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# Modelling the economic impacts of an accident at major hazard sites

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# Modelling the economic impacts of an accident at major hazard sites

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This report documents the development, implementation and results of a model to estimate the economic costs of accidents at major hazard sites in Great Britain, focusing on the impacts of the accident, and taking into consideration a broad spectrum of losses. A catastrophe-modelling type approach was used to structure the work, based around model components for hazard, vulnerability and economic cost. The model was developed by the Health and Safety Laboratory in Buxton (HSL) with further input from the Welsh Economic Research Unit at Cardiff Business School and HSE, and used the COCO-2 model developed by Public Health England for nuclear site accidents as a starting point of reference.

Hazard models were developed to take advantage of existing information regarding the risk around major hazard sites that is used to inform HSE's land-use planning advice. The model also took advantage of national geographic datasets on the types and locations of buildings and population, including HSE's National Population Database. The costs considered included casualty impact costs, business disruptions, business temporary locations, building damage and evacuation costs.

The model was applied to all major hazard sites in Great Britain, with average costs estimated across all sites, and for subsets based on the expected hazard, type of site, Control Of Major Accident Hazards (COMAH) classification and geographical administrative regions.

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# EXECUTIVE SUMMARY

The Seveso II Directive (Council of the European Union, 1996) aims to prevent major accidents involving dangerous substances, and to limit their consequences on people and the environment. Within Great Britain, HSE work in partnership with the Environment Agency, Scottish Environmental Protection Agency and Natural Resources Wales to implement the Seveso II Directive legislation via the enforcement of COMAH (Control of Major Accident Hazards) regulations as part of the COMAH Competent Authority, who oversee and coordinate the regulation of major hazards in Great Britain.

As part of this role, HSE has a responsibility as a regulator for 'major hazard sites', i.e. operations that manufacture, store or use hazardous substances in quantities that have the potential to cause major harm to employees, the public or the environment. There are approximately 1,700 of these sites in Great Britain, and they include a broad range of types, each holding different substances or combinations of substances, and presenting a wide range of potential hazards and associated risks. Their scale also varies, with some sites holding relatively small quantities of dangerous substances (for example poultry farms storing fuel for heating) compared to others operating on a much larger scale, such as oil refineries. Offshore, nuclear and pipelines are also subject to major hazard regulations but are outside of the scope of this project.

Accidents at major hazard sites are rare, but when they do occur the consequences can be significant. The accident at Buncefield in 2005 was the most recent example of a major accident in the UK. There were no fatalities but there were injuries as well as damage to buildings, and impacts on business and the environment. The overall costs were estimated at £894m (2008 prices).

**Objectives**

The potential costs of further major hazard site accidents are of interest to HSE as regulators. The aims of this work were to estimate the potential costs of accidents at major hazard sites in Great Britain, focusing on the impacts of an accident, and taking into consideration a broad spectrum of loss types.

**Methodology**

A model has been developed by HSL to estimate the potential costs of an accident occurring at a major hazard site, based on a representative worst-case scenario. The model implements a 'catastrophe-modelling' style approach, built around the development of three main components for hazard, vulnerability and economic cost.

The hazard component details the distribution and intensity of the hazard and develops methods for representing the hazard using existing information regarding the risk around major hazard sites. It takes advantage of datasets that provide consistent advice around these sites for land-use planning purposes. Based on this information, methods have been set up to model the types of risk that the hazard site presents.

The vulnerability component describes the activity that might be affected by the hazard, and how it might be affected. One of the main elements of this is information on the exposure; this describes the types of receptors that might be exposed to the hazardous event and include population, property and business. The combination of the hazard and vulnerability components allows the potential impacts to be estimated.

The economic component associates an economic value with the impacts, building on the approach implemented for the COCO-2 model for nuclear sites, and using national datasets.

**Main Findings**

The model was run for all major hazard sites in Great Britain, of which there are approximately 1,700. Three main hazard types were modelled, for sites with overpressure, flammable and toxic effects. Total costs were reported for all sites, and for subsets based on the site classification, model type, COMAH site status, and geographical administrative areas for government office region and HSE region. The reported costs were broken down into component costs based on the following:

- Harm to people (Non-financial human costs and financial costs)
- Evacuation (immediate and long-term)
- Building damage (residential and non-residential)
- Business disruption (loss of business and relocation)
- Emergency services

The mean cost of the impacts per site was estimated at £110,000,000. The median was £26,000,000. The main contributor of cost was the non-financial, human costs, which made up 60.8% of the total. The results showed a range, but were of a broadly similar magnitude to those estimated for Buncefield, albeit based on a different methodology. Table ES1 details the mean and median costs for all sites broken down by the different components of loss modelled. Figure ES1 illustrates the cost breakdown of the mean averages graphically.

**Table ES1** Average costs per site for all sites

| | **Mean per site** | **Median per site** |
|---|---|---|
| Site count | 1725 | |
| **Population Impact** | | |
| Non-financial human costs | £68,000,000 | £14,000,000 |
| Financial costs | £29,000,000 | £6,000,000 |
| **Total population impact** | **£97,000,000** | **£20,000,000** |
| Evacuation | £170,000 | £6,300 |
| Building damage | £4,700,000 | £1,300,000 |
| Business disruption | £5,100,000 | £520,000 |
| Business temporary relocation | £340,000 | £96,000 |
| Emergency services | £2,100,000 | £520,000 |
| **Total cost** | **£110,000,000** | **£26,000,000** |

**Note:** totals may not sum due to rounding. The median cost components and the total cost are all independent so will not sum.

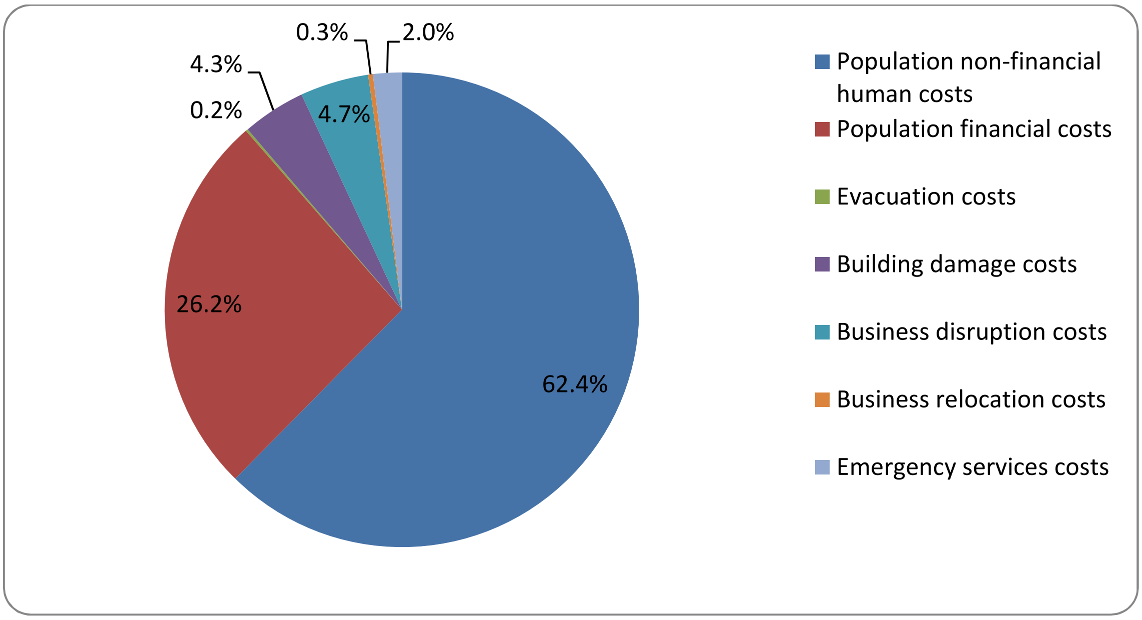


**Figure ES1** Breakdown of average (mean) costs per site

**Recommendations**

The development and implementation of this model has demonstrated the possibilities for the large-scale analysis of the potential costs of accidents at major hazard sites, and has highlighted the potential utility of some of the national scale comprehensive datasets that are available. The model leaves room for updates, in the form of additional sources of loss not modelled so far (e.g. environmental impacts) or for updates of economic and non-economic multipliers.

The information is held in a database that includes spatial referencing, which means that further information could be added based on the sites' geographical location (e.g. urban/rural contexts or alternative administration boundaries). Although costs have been estimated for individual sites, they are most effective when considered as an aggregate as the methodologies used are more sensitive to uncertainties at the local level than when combined across several sites. Estimates for individual sites are not presented in this report due to the potential sensitivities associated with accidents of this nature, such as loss of life, business, or site reputation. Further statistical analysis of the data could yield further insights and could clarify the sensitivities in the methodologies.

# 1 INTRODUCTION

## 1.1 BACKGROUND

1. The Seveso II Directive (Council of the European Union, 1996) aims to prevent major accidents involving dangerous substances, and to limit their consequences on people and the environment. Within Great Britain, HSE works in partnership with the Environment Agency, Scottish Environmental Protection Agency and Natural Resources Wales to implement the Seveso II Directive legislation via the enforcement of COMAH (Control of Major Accident Hazards) regulations as part of the COMAH Competent Authority, who oversee and coordinate the regulation of major hazards in Great Britain.

2. As part of this role, HSE has a responsibility as a regulator for 'major hazard sites', i.e. operations that manufacture, store or use hazardous substances in quantities that have the potential to cause major harm to employees, the public or the environment. One element of this role is to limit the impacts on the general public of an accident occurring on site which HSE implements through its function as a statutory consultee in the land use planning process, providing advice to Local Authorities with regard to developments in the vicinity of major hazard sites and pipelines. This function is undertaken with the aim of minimising the risk of death or injury in the event of an accident occurring on site.

3. Article 12 of the Seveso II Directive (Council of the European Union, 1996) requires that EC member states "shall ensure that the objectives of preventing major accidents and limiting the consequences of such accidents are taken into account in their land-use policies and/or other relevant policies". HSE's land use planning advice is offered through the PADHI+ system, which implements the PADHI (Planning Advice for Developments near Hazardous Installations) methodology (HSE website, g).

4. For developments proposed near to major hazard sites, the PADHI methodology takes into account the type and scale of development, and assesses the level of harm as a result of an accident occurring at the site.

5. From 1st June 2015 Seveso II will be superseded by the Seveso III Directive (The European Parliament and the Council of the European Union, 2012). This has similar aims to its predecessor including Article 13 of Seveso III which has similar requirements to Article 12 in Seveso II.

6. The term major hazard site describes sites that manufacture, store or use more than specified quantities of hazardous substances that have the potential to cause major harm to employees, the public or the environment (HSE website, h). This term covers a broad range of site types, each holding different substances or combinations of substances, and presenting a wide variety of risks. Their scale also varies, with some sites holding relatively small quantities of dangerous substances (for example poultry farms storing fuel for heating) compared to others operating on a much larger scale, such as oil refineries. As well as major hazard sites, HSE also has responsibility with regard to major hazard pipelines, which are used to transport dangerous substances around the country. The land use planning advice relating to pipelines is provided using the same PADHI methodology. Major hazard sites that wish to hold more than specified quantities of hazardous substances must apply for consent to the relevant Hazardous Substances Authority (HSA). HSE acts as a statutory consultee on these applications, providing advice as to whether they consider consent should be granted. This

advice is based on a consideration of the risks that may be created for the people in the surrounding area. There are currently around 1,700 major hazard sites in Great Britain that hold a hazardous substance consent. Just less than 1,000 of the major hazard sites hold substances (or combinations of substances) in sufficient quantities that they are also subject to COMAH regulations (HSE website, i). The COMAH regulations place the emphasis on the site operators to ensure that necessary measures are taken to prevent major accidents involving dangerous substances from occurring at these sites and limit the potential consequences.

### 1.1.1 Accidents at major hazard sites

7. Although HSE's role as a regulator helps to limit the likelihood and the consequences of an accident occurring at major hazard sites, the risk still exists. Accidents are thankfully rare, but when they do occur the impacts can be significant. Examples in the Netherlands at Enschede in 2000 (European Commission, 2000), in Toulouse, France in 2001 (European Commission, 2001), and in Ajka, Hungary in 2010 (Jávor and Hargitai, 2011) resulted in multiple fatalities and injuries, as well as other significant impacts to property and the environment, all with associated costs to the economy.

#### *1.1.1.1 Buncefield*

8. The most recent large-scale accident at a major hazard site in the UK was at the Buncefield oil terminal site in December 2005 when a series of explosions occurred, engulfing a large proportion of the site with a wide range of impacts (MIIB, 2010). Although there were no fatalities or serious injuries, 43 people were injured, and there was significant damage to property, the environment, and business. The low level of human impact can be attributed to the timing of the accident; it occurred in the early hours of a Sunday morning, when there were relatively few people on site or in the surrounding industrial estates. To investigate the accident and assess the causes and consequences, a Major Incident Investigation Board (MIIB) was set up. The MIIB produced a comprehensive set of reports detailing their findings; the final report was published in December 2008. Their work is published on the Buncefield Investigation website (MIIB, 2010).

9. As part of the investigation, the MIIB made an assessment of the economic impact; these costs were estimated at £894 million in 2008. Adjusting to 2012 prices evaluates this to £980 million. This estimate of the total cost was built up from different components that were assessed individually, and then combined to give the overall figure. The final report and accompanying appendix, published on the Buncefield Investigation website have a full breakdown of how these were calculated; the components included in this estimate are listed in Table 1.

**Table 1** Components of the overall cost estimate**:** Buncefield

| **Localised Impacts** | | **Wider Impacts** |
|---|---|---|
| - Costs to business | | - National supply-chain implications |
| - Unemployment | | - Effects on the aviation industry |
| - Housing market | | - Site rebuilding costs |
| - Emergency response | | - Costs to the Government of the investigation response |
| - Environmental cost | | |
| - Personal injury | | |

10. The largest contributor to the costs identified by the MIIB was the cost to business as a result of increased operating costs, reduced orders, reduced ability to meet existing orders, and a lack of adequate insurance for smaller businesses. This cost to business was estimated based on claims, at £625m (2008 prices, equivalent to £680m today); i.e. 70% of the total estimated cost of the incident.

11. The MIIB go on to make a series of recommendations for improving the planning system following Buncefield. Among these is a recommendation for a review considering the full range of costs and benefits of land use planning, including costs to the relevant industry sectors, local businesses and regional economies to support the economic case for a revised land used planning system (Recommendation 3).

## 1.2 ECONOMIC IMPACT OF ACCIDENTS

12. As mentioned in Section 1.1, HSE's role as regulator for major hazard sites and their provision of land use planning advice is undertaken with the aim of minimising the risk of death and injury in the event of a major accident. The investigation into the accident at Buncefield provides us with evidence that demonstrates the impacts that can occur as a result of an accident at a major hazard site as well as their potential scale. It also shows us the wide scope of these costs, and that the impacts are much broader than the consequences linked to the harm of people that are of immediate interest to HSE. Given this, it could be hypothesised that HSE's LUP advice also has wider benefits by limiting the potential consequences of an accident across a broader scope of consequences which can be translated into economic terms. HSE, as a regulator, has an interest in all aspects of its advice and in particular the impact that its advice has on society, hence the potential consequences of accidents at major hazard sites is of particular interest.

13. HSE has an interest in the economic consequences of accidents to ensure that it can provide robust regulation and that the resources given to controlling risks are proportionate to the likely impacts. As the costs of such resources often have clear monetary values, a method for estimating monetary costs of major accidents is necessary to demonstrate how these resources should best be deployed. HSE also knows from the Costs to Britain research (HSE, 2013b) that the non-financial costs of accidents, such people's pain, grief and suffering, can be the greatest cost. By their nature, these costs need valuation research to be estimated. Quantifying the impact of these accidents on people's health and well-being ensures that the full economic cost is revealed and we can help regulation be proportionate to this full cost.

