposure

Table A8 Effects of Thermal Radiation [11, 12, 13]

BS 5908 [3] also gives the following criteria for assessing the effects of fireball dose criteria:

Dose Threshold	Effect
600 - 1800	Secondary Fires
375	3rd Degree Burns
250	2nd Degree Burns
200	Onset of serious injury
125	1st Degree Burns
65	Threshold of pain - no reddening or blistering of skin caused

Table A9 Effect of Fireball Thermal Radiation

	Threshold of Ignition	
	Spontaneous	Piloted
Fireball	$167.6\ kJ/m^2s^{1/5}$	N/A
Jet Fire - constant flux, building interior	$25.6\ kW/m^2$	$14.7\ kW/m^2$
Jet Fire - constant flux, building exterior	$40\ kW/m^2$	N/A
Jet Fire - Variable Flux	$167.6\ kJ/m^2s^{1/5}$	$118.4\ kJ/m^2s^{1/5}$
Pool Fire	$25.6\ kW/m^2$	$14.7\ kW/m^2$

Table A10 Draft HSE Criteria Associated with Thermal Radiation Effects on Buildings

A relationship has been reported [14] which gives the time dependency for the piloted ignition of wood. The relationship is as follows:

$$T = a\,(R - 12)^b$$

in which T = time to piloted ignition (s)
a = 17500
B = -2

If a relatively standard value of 12.5 kW/m^2 is taken for the thermal radiation level at which piloted ignition would occur, then the time for ignition would be 19.4 hours. It can be seen from the structure of the equation that piloted ignition is not predicted to occur below 12 kW/m^2 and if this value was just attained it would take an infinitely long period to reach a point where piloted ignition could possibly occur. This expression was seen to be somewhat complementary to the thermal radiation flux values quoted above.

TNO give details of a comprehensive and rigorous method for assessing the thermal radiation effects on process plant based on factors such as incident flux, shape, heat loss, loss of containment properties, etc. Although this method is very appropriate for detailed assessments it is considered to be much too detailed for domino assessments. Consequently generic guidelines, as detailed above, were considered to be the most appropriate method, hence effort was directed into identifying the most relevant values to use.

TNO differentiate between two damage levels, i.e.:

Level 1 - ignition of surfaces and then breakages or other types of structural failure,
Level 2 - discolouration, paint peeling / deformation of structural elements.

Critical radiation intensities are given for various combustible materials and a more detailed analysis method is given for assessing material damages. Using this detailed method they indicate that steel failure lies in the range 673 - 873 K i.e. 400 - 600°C. Thus an average value would be 500°C.

A1.3 Thermal Radiation / Human Vulnerability Models

Rather than use deterministic thermal radiation flux levels, alternative statistical models have been developed which take into account the variation in people's susceptibility to thermal radiation. An early example of this is the vulnerability model derived by Eisenberg [8] which incorporated the probit method used data for nuclear explosions [15]. For lethality the following probit was used

$$\text{Probit} = -38.48 + 2.56 \ln (t\, q^{1.33})$$

For non fatal injuries the following limiting values for 1% of the exposed population suffering the stated injury for nuclear explosions was used

First degree burns	$t\, q^{1.5} = 5.5 \times 10^5$
Second degree burns	$t\, q^{1.33} = 8.7 \times 10^6$

where t is in secs and q is in W/m^2

To some extent this model has been superseded by others due to its limitations in interpretation of base data. Stoll et al [16] adapted the nuclear data for hydrocarbon fires taking the difference in wave length of the thermal radiation into account and the resultant damage mechanisms. They inferred that the 1% limit value for first degree burns was a factor of 2.23 lower and derived the following probit relationship

$$\text{Probit} = -39.83 + 3.0186 \ln (t\, q^{1.33})$$

This same factor has been extended [17] for use with lethality predictions and second degree burns by deriving relationships assuming a similar gradient as for first degree burns.

$$\text{Lethality Probit} = -36.38 + 2.56 \ln (t\, q^{1.33})$$

$$\text{Second degree burns probit} = -43.14 + 3.0186 \ln (t\, q^{1.33})$$

The 1% limiting value for second degree burns was $tq^{1.33} = 3.9 \times 10^6$.

A1.4 Thermal Radiation Dose Assessment Methodologies

The TNO methodology [17] for assessing the radiation exposure is based on calculating the thermal radiation where the person is initially standing, assuming a 5 second reaction time , and an escape at 4 m/s. Assumptions are made regarding the thermal radiation field, i.e. intensity decreases as the inverse square of the distance and the edge of the radiation field occurs at 1 kW/m^2. Total dose is calculated by integrating dose whilst escaping.

Allowances are made for the protection due to clothing which will influence the number of casualties. However, it would not affect the maximum individual risk since it would be assumed that his clothing offered no protection.

Another criterion for fatality is whether the person's clothing is ignited. A value of 2.5×10^4 $kW^2\, m^{-4}$ s has been proposed as the limiting value and the relationship between intensity and duration to be $q^{2/7}t$. This criterion is generally used to extend the 100% fatality contour out beyond the dimensions of the flame where it would normally be on skin exposure alone.

Other approaches to assessing thermal effects are those reported in the HSE transportation study [18]. Two methods are reported due to different contractors undertaking various parts of the study. Technica [18] used a judgemental modification to Eisenburg's radiation probit to derive a value of 500 kJ/m^2 above which 75% of outdoor fatalities and 25% of indoor fatalities were deemed to occur.

SRD [18] on the other hand used the Eisenberg probit of

$$Y = 2.56 \ln(\text{dose}) - 14.9$$

and calculated the distances to 50% and 1% lethalities. The 50% level was also assumed to be the point at which wood spontaneously ignites.

Other HSE criteria for response of humans to thermal radiation were contained in a draft HSE Land Use Planning Document. These differentiate between the response of a normal population and a vulnerable population.

Thermal Hazard	**Equivalent dangerous dose**	
	Normal Population	**Vulnerable Population**
Fireball	1000 tdu	500 tdu
Jet Fire	1000 tdu	500 tdu
Pool Fire	1000 tdu	500 tdu
Flash Fire	within LFL envelope	none
Oxygen enrichment	within 30% concentration envelope	none

A1.5 Review of Human Response to Thermal Radiation

A review of human response to thermal radiation has recently been undertaken [19]. A wide range of methodologies and criteria have been studied in the light of their source data and the medical evidence available at the time of their formulation. As noted above the methods range from simple thermal flux criteria to probit expressions which take into account evacuation, clothing and population characteristics.

Model comparisons have been made which clearly demonstrate the underprediction of hazard distances by the older methods that are based on predominantly UV radiation rather than the more damaging infra red radiation.

Differences were also noted in assumptions regarding escape delay, escape rate and escape distance, but these were generally concluded to be less sensitive than the dosage criteria.

It was noted that the differences in dosage criteria were, however, of a similar magnitude to the uncertainty in the modelling of the fires themselves.

It was concluded that:

- there was broad agreement between the dosage criteria of 500 $(kW/m^2)^{4/3}$ s and the 1% fatality level predicted by the TNO method,
- the dosage criteria of 1000 $(kW/m^2)^{4/3}$ s for an average population seems reasonable, given the non conservatism arising from its nuclear incident data source being balanced by improved medical treatment.

These conclusions were qualified with the need for further assessment if a non standard level of clothing was worn, if the clothing could be ignited, if further burn data became available or if fire modelling uncertainties were reduced.

A1.6 Recommended Thermal Radiation Levels

The following values were considered to be the most appropriate for use in the Domino Assessment

Item	Thermal Radiation Flux (kW/m^2)
Pressure Vessels	37.5
Atmospheric Storage Tanks	37.5
Pipework	
Buildings	12.5
Control Buildings	25
People	1000 tdu[iii]

[iii] tdu = Thermal Dose Unit (kW/m^2)$^{4/3}$ s

A2. REVIEW OF BLAST OVERPRESSURE LIMITS

A2.1 Introduction

Criteria for assessing damage to process plant and structures can either be based on a determination of the dynamic strength by either simple or complex methods or by practical 'rules of thumb'.

The former by its very nature requires detailed examination of the target object. Even one of the simplest of these detailed methodologies involving the schematic representation of a process plant item as a simple single degree of freedom model can lead to inaccuracy in the determination of dynamic strength. As with thermal radiation effects, a detailed assessment methodology for specific plant items is too detailed and time consuming for a domino assessment methodology, and consequently it is considered that an empirical rule of thumb method is more appropriate.

Many examples of the rules of thumb exist in the literature and these provide estimates of the overpressure required to cause a specified degree of damage.

A2.2 Generic Overpressure Damage Guideline Limits for Process Plant

These empirical values are generalisations and do not take into account the impulse shape, but are only based on overpressure. An overview of the data in the literature has been undertaken by TNO [17] and is shown in the following table

Description of damage	P_s(kPa)
Connections between steel and aluminium ondulated plates have failed	7 - 14
Walls made of concrete blocks have collapsed	15 - 20
Brickstone walls, 20 -300 cm have collapsed	50
Minor damage to steel frames	8 - 10
Collapse of steel frames and displacement of foundations	20
Industrial steel framing structure collapsed	20 - 30
Cladding of light industry building ripped-off	30
The roof of a storage tank has collapsed	7
The supporting structure of a round storage tank has collapsed	100
Cracking of empty oil storage tanks	20 - 30
Displacement of a cylindrical storage tank, failure of connecting pipes	50 - 100
Damage to a fractionating column	35 - 80
Slight deformation of a pipe bridge	20 - 30
Displacement of a pipe bridge, breakage of pipes	35 - 40
Collapse of a pipe bridge	40 - 55
Plating of cars and trucks pressed inwards	35
Breakage of wooden telephone poles	35
Loaded train carriages turned over	50
Large trees have fallen down	20 - 40

Table A11 Damage Criteria from TNO review

Damage Details	Incident Equivalent Peak Overpressure (kPa)
Effects on People	
Threshold for temporary hearing loss	0.69 - 1.38
Threshold for eardrum rupture	13.8
Minimum for penetration injury by small glass fragments	5.52
Threshold for skin laceration by missiles	6.9 - 13.8
persons knocked down or thrown to the ground	10.3 - 20
Possible death of persons by being projected against obstacles	13.8
50% probability of eardrum rupture	34.5 - 48.3
90% probability of eardrum rupture	68.9 - 103.4
Threshold of internal blast injuries	48.3
50% fatality from serious missile wounds	27.6 - 34.5
Near 100% fatality from serious missile wounds	48.3 - 68.9
Threshold for lung haemorrhage	82.7 - 103.4
Near 100% fatality from lung haemorrhage	137.9 - 172.4
50% fatality from lung haemorrhage	206.8 - 241.3
Immediate blast fatalities	482.6 - 1379
General Effects on Buildings	
5% of exposed glass panes broken	0.124 - 0.29
50% of exposed glass panes broken	0.552 - 1.31
Near 100% of exposed glass panes broken	4.62 - 11.03
Limited minor structural damage	2.07 - 2.76
Doors and window frames may be blown in	5.31 - 8.96
Partial demolition of houses rendered inhabitable	6.895
Lower limit of serious structural damage	13.79 - 20.68
Partial collapse of walls and roofs of houses	13.79
Near complete destruction of houses	34.47 - 48.26
Probable total destruction of houses	68.90
Effects on UK brick built houses	
Category A damage - completely demolished	68.95 - 182.70
Category B damage - badly damaged and beyond repair	24.47 - 58.61
Category Cb damage - uninhabitable without extensive repairs	13.79 - 24.13
Category Ca damage - uninhabitable but repairable	6.89 - 12.41
Category D damage - uninhabitable but repairs required	1.72 - 5.17
50% destruction of brickwork	27.58 - 48.26
Effects on Plant	
Reinforced structures distort and unpressurised storage tanks fail	21 - 34
Wagons and plant items overturned	34 - 48
Extensive damage	above 48
Failure of pressurised storage sphere	above 70

Table A12 Typical Effects of Blast Overpressure on People, Buildings and Plant[iv] (HSE) [20]

[iv] The information for plant has been compiled by HSE by reference to the Second Canvey Report

An example of a less extensive but similarly derived set of criteria is as follows:

Receiver	Incident Overpressure (bar)
Ordinary plant buildings	0.07
Fixed roof tanks containing highly flammable or toxic materials	0.10
Floating roof tanks, other fixed roof tanks	0.20
Plants with large atmospheric pressure vessels or units having large surface areas	0.30
Other hazardous plant	0.40
Non - hazardous (if unoccupied) plants. Control rooms designed for blast resistance	0.70

Table A13 Damage Criteria as Reported by Kletz [2]

Receiver	Incident Overpressure (bar)
Pressurised storage sphere / bullets	0.7
Storage of HF[v]	0.48
Storage of HF (0.4 probability of failure)[vi]	0.2 - 3.5

Table A14 Canvey Report Criteria [21]

	Walls	Roof Tiles	Glass
Completely destroyed	0.8	>0.1	0.06
Over 90% substantially broken and displaced	0.4 - 0.6	0.07	0.04
Up to 50% broken but no displacement	0.3 - 0.4	0.04 - 0.07	0.016
Cracked and distorted	0.15 - 0.3	0.03 - 0.04	>0.01
Undamaged	<=0.15	<=0.03	<=0.01

Table A15 Blast Effect on Buildings [4]

Item	Overpressure (psi)	Overpressure (bar)
Structural damage to 5% of typical brick buildings	1	0.07
Pressure plant items	5	0.35
Low pressure items	2	0.14
Structural damage to process plant buildings	2	0.14

Table A16 Highland Council Criteria [22]

Values for pressurised plant items and low pressure plant equipment are quoted by Wells [23] which are identical to those in Table A16.

A procedure for assessing the vulnerability of occupants of different types of building subject to overpressures produced from vapour cloud explosions has been reported [24]. The different types of building considered included housing, offices, retail and leisure developments, schools and hospitals. However, the report does not specifically consider blast resistant control rooms which would be important when assessing domino effects, i.e. the potential for loss of process control of a neighbouring plant through blast damage of the control room and death / injury of the control room staff.

Mecklenburg reports a detailed listing of the effects of blast on vulnerable process plant items. This indicates the range of overpressure over which 1 to 99% probability of failure for specific items is expected to occur. A

[v] Page 53
[vi] Page 50 (1 butane sphere and 4 propane spheres)

wide range of process plant items is reported and their vulnerability is determined on the basis of their expected response to blast effects from nuclear devices. This degree of breakdown in terms of different types of equipment is considered to be too detailed for a domino assessment methodology .

An interim empirical method which goes some way towards taking the impulse characteristic into consideration is that undertaken by Baker in which a pressure impulse diagram is constructed in which three isodamage lines are shown corresponding to different degrees of damage to masonry buildings. However, since this approach has not been extended to other items of interest such as process plant, it was not considered further.

A2.3 Blast Effects on Humans

The following information provides examples of the methodologies, guidelines and criteria that are available from past studies and published papers.

Level of Injury	Overpressure (bar)
50% mortality	>1.4
Lung Damage	>0.35
Eardrum damage	>0.17
Penetrating small glass fragments	>0.04

Table A17 Blast Effect on Humans

Overpressure		Casualty Probability
kPa	Psi	
<7	<1	0
7 - 21	1 -3	0.10
21 - 34	3 - 5	0.25
34 - 48	5 - 7	0.70
>48	>7	0.95

Table A18 Blast Effects on People

The values quoted in Table A18 are those taken from the IChemE Overpressure Monograph [25]. These are also those used in the Canvey Island study [26].

The effect on humans was assessed in the HSE transport study. The exposed group was assumed to be the public in their houses and a probit approach was used which was based on World War II data from V1 explosions. This had been modified to remove effects of bomb shelters. The following probit was quoted

$$Y = 1.47 + 1.37 \ln(P) \text{ where P is in psi}$$

The above was reported to have superseded that used by SRD which was based on the Kingery and Pannill probit of

$$Y = 2.47 + 1.43 \log_{10}(P)$$

A value has been quoted for a 1% fatality level [27] which would correspond to a dangerous dose level. The quoted value of 2.4 psi is in agreement with the 1% value calculated from the first of the probits given above.

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A2.4 Recommended Overpressure Levels

The following values were considered to be the most appropriate for use in a Domino Assessment.

Item	Overpressure Resulting in Destruction (bar)	Overpressure Resulting in Partial Damage (bar)
Pressure Vessel	0.48[vii]	0.38[viii]
Fixed Roof Storage Tank	0.21[ix]	0.07[x]
Floating Roof Storage Tank	0.45[xi]	0.45[xii]
Ordinary Plant Buildings	0.07[xiii]	0.01
Control Buildings	depends on design	depends on design
People - outside	0.14[xiv]	N/A
People - indoors	0.16[xv]	N/A
Pipework	0.4[xvi]	0.24[xvii]

[vii] based on lowest value in Mecklenburg diagram corresponding to unit overturns or is destroyed; bounds values used by 2nd Canvey study for spheres, TNO upper value for damage to fractionating column etc.
[viii] based on lowest value in Mecklenburg diagram corresponding to unit moves and pipes break; reasonable agreement with TNO lower value for damage to fractionating column.
[ix] based on Mecklenburg value for tank (cone roof) which is 50% filled; reasonable agreement with 2nd Canvey values of 0.21 - 0.34 bar, TNO cracking of empty tanks 0.2 - 0.3 bar; Highland Council value for low pressure items of 0.14 bar and Kletz value for fixed roof tanks ignored due to lack of detail.
[x] based on Mecklenburg and TNO values.
[xi] based on Mecklenburg value for tank (floating roof) which is 50% filled; Kletz value for floating roof tanks of 0.2 bar ignored due to lack of detail.
[xii] No values available, Mecklenburg indicates roof collapse occurs at a higher pressure than damage to tank walls.
[xiii] based on Kletz value (0.07 bar) for damage to ordinary plant buildings, Highland Council value (0.07 bar) for structural damage to 5% of brick buildings, >90% roof tiles broken / displaced and glass completely destroyed.
[xiv] based on 2nd Canvey value for probability of fatality due to projected against structures; IChemE monograph gives 10% fatality over the range 0.07 - 0.21 bar.
[xv] based on Crossthwaite value for 1% fatality and probit used in HSE in transport study; values in 2nd Canvey study, in Table A12 and Table A15 assumed to be threshold values.
[xvi] based on lower TNO value; good agreement with Mecklenburg value of 0.41 bar.
[xvii] based on Mecklenburg value; bounds the TNO range of 0.35 - 0.40 bar.

A3. REVIEW OF MISSILE IMPACT DAMAGE / PENETRATION CRITERIA

A number of factors affect the potential for domino effects that occur as a result of impact on chemical plant by fragments generated in catastrophic failure of pressure vessels located in a neighbouring hazardous installation.

The likelihood of secondary loss of containment will depend on:

- the fragment mass, velocity and associated kinetic energy
- the characteristics of the fragment, i.e. deformability on impact which will result in the fragment absorbing some of the impact energy
- the contact area on the target plant which has to absorb the transmitted impact energy
- the thickness of the target vessel, its material properties and the level of pre-stress in the vessel walls due to the internal storage conditions
- the presence of any significant defects in the target vessel in the vicinity of the impacted region
- the angle of the target surface with the fragment trajectory.

Although it would be possible to carry out very detailed analyses such as those done on dropped object studies for pipelines in the vicinity of North Sea platforms, the potential interactions with land based facilities are less well defined. Most of these offshore studies consider clearly defined objects which are predicted to interact with the pipelines with specified velocities and angles of orientation.

However, with missile interaction between land based installations there are such great uncertainties with fragments from a pressure vessel, such as the mass, the shape and even the velocity, that these would inhibit detailed analysis being carried out.

Consequently, various assumptions have been made in previous risk assessment methodologies regarding the probability of secondary damage from missile impact. It has been found that the likelihood of failure from impact is very sensitive to the assumptions made regarding the contact area and deformation of the impacting object.

The effect of these assumptions can result in predictions which range from very conservative, i.e. (i) loss of containment in all impact scenarios, to (ii) highly analysed interaction scenarios which are so specific that it is impossible to ascribe a probability of the fragment interacting in that manner.

Scilly and Crowther [28] argue that:

> *For vessels > 20 m^3 the frequency distribution of the missile masses is far less important than the frequency distribution of the missile ranges. This is because the great majority of the missiles will have sufficient energy to penetrate 15 mm or so of steel sheet.*

thus in their analysis methodology all impacts would be assumed to result in failure.

A detailed study [29] has been undertaken by WS Atkins to review the available mathematical models in the literature in order to identify which would be the most appropriate for use in a detailed consequence assessment. The study concentrated on the models simulating missiles travelling at speeds up to 300 m/s as would be expected from a failed pressure vessel. Missiles with a higher speed are generally generated by fragmentation of a high explosive device.

In terms of domino effects between chemical plants, the targets were assumed to be principally mild steel vessels and tanks, hardened steel vessels as in a pressure vessel, and pipework. The model for a concrete target was considered to have limited relevance unless vessels such as tanks either had concrete walls or were behind concrete barriers.

For a **mild steel target** the model for the High Pressure Safety Code (1975) [30] was selected

i.e. for rod shaped steel missiles impacting on a mild steel target

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$$MV^2 = 3 \times 10^9 D^3 \left(\frac{T}{D}\right)^{1.41}$$

For a **hardened steel target** such as a hardened pressure vessel being impacted by a blunt missile the model reported by Miyamoto [31] was used.

$$E = 2.9\, T^{1.5} D^{1.5}$$

and for conical missile

$$E = 2.9\, T^{1.5} (T\, [1 + 2.9(\tan(\theta/2))^{2.1}])^{1.5}$$

published validity ranges:

T = 7 -38 mm
M = 3 - 50 kg
V = 25 -170 m/s
D = 66 - 160 mm

For a **pipework** target the model of SCI [32] was selected

$$\frac{E}{D^3} = Au \left(\frac{T}{D}\right)^{1.7} \left(\frac{D}{D_P}\right)^{0.5}$$

published validity ranges:

T = 0.007 - 0.018 m
M = 4 - 50 kg
D = 0.025 - 0.17m
D_p = 0.15 m

where T = plate thickness or pipe wall thickness (m)
M = missile mass (kg)
D = missile diameter (m) except in the equation for mild steel (mm)
D_p = Pipe diameter (m) except in the equation for mild steel (mm
V = missile velocity (ms^{-1})
θ = Total nose angle of conical missiles (degrees)
E = perforation energy (joules) 1/2 mV^2
Au = empirically derived constant 8×10^9 ($J\, m^{-3}$)

A3.1 General Guidelines

In order to derive general guidelines, the orientation of the fragment and the target vessel has been categorised into broad bands, i.e.

a) the largest face of the fragment essentially impacting normal to the vessel, i.e. a large area of contact,
b) the fragment edge impacting normal to the vessel, and
c) the fragment hitting with a glancing blow.