### 1.2.1 HSE Requirements

14. The Economic Analysis Unit of HSE commissioned HSL to undertake an analysis of the potential impacts of accidents occurring at major hazard sites, and to estimate the associated economic cost. Cost-benefit analyses of changes in policy that affect major hazard sites and land use planning decisions have been generally 'scaled-up' from a limited number of example sites to give a national picture. However, as there is a wide variation in the nature of sites, such scaling from a limited number of sample sites results in a significant error in estimates of costs and benefits. The aim of this project is to move from scaling to direct estimation of the effects of policy changes, using locally specific information for each site. The analysis needs to be designed to model a comprehensive range of sites and accident scenarios, so this work is based on estimates of the *representative* worst-case scenarios. This approach is suitable as it aligns with HSE's approach to land use planning.

15. Using the very worst case accident that could be imagined could be misleading because the combination of circumstances required at some sites could result in a very low frequency indeed. At such low frequencies, there is a great deal of uncertainty. Furthermore, there would be great variation in the frequency across the range of sites. So the approach used is taken from the land use planning advice where a representative worst case accident is used together with levels of harm that provide a worthwhile level of protection from worst case events and almost complete protection from lesser events. .

### 1.2.2 COCO-2: Economic model for nuclear site accident consequences

16. The COCO-2 model was created to assess the potential economic costs likely to arise off-site following an accident at a nuclear reactor site (Higgins et al., 2008). The project used an Input-Output modelling approach to assess the impacts of an accident, focusing on the off-site consequences and taking advantage of up-to-date modelling techniques and official sources of data. It considered a wide selection of impacts, with an assessment of tangible and intangible losses. The economic costs that were modelled were classified into direct and indirect losses, the sources of which are outlined in Table 2.

**Table 2** Sources of loss considered in COCO-2

| **Direct Losses** | **Indirect Losses** |
|---|---|
| - Emergency Services costs<br>- Population exposure to radiation<br>- Contamination of agriculture<br>- External contamination of buildings (residential and non-residential)<br>- Internal contamination of buildings (residential and non-residential)<br>- Relocation of people<br>- Relocation of business | - Disruption of business<br>- Disruption of public services<br>- Disruption of networks (transport & utilities)<br>- Disruption of households<br>- Tourism losses |

17. To model the economic cost, COCO-2 presented a methodology that modelled the different sources of loss, and associated economic multipliers to assess the cost in economic terms. In addition to this, COCO-2 also identified data sources and attribute information to be used in an implementation. Although it had a different scope, the COCO-2 work provides a useful starting point for our analysis as it had a similar aim of modelling the economic costs of an industrial accident. Furthermore, some of the impacts will be similar (e.g. disruption to business, relocation of people), so the methods used to estimate the economic costs can be considered for adoption here. It should be noted however, that the COCO-2 approach cannot simply be reused here due to the differences between the models, for example, many of the economic costs modelled in COCO-2 were the result of contamination from radiation (e.g. to tourism, agriculture), which is not expected to be an issue here.

18. Prior to this work, a scoping study was undertaken by HSL looking at the feasibility of adapting the COCO-2 model for an assessment of the economic impact of accidents at major hazard sites (i.e. the aim of this work) (Aldridge et al., 2011). The study concentrated on the data sources and the approach, and took into account the differences between the requirements of each model. It also looked into ways of rescaling the COCO-2 approach (which used a 1km resolution grid in its data analysis) to the comparatively smaller resolution major hazard sites, considering the use of smaller grid cells but with an acknowledgement of the potential large data storage and processing costs that would result. In the summary of the scoping study,

data sources are recommended and an approach using exemplar sites and data formatted to 100 m resolution grid cells is suggested.

### 1.2.3 Catastrophe Modelling

19. Catastrophe Modelling is a method of assessing the potential economic losses as a result of a catastrophic event (Woo, 2011). It is a commonly used tool in the insurance industry where it is used to evaluate and quantify the risk from hazards to assets such as buildings and infrastructure as well as people. The model provides an outline that can be used to assess natural hazards such as floods, landslides and wildfire, as well as societal hazards like major accidents, terrorism or pandemic flu. Although the nature of these hazards can be disparate and the consequences quite varied, the concepts and the general structure of how they fit together can be outlined in a similar way. In general, the application of catastrophe modelling uses three common components, covering three distinct areas of science, these components being:

- The hazard component

  This models the catastrophe event, outputting measures describing the hazard intensity. The hazard component is commonly in the form of a footprint, or areas with different levels of risk. For example, in an accident scenario involving a toxic substance the hazard might be described by mapped information detailing the extent and concentration of a plume.

- The vulnerability component

  The vulnerability component makes an assessment of the exposure to the hazard, based on what might be at risk. Key to this component is useful information describing the receptors (or elements) that might be impacted by the hazard, including information about their vulnerability to that particular hazard. The vulnerability for each element is specific to the hazard and the element, an example might be information on the estimated mortality or injury rate for concentrations of a toxic substance, combined with information about the locations of the people who might be exposed.

- The economic loss component

  From the interaction of the hazard and vulnerability components it is possible to estimate the impact on the receptors, which can then be translated into an economic loss. This could be realised as the cost of damages to buildings for example, or by valuations associated with morbidity or mortality.

20. The catastrophe modelling approach is a useful and scientifically robust way of estimating the economic impacts from hazards, although the use of the term catastrophe for this work does suggest a level of criticality that might not fit with the full scope of the major hazard sites that we are attempting to model here. However, the approach and the concepts used are well suited to this type of work, and provide a structure that can be fitted to our objectives. Hence, the catastrophe modelling structure described will be used in this work, but will be referred to as impact modelling in this document.

21. This report documents the work carried out, describing the approach and models used, the rationale behind the work and the assumptions. The report uses a similar structure to the catastrophe modelling approach implemented.

Chapter 2 outlines the general approach proposed for the work.

Chapter 3 details the methodology used for the hazard component.

Chapter 4 outlines the approach for the vulnerability component, detailing the datasets used for the exposure element.

Chapter 5 describes the economic methodology, detailing the data sources used to associate the costs with the impacts. The Welsh Economic Research Unit at Cardiff Business School were the lead authors of this chapter.

Chapter 6 includes a note on the implementation and a discussion of the results, as well as a demonstration of the model implementation using (mocked-up) case study sites.

Chapter 7 includes the conclusions and potential next steps. It also includes a discussion of the model limitations and updates.

# 2 METHOD

22. The impact modelling approach described above provides a useful structure which we can apply to this work, and identifies three distinct subject areas in the *hazard*, *vulnerability* and *economic* components. To implement this we need to take advantage of existing scientific models, datasets and expertise within HSE and HSL, backed up by evidence from the scientific literature as there is limited scope within the current work for producing new models, surveying new input datasets or developing complex novel routines. The exemplar site approach suggested in the scoping study (Aldridge et. al 2011) has potential application here but the difficulty in trying to define the characteristics of exemplar sites and the groupings that they represent creates an additional difficulty requiring potentially broad assumptions. Instead an *all sites* approach modelling the impact for every site within scope has been adopted, taking advantage of consistent national scale datasets, and using a limited set of classifications with which to define the different hazards. The 100 m grid approach suggested in the scoping study is also not proposed to be taken forward here. Although a grid-based model should work and was implemented effectively for COCO-2, it would not necessarily utilise the vector-based datasets available (which commonly locate entities to a high level of accuracy, e.g. to a building) to their full potential. Furthermore, the 100 m resolution may be insufficient to model smaller sites in detail, as the variation in the hazard and the activity affected could be variable at even smaller scales. The use of Geographical Information Systems (GIS) and high resolution national datasets was used as the means to combine the different model components for this work.

## 2.1 APPLICATION OF IMPACT MODELLING APPROACH

23. In order to apply the impact modelling approach, it is necessary to describe how the structure fits what we are trying to model here, and how the different components can be addressed.

24. The *Hazard* component of the model describes and quantifies the effects and associated intensities of an accident occurring at a major hazard site. The Risk Assessment (RA) team at HSL has a role in assisting HSE with its management of major hazard sites, by providing models for the assessment of the potential danger to life as a result of an accident in terms of the risk or hazard in question. These risk assessment models are used to support HSE's role in the land use planning process, and hence there is a wealth of standardised quantified information on the risk at all major hazard sites. This information, combined with the knowledge of the RA team, provides the basis of the hazard component of the impact model.

25. The *Vulnerability* component of the model requires an understanding of what might be at risk from the accident hazard, and how (i.e. what makes it vulnerable). The approach taken here has been to identify the potential impacts, and then determine what information and data sources can be used in combination with the outputs of the hazard model. The COCO-2 model and the post-event analysis for Buncefield help to provide a list of potential impacts, and were used as a starting point for the vulnerability component of the model. Table 3 details the impacts considered in this assessment linked to the associated source of economic loss.

26. The *Economic Loss* component takes the analysis of impact and attaches a measure of the consequential economic loss. This needs to link to the impacts identified in the vulnerability component, and be tangible. To assist with this, the Welsh Economy Research Unit at Cardiff Business School (WERU) were approached to help identify the sources of loss, as well as the

rationale and methods that could be used to apply them to the model. The sources of economic loss are outlined in Table 3.

**Table 3** Sources of loss included in the model

| **Source of Impact** | **Costs realised and how modelled** |
|---|---|
| Casualty impact cost | The cost of injuries and fatalities of people affected by the accident.<br>Modelled as the exposure of population to the accident hazard through identification of at-risk locations. |
| Business disruptions | The potential losses to businesses (value added) through reduced operating capacity due to being affected by an accident.<br>Modelled based on business locations and activity in areas at-risk from the accident hazard. |
| Business temporary location | The costs arising to commercial enterprises in setting up temporary operations at an alternative site.<br>Modelled based on recovery, resulting from damage to workplace buildings. |
| Building damage | The likely rebuild or repair costs to physical structures (residential and non-residential/commercial, including the site itself)<br>Modelled as the cost of repair stemming from different levels of building damage, including loss of contents. |
| Evacuation costs | The immediate costs of evacuating the population affected in the major hazard site accident area, with any longer term temporary accommodation expenses, and additional expenditures to rescue services/ local authorities.<br>Modelled through identification of population in at-risk areas requiring evacuation. |

27. The sources of impact identified in Table 3 do not include all of the effects that might be expected from an accident at a major hazard site. There are other effects that are not due for consideration in this model, but are acknowledged as potential further sources of loss. Significant among these are impacts with an environmental aspect, such as the contamination of land and rivers through pollution as a result of the loss of containment of harmful substances. The economic costs associated with this could be realised through the restrictions on the sale of food and livestock, access restrictions, countermeasures, damage to ecosystems and clean-up costs. Environmental costs were modelled in COCO-2 based on contamination from radiation of agriculture and tourism. For this work, the Environment Agency was approached with a view to providing an input on the potential environmental consequences. This was not taken forward as a piece of work to run alongside HSL's work, however the model has been designed so that it can be appended with the results of impact analyses from further models.

### 2.1.1 GIS Implementation

28. The implementation of a catastrophe modelling approach requires a platform that can handle the interface between the different components. In our model, the hazard component requires a spatial representation in the form of a footprint describing different levels of hazard. Similarly, the vulnerability component is based around a spatial exposure element,

detailing what might be at risk. Given this, and the fact that the relationship between the two is also spatial, Geographical Information Systems (GIS) provides the logical means with which to undertake this analysis. Further to this, the scale of the task at hand, requiring the assessment of a large number of major hazard sites, means that whatever platform is used needs to be able to handle large databases and processes and capable of running coded models. For these reasons, the GIS-based approach was taken forward as the primary tool of analysis. GIS is a common means with which to undertake catastrophe modelling, particularly when the hazards can be described spatially.

#### 2.1.2 Scope of work

29. The aims of the work call for a methodology that provides estimated accident costs that are representative of all non-nuclear major hazard sites, capturing the full range of sites and the many factors that could influence the economic cost should an accident occur. The 2 site-specific spatial factors below will affect the economic cost of a major accident and in combination provide a huge number of possible variations:

- Nature of area

  The area surrounding a major hazard site determines the types of costs that might be incurred. For example, a site in a rural or isolated coastal location could have relatively low impacts on people and business compared to an urban site with a lot of activity nearby. Similarly, residential areas will be affected in different ways from commercial areas. All sites are different with regard to the activity around that might be impacted.

- Type and size of site

  The extent and intensity of the hazard (and the consequential impacts) are largely determined by the site type, based on the amount, type and storage of substances that might be held on site. The effects from an accident at a site holding flammable substances will be very different from a site storing toxic substances. The amount of substance held on site also influences the potential scale of an accident and consequent impacts. Generally, the greater the amount of substance held, the larger and more intense the impacts, although the type of storage is important too.

30. For these reasons, and the data analysis functionalities of GIS, it was decided to incorporate all major hazard sites in the model, rather than trying to obtain detailed case-by-case estimates for ‘typical’ sites or trying to sample a representative subset.

31. Further advantages of the all-sites approach can be identified, and are listed below:

- Variation in sites

  Although they may be similar, no two major hazard sites will have identical circumstances, and the impacts will differ depending on the factors above. Categorising the sites is a similar challenge; although there may be ways of stratifying based on the substance or size of site, the activity around the site is rarely consistent nor able to be easily categorised. However, it is possible to identify the nature of an area locally for each site, through the use of appropriate databases and information sources.

- Impact modelling approach

The impact modelling approach being implemented provides a standardised structure that can be applied to all sites.  Regardless of the variation in sites included in the analysis, the accident scenarios can all be described using the same conceptual structure.

- Consistency and completeness of data

  Information on individual major hazard sites is held by HSE in its role of providing safety advice to the planning system and is stored in a consistent and standardised way.  This includes information on the substances held, the locations, and the land use planning zones which provides a means to consider each site as an individual entity in the model in a consistent way.  Datasets on the off-site activity in the form of national scale population and building databases also allow for a consistent approach.  Similarly, economic multipliers developed to assess the economic cost are consistent and can be implemented across all sites.

- Standardised hazard models

  The majority of major hazard sites can be categorised according to substance and storage type and the main hazards identified.  Once the hazard is identified and the model established, it can be implemented across all sites within the category.

- Processing methods

  Given the standardised methods and consistent data being used in the model, it is possible to automate the running of the model to speed up the output of results.  Running the models in a GIS for approximately 1,700 sites is well within the computational capabilities of the project team and the software used.

# 3 HAZARD COMPONENT

## 3.1 INTRODUCTION

32. The hazard component of the model provides an estimate of how people and buildings in the vicinity of a major hazard site would be affected by an accident at the site. This entails estimating the proportion of the exposed population that would be killed or injured, the proportion of buildings that would be damaged, and the severity of the building damage.

33. To calculate the number of fatalities and injuries from first principles would require detailed societal risk calculations for each of the approximately 1,700 on-shore non-nuclear major hazard sites. This would be a huge undertaking and is beyond the scope of this project. It was therefore necessary to find a cost-effective way of making use of existing information.

34. The main source of information for this work has been the consultation zone maps, which are produced by HSE for all sites that require hazardous substances consent under Planning Legislation (HSE website, a; HMSO, 2009). These maps are used to inform HSE's Land Use Planning (LUP) advice in the vicinity of major hazard sites. They give an indication of how the hazard, or risk, posed by the site decreases with distance from the site. A consultation zone map for a fictitious site is shown in Figure 1. Most consultation zone maps have three zones representing criterion levels of risk or consequence, known as the inner, middle and outer zones, and are therefore commonly known as three-zone maps.