In the case of impact scenario (a), it is considered conservative to consider the fragment as a blunt object, whereas scenario (b) will have a very localised area of impact with high stress concentrations much greater than those caused by a blunt object. Scenario (c) is likely to be deflected without any significant damage being caused.

A3.1.1 General Guidelines for Impacts on Pressure Vessels

General guidelines have been developed from analyses which have investigated the impact of blunt objects on a pressure vessel constructed from hardened steel. In the case of a blunt object the mass of the fragment is taken as a spherical object and the area of impact is assumed to be the projected cross sectional area of the sphere. Making the basic assumption that the thickness of the pressure vessels is 15 mm, then, it has been shown that a 50 kg blunt object requires an impact velocity of 153 m/s (i.e. a kinetic energy of 0.587 MJ) for penetration to occur, whereas a 1000 kg object requires a lower impact velocity of 72.5 m/s (i.e. a kinetic energy of 2.628 MJ).

Analysis of intermediate points showed that it is conservative to interpolate linearly between these two mass / velocity points using the kinetic energy / mass relationship to obtain intermediate kinetic energies for specified masses and then derive an estimate of the penetration velocity from the interpolated kinetic energy. However, it is not recommended that penetration velocities be obtained directly by linearly interpolating using velocities.

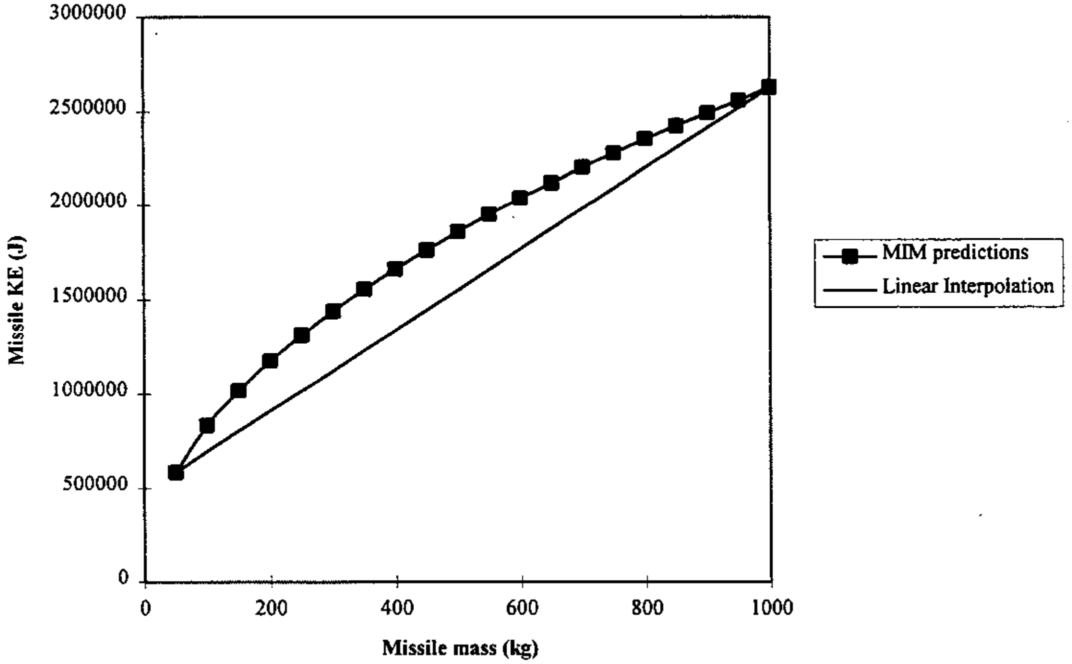

Figure A1 Penetration characteristics of 15 mm pressure vessel steel by missiles

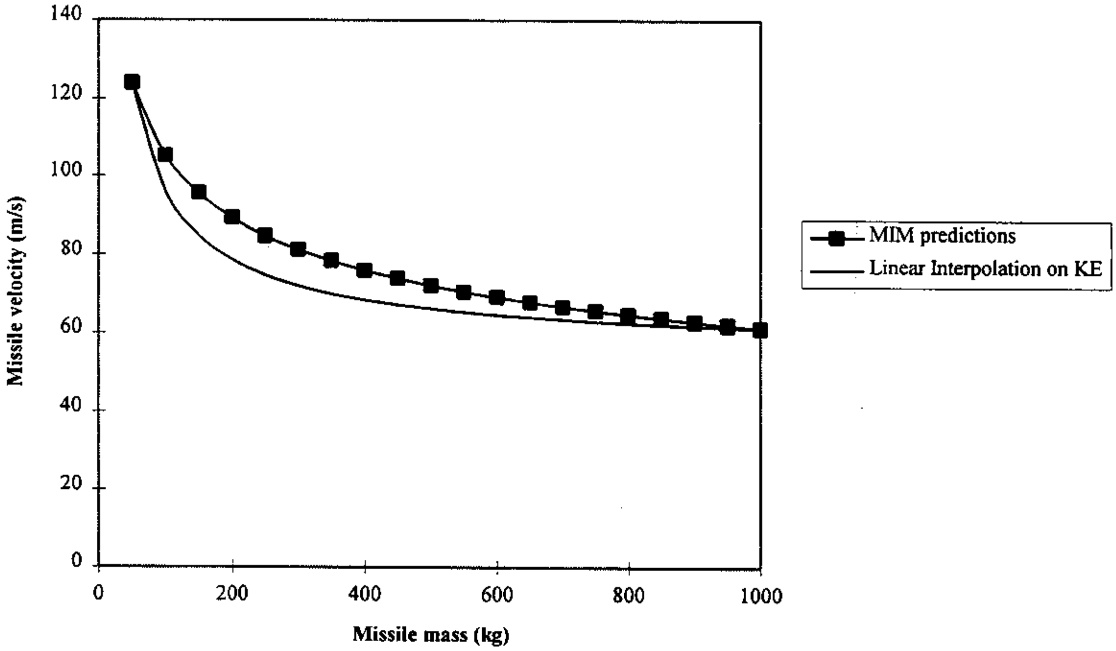

Figure A2 Penetration characteristics of 15 mm pressure vessel steel by missiles

A similar relationship can be derived for impact of objects on 15 mm mild steel plate, i.e. penetration velocities of 124 m/s (KE = 0.384 MJ) and 61.2 m/s (KE = 1.87 MJ) are predicted for 50 and 1000 kg fragments respectively.

Peiterson [33] considered the impact of fragments from a vessel which had just experienced a BLEVE of an adjacent sphere. He made assumptions that the impact area was five times the wall thickness regardless of the size of the fragment, that the energy needed to deform the sphere up to the yield point was 7 kJ and the additional energy to deform the sphere in the plastic region was 64 kJ, and that the plastic deformation of the impacting fragment uses up energy equal to that used up in the sphere itself. Thus the total energy required was predicted to be 135 kJ. He quoted the required impact velocity for two sizes of fragments, i.e. 3.7 m/s and 11.6 m/s for a 20 te and a 2 te fragment respectively.

The assumptions inherent in the Peiterson criteria regarding impact area were utilised with the equation for a hardened steel target. This gave a predicted kinetic energy of 109 kJ for penetration. Thus, reasonable agreement was observed with the Peiterson assumption i.e. the kinetic energy of 135 kJ was required for failure. However, both these approaches gave impact velocities which were well below that predicted for blunt objects (see Figure A3).

Contents

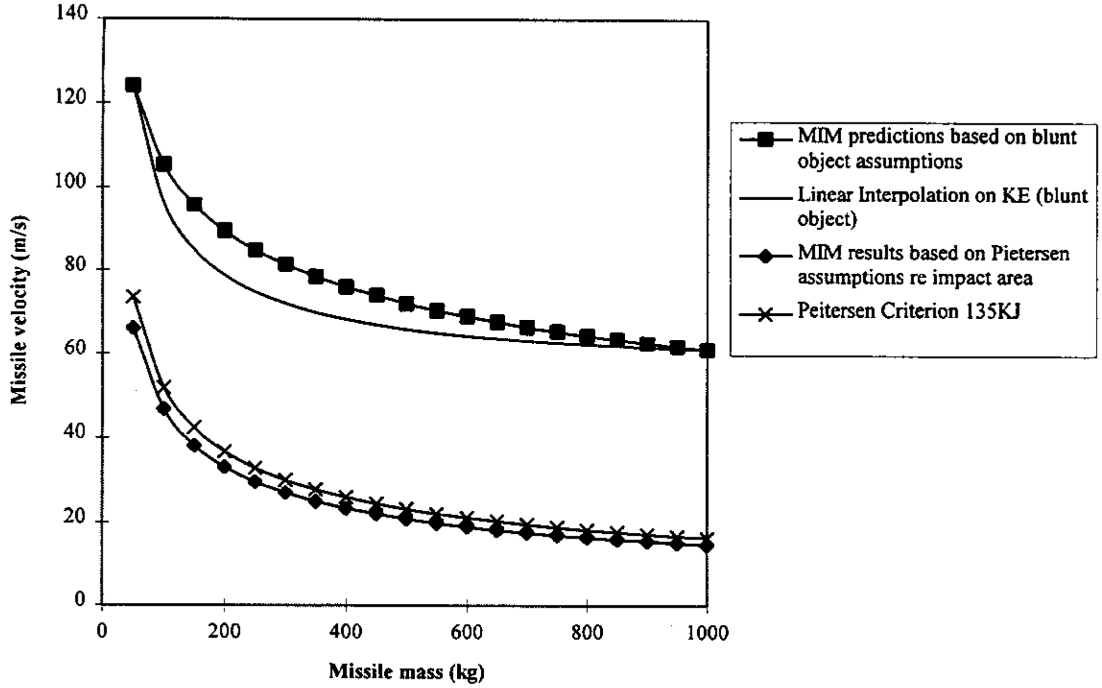

Figure A3 Penetration characteristics for 15 mm pressure vessel steel by missiles

It is considered that the criterion of using a contact area of 5 times the wall thickness would be more appropriate to a object impacting edge on rather than in a blunt (face on) manner.

A3.1.2 Pipework

Generalisations of the impact damage to pipework from fragments is more difficult to develop due to the vast range of pipe sizes on a plant and also the different wall thicknesses which pipes of the same notional diameter can have.

It can however be argued that there is a much lower probability that small diameter pipes will actually result in a domino event since the fire affected area is much smaller coupled with a greater probability of effective fire fighting leading to extinction of the smaller scale fires.

The above mentioned formulae could be utilised in order to predict the impact velocity required to result in penetration for each and every pipe on a site, this degree of analysis would not be justified in the majority of cases. Consequently, it is assumed that pipes can be damaged by 50 kg missiles travelling at 90 m/s and 1000 kg missiles travelling at 50 m/s. Supporting analysis indicates that these values are appropriate to wall thicknesses which are not atypical for pipe diameters less than 0.15m.

A3.2 Summary of Missile Penetration Criteria

The following criteria are recommended for assessing whether impacts on vessels will result in loss of containment

Impact Scenario	General relationship	Specific relationship
Fragment impacting as a blunt object (face on) with pressure vessel	Miyamoto model, Impact area = projected area of equivalent volumetric sphere	50 kg @ 153 m/s and 1000 kg @ 72.5 m/s with linear interpolation using kinetic energy
Fragment impacting edge onto pressure vessel	Miyamoto model, Impact area = 5 x target vessel wall thickness	Constant 109 kJ[xviii] for 15 mm thick steel pressure vessels
Fragment impacting as a glancing blow on pressure vessel	Assumed not to result in loss of containment	N/A
Fragment impacting as a blunt object (face on) with atmospheric storage tanks	High Pressure Safety Code, Impact area = projected area of equivalent volumetric sphere	50 kg @ 124 m/s and 1000 kg @ 61.2 m/s with linear interpolation using kinetic energy
Fragment impacting edge on with atmospheric storage tank	High Pressure Safety Code, Impact area = 5 x target vessel wall thickness	65 kJ[xix] for 15 mm thick mild steel plate
Fragment impacting as a glancing blow on atmospheric storage tank	Assumed not to result in loss of containment	N/A
Fragment impacting on Pipework	SCI model	50 kg @ 90 m/s or 1000 kg @ 50 m/s with linear interpolation using kinetic energy

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[xviii] If Miyamoto equation is used with Pietersen assumption re contact area (i.e. D = 5T) then

$$E = 2.9\ T^{1.5}\ D^{1.5} = 2.9\ T^{1.5}\ (5T)^{1.5} = 2.9\ T^3\ (5)^{1.5} = 32.4\ T^3$$

[xix] If High Pressure steel equation is used with Pietersen assumption re contact area

$$MV^2 = 3 \times 10^9\ D^3 \left(\frac{T}{D}\right)^{1.41} = 3 \times 10^9\ (5T)^3\ (1/5)^{1.41} = 3 \times 10^9\ (5 \times 15 \times 10^{-3})^3\ (1/5)^{1.41}$$

$$E = 0.5\ MV^2 = 0.5 \times 3 \times 10^9\ (5 \times 15 \times 10^{-3})^3\ (1/5)^{1.41} = 65{,}000\ J$$

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APPENDIX B

TOXICITY EFFECTS

B1. TOXICITY EFFECTS

B1.1 Introduction

The probability of a toxic release affecting a neighbouring hazardous installation is a function of the intrinsic safety of the processes being controlled, the actions required to be taken by the operator, the time available to undertake these actions and the behaviour of the operator under this set of circumstances.

The time available to the operator is not just a function of the actual hazard but also the hazard he perceives to be about to affect him.

For the actual hazard to be a factor in a domino event it would have to be sufficient to incapacitate the operator before he could take whatever actions were necessary to render the plant safe. At lower concentrations, it is not the actual hazard which might stop the operator from leaving the plant in a safe state but rather his response to the perceived hazard.

The latter is in part a function of the concentration, i.e. the degree of warning which he may have and the concentration at which the hazard causes him distress. His awareness of an imminent hazard will be triggered either by his physiological threshold limit of detection, by being warned by the initiating site personnel or by gas sensors on his own site.

It is possible that additional warning could be given by the control room / emergency response team at the neighbouring site but this would probably only be expected if a detailed on-site emergency plan had been prepared and exercised. Another possibility is direct action by the domino site control staff on hearing the warning sirens on the neighbouring site, but it is expected again that this would only occur if the emergency plan had been exercised and the staff knew which alarms signalled a potential danger to them.

The possibility of being able to respond to gas sensors on their own site, would require either:

i. gas sensors being already fitted because the domino site had a similar toxic hazard to the initiating site (a remote but feasible possibility),
ii. the sensors having been fitted specifically to guard against the hazards from the other site (a farsighted risk mitigation measure on behalf of the domino site safety management team), or
iii. a general gas sensor responding. (The most likely gas sensor is expected to be a general hydrocarbon flammable gas detector, which is unlikely to give much warning if it is set to alarm at say 20% LFL or approximately 1% flammable gas concentration).

The concentrations which can be considered as giving rise to an actual hazard (i.e. lethal exposure) and a perceived hazard (i.e. one which could the operator to take an emergency evacuation response) are discussed below.

B1.2 Lethal Exposure Hazard

A number of measures have been developed for use as benchmarks for predicting the likelihood that a release will result in serious injury or death. The following review of the various toxicological criteria has been carried out in order to identify whether any are appropriate for use in domino assessment. The criteria include:

- Emergency Response Planning Guidelines (ERPG) for Air Contaminants issued by American Industrial Hygiene Association (AIHA)
- Immediately Dangerous to Life or Health (IDLH) established by NIOSH
- Emergency Exposure Guidance Levels (EEGL) and Short Term Public Emergency Guidance Levels (SPEGL) issued by National Academy of Sciences / National Research Council
- Threshold Limit Values (TLVs) and Short Term Exposure Limits (STEL) issued by HSE
- Permissible Exposure Limits (PEL) established by Occupational Safety and Health Administration
- Probit expressions.

Of the ERPGs, ERPG -3 is the most severe as it is defined as the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for an hour without experiencing or developing life threatening health effects.

The IDLH level represents the maximum airborne concentration of a substance which a male healthy worker can be exposed to for as long as 30 minutes and still be able to escape without loss of life or irreversible organ damage.

EEGL is defined as a concentration of gas vapour or aerosol that is judged to be acceptable and that will allow exposed individuals to perform specific tests during emergency conditions lasting from 1 to 24 hours. SPEGL have been developed to complement EEGLs and are appropriate to the public as they take account of exposure of sensitive heterogeneous populations.

The TLVs and STELs are designed to protect workers from planned and repeated exposure to toxic substances. TLVs are 8 hour time weighted average designed to protect against the long term effects of exposure. The STELs are based on a 15 minute exposure and are set at a concentration which is aimed at avoiding acute effects.

PELs are also based on 8-hour time weighted average exposures.

The use of a probit expression will allow any percentage fatality level to be defined for a typical population in terms of a toxic load, i.e. a function of concentration and exposure duration. A concentration can then be determined for a specified exposure duration. Probits are available for some but not all toxic chemicals. A discussion document produced by HSE [1] provides a general approach for determining the health hazard posed by the release of a toxic substance in terms of significant levels of toxicity (SLOTs) and the associated toxic load relationships.

Lethal Hazard Level

When assessing the actual lethal hazard level it is considered that none of the above concentration criteria would be appropriate for assessing the possibility of a domino event occurring as a result of the operator being incapacitated before he has the opportunity of taking emergency shutdown action. Rather the toxicological information for a specific substance needs to be reviewed in order to determine the concentration level which would incapacitate the operator over a very short duration period.

As an example of the type of information available for some toxic chemicals and in order to discuss selection of an appropriate value for immediate actual hazard to operators, the following table of information on chlorine [2] has been included.

Concentration (ppm)	Effect
1000	May be fatal even when exposure is brief (a few breaths)
400 - 300	A predicted average lethal concentration for 50% of active healthy people for 30 minute exposure
150 - 100	More vulnerable people might suffer fatality from 5 - 10 minute exposure
20 - 10	Is dangerous for half to 1 hour exposure. Effects are immediate irritation of nose, throat, eyes with coughing and lachrymation
10	Exposure for less than 1 minute causes coughing
3 - 6	Causes stinging and burning sensation but tolerated without undue ill effect for up to 1 hour

Table B1 Chlorine Toxicity Information

Using the example of the hazard posed by chlorine installations, then a concentration which would be considered as inhibiting the response of operator would be 1000 ppm, i.e. may be fatal even when exposure is brief (a few breaths). This value would be appropriate for any operator who is effectively in the open when engulfed by a chlorine gas cloud or plume. This value was also in an example of a quantitative assessment of a

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Cl_2 installation using the HSE Risk Assessment Tool [3] as the concentration out of doors which would result in a probability of 0 of those people exposed being able to escape indoors.

The hazard will, however, also be different when the operator is in a control room which is ventilated, rather than at a control panel in the open air. Taking a ventilation rate of 4 air changes per hour (ACH) and the assumption that the control room atmosphere is well mixed then the relationship between the external and internal concentrations can be determined from the following expression

$$C_i = C_o (1 - \exp(-\lambda t_o))$$

Using the above expression with the assumption of 4 ACH and a 1 minute time delay of reaching an internal concentration of 1000 ppm, then the required external concentration, $C_{o,}$, can be determined:

$$C_i = C_o (1 - \exp(-\lambda t_o))$$
$$C_o = C_i / (1 - \exp(-\lambda t_o)$$
$$C_o = 1000\text{ppm} / (1 - \exp(-4 \times 1/60))$$
$$C_o = 15{,}500 \text{ ppm}$$

where C_i = internal concentration
C_o = external concentration
λ = air change rate (4/hour)
t_o = time (1 minute = 1/60 hours)

This would require a dilution factor of 65, i.e. from 1,000,000 ppm (equivalent to 100% toxic gas) to 15,500 ppm. For this example of chlorine releases, this degree of dilution is likely to be achieved very shortly after release if the release is a turbulent jet or if there is a catastrophic failure with entrainment of air.

B1.3 Lethal Hazard Model

A similar approach to that above should be taken to establish the acute hazard concentration for outdoor exposure and for indoor exposure. The hazard radii should be determined using a suitable gas dispersion model and then superimposed on a map of the incident and potential domino sites to assess whether any control positions are enveloped by the appropriate indoor and outdoor contours. If these are enveloped, and the plant relies on operator control to stop a dangerous occurrence, then the probability of a domino event should be taken to be 1.0.

B1.4 Perceived Hazard Level

It is considered that the most common way in which an operator will become aware of a toxic release is due to his own physiological responses. The point at which he perceives a threat to himself will be subjective and is possibly best discussed by reference to the effects of chlorine. A summary of the general effects of typical exposures has already been presented above in Table B1.

It can be seen that an exposure of say 10 ppm chlorine would cause sufficient distress to result in the operator perceiving himself to be in danger and would take steps to remove himself from the hazard. It has been assumed that at concentrations above this value up to the lethal exposure hazard level there would still be sufficient time for the operator to take action to shut down the process before evacuating if he wanted.

B1.5 Perceived Hazard Model

The behaviour of an operator will depend to some extent on his training. If the toxic hazard has been recognised as a possible external hazard, and as such has been addressed in the on site emergency plan then actions to be taken in the event of a release will be specified. Whether the operator actually carries out these actions will then depend on whether he perceives the hazard to be more of a threat to himself than the threat of his own process if he left it immediately.

One human factors technique which takes account of the factors which are relevant in assessing the probability that an operator will carry out actions before evacuating is the TESEO (Technica Empirica Stima Errori Operatori) [4] method for estimating the probability of human error. In this method the probability is estimated from the product of five parameters K_1-K_5 as follows

$$q = K_1 K_2 K_3 K_4 K_5$$

where K_1 represents the type of activity
K_2 is the temporary stress factor
K_3 is the operator qualities
K_4 is the activity anxiety factor, and
K_5 is the activity ergonomic factor.

If two basic cases are taken as examples, i.e.

a) an automated control room in which shutdown can be effected by a simple operation involving say the operation of a simple emergency stop button following which the control system will ensure that the plant is left in a safe configuration,
b) a plant which relies on a high degree of operator intervention to leave it in a safe configuration and that the operators have not been previously briefed on the possibility of a toxic release and appropriate emergency actions.