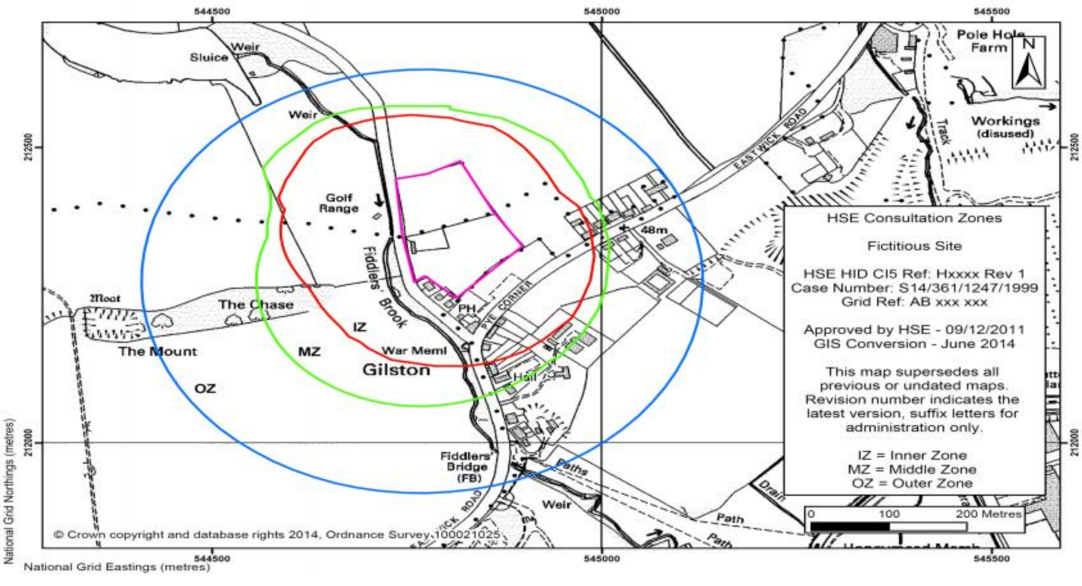


**Figure 1** Example of Consultation Zone Map

35. When a planning authority seeks HSE's advice about a planning application close to a particular site, HSE uses the consultation zone map in conjunction with a decision matrix to determine its response (HSE website, b). This approach considers both the proximity of the development to the major hazard site and the size and sensitivity of the development. The sensitivity of the proposed development reflects the vulnerability of the population who would use the development. For example, a development for the ill or elderly, such as a hospital, would have a higher sensitivity level than a residential development. Using this approach, HSE would advise against any proposed residential development in the inner zone, any large-scale

residential development in the middle zone and large scale developments for vulnerable populations in the outer zone.

#### 3.1.1 Calculation of consultation zone maps

36. The consultation zone maps are determined by detailed risk or hazard assessment calculations, which take account of the hazardous substances that the company is entitled to handle or store on site. The risk or hazard assessment considers what release scenarios could occur (such as, for example, the catastrophic failure of a storage tank or a leak from pipework), and the hazards that these scenarios would pose. For a toxic substance such as chlorine, the primary hazard is a toxic cloud formed from material released from pipework or a storage tank, which disperses with the wind away from the site. For bulk storage of liquefied petroleum gas (LPG), the primary hazard is a BLEVE (Boiling Liquid Expanding Vapour Explosion), which could occur if a fire impinges on a LPG storage vessel, causing it to rupture.

37. Consequence modelling calculations are carried out to determine the extent of the hazard. For a release of chlorine, this would involve using dispersion modelling to calculate how far downwind the toxic cloud would travel in particular weather conditions. For a release of LPG from bulk storage, the thermal radiation flux emitted from the BLEVE would be calculated, together with the variation in the heat flux with distance from source.

38. A full risk assessment considers a large representative range of the scenarios that could occur and the consequence of each scenario is weighted according to its likelihood. This involves a consideration of the event frequency of each scenario (which may be the failure frequency of a particular piece of plant).

39. A full risk assessment is beneficial for sites that store toxic or very toxic substances because the hazard range of some events can be very large under certain weather conditions. The consultation zones are defined in terms of the risk of a hypothetical house resident receiving a dangerous dose of the toxic material, where the dangerous dose (HSE website, c) is defined as the dose which is sufficient to cause:

- Severe distress to almost every one exposed to it;
- A substantial fraction of the exposed population to require medical attention;
- Serious injuries to some people, requiring prolonged treatment; and
- Possible fatalities to highly susceptible people.

40. Between 1% and 5% of an exposed population would be expected to be killed if they were exposed to an HSE dangerous dose. HSE’s toxicology unit has determined the HSE dangerous dose for a large number of substances and these are listed on the HSE website (HSE website, c).

41. For some types of hazard, however, insufficient data on event frequencies are available, and it is either not feasible to carry out a full risk assessment, or limited benefit would be gained from the additional work required. This is particularly true of flammable events, for which the calculated risk is very sensitive to inputs such as the ignition likelihood and timing and the fire brigade response time, which have a large associated uncertainty. In such cases, an alternative hazard-based methodology, known as the Protection Concept approach (Franks, 2004), is used. In the simplest cases, the consultation zones are set by considering the hazard posed by a 'representative worst case' scenario. This is not necessarily the absolute worst case scenario that could occur, but it is the worst case of sufficient frequency to be relevant. For large-scale

LPG storage sites, the representative worst case scenario would be a BLEVE involving half the inventory of a storage vessel. The Protection Concept methodology is most appropriate for installations with clearly identifiable dominating events, where the hazard ranges are generally no more than a few hundred metres, and the extent of the consequences of events is easily defined.

42. For sites that are assessed using the Protection Concept approach, the consultation zones are defined as the distances to specified levels of harm, and relate to the 'dangerous dose' for the representative worst case scenario. For example, for a fireball, the harm is measured in terms of thermal dose, and the consultation zone map provides information about the regions within which the population would be exposed to a 'dangerous dose' or worse of thermal radiation.

### 3.1.2 Estimation of economic impact from consultation zone maps

43. The consultation zone maps provide information about regions within which a person might be exposed to a dangerous dose of a substance, but they do not directly provide information about the proportion of people who are killed or injured, or the severity of the damage to buildings. It was therefore necessary to convert the information contained within the consultation zone maps into a format that is useful for the current analysis. This involved developing a set of methodologies, which could be used to derive the required information.

44. The consultation zone maps were not designed to provide information about the economic impact of an accident at a major hazard site. Therefore, many simplifying assumptions have had to be made in the analysis, and the results that have been obtained should be viewed as estimates.

45. The methodology required to convert the available information into an appropriate format is dependent on how the consultation zone map itself has been derived, and what harm criterion each zone corresponds to. For the purposes of this analysis, each major hazard site has been classified according to the substances that are handled or stored on site, and the type of storage. Examples of site classifications include chlorine (bulk storage), liquefied petroleum gas (cylinder storage) and natural gas (high pressure storage). The site classifications have been grouped according to how the consultation zone map for that classification is derived. The majority of site classifications fall into one of the three main categories:

- Sites handling or storing toxic or very toxic substances, which have risk-based zones (Section 3.2);
- Sites with hazard-based zones set by overpressure criteria (Section 3.5)
- Sites with hazard-based zones set by thermal dose criteria (Section 3.6)

46. Site classifications which do not fit into any of the above categories, such as liquid oxygen storage or cylinder storage of liquefied petroleum gas (LPG), have been considered separately. Substances which are dangerous to the environment have been neglected in the analysis, since the environmental impact of an accident at a major hazard site is beyond the scope of this project.

47. The following sections describe the methodologies that have been derived for the different site categories. For each category, the proportion of the normal and vulnerable populations who would be killed or injured by a representative worst-case accident, and the proportion of buildings that would be damaged, has been estimated. Figures are provided for each of the

zones of the consultation zone map. These are the outputs of the 'hazard' component of the model, and, as described in Section 2.1, these can be used in conjunction with population data (the 'vulnerability' component) and economic data (the 'economic' component), to model the economic impact of an accident.

48. Complex sites, such as refineries, store a variety of substances and therefore fall under more than one site classification. Such sites were considered on an individual basis, to determine which of the methodologies was most applicable. In some cases, this required the hazard component to be divided geographically based on the locations of substances around the site. Different methodologies were then applied to the different zones on the split site.

49. In reality, at nearly all sites, the economic impact of an incident would result from a range of hazards. For example, following the Buncefield incident, disruption was caused by road closures and emergency evacuation due to the smoke plume, but the majority of the economic disruption was caused by the explosion overpressure, which led to building damage and business disruption. In the context of this economic model it is reasonable to identify a single methodology to represent the complex range of possible economic impacts.

## 3.2 METHODOLOGY FOR SITES HANDLING OR STORING TOXIC OR VERY TOXIC SUBSTANCES

50. The site classifications for which the methodology for sites handling or storing toxic or very toxic substances should be used are shown in Table 4. The primary hazard at these sites is a release of a toxic or very toxic substance. HSE's assessment of the hazards at such sites takes account of the likelihood of an accident occurring as well as the consequences. Results are expressed as the individual risk of receiving a dangerous dose of the toxic or very toxic substance.

**Table 4** Site classifications for which the methodology for sites handling or storing toxic or very toxic substances should be used

| Site classification | Comments |
|---|---|
| B1 (very toxic) | This is a generic classification where HSE has used a single exemplar substance to represent the effects of substances within this group. |
| B2 (toxic) | This is a generic classification where HSE has used a single exemplar substance to represent the effects of substances within this group. |
| B1 & B2 (very toxic and toxic) | These are generic classifications where HSE has used a single exemplar substance to represent the effects of substances within each group. |
| Chlorine: bulk storage | This site classification also includes other pressure-liquefied toxic substances that behave in a similar way to chlorine, such as ammonia, sulphur dioxide and bromine. |
| Chlorine: drum storage | Maximum release: 1 tonne. Drum storage of sulphur dioxide is also included in this site classification. |
| Ethylene oxide and propylene oxide that are *not* stored under pressure | For sites at which ethylene oxide and propylene oxide are stored under pressure, the primary hazard is a vapour cloud explosion (VCE), so the overpressure methodology described in Section 3.5 should be used.<br>Smooth, concentric zones will be obtained if the three-zone map is defined by overpressure, whereas irregular zones will be obtained if the three-zone map is determined by toxic risk. |
| Low volatility toxic (LVT) | These usually produce very small zones due to the small amount of toxic vapour produced. |
| Various toxic | A combination of some or all of the above. |

51. As discussed in Section 3.1.1, HSE (HSE website, c) defines the dangerous dose as the dose which is sufficient to cause:

- Severe distress to almost every one exposed to it;
- A substantial fraction of the exposed population to require medical attention;
- Serious injuries to some people, requiring prolonged treatment; and
- Possible fatalities to highly susceptible people.

52. Between 1% and 5% of an exposed population would be expected to be killed if they were exposed to an HSE dangerous dose. The risk is expressed as chances per million (cpm) per year of a hypothetical house resident receiving the HSE dangerous dose of the toxic or very toxic substance. The model assumes 100% occupancy and for land-use-planning purposes HSE generally assumes that 10% of the population is outside during the day and 1% of the population is outside during the night. These assumptions are based on an analysis of population data by Petts et al. (1987). The zones of the three-zone map are set according to the criteria shown in Table 5. These criteria are chosen to ensure that the risk of death posed to a normal population by the major hazard site is not significant compared to other risks in daily life.

**Table 5** Definitions of land-use-planning zones for sites handling or storing toxic or very toxic substances

| Zone | Risk of receiving the HSE dangerous dose |
|---|---|
| Inner | At least 10 cpm per year |
| Middle | At least 1 cpm per year |
| Outer | At least 0.3 cpm per year |

### 3.2.1 Derivation of economic impact criteria

53. It has been agreed that no additional risk assessment calculations will be carried out for this exercise. Therefore, the information available for deriving economic impact criteria comprises the three-zone land-use-planning consultation maps, together with population data within the three zones (inner, middle and outer) derived from the National Population Database (NPD) (see Section 4.4 for more detail of the NPD and the population model used for this work).

54. As shown in Table 4, the three-zone maps have been allocated to a small number of different classifications, such as very toxic, toxic and chlorine. However, a significant amount of analysis on individual completed LUP assessments would be required in order to identify a representative worst case event for each of these classifications.

55. This section describes one possible approach to estimating the number of fatalities and injuries that would arise from an accident at a site handling or storing toxic or very toxic substances from the site's three-zone map. It should be noted that the values obtained will be approximations, because the three-zone map is not designed to provide information on the economic impact of an accident.

#### *3.2.1.1 Assumption about frequency*

56. If it is assumed that an event frequency of around 10 cpm per year is about the right frequency for a representative worst case event, then it is possible to make use of the three-zone maps using the approach outlined below. This is not the frequency of the absolute worst case scenario, which will be much lower due to a combination of failure frequency, wind direction and weather conditions. However, it is the same order of magnitude as the frequency associated with sudden large scale events, such as a large hole in a pressure vessel. Toxic risk assessments, particularly for pressure liquefied toxics such as chlorine, tend to produce middle and outer zones which are dominated by large vessel holes, with a contribution from catastrophic failure. HSE generally assumes a failure rate of 5 cpm per vessel year for large holes in pressure vessels (HSE website, d), and there is often more than one vessel on site. There is also a contribution from catastrophic failure, which typically has an associated failure rate of 2 cpm per vessel year. This means that the frequency of the initiating event that would give rise to a large toxic gas plume downwind (and which is the event that would give rise to the greatest number of casualties) is greater than 1 cpm per year and often nearer to 10 cpm per year.

57. Furthermore, 10 cpm per year is the order of magnitude of frequency that is used for the selection of representative worst case events in Protection Concept assessments (Franks, 2004) for land use planning. These events are used to set three-zone maps for hazard-based assessments, such as those carried out for sites where the primary hazard is a vapour cloud explosion (see Section 3.5) or a fireball (see Section 3.6).

#### *3.2.1.2 Estimation of the number of fatalities*

58. The inner zone boundary is the contour for a risk of 10 cpm per year of receiving a dangerous dose (DD) or worse. Although the effect of the dangerous dose is not precisely defined numerically, it is expected that between 1% and 5% of an exposed population would be killed if they were exposed to an HSE dangerous dose. For the purpose of this study, the higher end of the range has been adopted and a fatality probability of 5% has been assumed at the inner zone boundary.

59. This fatality probability could be applied to the whole of the population within the inner zone. However, this would underestimate the impact because it would take no account of the fact that people closer to the point of the toxic release would actually experience a much higher dose of toxic substance and would be more likely to die.

60. Information relating to different doses cannot be obtained directly from the three-zone map because it only records the contours that represent lower frequencies of receiving the defined dangerous dose (the 1 cpm per year and 0.3 cpm per year contours). The three-zone map does not tell us directly about the increased fatality probability within the inner zone. Although risks of higher dose levels could be calculated, the amount of work involved is outside the scope of this study. It is therefore necessary to use other techniques to estimate the additional number of fatalities closer in to the site.

61. Franks et al. (1996) established a relationship between the risk of receiving a dangerous dose and the risk of receiving a dose that would lead to a higher likelihood of death. This was based on comparisons of risk calculations for dangerous dose, which was referred to as DTL (dangerous toxic load), and a higher harm criterion based on 50% fatality probability, which was denoted LD50 (lethal dose, 50%). The equation derived by Franks et al. is reproduced below:

$$\text{Risk of LD50} = \frac{\text{Risk of DTL}^{\ 1.11}}{2.59} \qquad \text{Equation \{1\}}$$

62. This relationship is based on an analysis of chlorine, ammonia and hydrogen fluoride data. For the current study, a frequency of around 10 cpm per year is of interest, and from Equation {1} it is possible to derive the risk of dangerous dose that is associated with a 10 cpm per year risk of LD50:

$$\text{Risk of DTL associated with a 10 cpm per year risk of LD50} = 10 \times 2.59^{\ 1/1.11}$$

$$= 18.8 \text{ cpm per year}$$

63. If a log-linear relationship between risk and distance (i.e. logarithmic in risk but linear in distance) is assumed across the inner and middle zones, then the distance to an 18.8 cpm per year risk of dangerous dose can be found from the following relationship:

$$\frac{\log 10 - \log 1}{\log 18.8 - \log 10} = \frac{D_1 - D_{10}}{D_{10} - D_{18.8}}$$

This rearranges to:

$$D_{18.8} = D_{10} - 0.27\ \ D_1 - D_{10}\ ,\qquad \text{Equation \{2\}}$$

where $D_1$ and $D_{10}$ are the distances to the 1 cpm per year and 10 cpm per year contours respectively, measured from some nominal centre. The exact location of the nominal centre is not critical provided that all three distances are measured from the same point. Log-linear interpolation of this type is also utilised within HSE's risk assessment calculation tool, Toxic RISKAT (Hurst et al., 1989).

64. Using the 18.8 cpm per year contour, a new area can be defined, within which the higher fatality probability of 50% can be applied. Although the fatality probability may increase further as the source is approached, for a toxic release, the fatality probability may never reach 100%, even at the source. For this reason, the fatality probability of 50% has been applied across the whole of this area. (In contrast, a person positioned at the source of a fireball or a pool fire would be engulfed in flames and it would be reasonable to assume a fatality probability of 100% at the source).