Using TESEO

for Case a), the following values are selected:

K1	=	0.001	simple, routine (Type of activity)
K2	=	10	2 minutes available (temporary stress factor)
K3	=	0.5	carefully selected, expert, well trained (operator qualities)
K4	=	3	situation of grave emergency (activity anxiety factor)
K5	=	1	good microclimate, good interface with plant (activity ergonomic factor)

K1 x K2 x K3 x K4 x K5 = 0.015

and for Case b), the following values were selected:

K1	=	0.01	requiring attention, routine (Type of activity)
K2	=	0	2 minutes available (temporary stress factor)
K3	=	1	average knowledge and trained (operator qualities)
K4	=	3	situation of grave emergency (activity anxiety factor)
K5	=	3	discrete microclimate, discrete interface with plant (activity ergonomic factor)

K1 x K2 x K3 x K4 x K5 = approx. 1.0

Thus for ventilated control rooms / buildings, the potential for a toxic hazard is most likely to be due to the operators responding to a perceived hazard and not performing the necessary emergency shutdowns before evacuating, rather than an immediately acute hazard which incapacitates them before they have opportunity to respond.

For an operator at a control panel which is effectively in the open, both acute and perceived hazard levels are appropriate.

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APPENDIX C

APPROACH TO MISSILE EFFECTS

C1. APPROACH TO MISSILE EFFECTS

C1.1 Introduction

Although the probability of domino events due to missile effects has often been omitted in previous studies on the basis that there was considered to be a low frequency for missile generating incidents combined with a low probability of hitting a specified target, it is considered that a methodology should be included in this study for completeness. The discussion has been limited to catastrophic failure of pressure vessels as these are considered to be the most relevant to major hazard installations. It is recognised, however, that missiles could also be generated by disintegration of large high speed rotating equipment.

C1.2 Maximum Hazard Distance

The number of missiles produced by fragmentation of a pressure vessel is a function not just of the size, shape and contents of the pressure vessel but also of the manner in which it fails. A distinction has to be made between vessels which fail in a ductile manner and those which fail in a brittle manner.

Ductile failures typically occur in a BLEVE situation whereas brittle failures are caused by accidents such as sudden overpressurisation resulting from pressure breakthrough etc. Historical evidence from accidents has shown that a brittle failure produces more missiles, and hence the two have to be evaluated differently.

A distinction also has to be made between cylindrical and spherical vessels when considering ductile failures since cylindrical vessels have been known to fail by loss of an end cap. With this type of failure the bulk of the vessel (termed an end tub) remains intact but residual flashing liquid exhausted through the open end causes it to 'rocket' over long distances.

A methodology for determining the maximum hazard distance for missiles is shown in Figure C1.

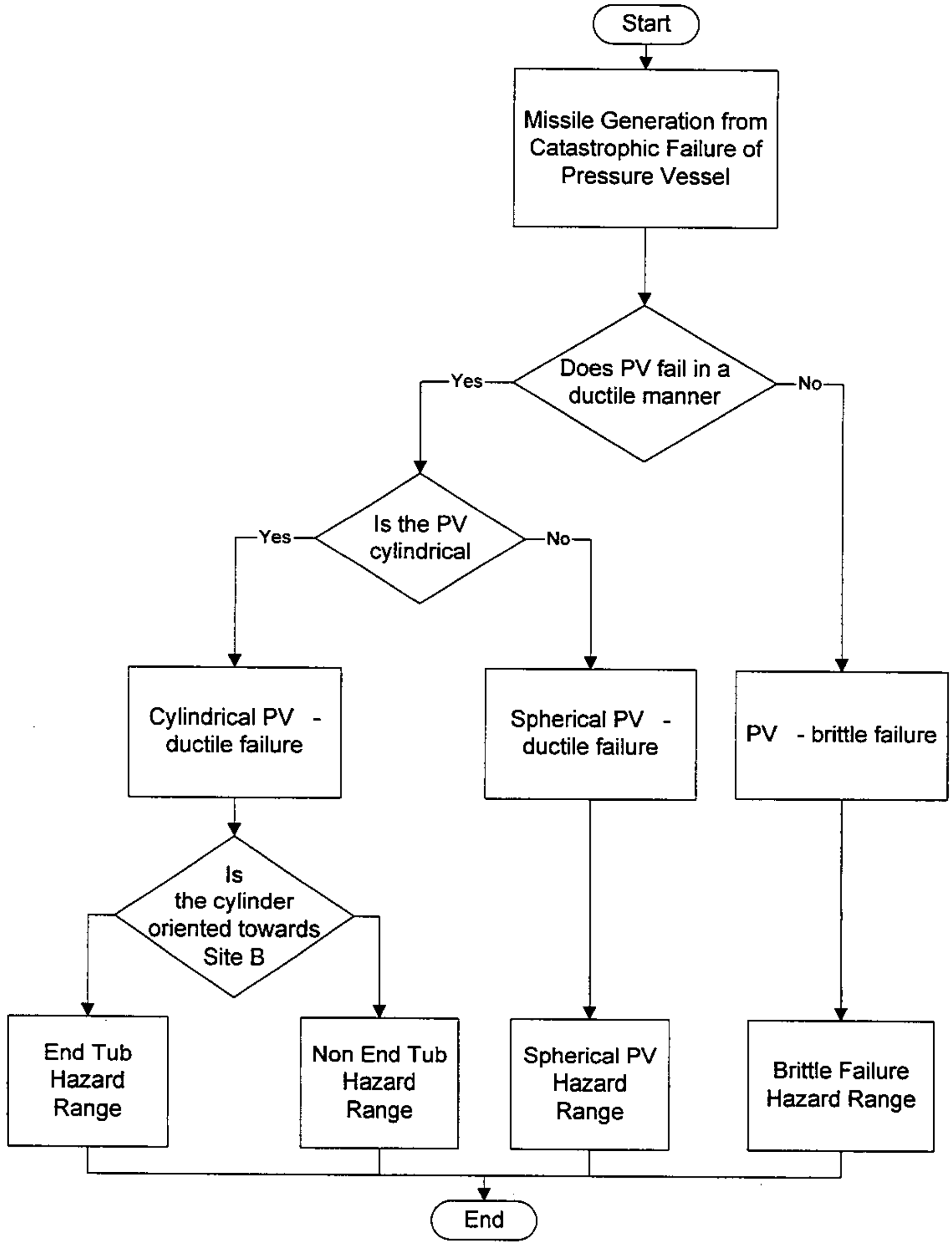

Figure C1 Maximum Hazard Range Flowchart

<u>Maximum Hazard Range for BLEVE End Tubs</u>

Theoretical Approach

The maximum hazard distance for end tubs can either be determined using a theoretical, probabilistic or deterministic approach.

It can be shown that, when the drag and lift forces on a missile are ignored and an optimum launch angle of 45 degrees is used, the theoretical maximum range can be estimated using

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$R = V^2/g$

where R is the range
V is the launch velocity
g is the acceleration due to gravity

For non ideal missiles Baum [1] suggests that when the total drag force was less than Mg (where M is the mass of the tank) and the lift force was less than five times the drag force, then the above equation could still be used.

It was also suggested that when the fragment has lift and the lift force was more than five times the drag force then the range is reported to be predicted using

$R < 3\ V^2/g$

For intermediate cases it was recommended that the methods described by Baker [2] could be used. For ease these have been presented in graphical form.

If a launch velocity for fragments from rupture of a propane LPG vessel of 283 m/s is used [3] with the first of these equations, then

$R = V^2/g = 283^2 / 9.81 \quad = \quad 8164 \text{ m}$

This is well in excess of any known missile trajectory range and therefore the above equations are considered to be so conservative as to be totally inappropriate.

In order to use of the Baker method it was necessary to make certain assumptions regarding the dynamic forces acting on the missile whilst it was in flight. Thus a 2m diameter end tub was considered which had a 5m cylindrical length plus a hemispherical end cap with an assumed wall thickness, the weight was predicted to be 4400 kg, the drag area 3.142 m^2 and a drag coefficient of 0.82 appropriate to a rod was taken. There was assumed to be no lift associated with this missile.

The scaled initial velocity was therefore calculated 612 which gave a scaled maximum range of 2 using the Baker graph. This corresponded to a predicted range of 2650m which again was well in excess of observed values.

Thus theoretically derived ranges were not considered further.

Deterministic Approach

An example of a deterministic approach is that reported by Birk [6] who used the data from five incidents and tests to determine a relationship between severe rocket tub ranges and the liquid mass. Only five data points were used because only the worst rocket tubs were included. The expressions derived for rocket tub ranges were correlated with liquid mass and were as follows:

$R_{tub} = 90\ m^{0.33}$ for tanks $< 5\ m^3$ capacity

and

$R_{tub} = 465\ m^{0.10}$ for tanks $> 5\ m^3$ capacity

It is acknowledged that even larger ranges could occur since it was thought that the launch angles were shallower than the optimum trajectory angle. It is also not possible to estimate what the probability of the tub rocket was in reaching this range since only the worst tub rocket ranges were included in their analyses. Therefore the data can only be really considered as a most likely maximum range.

Using the Birk equations then for a 100 tonne LPG vessel the maximum hazard range is predicted to be $R_{tub} = 465\ m^{0.10} = 465\ (100)^{0.10} = 750$ m.

Probabilistic Approach

An example of a probabilistic approach for end tub missiles from LPG vessels can be derived from graphical information given by Holden and Reeves [4]. It is possible to derive the following expression for the probability range relationship.

$$P = e^{-0.006R}$$

where P is the probability of an end tub fragment having a range greater than R metres.

Another equation for end projectiles are by Pietersen [5] for data from Mexico City is:

$$P = e^{-0.004R}$$

and by Birk and Cunningham [6] for 400 litre propane tanks:

$$P = e^{-0.03R}$$

The last two equations are not exclusively for end tubs, however, it is indicated that for the Mexico City fragments the furthest reaching fragments were end tubs. Out of the three equations, the Pietersen equation will give the greater distances and therefore this is recommended for use in predicting end tub travel distances.

Using a probabilistic approach an arbitrary decision has to be made as to what cut off value should be used for as a negligible residual probability. Given that the missile is extremely directional and may not land on vulnerable plant even if it is within range then a residual probability of 10^{-2} was considered appropriate, i.e. a 1 in a 100 chance that the missile will travel further. Extrapolation to a smaller probability value was discounted as it would have utilised a part of the curve well outside the data region.

The maximum hazard range for LPG using this cut off value is $R = -\ln(P)/0.004$, i.e. 1150 m.

Using the 99th percentile with the Holden and Reeves probabilistic equation i.e. $R = -\ln(P)/0.006$, $= \ln(0.01)/0.006$ i.e. 770 m, gave reasonable agreement with the deterministic approach described above. Even though these appeared to support each other, the Pietersen equation was still used in preference to these as there was no evidence to ignore it and it was more conservative than the others.

Most information is available on LPG since this is one of the most commonly encountered flammable substances and one for which there is a large amount of data from accidental BLEVEs. There is a paucity of information for other chemicals.

<u>Maximum Hazard Range for BLEVE Non End Tub Missiles</u>

A number of probabilistic equations have been reported or can be derived on the basis of data from accidents or tests which describe the probability of missiles exceeding different ranges. Examples of these are:

- The Schultz-Forberg data for three tests of 4850 litre tanks filled to 50 % capacity with propane as reported in a review by Birk [6]

  $$P = e^{-0.006R}$$

- The range distribution for the missiles landing in the side zones as reported by Pietersen [5] for data from Mexico City:

  $$P = e^{-0.0093R}$$

- The range distribution for the side primary projectiles from BLEVEs of 400 litre propane tanks as reported by Birk and Cunningham[6]:

  $$P = e^{-0.03R}$$

- An exponential equation was fitted to the Holden and Reeves [4] non end-tub events for LPG vessels which gave the following expression:

$$P = e^{-0.0093R}$$

The Schultz-Forberg equation is the most conservative of the above equations and using this expression, with a residual probability of 10^{-2}, a maximum hazard range of R = -ln(P)/0.006, i.e. 770m was predicted.

As with the end tub data there is very little information on chemicals other than LPG.

Maximum Hazard Distance for Spherical Pressure Vessel BLEVE Missiles

In a similar manner to that used for end tub missiles, using the graphical information given by Holden and Reeves [4] it is possible to a probabilistic expression for the probability range relationship for missiles generated by BLEVEs involving spherical LPG vessels

$$P = e^{-0.00567\,R}$$

Thus using this equation and a residual probability of 10^{-2} then a maximum hazard range of R = -ln(P)/0.00567, i.e. 812m

Maximum Hazard Range for Brittle Failure Missiles

One possible methodology for predicting the maximum hazard range of the missiles arising from brittle pressure vessel fragmentation is that of Scilly and Crowther [7]

Vessel and operating parameters are used to determine the burst pressure, which in turn is used to determine the median distance (R_m) travelled by missiles.

The range - frequency distribution for missiles is then derived from the number of missiles (N) which could be generated (obtained by matching the incident of concern with past incidents to select the most appropriate value) and the assumption that the range of the penultimate missile (R_{pen}) is given by

$$R_{pen} = 4.1\ R_m$$

These two range values together with their associated probabilities, i.e. 50% for the median and (N-1)/N for the penultimate missile can be used to derive the underlying probit relationship.

Thus, assuming that the maximum hazard range is based on a residual probability of 10^{-2}, the corresponding probit can be calculated and the probit - range equation used to predict the appropriate maximum hazard range.

For a cold catastrophic (brittle) failure the temperature of the vessel contents will be ambient rather than elevated as in the case of a BLEVE. The vapour pressure of propane at 10°C is predicted to be 6.33 bar [8].

Using this value in the Scilly and Crowther methodology gives the mean distance travelled (Rm) as

$$R_m = 2.8\ P \text{ (where P is the pressure in bar)}$$
$$= 2.8 * 6.33 = 17.74\ m$$

This mean distance has a corresponding probit of 5 by definition.

Rpen, the distance travelled by the penultimate missile can be predicted as follows

$$R_{pen} = 4.1\ R_m = 72.66\ m$$

The probability of the penultimate missile is a function of the number of missiles. The number of missiles generated in a cold catastrophic failure is expected to range between 20 -60. Due to the nature of the mathematics in the Scilly and Crowther method (i.e. the inherent uncertainty), then lower numbers of missiles tend to give a more conservative estimate of the maximum distance travelled.

Thus using the assumption of 20 missiles to derive the probability distance relationship, the probability of the penultimate missile is 19/20 i.e. 0.95. This has an associated probit of 6.64.

If the expression of the probit equation is

$$Y = m \log(R) + C$$

where Y is in probits and R is in metres, then two simultaneous equations can be derived from the above information

i.e.

$$5 = m \log(17.74) + C$$
$$6.64 = m \log(72.66) + C$$

Solving these gives a probit expression of $Y = 2.67 \log(R) + 1.66$

The residual probability of 10^{-2} corresponds to the 99 percentile which in turn corresponds to a probit of 7.33. Thus rearranging the probit expression and substituting gives

$$R = 10^{((7.33 - 1.66)/2.67)} = 132 \text{ m.}$$

There is some evidence that brittle failures could occur at elevated temperatures [9] in which case the internal pressure in a propane vessel could approach that of the PRV setpoint pressure. If this is assumed to be 19 bar then the corresponding maximum travel distance is 391 m.

C1.3 Frequency Limitation Approach

<u>Overview of Calculation Steps</u>

The probability of a domino effect being initiated by a fragmenting pressure vessel is a function of:

i) the frequency of pressure vessels on the incident site (Site A) failing catastrophically with the ejection of fragments which act as missiles,
ii) the number of missiles produced,
iii) the probability of one of the resultant missiles reaching the critical vessels or components on the target site (Site B), and
iv) the probability that the missiles have sufficient kinetic energy and impact characteristics to cause failure of the critical plant.

With regards the frequency of missile generation (i.e. Step (i) above), the frequency of catastrophic failure can be estimated using either:

1. detailed fault tree analysis for each vessel which investigates causes of catastrophic failure, e.g. in the case of a BLEVE this would require estimation of the frequency of small fires and the possibility of escalation leading to catastrophic failure,
2. an estimate based on the historical frequency of catastrophic failure (either directly or indirectly). An indirect estimate of a BLEVE could be based on an assessment of the incidence of fire and the recorded probability of catastrophic failure given fire engulfment, whereas a direct estimate would be based on the recorded incidence of BLEVE / pressure vessel year.
3. a very conservative estimate.

As discussed earlier in the maximum hazard distance approach, the number of missiles produced, i.e. step (ii) above, is a function of the vessel shape and failure mechanism.

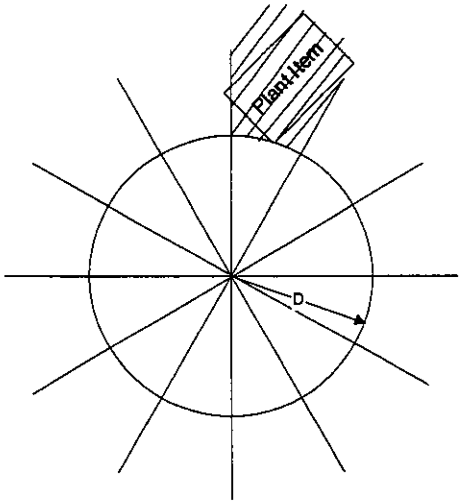
For a preliminary methodology, it is assumed in that any missile landing on critical target plant on Site B will cause a failure and hence a domino effect, i.e. in Step (iv) above the probability is assumed conservatively to be 1.

General Methodology for Determining the Probability of 1 out of N Missiles Impacting a Vessel

Two approaches were considered for Step (iii) in order to estimate the probability of one out of N missiles impacting one or more of the vulnerable vessels and plant on Site B:

- an approach based on modelling the target vessel area as a segment of a concentric ring where the inner radius is the minimum distance from the incident plant to a plant item on Site B, the outer radius corresponds to the limit of the height of the plant item onto the ground behind the item (as in the Scilly and Crowther methodology), and the radial edges of the sector are the lateral extremes of plant item.
- a simpler approach based on the assumption that a plant item occupies a sector beyond a specified radius. Thus if a vulnerable vessel occupied Sector A and the closest point was D metres then any missile travelling in the direction of Sector A which had a probability of travelling D or more metres would be assumed to impact the item. This would be conservative as it assumes that any missile which in theory might overshoot the item is still included in the estimate.

Representation of the location of a vulnerable plant item on Site B relative to a missile generating vessel at a separation distance, D, for this second method is shown in Figure C2. The associated logic to derive the probability of interaction given N fragments, a separation distance, D, and the site occupying Sector A is shown in the associated fault tree.



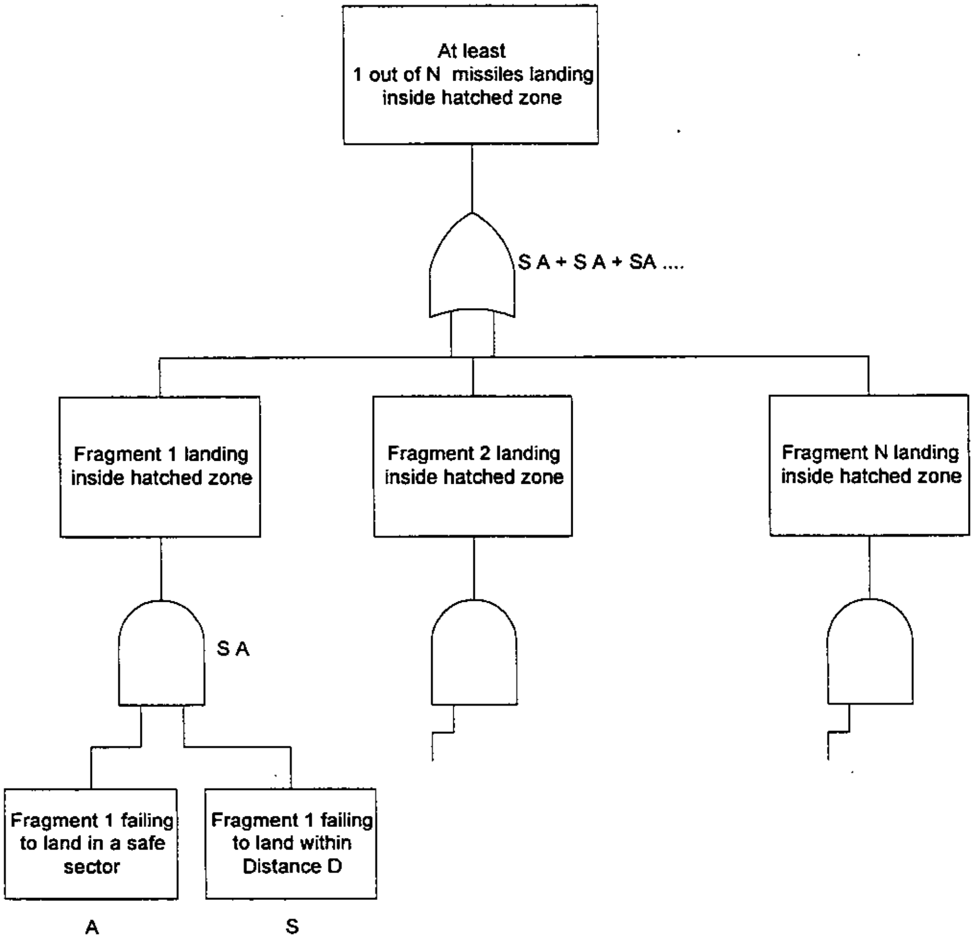


Figure C2 Fault Tree for 1 out of N Missiles Impacting a Plant Item

The above fault tree has the following logic expression

$$Top = S_1A_1 + S_2A_2 + S_3A_3 \ .....$$

This equates to a probability expression of

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$P_{top} = Prob(S_1A_1 + S_2A_2 + S_3A_3.....)$

If it is assumed that all fragments behave in a similar manner then the above expression can be simplified to:

$P_{top} = Prob(SA + SA + SA .....)$

To avoid having to calculate the cross product terms, then this can be approximated to

$P_{top} = 1 - \{1-P_S P_A\}^N$

Where

P_{top} = Probability of a missile impacting on a plant item on Site B (assumed to be the hatched zone)

P_S = Prob of failure to land in a safe sector

= Prob of landing in Sector A = $\frac{\alpha}{360}$ (assuming that there is a random probability of missile landing in any one sector)

α = the actual angle subtended by the vulnerable equipment on the site

and P_A = probability of landing beyond D.