65. If a log-linear relationship is also assumed across the remainder of the inner zone, a fatality probability of 15.8% is obtained at the mid-point of this area. A fatality probability of 15% has therefore been assumed across the remainder of the inner zone.

66. A fatality probability of 5% has been assumed across the middle zone. This is a cautious simplifying assumption, based on the fatality probability at the inner zone boundary, which is the inner extreme of the middle zone. No fatalities to the normal population (i.e. the population that is not physiologically vulnerable to the harm from major accidents) have been assumed in the outer zone. This reflects the fact that HSE would not advise against developments for normal populations within the outer zone.

#### *3.2.1.3 Sensitive residential populations*

67. The approach outlined in Section 3.2.1.2 above takes no account of more sensitive populations because it is based on calculated levels of risk to a hypothetical house resident, who is assumed to come from the normal population. However, there are some permanent residential populations that are more sensitive to the harm from major accidents. In this analysis, only populations that are more sensitive because of their physiological vulnerability are of interest. This includes patients in hospitals and residents of nursing homes or care homes for the elderly, who might have underlying health issues making them more likely to be harmed, but does not include school children, nursery school children or prisoners. HSE's land-use-planning advice sometimes considers school children and prisoners as sensitive populations, because of the element of social care and societal concern arising from the duty of care. However, in this model school children and prisoners are not classed as sensitive populations, because they are not physiologically vulnerable to the harm from major accidents.

68. Where these sensitive residential populations can be individually identified from the NPD higher fatality probabilities have been applied of 100% in the 18.8 cpm per year zone, 50% in the remaining inner zone and 5% in the middle and outer zones. The fatality probabilities that have been applied are based on the expert judgement of risk assessment specialists at HSE and HSL.

#### *3.2.1.4 Estimation of the number of injuries*

69. The number of injuries is estimated using a methodology derived by Rushton and Glossop (2005). From an analysis of historical incident data, these authors derived simple ratios linking the number of reported injuries to the number of deaths resulting from an incident, for a variety of event types (including, for example, fireball, explosion and toxic release).

70. For toxic releases, the weighted mean ratio of injuries to deaths is given as 13, and the authors state that this provides a fairly good estimate of the number of injuries. A more cautious estimate is provided by the 80$^{th}$ percentile value of the ratio, which is given as 26. Rushton and Glossop state that the historical data appear insufficient to distinguish 'major' and 'minor' injuries. The approach adopted in the current study is to associate the weighted mean with major injuries and the 80$^{th}$ percentile value with minor injuries. In this example, the number of major injuries is therefore 13 × the number of fatalities, and the number of minor injuries is (26 – 13) × the number of fatalities.

71. Using the ratios derived by Rushton and Glossop across the inner zone would lead to an overestimate of the number of injuries, because the predicted number of fatalities and injuries would be significantly higher than the total number of people within the inner zone. Within the inner zone it is therefore assumed that all those who are not killed sustain major injuries. In the middle zone, the number of major injuries is calculated using the weighted mean ratio derived by Rushton and Glossop. It is assumed that the remaining population in this zone sustains minor injuries. A similar approach is used in the outer zone, but in this case, only the sensitive population is assumed to sustain injuries.

72. It should be noted that Rushton and Glossop state that the correlation that they derive for toxic releases is poor and has a greater than 5% chance of occurring at random.

### 3.2.2 Criteria to be used for economic impact assessment

73. The criteria to be used for economic impact assessment for sites handling or storing toxic or very toxic substances are summarised in Table 6.

**Table 6** Criteria to be used for economic impact assessment for sites handling or storing toxic or very toxic substances

| Probability of receiving the HSE dangerous dose (of the substance) | Loss of life | | Injury | Building damage |
|---|---|---|---|---|
| | **Normal population** | **Sensitive population**[1] | | |
| **Inner section of inner LUP zone:** At least 18.8 cpm per year (this is assumed to be equivalent to a probability of at least 10 cpm per year of receiving the LD50) | 50% fatality probability | 100% fatality probability | Major injuries to 50% of the normal population (i.e. all those who are not fatalities) | None |
| **Outer section of inner LUP zone:** 10 cpm per year to 18.8 cpm per year | 15% fatality probability | 50% fatality probability | Major injuries to 85% of the normal population and 50% of the sensitive population (i.e. all those who are not fatalities) | None |
| **Middle LUP zone:** 1 cpm per year to 10 cpm per year | 5% fatality probability | 5% fatality probability | Major injuries to the normal and sensitive population: (13 × number of fatalities in this zone)<br>Minor injuries to the remaining population in this zone (both normal and sensitive) | None |
| **Outer LUP zone:** 0.3 cpm per year to 1 cpm per year | None | 5% fatality probability | Major injuries to the sensitive population: (13 × number of fatalities in this zone)<br>Minor injuries to the remaining sensitive population in this zone<br>No injuries to the normal population in this zone | None |

[1]In this context, the sensitive population comprises the old and ill (i.e. those with physiological sensitivity), in care homes or hospitals. Children and prisoners are not classed as sensitive.

74. The 18.8 cpm per year contour is derived from a log-linear extrapolation of the positions of the inner (10 cpm per year) and middle (1 cpm per year) zones of the three-zone map, as described in Section 3.2.1.2. The 10 cpm per year, 1 cpm per year and 0.3 cpm per year contours are taken from the existing three-zone map.

75. The fatality probabilities quoted in Table 6 should be applied to both indoor and outdoor populations, as the methodology used to derive the three-zone maps accounts for both populations.

## 3.3 METHODOLOGY FOR SITES HANDLING OR STORING REFRIGERATED FLAMMABLE LIQUIDS

76. Refrigerated flammable liquids (RFLs) include LNG (liquefied natural gas) and LPG (liquefied petroleum gas). The primary hazard at sites handling or storing RFLs is a flash fire. If an RFL is

accidentally released from storage, a flammable vapour cloud is formed. A flash fire occurs if the edge of the vapour cloud is ignited when the vapour concentration in the bulk of the cloud is still above the upper flammable limit (UFL). Combustion takes place relatively slowly and there is no significant overpressure.

77. The HSE assessment methodology for such sites calculates the risk that a given location will experience an outdoor flammable concentration of vapour. This is assumed to be equivalent to the risk of a typical person outdoors experiencing a dangerous dose of thermal radiation from a flash fire.

78. The risk is expressed as chances per million (cpm) per year of receiving the dangerous dose of thermal radiation. The zones of the three-zone map are set according to the criteria shown in Table 7. These criteria are equivalent to those used for sites handling or storing toxic or very toxic substances. However, the approach used to derive economic impact criteria for toxic and very toxic sites is not applicable to sites where the primary hazard is a flash fire. This is because the relationship between the risk of receiving the LD50 and the risk of receiving the LD1 (Franks et al., 1996) that underpins the methodology for toxic and very toxic sites is derived from data for toxic releases. An alternative approach has therefore been adopted.

**Table 7** Land-use-planning zones for sites handling or storing refrigerated flammable liquids

| Zone | Risk of receiving the HSE dangerous dose |
|---|---|
| Inner | At least 10 cpm per year |
| Middle | At least 1 cpm per year |
| Outer | At least 0.3 cpm per year |

### 3.3.1 Derivation of economic impact criteria

79. The effect of a flash fire on a person will depend on whether that person is indoors or outdoors. Most risk models assume a fatality probability of 100% for people who are outdoors in a flash fire, because of thermal effects, the fact that their clothes could be on fire, and the possibility of asphyxiation. Therefore, across the inner and middle zones, the fatality probability has been set equal to the percentage of the population that is assumed to be outdoors. For land-use-planning purposes, HSE generally assumes that 10% of the population is outside during the day and 1% of the population is outside during the night. These assumptions are based on an analysis of population data by Petts et al. (1987). These values have been used within both the inner zone and the middle zone. Although the likelihood of being exposed to a flash fire is greater in the inner zone than the middle zone, because there are more events with a hazard range that reaches this shorter distance, the impact of a flammable vapour cloud is different to that of a toxic cloud. It is not dose dependent, but is instead dependent on the conditional probabilities of a) the vapour cloud igniting; and b) the target person being outdoors.

80. No fatalities to the normal population (i.e. the population that is not physiologically vulnerable to the harm from major accidents) have been assumed in the outer zone. This reflects the fact that HSE would not advise against developments for normal populations within the outer zone. For sensitive populations, the fatality probability in the outer zone has been set equal to the percentage of the population that is assumed to be outdoors.

#### *3.3.1.1* Estimation of building damage and indoor fatalities

81. Studies have been carried out to relate the degree of damage to buildings to the incident heat flux (see Ashe and Rew, 2003; Lawson and Simms, 1952). However, it is difficult to use this information in conjunction with the risk-based zones that are derived for sites at which the primary hazard is a flash fire. The degree of building damage is therefore estimated from a set of simple assumptions.

82. A flash fire is a short duration event, so the probability that it will set a building on fire is small. In the inner zone, it has been assumed that 5% of buildings are set on fire, and in middle zone, it has been assumed that 1% of buildings are set on fire. These values are low, so it has been assumed that there are no indoor fatalities.

#### *3.3.1.2* Estimation of the number of injuries

83. The number of injuries is estimated using the methodology derived by Rushton and Glossop (2005), which is described in more detail in Section 3.2.1.4. The data relating to Rushton and Glossop's general 'fire' category have been used, although the authors note that a poor correlation is obtained. For fires, the weighted mean ratio of injuries to deaths is given as 2.2 (Rushton and Glossop state that the weighted mean provides a fairly good estimate of the number of injuries). A more cautious estimate is provided by the 80$^{th}$ percentile value of the ratio, which is given as 8. Rushton and Glossop state that the historical data appear insufficient to distinguish 'major' and 'minor' injuries. Therefore, in this work, the weighted mean is assumed to correspond to major injuries, and the difference between the weighted mean and the 80$^{th}$ percentile value is assumed to correspond to minor injuries.

### 3.3.2 Criteria to be used for economic impact assessment

84. The criteria to be used for economic impact assessment for sites handling or storing refrigerated flammable liquids are summarised in Table 8.

**Table 8** Criteria to be used for economic impact assessment for sites handling or storing refrigerated flammable liquids

| LUP zone | Loss of life | | Injury | Building damage |
|---|---|---|---|---|
| | Day | Night | | |
| Inner (probability of receiving the HSE dangerous dose of the substance is at least 10 cpm per year) | 10% of entire population | 1% of entire population | Major injuries: (2.2 × total number of fatalities) Minor injuries: (5.8 × number of fatalities) | 5% setting on fire |
| Middle (probability of receiving the HSE dangerous dose of the substance is between 1 cpm per year and 10 cpm per year) | 10% of entire population | 1% of entire population | | 1% setting on fire |
| Outer (probability of receiving the HSE dangerous dose of the substance is between 0.3 cpm per year and 1 cpm per year) | 10% of sensitive population [1] | 1% of sensitive population [1] | | None |

[1]In this context, the sensitive population comprises the old and ill (i.e. those with physiological sensitivity), in care homes or hospitals. Children and prisoners are not classed as sensitive.

## 3.4 METHODOLOGY FOR SITES HANDLING OR STORING LIQUID OXYGEN

85. If the oxygen level is increased above the normal atmospheric level of 21%, the ease with which common materials may be ignited and the rate at which they burn are both increased. The primary hazard posed by sites handling or storing liquid oxygen is enhanced ignition and combustion of people's clothing. For combustion of clothing to occur, an ignition source is required. The most common ignition source is a lighter or a cigarette (Jones, 1983).

86. The HSE assessment methodology considers the likelihood of a release of liquid oxygen occurring and the subsequent dispersion of the oxygen cloud. The zone boundaries of the three-zone map are expressed in terms of the probability of receiving the HSE dangerous dose, which is discussed in more detail in Section 3.2.

87. A concentration of 35% oxygen is assumed to constitute a 'dangerous dose'. This level is based on a study undertaken by a joint HSE and BCGA (British Compressed Gases Association) working group in the early 1980s (Jones, 1983), which was updated in the late 1990s. The derivation of this harm criterion takes into account the proportion of the adult population that smokes and the relative linear burning rate as a function of oxygen concentration. It is recognised that the proportion of the adult population that smokes has decreased since the late 1990s, but it is believed that the harm criterion derived from these data provides a suitable basis for estimating the loss of life and number of injuries that would arise following a release of liquid oxygen.

### 3.4.1 Derivation of economic impact criteria

88. The HSE dangerous dose is assumed to correspond to a fatality probability of 1% to 5% of the exposed population (HSE website, c). A fatality probability of 5% has therefore been applied across the inner and middle zones. In the outer zone, a 5% fatality probability has been applied to sensitive populations. This approach is consistent with that used for sensitive populations in the outer zone for sites handling or storing toxic or very toxic substances (as described in Section 3.2.1.3).

89. For combustion to occur, an ignition source is required, so it has been assumed that only smokers are at risk of harm from a release of liquid oxygen. Currently, approximately 20% of adult population smoke (ASH, 2014), so it has been assumed that the total percentage of the population that comes to harm (the sum of the fatalities and injuries) is 20%. This is a cautious assumption, as not all smokers will light up whilst the oxygen cloud is passing.

90. No building damage has been assumed in this analysis. It has been assumed that the damage caused by the combustion of people's clothing will be localised and will not cause significant building damage.

### 3.4.2 Criteria to be used for economic impact assessment

91. The criteria to be used for economic impact assessment for sites handling or storing liquid oxygen are summarised in Table 9. These criteria apply to the entire population, both indoors and outdoors.

**Table 9** Criteria to be used for economic impact assessment for sites handling or storing liquid oxygen

| LUP zone | Loss of life | Injury | Building damage |
|---|---|---|---|
| Inner (probability of receiving the HSE dangerous dose of the substance is at least 10 cpm per year) | 5% of entire population | 5% major injuries; 10 % minor injuries (applies to entire population) | None |
| Middle (probability of receiving the HSE dangerous dose of the substance is between 1 cpm per year and 10 cpm per year) | 5% of entire population | 5% major injuries; 10 % minor injuries (applies to entire population) | None |
| Outer (probability of receiving the HSE dangerous dose of the substance is between 0.3 cpm per year and 1 cpm per year) | 5% of sensitive population [1] | Major injuries to 5% of sensitive population [1]; Minor injuries to 10% of sensitive population [1] | None |

[1]In this context, the sensitive population comprises the old and ill (i.e. those with physiological sensitivity), in care homes or hospitals. Children and prisoners are not classed as sensitive.

## 3.5 METHODOLOGY FOR SITES WITH ZONES SET BY OVERPRESSURE CRITERIA

92. The site classifications for which the methodology for sites with zones set by overpressure criteria should be used are summarised in Table 10. The primary hazard at these sites is either a condensed phase explosion or a vapour cloud explosion (VCE). A condensed phase explosion

may occur when the released material is present in the form of a solid or a non-volatile liquid. If, however, a gas or volatile liquid is released from containment, the resulting gas or vapour cloud may mix with air to form a flammable mixture. If the flammable mixture is confined by some form of structure (typically the matrix of pipework associated with a chemical plant) and ignition occurs, this may result in a vapour cloud explosion. Land-use-planning zones for these sites are hazard based and are defined in terms of the overpressure. The overpressure is the pressure in excess of normal atmospheric pressure, caused by the explosion's shock wave. Inner, middle and outer zone boundaries are normally based on the distances to peak overpressures of 600 mbar, 140 mbar and 70 mbar respectively.

**Table 10** Site classifications for which the methodology for sites with zones set by overpressure criteria should be used

| Site classification | Primary hazard | Comments |
|---|---|---|
| Large-scale petrol storage | Vapour cloud explosion (VCE) | This classification includes Buncefield type sites |
| Ethylene oxide and propylene oxide that are stored under pressure | Vapour cloud explosion (VCE) | For sites at which ethylene oxide and propylene oxide are *not* stored under pressure, the primary hazard is a toxic release, so the methodology described in Section 3.2 should be used.<br>Smooth, concentric zones will be obtained if the three-zone map is defined by overpressure, whereas irregular zones will be obtained if the three-zone map is determined by toxic risk. |
| B3 (oxidising) | Condensed phase explosion | B3 substances include organic peroxides and hydrogen peroxide This classification also includes named substances with similar properties such as sodium chlorate. |
| Ammonium nitrate | Condensed phase explosion | There has been a recent change to the assessment methodology for ammonium nitrate (see HSE website, e). The new methodology is gradually being applied to all ammonium nitrate sites. Generic zones have been used for sites whose three-zone maps have not yet been updated.<br>The assessment methodology for ammonium nitrate sites is more complex than that used for other sites with zones set by overpressure criteria, so ammonium nitrate sites have been considered separately in Section 3.5.2. |

### 3.5.1 Derivation of economic impact criteria for sites not storing ammonium nitrate

93. Sites where the primary hazard is a vapour cloud explosion or a condensed phase explosion are assessed by HSE using a Protection Concept methodology (Franks, 2004), and zones are defined in terms of overpressure. The Protection Concept methodology is most appropriate for installations with clearly identifiable dominating events, where the hazard ranges are generally no more than a few hundred metres, and the extent of the consequences of events is easily defined.

94. Where a Protection Concept assessment is carried out, the three zones are set so that there is almost complete protection from lesser but more likely events and worthwhile protection against unlikely but foreseeable large scale events. The criteria used to determine the maximum credible incidents for setting the three zones are shown in Table 11.

**Table 11** Criteria used to determine the maximum credible incidents for setting the three zones in a Protection Concept assessment (HSE website, e)

| Zone | Criteria |
|---|---|
| Inner | Frequency ≥ 10 cpm per year with indoor or outdoor dangerous dose<br>Frequency ≥ 3 cpm per year with indoor or outdoor risk of death |
| Middle | Frequency ≥ 1 cpm per year with indoor or outdoor dangerous dose<br>Frequency ≥ 0.3 cpm per year with indoor or outdoor risk of death |
| Outer | Frequency ≥ 1 cpm per year with indoor or outdoor sensitive dose<br>Frequency ≥ 0.3 cpm per year with indoor or outdoor dangerous dose<br>Frequency ≥ 0.1 cpm per year with indoor or outdoor risk of death |

95. In the simplest cases, a single event is used to define all three zones. In such cases, the overpressure at the inner zone boundary (600 mbar) is chosen to correspond to the mortality of 50% of the exposed population. The middle zone boundary (140 mbar) is chosen to correspond to the 'dangerous dose' for the normal population (1% to 5% fatalities) and the outer zone boundary (70 mbar) is chosen to correspond to the 'dangerous dose' for vulnerable populations.

#### *3.5.1.1 Outdoor fatalities*

96. It has been assumed that there are no outdoor fatalities. The peak overpressures experienced within the land-use-planning zones would cause injury or discomfort to someone outdoors, but would be unlikely to be fatal. An outdoor fatality is more likely to be caused by a person being thrown against an obstacle or hit by a missile generated in the explosion. If a person were hit by a missile in the inner zone, there would be a high likelihood of death, but the probability of this occurring is low.

#### *3.5.1.2* **Estimation of building damage**

97. VCEs and condensed phase explosions generally lead to a significant amount of building damage. In the 1950s, an analysis of approximately 100 reported explosions and data collected on bomb damage caused during World War II was carried out for the Government Explosive Storage and Transport committee (see Scilly and High (1986) and references within). In this analysis, the peak overpressures that would be required for brick built houses to undergo certain levels of damage were calculated for different sizes of explosion. The results of the analysis are summarised in Table 12. As the TNT tonnage increases, the peak overpressure required to cause a specified level of damage decreases. This is because the level of damage is also dependent on the duration of the blast wave, which increases as the size of the explosion increases. However, above 10 tonnes of TNT, there is little change in the peak overpressure required to cause a specified level of damage. For categories A, Cb and Ca, the peak overpressures from a 100 tonne TNT explosion that are required to cause the specified level of

damage correspond reasonably well to the consultation zone map boundaries. These levels of damage have therefore been associated with the LUP zones in the current analysis. It is recognised that the damage caused by an explosion at a major hazard site will not be directly equivalent to the damage caused by a TNT explosion, but it is believed that these data provide a suitable basis for estimating building damage for the current analysis.

**Table 12** Building damage as a function of overpressure (columns 1 to 4 reproduced from Scilly and High, 1986)

| **Damage to UK brick built houses** | **Approximate peak side on overpressure in mbar** | | | **Threshold overpressure used in current analysis (mbar)** |
|---|---|---|---|---|
| | **1 tonne TNT** | **10 tonne TNT** | **100 tonne TNT** | |
| Category A: completely demolished | 1830 | 793 | 758 | 600 |
| Category B: badly damaged and beyond repair (serious structural damage) | 793 | 359 | 345 | 350 |
| Category Cb: Uninhabitable without extensive repairs (serious structural damage) | 276 | 165 | 159 | 140 |
| Category Ca: Uninhabitable but repairable | 124 | 79.3 | 75.8 | 70 |

98. To distinguish between category B damage and category Cb damage, an additional overpressure contour is required. Based on the information on building damage presented in Scilly and High (1986) and reproduced in Table 12, this additional threshold has been set at 350 mbar.

99. The position of the 350 mbar contour may be estimated from the positions of the inner and middle zones on the three-zone map. If it is assumed that there is an approximate log-log relationship between distance and overpressure (an analysis of the outputs of HSE's in-house implementation of the TNO Multi-Energy Method (Irx and van den Berg, 2005) supports this), the distance to an overpressure of 350 mbar, $D_{350}$, can be found from the following relationship:

$$\frac{\log 600 - \log 140}{\log 600 - \log 350} = \frac{\log D_{140} - \log D_{600}}{\log D_{350} - \log D_{600}}$$

This rearranges to:

$$D_{350} = D_{600} \, {\frac{D_{140}}{D_{600}}}^{0.37}, \qquad \text{Equation \{3\}}$$

where $D_{600}$ and $D_{140}$ are the distances to the 600 mbar (inner zone) and 140 mbar (middle zone) contours, respectively.

#### *3.5.1.3* Estimation of the number of indoor fatalities

100. It is anticipated that the large amount of building damage caused by VCEs and condensed phase explosions will lead to a significant number of indoor fatalities. The number of indoor fatalities may be estimated by making use of the fact that the inner and middle zone boundaries are chosen to correspond to the mortality of 50% and 1% to 5% of the exposed population, respectively.

101. The overpressure decreases smoothly with distance from the source. Therefore, it would not be cautious to apply the fatality probability corresponding to the inner zone boundary across the entire inner zone. For the purposes of this analysis, the proportion of indoor fatalities in the inner zone is assumed to be 75%. This is the arithmetic mean of the fatality probability at the source (which is assumed to be 100%) and the fatality probability at the zone boundary. It is the value used by HSE in the TROD (Total Risk Of Death) methodology (Rushton and Carter, 2009; Quinn and Davies, 2004). The proportion of indoor fatalities in the middle zone is assumed to be 25%, which is the approximate arithmetic mean of the fatality probabilities at the inner and middle zone boundaries.

102. The outer zone boundary is chosen to correspond to the HSE dangerous dose (HSE website, c) for sensitive populations. It is generally assumed that between 1% and 5% of an exposed population would be expected to be killed if they were exposed to an HSE dangerous dose. For the purpose of this study, a fatality probability of 5% has been adopted for the sensitive population across the whole outer zone. In this context, the sensitive population comprises those with physiological sensitivity. This includes ill and elderly people in hospitals, nursing homes and full time residential care, but does not include prisoners or children at schools or nursery schools.

103. For simplicity, the sensitive population is not considered separately in the inner zone or middle zone. Generally, the proportion of the population within these zones that is classified as sensitive is very low. No fatalities amongst the general (non-sensitive) population have been assumed in the outer zone.

104. These fatality rates are applied to the proportion of the population that is indoors. For land-use-planning purposes, HSE generally assumes that 90% of the population is indoors during the day and 99% of the population is indoors at night, based on the work of Petts et al. (1987).

#### *3.5.1.4 Estimation of the number of injuries*

105. The number of injuries in the outer zone is estimated using the methodology derived by Rushton and Glossop (2005), which is described in more detail in Section 3.2.1.4. For explosions, the weighted mean ratio of injuries to deaths is given as 2.4 and the $80^{th}$ percentile value of the ratio is 5. For VCEs, the weighted mean ratio of injuries to deaths is given as 5.9 and the $80^{th}$ percentile value of the ratio is 10. For VCEs, the ratios which exclude two rail incidents have been used, as these are more likely to be applicable to a fixed installation. As discussed in Section 3.2.1.4, in this work, the weighted mean is assumed to correspond to major injuries, and the difference between the weighted mean and the $80^{th}$ percentile value is assumed to correspond to minor injuries.

106. In the inner zone and middle zone a large number of indoor fatalities is assumed, so it is reasonable to assume that those indoors who are not killed will be seriously injured. Using the

Rushton and Glossop methodology in these zones would lead to an overestimate of the number of injuries.

### 3.5.2 Derivation of economic impact criteria for sites storing ammonium nitrate

107. The assessment methodology for ammonium nitrate sites has recently been revised. The previous ammonium nitrate LUP methodology was primarily based on the risks posed by toxic fumes of NO (nitric oxide) and $NO_2$ (nitrogen dioxide) from the decomposition of ammonium nitrate. However, a review of this methodology concluded that the risks from the dispersing toxic cloud were overestimated and that the explosion risk was underestimated. It was therefore replaced in August 2012 by an explosion-based LUP methodology, in which the zones are generally set using overpressure criteria (HSE website, e).

108. The new assessment methodology takes into account a number of different accident scenarios, ranging from a truck explosion involving 25 tonnes of ammonium nitrate, through a bagged stack explosion of 300 tonnes of ammonium nitrate, up to multi stack explosions or even a large bulk heap explosion. The frequencies of the accident scenarios determine which of the scenarios are used to set the LUP zones. In many cases, the zones are not all set by the same scenario. Furthermore, the inner, middle and outer zones do not necessarily correspond to overpressures of 600 mbar, 140 mbar and 70 mbar.

109. The assessment methodology is much more complex than that used for other sites with zones set by overpressure criteria, for which the consultation zone map is based on a single omnidirectional event. This presents some difficulties when trying to derive simple criteria about harm and damage in relation to the consultation zone map. In particular, some of the arguments used to justify the approach adopted for other sites with zones set by overpressure criteria are not valid for ammonium nitrate sites. The following sections describe the modified approach that has been adopted for ammonium nitrate sites.

110. The three-zone maps for ammonium nitrate sites are gradually being reassessed using the new methodology, but at the time of writing this process was not complete. At the time of the analysis, 17 of the 170 ammonium nitrate sites had been reassessed and new zones created. Zones which have not yet been reassessed (and which have therefore been derived using the old methodology) are not based on an explosion event, so it is not appropriate to assess the economic impact of an accident by using these zones in conjunction with overpressure criteria. To allow the overpressure methodology described below to be applied to these sites, generic zones have been produced using the new methodology. The generic zones are based on typical site inventories, and have been calculated for two different types of site: a coastal or estuary site and an inland site. The inputs used to derive the generic zones for ammonium nitrate sites are described in Appendix 1. The generic zones are not used for sites whose three-zone maps have already been reassessed using the new methodology: for such sites, the current three-zone map is used.

#### *3.5.2.1 Outdoor fatalities*

111. As for other types of site with zones set by overpressure criteria, it has been assumed that there are no outdoor fatalities. The peak overpressures experienced within the land-use-planning zones would cause injury or discomfort to someone outdoors, but would be unlikely to be fatal.

#### *3.5.2.2 Estimation of building damage*

112. For other types of sites with zones set by overpressure criteria, an additional 350 mbar contour was plotted to distinguish between different levels of building damage in the middle zone (see Section 3.5.1.2 for further details). As discussed in Section 3.5.2, the inner and middle zones for ammonium nitrate sites do not always correspond to pressures of 600 mbar and 140 mbar, so the position of the 350 mbar contour cannot be estimated from the positions of these zones. It has therefore simply been assumed that the level of building damage in the middle zone ranges from badly damaged and beyond repair (serious structural damage) to uninhabitable without extensive repairs (serious structural damage).

113. As for other types of site with zones set by overpressure criteria, it has been assumed that buildings within the inner zone are completely demolished and that buildings in the outer zone are uninhabitable but repairable.

#### *3.5.2.3 Estimation of the number of indoor fatalities*

114. The new assessment approach for ammonium nitrate sites predicts a range of types of inner zone, depending on factors such as the site inventory, storage conditions and operating procedures. For example, some sites have an inner zone corresponding to a 3 cpm per year of higher risk of being exposed to an overpressure of 600 mbar, whereas other sites have an inner zone corresponding to a 10 cpm per year or higher risk of being exposed to an overpressure of 140 mbar. Therefore, the inner zone boundary does not always correspond to a mortality of 50%, and assuming an indoor fatality probability of 75% across the whole of the inner zone (as was assumed for other sites with zones set by overpressure criteria) may lead to an overestimate of the number of fatalities. For ammonium nitrate sites, a reduced indoor fatality probability of 50% has been assumed across the inner zone. All other assumptions relating to indoor loss of life are the same as those used for other sites with zones set by overpressure criteria.

#### *3.5.2.4 Estimation of the number of injuries*

115. The number of injuries was estimated using the same approach as was used for other sites with zones set by overpressure criteria. The ratios derived by Rushton and Glossop (2005) for explosions have been used.

### 3.5.3 Criteria to be used for economic impact assessment

116. In the analysis of overpressure sites, the vulnerable population comprises occupants of hospitals, care homes and nursing homes, who are old or ill and therefore more sensitive to the effects of overpressure, and are less likely to be able to escape. Prisoners are also considered to be vulnerable, as they are an immobile population.

117. The criteria to be used for economic impact assessment for sites with zones set by overpressure criteria, other than those storing ammonium nitrate, are summarised in Table 13.

**Table 13** Criteria to be used for economic impact assessment for sites with zones set by overpressure criteria (excluding ammonium nitrate sites)

<table>
<tr><th>Criterion</th><th>Loss of life</th><th>Injury</th><th>Building damage</th></tr>
<tr><td>Overpressure greater than 600 mbar (corresponds to inner zone of three-zone map)</td><td>75% mortality for all indoors</td><td>25% of those indoors will receive major injuries</td><td>Completely demolished</td></tr>
<tr><td>Overpressure between 350 mbar and 600 mbar</td><td rowspan="2">25% mortality for all indoors</td><td rowspan="2">VCE<br>75% of those indoors will receive major injuries<br>Explosion<br>60% of those indoors will receive major injuries (2.4 × number of fatalities in this zone)<br>15% of those indoors will receive minor injuries (remaining indoor population in this zone)</td><td>Badly damaged and beyond repair (serious structural damage)</td></tr>
<tr><td>Overpressure between 140 mbar and 350 mbar</td><td>Uninhabitable without extensive repairs (serious structural damage)</td></tr>
<tr><td>Overpressure between 70 mbar and 140 mbar (corresponds to outer zone of three-zone map)</td><td>5% mortality for all vulnerable people indoors</td><td>VCE<br>Major injuries: (5.9 × number of fatalities in this zone)<br>Minor injuries: (4.1 × number of fatalities in this zone)<br>Explosion<br>Major injuries: (2.4 × number of fatalities in this zone)<br>Minor injuries: (2.6 × number of fatalities in this zone)</td><td>Uninhabitable but repairable</td></tr>
</table>

118. For large-scale petrol storage sites, there is an additional LUP consultation zone within the inner zone, named the Development Proximity Zone (DPZ). The DPZ is a policy construct based on one of the options in consultation document CD211 (see HSE website, f and HSE, 2007), which was prepared in response to the Buncefield Major Incident Investigation Board (MIIB) recommendations. The DPZ does not represent a physical effect, or a level of harm, so it has not been assigned a specific fatality probability; the area within the DPZ is therefore treated the same as the rest of the inner zone.