Thus if there was a separation distance, D, between the incident pressure vessel which generated the missiles and the vulnerable equipment on Site B, and the relationship between probability of a missile travelling more than D metres and the actual separation distance D was known, then the probability of a missile landing on site B could be determined.

Alternatively, if it is required to determine an acceptable separation distance based on a specified probability a missile landing on a plant item on Site B, then the above equation can be rearranged

$(1- P_{top})^{1/N} = 1 - P_S P_A$

$P_A = (1 -(1- P_{top})^{1/N}) / P_S$

Thus this value can be used with the appropriate probability - range to determine the required separation distance D.

The above logic would also apply to the more rigorous approach in which the impact area of the target vessel was considered as segment of a concentric ring, however in this case P_A would be the probability of landing beyond D_1 but within D_2, where D_1 and D_2 are the inner and outer radii of the concentric ring.

Overview of Failure Scenarios

As with the maximum hazard distance approach a number of different calculation procedures have to be considered depending on the vessel shape and failure mechanism. These are shown Figure C3 . Each of the calculation procedures has been developed separately (see Figure C4 - Figure C6)

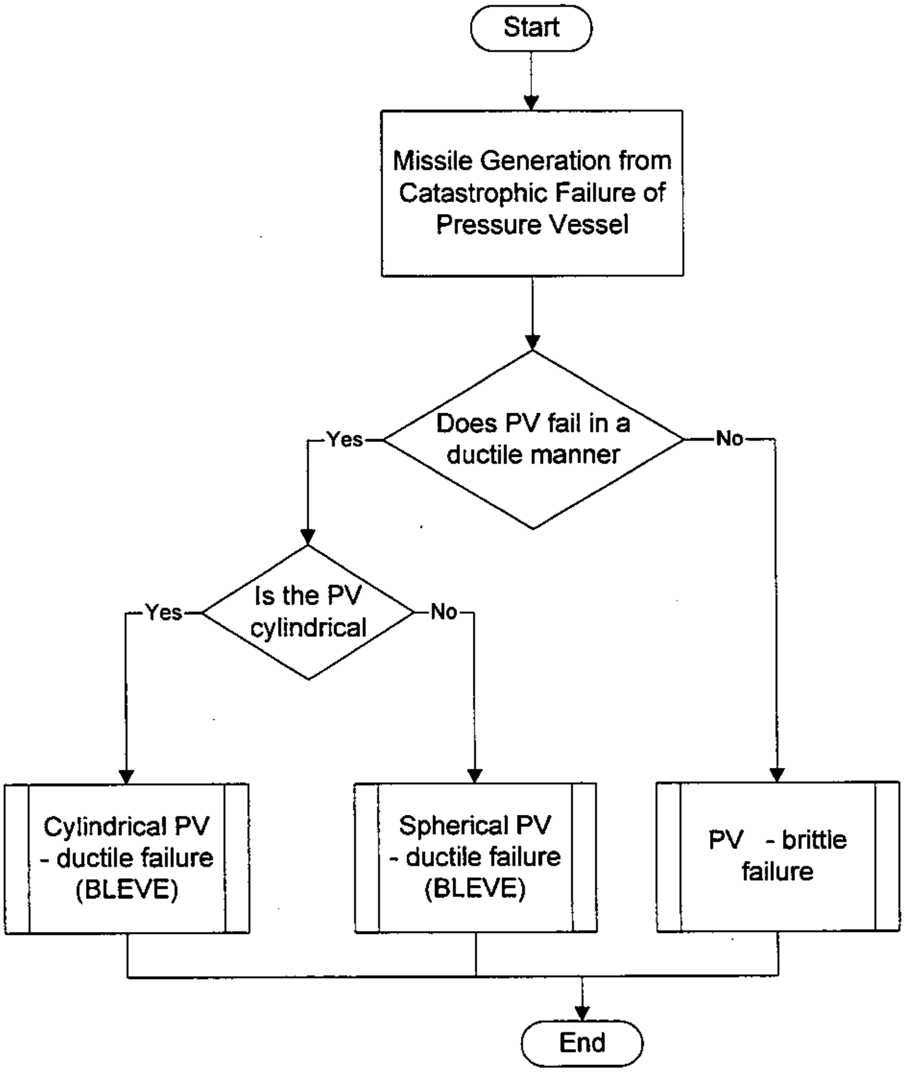

Figure C3 Overview of Missile Generation Scenarios

C1.3.1 Cylindrical Pressure Vessel BLEVE Missile Hazards

Information provided by Holden and Reeves [4] on the generation of missiles includes data on ductile (BLEVE type) failures. Although failure of pressurised liquefied gas vessels generally produces fragments of the pressure vessel shell, as is the case with spherical vessels and with the majority of parts from cylinders (bullets), under some conditions cylindrical vessels can fail by loss of an end cap. In this case, the bulk of the vessel (termed a end tub or tub rocket) remains intact with an open end. The section can still contain a large amount of residual liquid which produces additional thrust on the missile causing it to 'rocket'. Thus there is a distinct difference between the behaviour of these two kinds of missiles, i.e. end tubs and fragments of pressure vessel shell (non end tub missiles) and this is reflected in the procedure shown in Figure C4.

The data on catastrophic failure induced by fire that was collated by Holden and Reeves indicate that the proportion of failures which have resulted in the generation of missiles is 89/113 i.e. 0.8. However, there is insufficient detail to be able to subdivide this into those which have and have not produced end tubs, consequently it has been conservatively assumed here that this conditional probability is unity, i.e. every fire induced failure of a cylindrical pressure vessel which produces missiles also includes an end tub.

End Tub Effects

The direction of travel of an end tub generally tends to be within a few degrees of the axis of the cylinder, thus the probability of a tub missile striking a nearby hazardous installation is dependent on the orientation of the cylinder relative to the installation.

These directional effects were utilised in the domino assessment by ignoring end tub initiated domino effects if the vulnerable components on an adjacent site were not within an angle of plus or minus 20 degrees of the vessel axis. Within this sector it could be either assumed that there is a random (uniform) probability of the end tub travelling along a particular direction, alternatively the graphical evidence included in the Holden and Reeves paper indicate a biasing along the axis itself. This could be simulated by a normal distribution with three standard deviations within the plus and minus 20 degree sector.

Holden and Reeves considered that the greater mass and stiffness of end tubs compared to other fragments would result in them being more likely to damage equipment. Consequently, from a risk assessment point of view the assumption of impacts by end tubs always resulting in failure is not overly conservative.

The distance travelled by end tubs could either be calculated by:

- The equation derived from graphical information for LPG end tub events reported by Holden and Reeves[4], $P = e^{-0.006R}$.
- Pietersen [5] for data from Mexico City, $P = e^{-0.004R}$
- Birk and Cunningham [6]for 400 litre propane tanks, $P = e^{-0.03R}$

where P is the probability of an end tub fragment having a range greater than R metres.

Non End-tub Effects

Holden and Reeves reported that for cylindrical vessels which were subjected to fire, the number of missiles ranged from 0 - 10 with the most probable number being 4. Thus assuming that one of these would be an end tub it is expected that 3 non end tub fragments would form missiles.

As with the maximum hazard distance approach a number of equations have been reported or can be derived on the basis of data from accidents or tests which describe the probability of missiles exceeding different ranges. Examples of these are

- The Schultz-Forberg expression [6], $P = e^{-0.006R}$
- The range distribution by Pietersen [5] for data from Mexico City, $P = e^{-0.004R}$
- The range distribution reported by Birk and Cunningham [6], $P = e^{-0.003R}$

BLEVE model for a Cylindrical Vessel

A probability expression similar to the general expression above can be derived which takes into account the difference between end tub and non end tubs.

Thus in the general probability expression of

$$P_{top} = \text{Prob}(S_1A_1 + S_2A_2 + S_3A_3 \ldots\ldots S_NA_N)$$

thus out of the N fragments it is assumed that there are two types of fragments, i.e. one end and the remaining N-1 are non end tub fragments. If the latter are assumed to behave in a similar manner then the above expression can be simplified to:

$$P_{top} = \text{Prob}(S_1A_1 + S_2A_2 + S_2A_2 \ldots\ldots)$$

To avoid having to calculate the cross product terms, then this can be approximated to

$$P_{top} = 1 - \{1-P_{S1}\, P_{A1}\}\{1-P_{S2}\, P_{A2}\}^{N-1}$$

Where

	P_{top}	= Probability of a missile landing on Site B (assumed to be the hatched zone in Figure C2)
	P_{S1}	= Prob of failure of the end tub to land in a safe sector
		= Prob of that the site is within +/- X degrees of the cylinder axis
and	P_{A1}	= probability of the end tub of landing beyond D.
	P_{S2}	= Prob of failure of the non end tub to land in a safe sector
and	P_{A2}	= probability of the non end tub of landing beyond D.

BLEVE model for a Spherical Vessel

Unlike the cylindrical pressure vessels which can produce an end tub, this type of fragment is not produced with spherical vessels, consequently, there are no axial alignment considerations which have to be taken into account.

Holden and Reeves, however, reported some directional biasing of fragments, i.e. the directional distribution was not uniform and there was a favoured direction. This was attributed to the nature of flame impingement and failure initiation. They concluded that unless there is a particular reason to favour a certain direction of projection then it is recommended that a random distribution be assumed.

They recommended that a mean number of fragments of 8 should be regarded as a best estimate. A judgemental upper bound confidence limit could be obtained by taking twice this mean number (i.e. 16) with the assumption that the target is in one of the favoured sectors, i.e. a probability of 0.138, however, they concluded that this degree of sophistication cannot generally be justified in missile assessments.

Therefore, for use in an initial domino assessment it is considered that the random distribution be adopted because consideration of direction of flame impingement etc. would require an in-depth analysis of the location of spherical pressure vessels on site relative to the process plant items around them. If this degree of analysis were to be included then it is considered it would only be justified in a full quantified risk assessment.

A range distribution relationship for fragments for LPG sphere BLEVE's can be derived from the information presented in the paper by Holden and Reeves[4]. Thus P_A. can be derived using the equation $P = e^{-0.00567\,R}$.

Using a random probability of landing in a particular sector then $P_S = \alpha/360$.

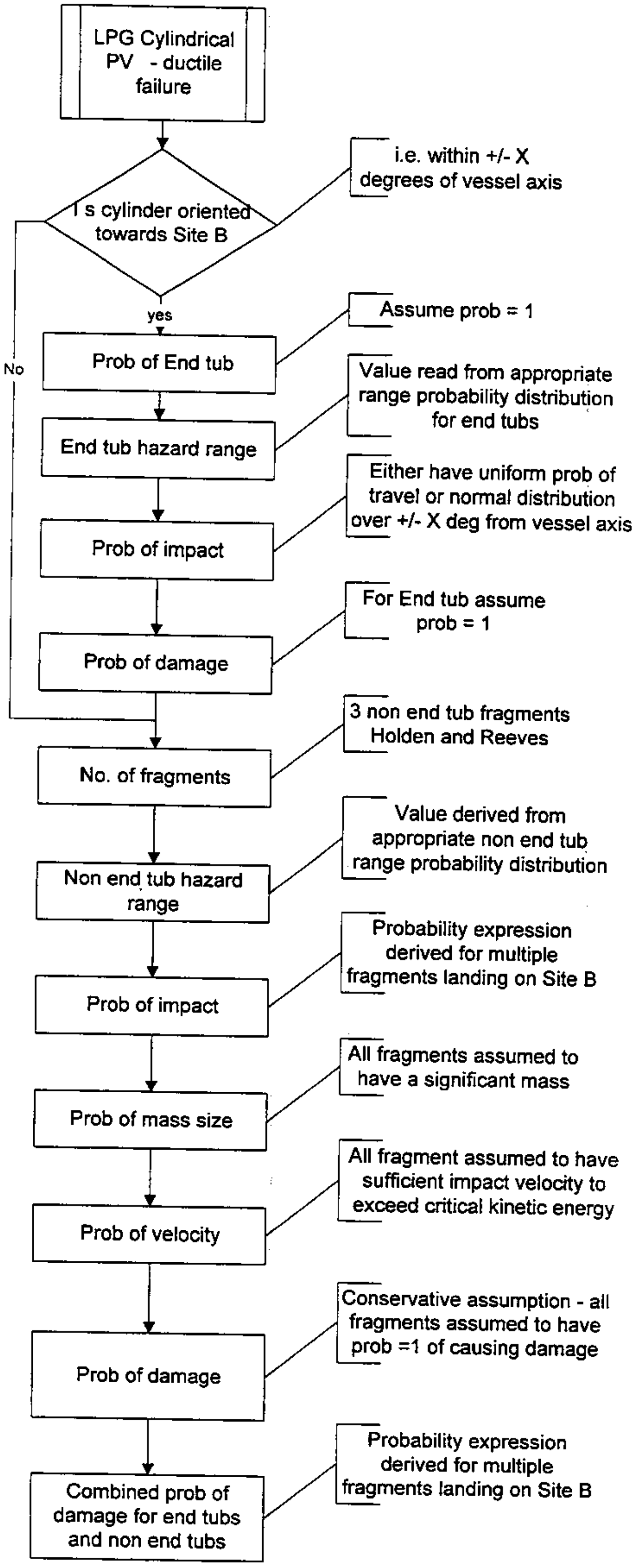

Figure C4 LPG Cylindrical PV BLEVE Missile Methodology

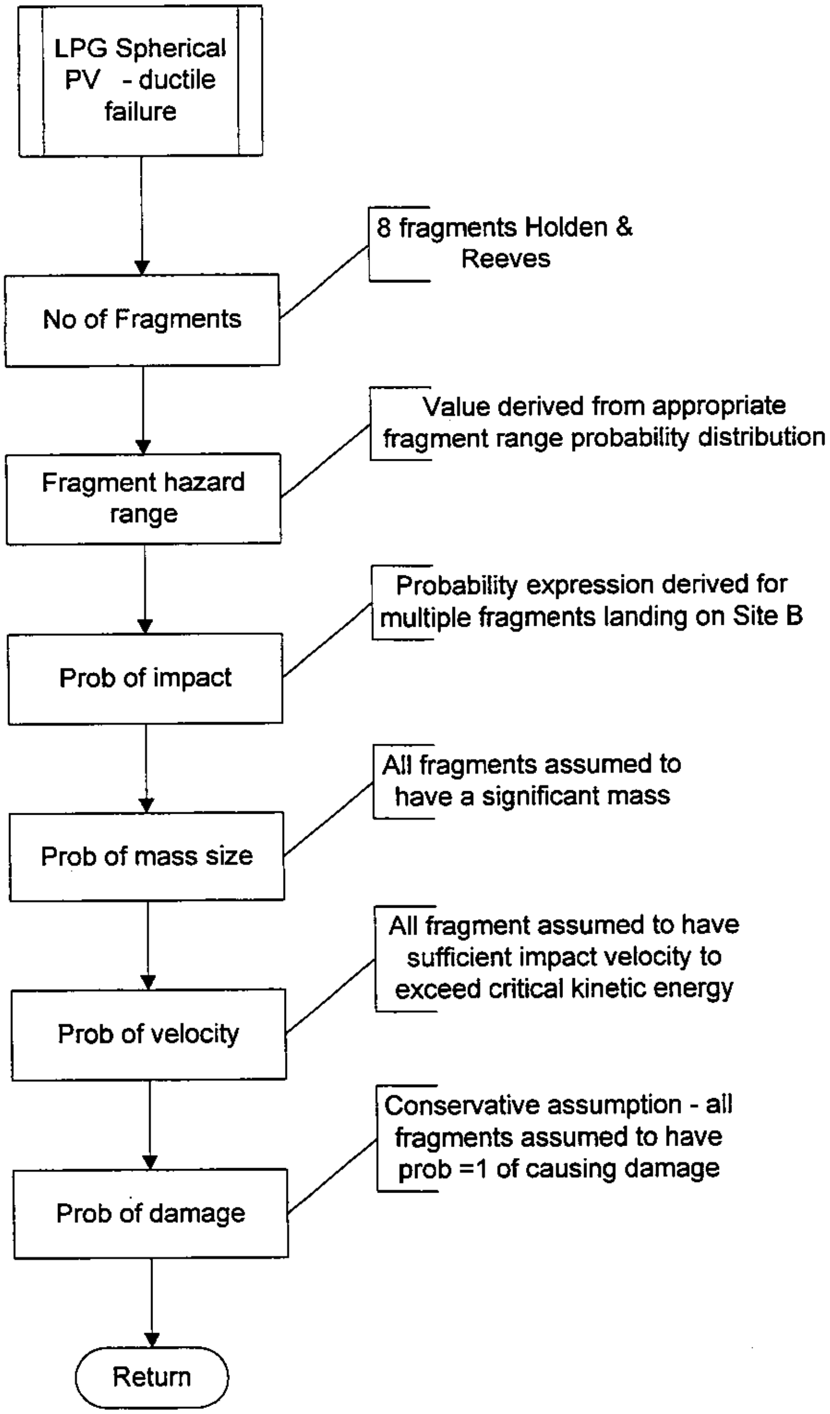

Figure C5 LPG Spherical PV BLEVE missile methodology

C1.3.2 Pressure Vessel (Brittle Failure) Missile Hazards

One possible methodology for assessing the missile effects arising from brittle pressure vessel fragmentation is to use that of Scilly and Crowther [7]. This methodology provides a detailed approach to assessing the probability of impact given the generation of a number of missiles at Site A impacting on a vessel of known dimensions at a specified distance away from the original incident. Factors such as the trajectory of the missile and the effect that this has on the target area of the vessel are included in the methodology. This is essentially steps (ii) and (iii) above.

This methodology could become very time consuming if the dimensions and position of every possible target vessel on Site B have to be considered, especially if there are several potential incident vessels on Site A. Consequently it is proposed that the methodology as outlined in Section 0 be adopted based on area of the site rather than individual vessels.

Prediction of the number of missiles generated in Scilly and Crowther method is based on matching the incident of concern with past incidents to select the most appropriate value. This is then also used as one of the parameters in the calculation of the range probability relationship.

Vessel and operating parameters are used to determine the burst pressure, which in turn is used to determine the median distance travelled by missiles.

$$Rm = 2.8\ P$$

where Rm is in metres, and
P is the calculate burst pressure in bars

The frequency distribution for missile ranges is then derived from the number of missiles (N) which could be generated (obtained by inspection of the Table 1 in the paper) and the range constructed assuming that the range of the penultimate missile (R_{pen}) is given by

$$R_{pen} = 4.1\ Rm$$

These two range values together with their associated probabilities, i.e. 50% for the median and (N-1)/N for the penultimate can be used to derive the underlying probit relationship.

As there may be some subjective judgement as to which past incident best fits the failure scenario to be studied then there may be some uncertainty in the number of fragments generated. It has been found form analysis of the equations that when considering the maximum hazard range or when trying specify a separation distance which will satisfy a predetermined probability of interaction that the hazard range increases inversely with the number of fragments generated. Thus to be conservative, if there is uncertainty regarding the possible number of fragments which could be generated then the smallest number of fragments in the possible range should be used in the analysis.

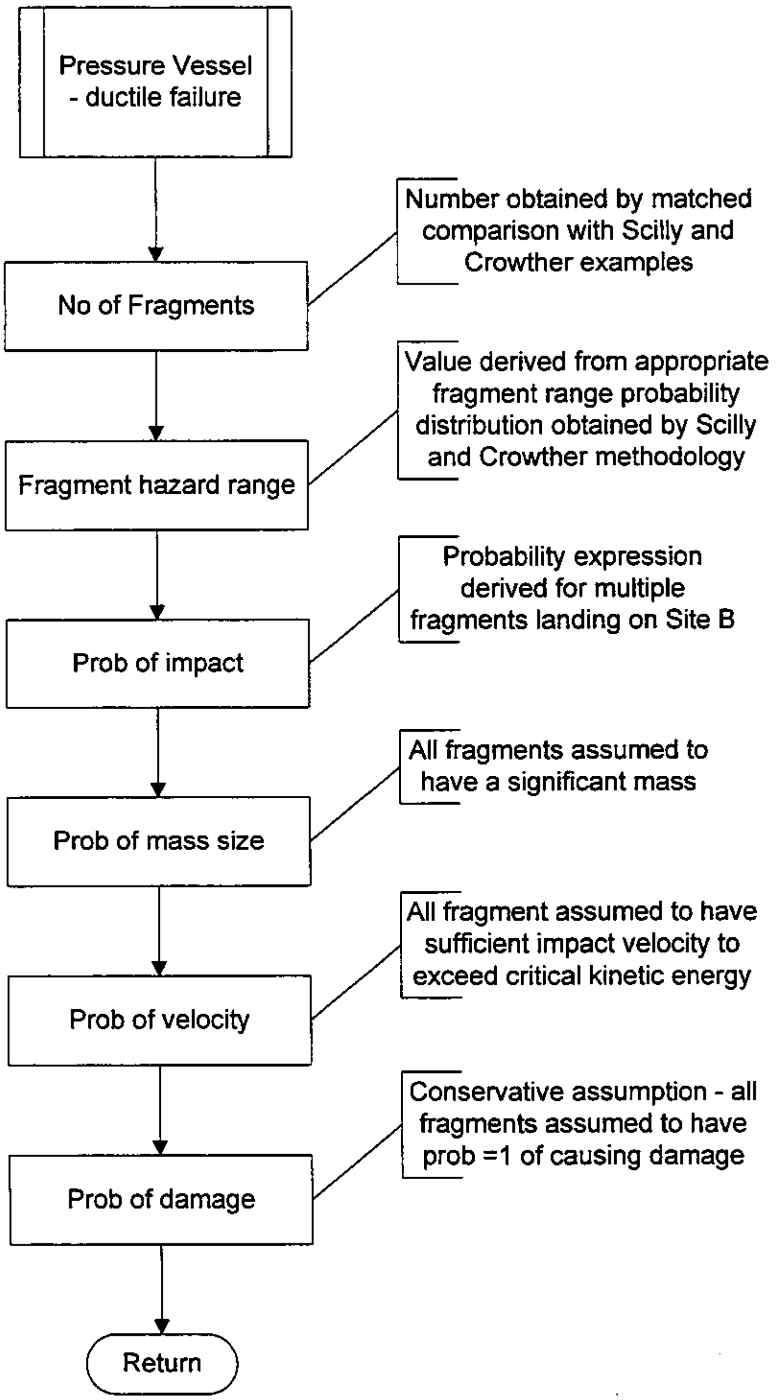

Figure C6 Pressure Vessel - Brittle Hazard

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