119. The criteria to be used for economic impact assessment for ammonium nitrate sites are summarised in Table 14.

**Table 14** Criteria to be used for economic impact assessment for ammonium nitrate sites

| **Location** | **Loss of life** | **Injury** | **Building damage** |
|---|---|---|---|
| Inner zone | 50% mortality for all *indoors* | 50% of those *indoors* will receive major injuries | Completely demolished |
| Middle zone | 25% mortality for all *indoors* | 60% of those *indoors* will receive major injuries (2.4 × number of fatalities in this zone)<br>15% of those *indoors* will receive minor injuries (remaining indoor population in this zone) | Damage ranges from badly damaged and beyond repair (serious structural damage) to uninhabitable without extensive repairs (serious structural damage) |
| Outer zone | 5% mortality for all vulnerable people *indoors* | Major injuries: (2.4 × number of fatalities in this zone)<br>Minor injuries: (2.6 × number of fatalities in this zone) | Uninhabitable but repairable |

## 3.6 METHODOLOGY FOR SITES WITH ZONES SET BY THERMAL DOSE CRITERIA

120. Site classifications for which the methodology for sites with zones set by thermal dose criteria should be used are summarised in Table 15. At such sites, the primary hazard is a jet fire, fireball, BLEVE (Boiling Liquid Expanding Vapour Explosion) or pool fire and the land-use-planning zones are set by thermal dose criteria. The harm from these hazards is measured in terms of thermal dose units (tdu), where 1 tdu is equal to 1 s.$(kW/m^2)^{4/3}$. The inner, middle and outer LUP zone boundaries are normally based on the distances to 1800, 1000 and 500 thermal dose units respectively.

121. Flash fires are assessed using a risk based methodology, which is described in Section 3.3.

**Table 15** Site classifications for which the methodology for sites with zones set by thermal dose criteria should be used

| **Site classification** | **Primary hazard** | **Comments** |
|---|---|---|
| Natural gas: high pressure | Fireball or jet fire | This site classification includes high pressure storage of natural gas, underground storage, compressor stations and high pressure gas at terminals. |
| Natural gas: low pressure gas holders | Fireball | - |
| Liquefied petroleum gas (LPG): bulk storage | BLEVE (Boiling Liquid Expanding Vapour Explosion) | This site classification also includes substances that can give rise to a fireball event, such as VCM (vinyl chloride monomer) |
| Various flammable liquids | Normally dominated by pool fire | This classification includes flammable liquids, highly flammable liquids and extremely flammable liquids (all show similar types of zones). |

### 3.6.1 Derivation of economic impact criteria

122. Flammables sites (except those where the primary hazard is a flash fire) are assessed by HSE using a Protection Concept methodology (Franks, 2004), and zones are defined in terms of thermal dose. The Protection Concept methodology is described in more detail in Section 3.5.1.

#### *3.6.1.1 Estimation of number of outdoor fatalities*

123. The NPD (Section 4.4) provides estimates of the indoor population. The corresponding outdoor population may be estimated by assuming that 10% of the population is outside during the day and 1% of the population is outside during the night. These are standard assumptions used by HSE for land-use-planning purposes and are based on an analysis of population data by Petts et al. (1987).

124. The proportion of fatalities amongst the outdoor population is dependent on the thermal dose received. The land-use-planning zones are set by thermal dose criteria and the inner zone boundary (1800 tdu) is chosen to correspond to the mortality of 50% of the exposed population. The middle zone boundary (1000 tdu) is chosen to correspond to the 'dangerous dose' for the normal population (1 to 5% fatalities) and the outer zone boundary (500 tdu) is chosen to correspond to the 'dangerous dose' for vulnerable populations. Further information relating to the choice of these criteria is provided in a series of research reports prepared for HSE by WS Atkins (Rew, 1997; Hockey and Rew, 1996; Daycock and Rew, 2000). The key points are summarised in Table 16.

**Table 16** Land-use-planning zones for sites with zones set by thermal dose criteria

| Zone | Thermal dose at zone boundary (tdu) | Harm experienced by a person receiving this thermal dose | Loss of life corresponding to this thermal dose |
|---|---|---|---|
| Inner | 1800 | Clothing ignition and full thickness (3rd degree) burns (Rew, 1997). | 50% mortality for all *outdoors* |
| Middle | 1000 | The area of skin suffering full thickness burns would be equivalent to half the unclothed area. The likely burn area would therefore be 10% for adults and 15% for children (see Hockey and Rew, 1996). The threshold for severe burns is 15% for adults and 10% for children and the elderly (see Daycock and Rew, 2000). | 1% mortality for all *outdoors* |
| Outer | 500 | 'Mid-range' partial thickness (2nd degree) burns for vulnerable people (Daycock and Rew, 2000). | 1% mortality for vulnerable people *outdoors* |

125. The thermal dose decreases smoothly with distance from the source. Therefore, it would not be cautious to apply the fatality probability corresponding to the inner zone boundary across the entire inner zone. For the purposes of this analysis, the proportion of outdoor fatalities in the inner zone is assumed to be 75%. This is arithmetic mean of the fatality probability at the source (which is assumed to be 100%, as the person would be engulfed by the pool fire, jet fire or fireball) and the fatality probability at the zone boundary. It is the value used by HSE in the

TROD (Total Risk Of Death) methodology (Rushton and Carter, 2009; Quinn and Davies, 2004). The proportion of outdoor fatalities in the middle zone is assumed to be 25%, which is the approximate arithmetic mean of the fatality probabilities at the inner and middle zone boundaries.

126. The outer zone boundary is chosen to correspond to the HSE dangerous dose (HSE website, c) for sensitive populations. It is generally assumed that between 1% and 5% of an exposed population would be expected to be killed if they were exposed to an HSE dangerous dose. For the purpose of this study, a fatality probability of 5% has been adopted for the sensitive population across the whole outer zone. In this context, the sensitive population comprises those with physiological sensitivity. This includes ill and elderly people in hospitals, nursing homes and full time residential care, but does not include prisoners or children at schools or nursery schools.

127. For simplicity, the sensitive population is not considered separately in the inner zone or middle zone. Generally, the proportion of the population within these zones that is classified as sensitive is very low. No fatalities amongst the general (non-sensitive) population have been assumed in the outer zone.

#### *3.6.1.2 Estimation of building damage*

128. For the purpose of Hazardous Substances Consent assessment, HSE uses two criteria to estimate the level of building damage: the spontaneous ignition (SI) distance and the piloted ignition (PI) distance. Within the spontaneous ignition distance, the incident heat flux is sufficiently high to ignite the combustible parts of the building exterior, whereas for piloted ignition to occur, a source of ignition such as a burning brand is required for the heated combustible material to ignite.

129. To assess the consequences of a long duration flammable event, such as a pool fire or a jet fire, HSE requires values for the incident heat flux needed for spontaneous or piloted ignition to occur. The currently used values are based on the lowest ignition thresholds for American whitewood, and are 25.6 $kW/m^2$ for spontaneous ignition and 14.7 $kW/m^2$ for piloted ignition (Lawson and Simms, 1952; Burrell and Hare, 2006). Fireballs, BLEVEs and other transitory events do not establish heat-transfer equilibrium and are assessed separately.

130. In HSE's assessment methodologies for fireballs, pool fires and jet fires, the spontaneous and piloted ignition distances are calculated together with the distances to the inner, middle and outer zone boundaries. Generally, the boundary of the inner zone lies within the spontaneous ignition distance and the boundary of the middle zone lies between the spontaneous and piloted ignition distances. It is possible to derive correlations linking the spontaneous and piloted ignition distances to the positions of the inner and middle zones, for each event type (fireball, pool fire or jet fire). However, the correlations are dependent on the source position and size, which are not recorded on the three-zone map, so there is no straightforward way of implementing these correlations in the mapping software. Therefore, the spontaneous ignition distance has been assumed to be equal to the distance to the inner zone boundary and the piloted ignition distance has been assumed to be equal to the distance to the middle zone boundary.

131. For the purposes of this analysis, it is assumed that all buildings within the spontaneous ignition distance ignite, and that half are extensively damaged and half are superficially damaged. Between the spontaneous ignition distance and the piloted ignition distance, a

lower proportion of buildings will ignite and it is therefore assumed that 10% of buildings are extensively damaged and 10% are superficially damaged. Beyond the piloted ignition distance, no building damage is assumed.

#### *3.6.1.3 Estimation of number of indoor fatalities*

132. HSE assumes that people inside a building will be protected against thermal radiation if the building itself does not ignite. Therefore, the number of indoor fatalities will be dependent on the position of the building relative to the spontaneous and piloted ignition distances. It should be noted that people who have successfully evacuated a building would still be subject to thermal radiation from the external fire event during the subsequent escape.

133. A report on the effects of flash fires on building occupants, prepared for HSE by WS Atkins (Ashe and Rew, 2003), contains information that is relevant to short and long duration external flammable events and the resulting effects on building occupants. Ashe and Rew use Home Office fire statistics for fatalities and non-fatal casualties for dwellings and other buildings, such as the percentages of fatalities and injuries from malicious fires between 1988 and 1993. The authors liken the building evacuation probability for a malicious fire to that for building ignition due to an external fire from a major hazard event. In both cases, a rapidly growing fire may be produced with little or no warning. Fault tree analysis was used to determine the proportion of fatalities for occupants of buildings subject to steady-state fires. The outputs of the fault tree analysis are reproduced in Table 17.

**Table 17** Proportion of fatalities for occupants of buildings subject to steady-state fires. Reproduced from Ashe and Rew (2003).

| | **Dwelling** | | | **Office Building** | |
|---|---|---|---|---|---|
| | **Heat flux ($kW/m^2$)** | **% fatalities** | | **Heat flux ($kW/m^2$)** | **% fatalities** |
| | | **Day** | **Night** | | |
| Ignition of exterior | 14.7 | 0.6 | 1.8 | 15 | 0.2 |
| Ignition of interior | 31.2 | 1.2 | 3.5 | 41.3 | 0.4 |

134. The radiative flux that is assumed to result in ignition of the building exterior (14.7 $kW/m^2$ for dwellings and 15 $kW/m^2$ for office buildings) is equivalent to HSE's criterion for piloted ignition. The incident flux that is assumed to result in ignition of the building interior, leading to secondary fires (31.2 $kW/m^2$ for dwellings and 41.3 $kW/m^2$ for office buildings) is significantly higher than HSE's criterion for spontaneous ignition. This suggests that it would be cautious to use the reported fatality probabilities within areas exposed to the HSE's spontaneous ignition heat flux.

135. A team of risk assessment specialists within HSE reviewed the fatality probabilities in Ashe and Rew (2003) to determine their applicability to Hazardous Substances Consent assessment. It was noted that Ashe and Rew give fatality probabilities for occupants of buildings exposed to two specific flux levels, whereas in practice buildings may be subject to intermediate levels of flux. To account for this, and to make some allowance for uncertainties in the method, it was proposed that the probabilities given by Ashe and Rew should be increased to ensure a cautious best-estimate of the numbers of fatalities. The proposed indoor fatality probabilities for use by HSE in Hazardous Substances Consent assessment are presented in Table 18. These values are not currently used by HSE for assessment purposes, but are useful to inform the

current study. It has been assumed that the heat flux required for ignition of the exterior is equivalent to the heat flux required for piloted ignition and that the heat flux required for ignition of the interior is equivalent to the heat flux required for spontaneous ignition. Beyond the piloted ignition distance, the building is assumed to provide indefinite protection to its occupants.

**Table 18** Proposed indoor fatality probabilities for long duration external flammable events for use by HSE in Hazardous Substances Consent assessment

| | **Loss of life indoors** | | | |
|---|---|---|---|---|
| **Building Location** | **Working populations** | **Normal populations (e.g. dwellings, retail)** | **Sensitive populations (e.g. hospitals, homes for the elderly)** | **Immobile populations (e.g. prisons)** |
| Within SI distance | 5%<br>Value of 0.4% (office building) increased to ensure cautious best-estimate value | 10%<br>Value of 3.5% (dwelling, night-time) increased to ensure cautious best-estimate value | 20%<br>2 × normal population value because of reduced mobility and organisational difficulties compared to dwellings | 100%<br>Difficulties with speedy evacuation |
| Between SI and PI distances | 2.5%<br>Value of 0.2% (office building) increased to ensure cautious best-estimate value | 5%<br>Value of 1.8% (dwelling, night-time) increased to ensure cautious best-estimate value | 10%<br>2 × normal population value because of reduced mobility and organisational difficulties compared to dwellings | 100%<br>Difficulties with speedy evacuation |

136. In the current study, the fatality probabilities presented in Table 18 have been used and, as discussed in Section 3.6.1.2, the spontaneous ignition distance has been assumed to be equal to the distance to the inner zone boundary and the piloted ignition distance has been assumed to be equal to the distance to the middle zone boundary.

137. One limitation of this approach is that it does not account for the even greater loss of life and building damage that would occur within the jet flame distance or the pool fire radius. The jet flame distance and pool fire radius are output by HSE's modelling tools and correlations can be derived linking these distances to the dose criteria used to set the zone boundaries. However, as was the case for the spontaneous and piloted ignition distances, the correlations are dependent on the source position and size, so cannot be implemented in the mapping software. This means that it is not possible to define an area within which higher fatality probabilities could be applied. For jet and pool fires, this may lead to a slight underestimate in the number of fatalities within the inner zone.

138. The proposed approach does not explicitly account for people who escape outdoors and are subsequently exposed to thermal radiation from the external fire event. However, it can be assumed that this eventuality is implicitly accounted for by increasing the fatality probabilities derived by Ashe and Rew (2003).

139. The indoor fatality probabilities given in Tables 17 and 18 are applicable to long duration flammable events such as pool or jet fires. For short duration flammable events such as

fireballs, higher heat fluxes would be needed for ignition to occur, and an alternative approach to estimating the number of indoor fatalities is required.

140. Within the fireball, buildings are assumed to provide little or no protection (due to flame ingress into buildings, buildings catching fire, or asphyxiation) and therefore the indoor fatality probability is assumed to be close to 100%. For the purposes of this analysis, the fireball radius is assumed to be equivalent to the distance to the inner zone boundary, and the proportion of indoor fatalities within the inner zone is assumed to be 75%. The proportion of indoor fatalities is assumed to be less than100% because for sites with a large fireball inventory, not all the inner zone is within the fireball radius. For sites with a small fireball inventory, the inner zone radius is generally approximately equal to the fireball radius. Assuming an indoor fatality probability of 75% within the inner zone of these sites may therefore lead to a slight underestimate of the number of indoor fatalities. However, the inner zone for such sites will be relatively small, so it is likely that the populations affected will be low.

141. Beyond the fireball radius, the proportion of indoor fatalities is assumed to be the same as that assumed for longer duration events.

#### *3.6.1.4 Estimation of the number of injuries*

142. The number of injuries must be taken into account, as many people will have severe but not fatal burns. The number of injuries is estimated using the methodology derived by Rushton and Glossop (2005). From an analysis of historical incident data, these authors derived simple ratios linking the number of reported injuries to the number of deaths resulting from an incident, for a variety of event types (including, for example, fireball, explosion and toxic release).

143. The majority of sites within the high-pressure natural gas classification are either underground storage sites or compressor stations, whose land-use-planning zones are determined by the consequences of a jet fire. Therefore, the ratios derived by Rushton and Glossop for fires have been adopted for such sites. For fires, the weighted mean ratio of injuries to deaths is given as 2.2. A more cautious estimate is provided by the $80^{th}$ percentile value of the ratio, which is given as 8.

144. For sites at which the primary hazard is a fireball or a BLEVE, the ratios derived by Rushton and Glossop for fireballs have been used. For fireballs, the weighted mean ratio of injuries to deaths is given as 2.9 and the $80^{th}$ percentile value of the ratio is given as 5.

145. In this study, the weighted mean is assumed to correspond to major injuries, and the difference between the weighted mean and the $80^{th}$ percentile value is assumed to correspond to minor injuries.

146. In some cases (for example, for the outdoor population in the middle zone of a site where the primary hazard is a fireball or a BLEVE), the use of the ratios derived by Rushton and Glossop predicts more injuries than there are people present. In such cases, all the surviving population is assumed to sustain injuries and the assumed split between major and minor injuries is shown in Tables 19 and 20.

### 3.6.2 Criteria to be used for economic impact assessment

#### *3.6.2.1 Fireballs and BLEVEs*

147. Table 19 summarises the criteria to be used for economic impact assessment for sites where the primary hazard is a fireball or BLEVE, such as low-pressure gas holders and LPG bulk storage sites.

**Table 19** Criteria to be used for economic impact assessment for sites where the primary hazard is a fireball or BLEVE

| **Location** | **Loss of life outdoors** | **Building damage** | **Loss of life indoors** | | | | **Injury** |
|---|---|---|---|---|---|---|---|
| | | | **Working populations** | **Normal populations (e.g. dwellings, retail)** [1] | **Sensitive populations (e.g. homes for the elderly, hospitals)** | **Immobile populations (e.g. prisons)** | |
| Inner zone | 75% | 50% of buildings extensively damaged; 50% of buildings superficially damaged | 75% | 75% | 75% | 100% | Major injuries to all those who are not fatalities |
| Middle zone | 25% | 10% of buildings extensively damaged; 10% of buildings superficially damaged | 2.5% | 5% | 10% | 100% | **Outdoors:** 50% receive major injuries; 25% receive minor injuries **Indoors (excluding immobile populations):** Major injuries: (2.9 × number of fatalities in middle zone) Minor injuries: (2.1 × number of fatalities in middle zone) |
| Outer zone | 5% of sensitive population | None | None | None | None | None | Major injuries: (2.9 × number of fatalities in outer zone) Minor injuries: (2.1 × number of fatalities in outer zone) |

[1]People out shopping are classed as normal populations, whereas people working in retail are classed as working populations. It is assumed that working populations are easier to organise in the event of an emergency than members of the public.

### *3.6.2.2 Jet fires and pool fires*

148. Table 20 summarises the criteria to be used for economic impact assessment for sites where the primary hazard is a jet fire or a pool fire, such as sites handling or storing flammable liquids or high pressure natural gas storage.

**Table 20** Criteria to be used for economic impact assessment for sites with zones set by jet fire or pool fire events

| **Location** | **Loss of life outdoors** | **Building damage** | **Loss of life indoors** | | | | **Injury** |
|---|---|---|---|---|---|---|---|
| | | | **Working populations** | **Normal populations (e.g. dwellings, retail)** [1] | **Sensitive populations (e.g. homes for the elderly, hospitals)** | **Immobile populations (e.g. prisons)** | |
| Inner zone | 75% | 50% of buildings extensively damaged; 50% of buildings superficially damaged | 5% | 10% | 20% | 100% | **Outdoors:** Major injuries to all those who are not fatalities<br>**Indoors – working and normal populations:** Major injuries: (2.2 × number of fatalities in inner zone) Minor injuries: (5.8 × number of fatalities in inner zone)<br>**Indoors – sensitive populations:** 20% receive major injuries; 60% receive minor injuries |
| Middle zone | 25% | 10% of buildings extensively damaged; 10% of buildings superficially damaged | 2.5% | 5% | 10% | 100% | **Outdoors:** 50% receive major injuries; 25% receive minor injuries<br>**Indoors (excluding immobile populations):** Major injuries: (2.2 × number of fatalities in middle zone) Minor injuries: (5.8 × number of fatalities in middle zone) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Outer zone | 5% of sensitive population | None | None | None | None | None | Major injuries: (2.2 × number of fatalities in outer zone)<br>Minor injuries: (5.8 × number of fatalities in outer zone) |

[1]People out shopping are classed as normal populations, whereas people working in retail are classed as working populations. It is assumed that working populations are easier to organise in the event of an emergency than members of the public.

## 3.7 METHODOLOGY FOR SITES STORING LIQUEFIED PETROLEUM GAS (LPG) IN CYLINDERS ONLY

149. LPG cylinder capacities range from 3 kg up to around 50 kg. When LPG cylinders are heated in a fire, the pressure rises until they rupture (if they have no pressure relief), generating missiles. These missiles can travel some distance off-site and it is this potential hazard that is used to set the zones around sites storing LPG cylinders.

150. When involved in a fire, LPG cylinders are also capable of causing a thermal hazard, both due to jet fires from relief valves and fireballs caused by cylinder rupture. However, these hazards are generally localised to the immediate vicinity of the fire and are not therefore considered to constitute a major accident hazard.

### 3.7.1 Derivation of economic impact criteria

151. It is assumed that a fatality will only occur if a person is hit by a missile, and therefore low fatality probabilities are used in this analysis. The values used are estimates based on the expert judgement of specialists within HSE. A more rigorous analysis involving trajectory calculations is beyond the scope of this project.

152. Significant building damage is only assumed to occur if a missile is still on fire when it lands. As above, the percentage of buildings that are completely destroyed by fire is based on expert judgement rather than detailed calculations.

#### *3.7.1.1 Estimation of the number of injuries*

153. The number of injuries is estimated using the methodology of Rushton and Glossop (2005), who derived simple ratios linking the number of reported injuries to the number of deaths resulting from an incident, for a variety of event types.

154. Of the event types considered by Rushton and Glossop, explosions are considered to give rise to hazards (such as the distribution of debris) which are of most relevance to the generation of missiles. Therefore, the ratios derived by Rushton and Glossop for explosions have been adopted for sites storing LPG in cylinders. For explosions, the weighted mean ratio of injuries to deaths is given as 2.4 and the $80^{th}$ percentile value of the ratio is given as 5.

155. In this study, the weighted mean is assumed to correspond to major injuries, and the difference between the weighted mean and the $80^{th}$ percentile value is assumed to correspond to minor injuries.

### 3.7.2 Criteria to be used for economic impact assessment

156. The criteria to be used for economic impact assessment for sites storing liquefied petroleum gas in cylinders only are summarised in Table 21.

**Table 21** Criteria to be used for economic impact assessment for sites storing LPG in cylinders only

<table>
<tr><th>LUP zone</th><th>Loss of life</th><th>Injury</th><th>Building damage</th></tr>
<tr><td>No inner zone</td><td>N/A</td><td rowspan="3">Major injuries: (2.4 × total number of fatalities)<br>Minor injuries: (2.6 × total number of fatalities)</td><td>N/A</td></tr>
<tr><td>Middle zone (40 m from site boundary)</td><td>1% mortality for all outdoors</td><td>All buildings in middle zone will experience some damage but in many cases this will be superficial. Some buildings could be completely destroyed by fire (assume 10%), if a missile is still on fire when it lands.</td></tr>
<tr><td>Outer zone (100 m from site boundary)</td><td>1% mortality for all vulnerable people outdoors</td><td>Superficial damage to windows etc.</td></tr>
</table>

# 4 VULNERABILITY COMPONENT

## 4.1 INTRODUCTION

157. This chapter describes the approach taken to create the vulnerability component of the economic model. There are two main requirements for an effective vulnerability component. First is an understanding of *what* is at-risk from the hazard, referred to here as the *Exposure* element. Second is information on *how* the things described in the *Exposure* might be affected (usually negatively if looking at costs) by the *Hazard* component; much of the latter has been described in Chapter 3.

## 4.2 EXPOSURE

158. In our model, the *Exposure* component is defined as the activity occurring on and off site that might be affected by an accident at a major hazard site. This activity can be categorized according to the different sources of loss, as outlined in Table 3. Using this table we can identify a set of criteria and associated indicators that we need to fulfil in order to build up our exposure element and vulnerability component. These are detailed in Table 22.

**Table 22** Sources of loss and required statistic

| Source of loss (criteria) | Required metric |
|---|---|
| Harm to people | Numbers and types of people at risk |
| Evacuation | Numbers of people affected |
| Damage to buildings (residential and non-residential) | Numbers and types of property at risk, including valuation information |
| Loss of business | Scale and types of business affected, including (rental) valuation information |
| Relocation of business | Types of business and potential relocation costs |
| Emergency Services | Percentage cost based on other factors |

159. The data used to model these sources of loss split logically into three outline categories: Buildings, Population and Business. These categories help to organise the information in the remainder of this chapter, detailing the approaches taken for each category to create the *vulnerability* component.

## 4.3 BUILDINGS

160. The approach taken for modelling buildings was to estimate the value for each building within range based on its size and type, using geographically appropriate economic multipliers. The first step for doing this was to source GIS data detailing the locations and types of buildings in at-risk areas. The National Receptors Dataset (NRD) is a collection of risk receptors which was produced by the Environment Agency (2010) primarily to assist in flood and coastal erosion risk management. It includes information within various themes such as buildings, environment, transport and heritage. The building information in the NRD ("property points") is based on Ordnance Survey (OS) data from the AddressLayer2 and MasterMap data products,

from 2010. AddressLayer2 data (Ordnance Survey, 2013) includes point location records for every address in GB, as well as a significant number of non-addressable locations such as some warehouses and pumping stations. The MasterMap topography dataset (Ordnance Survey, 2013) provides polygon information detailing the extents of real-world objects within Great Britain. This includes themes for buildings, land, roads and water.

161. The aim of the NRD property points data is to detail location and attribute information for every building in England and Wales that has a corresponding record in AddressLayer2 or has a 'footprint' (ground floor area) greater than 25 $m^2$. The dataset accounts for 31,370,666 building locations in England and Wales. The attribute information in the property points data includes a classification (based on OS AddressLayer2 data), footprint size (from MasterMap Topography buildings data) and dwelling type where appropriate.

162. Figure 2 illustrates the NRD property points data in context with AddressLayer2 and MasterMap. The NRD information has been used by the HSL project team previously for work in the area of flooding; it has been made available by the Environment Agency to HSL and HSE under licence for this project.




**Figure 2** NRD Property point information

### 4.3.1 Quality

163. The quality of the NRD is generally good. The location and completeness of information is excellent, and the classifications are generally adequate. From previous experience of using the data the project team are confident that it is appropriate in this context (and outside its normal domain in flooding), however it does have some limitations. Of particular note to this work are:

- Classifications

  The data includes some misclassifications, generally due to ambiguities in types. For example, 'plant nurseries' have been classified the same as nurseries providing childcare. Also, charity shops supporting hospices can be classified as 'hospices' if the name includes the key word 'hospice' (e.g. St Luke's Hospice Shop). Furthermore, some buildings have been misclassified as dwellings. These are exceptions rather than the norm however.

  Building locations whose primary source is OS MasterMap and not AddressLayer2 data do not have a classification attached. It is a reasonable assumption to classify them based on near neighbours and that is the approach implemented here.

  Some dwellings do not have a sub-type associated to identify the type of dwelling.

- Floor Area

  The calculated footprint of each building is as accurate as the OS MasterMap data (commonly 1 m spatial accuracy), and uses a consistent approach across the whole dataset. However, the footprint is only an indicator of the floorspace and so should be used with caution. The NRD property points data does not include any information on the internal floorspace or the number of floors in the building, hence for this work every property is modelled as single storey. This is knowingly incorrect but should be accurate enough for the broad all-sites approach that we are taking. It is also worth noting that where multiple addresses occupy the same building, the floor area is split evenly across all the addresses.

- Extent

  As mentioned above, the geographical range of the NRD property points data is England and Wales. Hence if we are looking to model sites in Scotland an alternative source of information is required.

- Spatial Accuracy

  The NRD property points are stored as point data which means that the attributes for each building are attached to a single coordinate pair. As a consequence, in the model the relative location of a building to an accident is based on a central point, rather than the extent of the building. Hence, buildings that straddle zones will be assumed to be in the zone in which its central point lies. Figure 3 illustrates this: the building marked as A overlaps the hazard zone. Analysis of individual or small numbers of buildings will be sensitive to this kind of error, but at the larger scale that we are focusing on these errors should cancel each other out.

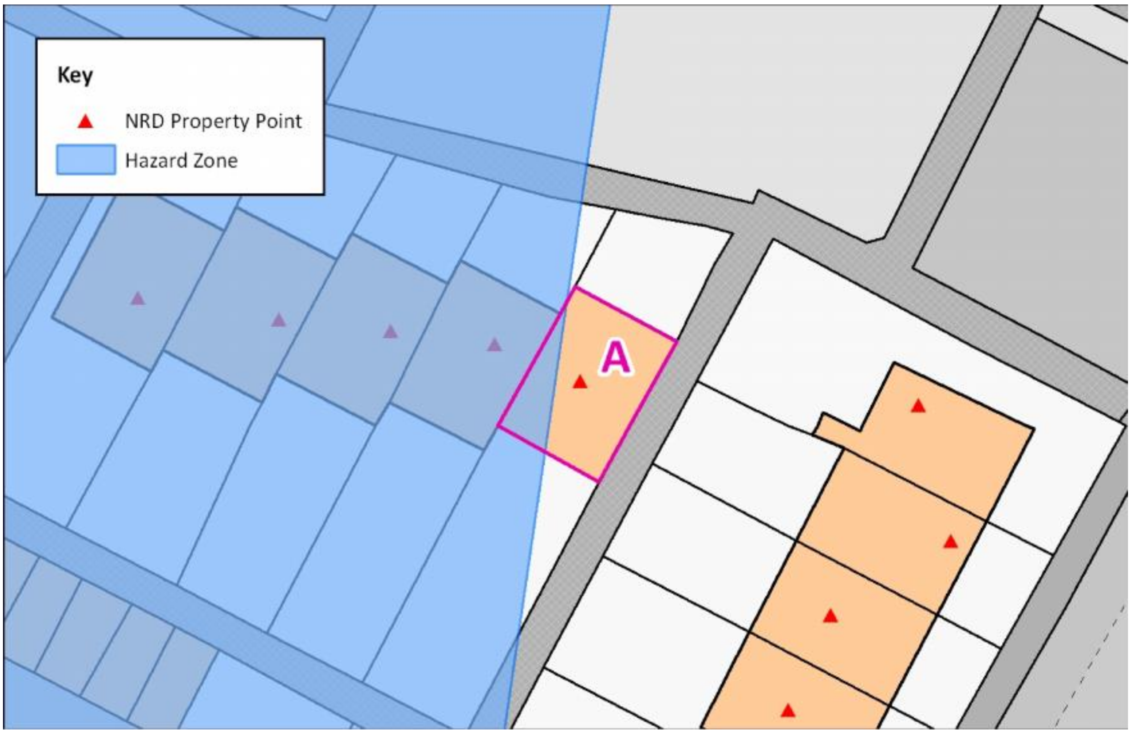




**Figure 3** Limitations of point representations of building (polygon) assets

### 4.3.2 Adopted approaches

164. By focusing the analysis on the hazard site zones, we can set bounding areas to be used to scale back the extent of the search for building data. This has advantages in terms of data volumes and the associated computational processing, as well as reducing the scope of activity that we need to model. The spatial area of interest for the work has been set as the postcode areas that overlap the land use planning zones for all of the major hazard sites within scope. The postcode areas cover a larger area than just using the site zones; the extra area is required to model the exposure effectively.

#### *4.3.2.1 Dwellings (England and Wales)*

The NRD property points data were filtered for residential locations based on a query on the OS_CLASS field (OS_CLASS = 'DWELLING'). Four dwelling types are used to identify the type of house, these are 'detached', 'semi-detached', 'terraced' and 'flat/maisonette'. These dwelling types correspond to the 4 types used by the Land Registry to report house prices (see Section 5.2.4 for more detail on the Land Registry house price information). Where no dwelling type is specified (0.81% of dwellings in the area of interest), the average house price has been used. Figure 4 illustrates dwelling information used in England and Wales.




**Figure 4** Dwelling property information in England and Wales

165. In an effort to reduce the impact of buildings misclassified as dwellings, a maximum dwelling size has been set. This was identified as a relatively straightforward correction, accounting for many buildings (often on industrial estates) that are far too big to be classified realistically as dwellings. Identifying an appropriate threshold for this is a bit more difficult, so both 190 $m^2$ and 230 $m^2$ have been used and incorporated in a sensitivity analysis, running both thresholds through the model. These thresholds are based on the HSL project team judgement and experience of using OS data. Where these limits were exceeded, the buildings were marked as 'unclassified' and incorporated in the processing for non-residential buildings. The sensitivity analysis focused on the building damage impacts across all sites, and revealed differences in the two thresholds of only 0.3% suggesting that the choice of either value would be sufficient. Hence 230 $m^2$ has been adopted as the threshold for the final results.

#### *4.3.2.2 Non-Residential Buildings (England and Wales)*

166. The requirement for non-residential buildings is for valuable assets, so the approach for non-residential buildings was to filter the NRD property points for anything that was *not* classified as a dwelling, and where the floor area was not zero. The results were split into two groups:

- *Classified* buildings (where the OS_CLASS contained a value)
- *Unclassified* buildings (where OS_CLASS was Null)

167. The valuation methodology requires a classification that can be used to attach appropriate economic multipliers. Hence for *Unclassified* buildings a classification needs to be added. The general approach used was to link each record to the geographically closest *Classified* location, and assign the classification from that location. This is well suited to sites with multiple buildings and only one central address that have limited spatial distribution, but is less appropriate in situations where the nearest classified location is some distance away, so two

exceptions were added. These exceptions were based on an inspection of the data and are outlined as (in order of application):

1. Where the floorspace is less than 100 $m^2$ and the location is within 30 m of a dwelling, the record is excluded from the analysis based on the assumption that they are residential outbuildings, and include locations such as garages, barns and housing annexes. The valuation of these is assumed to be included in that of the dwelling.

2. If the nearest classified location is greater than 400 m away, classify the record as a farm building. This rule makes an assumption that the criteria-meeting locations are rural and is based on the manual assessment.

**Valuation Office Agency Classification**

168. For valuation purposes the OS classification needs to be linked to a Valuation Office Agency (VOA) class to be assigned to each building location. For more information on these VOA classes please see Section 5.2.4. For reference purposes the basic VOA classes used here are listed as:
- Retail
- Warehouse
- Factory
- Office
- Other Bulk
- All Bulk (the average of the other classes)

169. This assignment of VOA classes to each building used a transformation of the OS classification, based on the VOA's published descriptions of their classes (VOA, 2008), and experience-based judgement from project partners at HSL and WERU. The full list of transformations is included in Appendix 2. There are 470 OS classifications in England and Wales; some examples are included in Table 23.

**Table 23** Sample of OS Classification to VOA class mappings

| **OS Class** | **VOA Class** |
|---|---|
| Farming | Factory |
| Brewery | Factory |
| Restaurant | Retail |
| Theatre | Other Bulk |
| Trade Distribution | Warehouse |
| Further education | All Bulk |

**Scotland**

170. As mentioned above, the NRD is produced for England and Wales only, so a different method was required for our analysis of sites in Scotland. The approach taken used a similar method as was used to create the NRD, but using equivalent source data for Scotland. Producing such

data for the whole of Scotland would entail a significant computational requirement, but by limiting the processing to the area of interest around major hazard sites the task was significantly more achievable. The data used to create the Scottish buildings data was OS MasterMap and OS AddressBase Premium. AddressBase Premium is a successor of AddressLayer2 and includes addressable and non-addressable locations for GB, as well as attribute information on the address and a usage classification.

**Approach**

171. Attribute information for the building footprint in MasterMap was attached to the address points in AddressBase Premium based on corresponding spatial locations. Where multiple address locations were found within a building polygon, the footprint was shared equally between each of the points. The classification of the building was based on the CLASSCODE attribute in AddressBase Premium; this provides information on the building type in a similar way to the OS Class in AddressLayer2. For dwellings, the CLASSCODE includes some breakdown of dwelling type but is not complete (23% of dwellings assigned a type). The CLASSCODE classifications were supplemented by looking at the address detail; where the word 'FLAT' appeared in the address attributes (SAO, PAO, Sub_Name columns) the dwelling was identified as a flat. Dwellings identified as caravans were removed from the analysis. Dwellings identified as residential institutions were investigated and classified as flats where appropriate. This increased the percentage of dwellings with assigned types to 32%.

172. Once the equivalent building data had been created for Scotland, the same assumptions were used as for England and a similar approach applied, using the same rules to attach classifications to unclassified buildings based on nearby classified buildings. The VOA equivalent in Scotland is the Scottish Assessors Association (SAA, see Section 5.2.4 for more information). An equivalent class mapping table was created using the same logic as for the VOA to OS class mapping in England and Wales. The full table is included in Appendix 2 and includes 162 non-residential classifications.

**Assumptions and Limitations**

173. In addition to the discussions above, the following limitations and assumptions also apply to the data and processes for England/Wales and Scotland:

- No attribute information on construction type was easily available so this is not accounted for. Hence the model assumes that the buildings are affected in the same way and are made of comparable materials.

- The VOA classifications are quite broad and so may not be effective when considered at an individual building or site level. At larger scales however they should be more representative.

**Output**

174. The outputs of this process were the following 4 GIS point datasets, produced for areas around the major hazard sites:

- English and Welsh dwellings, with house type attribute

- Scottish dwellings, with house type attribute

- English and Welsh non-residential buildings including a classification to be linked with VOA valuation data, and the floor area in $m^2$.

- Scottish non-residential buildings including a classification to be linked with the VOA valuation data, and the floor area in $m^2$.

## 4.4 POPULATION

175. The approach adopted for modelling population in the vulnerability component was to estimate the numbers of people who might be in the area at the time of an accident, considering who they are and how they might be affected.

176. The National Population Database (NPD) was originally developed by HSL for HSE (HSE, 2005 and 2008) to assist with individual and societal risk work around major hazard sites, but has since been used in a wider context including impact analysis for natural hazards (Cole et al., 2013). It provides estimates of population density and distribution for the whole of the UK, using a local scale representation that locates people within individual buildings. As well as modelling people within their homes, it also includes populations in other contexts, representing typical scenarios throughout the day. The NPD is set up as a series of GIS data layers, which represent five different population themes. The themes are Residential, Sensitive (including schools, hospitals, care homes, childcare facilities and prisons), Workplace, Transport and Leisure. The NPD population statistics were created using information from datasets sourced from government including ONS census information, and registers from government departments (e.g. Care Quality Commission, Department for Transport, Department for Education). The point location data in the NPD is derived from OS address and postcode data. The NPD has a regular update process; each layer is updated every two years.

177. The data layers within these themes can be combined to represent various population scenarios, which can account for variations with time. For this work, two basic scenarios were used, for day time and night time situations. These scenarios were compiled from different NPD population layers (Table 24). The scenarios allow for the selection of the worst-case.

**Table 24** NPD Population layers used to define the time scenarios

| Day Time Scenario | Night Time Scenario |
|---|---|
| Residential day time population<br>Workplace population<br>School population<br>Care home population<br>Hospital population<br>Prison population | Residential night time population<br>Care home population<br>Hospital population<br>Prison population |

178. People who might be more physically less resilient to harm were also distinguished. These were modelled using the *care home* and *hospital* populations. For the purposes of estimating evacuation, separate counts for resident and non-resident populations were also required. The *residential*, *care home* and *prison* populations were used to define the resident population, with the remaining layers used for the non-resident.

### 4.4.1 Workplaces

179. The workplace layer of the NPD is based on the Inter-Departmental Business Register (IDBR), a comprehensive listing of businesses in the UK with attribute data including the number of employees (full-time and part-time), and a (2007) Standard Industrial Classification (SIC) (ONS, 2014) describing the type of business. These workplace populations are represented using a different geography to the other population layers, as their locations are based on postcodes rather than individual address locations. Postcodes can cover quite large areas, often larger than a site's hazard zones so a methodology is required to convert the postcodes to a geography that is more suited to the scale. In an ideal situation the workplaces would be located to the actual workplace buildings based on their address, however the time and effort required to do this is substantial and unrealistic given the all-site approach that we are implementing.

**Approach**

180. Given the above, the approach taken for workplace populations in the analysis was to develop a method of distributing the postcode level populations to suitable building locations within the postcode area. These suitable address locations were identified based on the address classifications within the NRD property points layer and in our Scottish buildings data. Each classification (OS_CLASS in England/Wales, CLASSCODE in Scotland) was assessed to determine whether it was likely to be a place of work containing employees. The complete list of these workplace property points is included in Appendix 2, identified using a 'workplace flag'. For each postcode area, a multiplier was derived based on the postcode workplace population and the number of property points within it that were identified as potential workplaces. Equation 4 shows how the multiplier was calculated. Figure 5 illustrates how this approach was implemented.

$$m_{pc}=\frac{w_{pc}}{n_{pc}} \qquad \text{Equation \{4\}}$$

where:

$m_{pc}$ is the multiplier for the postcode, *pc*
$w_{pc}$ is the workplace population for postcode, *pc*
$n_{pc}$ is the number of property points identified as workplaces within postcode, *pc*

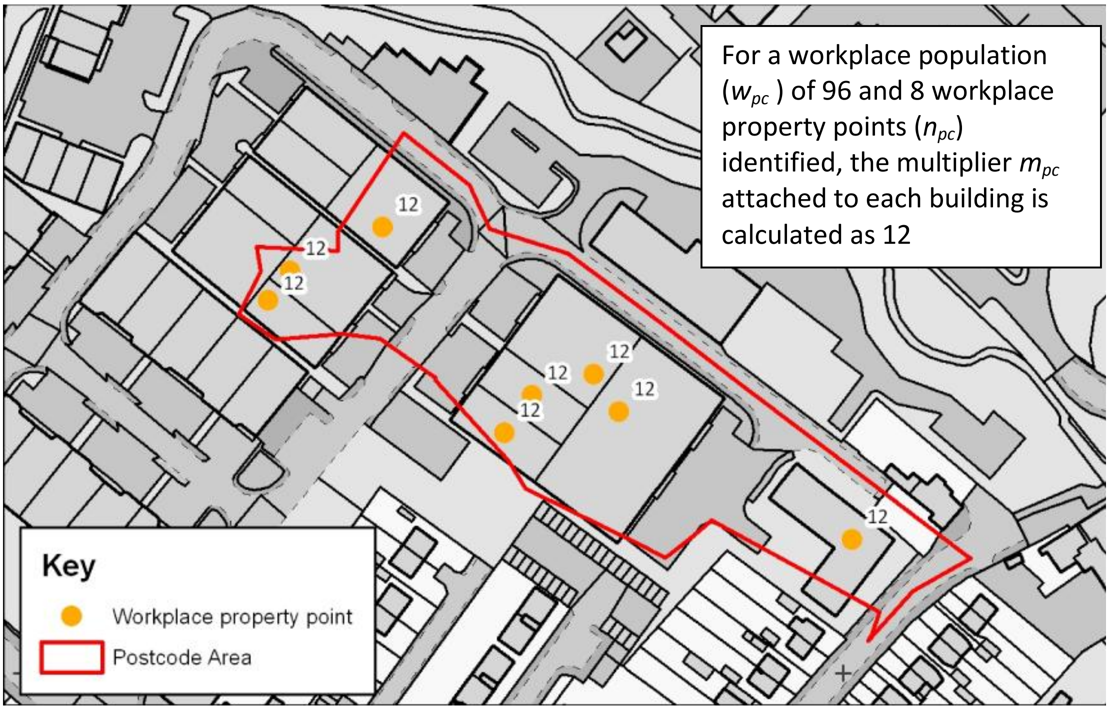



**Figure 5** Allocation of postcode workplace populations to buildings

181. Where no suitable workplace property points were identified within a workplace postcode area, the postcode centroid (centre point) was used as the workplace location (9% of cases).

182. The workplace population used was an estimate of the Full-Time Equivalent (FTE) employment. Full-Time Equivalent (FTE) employment was estimated for each business based on the number of employees and information on the number of part-time workers; an average 50% working-time arrangement for part-time workers was assumed.

**Limitations**

- Identification of vulnerable people is limited to those within sensitive establishments only. There will be elements of the other populations (residential and workplace) that will be more susceptible to the hazard event too, but they are not included in this methodology.

- The method for redistributing workplace populations within postcode areas assumes an even population weighting for each property. It is also sensitive to the size of the postcode areas. Where these areas are large, the population may be distributed over a wide area, while small postcodes may concentrate the population onto a single building location.

- The number of employees is assumed as the workplace population. This may not be reflective of the number of people in the workplace at the time but is a reasonable assumption. Alternative working arrangements such as home-working will not be accounted for here, however this does fit within the aim of a reasonable worst-case scenario.

- The IDBR is based on tax returns and so excludes some charitable organisations. Businesses with satellite sites may also be misrepresented in the dataset.

### 4.5 BUSINESS

183. The requirement of the business part of the *Exposure* element is for information estimating the scale and type of business activity taking place within the at-risk areas. The workplace population layer of the NPD was used as the means to do this. The SIC section code was used to identify the workplace within the 18 main Industry sectors (see Table 27 for the full listings of these sectors). The locations of the workplaces were re-used from the approach for the workplace populations (Section 4.4.1).

# 5 ECONOMIC COMPONENT

## 5.1 INTRODUCTION

184. A major hazard site 'accident' has a series of on and off-site consequences. Local people may need to be evacuated or other countermeasures applied and local business (and community activities) may be disrupted. The economic effects of a major hazard site accident are assumed in the approach outlined below to include those related to the site itself.

185. The costs incurred following an incident might comprise a mix of direct and indirect effects that come into play over different time scales. Table 25 outlines the broad scheme of effects adopted in COCO-2 (Higgins et al., 2008) for classifying accident losses. The more intangible and indirect costs are likely to be the most difficult to assess and in some circumstances the most significant. The direct and tangible losses following an accident are more easily understood.

**Table 25** Outline classification of accident losses: COCO-2

| Type of loss | Direct | Indirect |
|---|---|---|
| More Tangible (market values) | Costs that are closely related to the accident and can be valued via the market e.g. damage or contamination of infrastructure, buildings and contents, vehicles, boats, etc. human capital cost of illness, lost production, emergency response and relief, clean-up costs. | Costs that are not closely related to the accident but can be valued via the market e.g. loss of production due to ripple through effects, and any decline in tourism in the wider area. |
| More Intangible (non-market values) | Costs that are closely related to the accident and are not valued in the market e.g. death and injury (excluding human capital), loss of items of cultural significance and personal memorabilia. | Costs that are not closely related to the accident and are not valued in the market e.g. Inconvenience and disruption, especially to schooling and social life. Increased journey times. Stress induced ill health and mortality. Perception of area (affects tourism). |
| Adapted from Smith et al. (1995, p. 21)<br>Reproduced from COCO-2 report (Higgins et al., 2008) | | |

## 5.2 METHOD

186. There are a relatively large number of major hazard sites compared to sites covered in the previous COCO-2 assessment. Moreover, in comparison with nuclear sites there is some expectation that the impact of major hazard site incidents could be of shorter term duration and seriousness (accepting occasional incidents on the scale of the Buncefield fire). The larger number of sites, and shorter expected duration of incidents mean that a 'reduced-form' of the COCO-2 approach is advised here, focusing on the most transparent estimates of direct effect.

187. The approach taken was to subdivide the economic cost estimation into five components that aim to capture the major costs envisaged to arise from major hazard site accidents. It is

recognised that these components will not capture 100% of the costs involved in a major hazard site accident but instead present the main costs in a format that can be easily understood; for which data can be collated relatively easily from publicly available sources (as much as possible); and are enabled to be updated in a timely fashion as and when required. The five components are outlined in Table 3 and listed below for reference:

- Casualty impact cost
- Business disruptions
- Business temporary relocation
- Building damage
- Evacuation Costs

188. Items such as the value of lost schooling, as a result of evacuations/closures of educational centres, and the value of lost business assets are amongst the items not included in the calculations. These were seen as beyond the scope of this study. Each of the cost components are described below in more detail.

### 5.2.1 Casualty impact costs

189. In order to accurately inform decisions by policymakers on the appropriate level of expenditures on risk reduction and hazard mitigation, estimates are required on the monetary value of intangible losses such as injuries and deaths.

190. The direction taken in this study was to use a 'Willingness to Pay' (WTP) approach, whereby estimates are made of the amount that individuals are prepared to pay to reduce risks to their lives (or amounts accepted as compensation for bearing increased risk) in order to put a value on a 'statistical' life. The value people place on reducing risk to life is established by their preferences (either stated or revealed) and is seen as indicating the value of intangible elements such as 'quality of life' and 'joy of living'. To be exact it is not the life that is valued but the reduction in the risk of death, which is then re-expressed as a value of life. As might be anticipated, the funds allocated to saving statistical lives are typically much less than the amount that might be spent to save identified lives.

191. For each case study accident type (as described in Chapter 3) the impact model estimates the number and types of people at risk within different geographic zones around major hazard sites. For each hazard site the populations in both day and night scenarios are estimated (as these are likely to diverge depending on the daytime working population and the night-time resident population). From these are drawn estimates of the number of fatalities, major injuries (injuries that would be reportable under the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995, as amended 2012, RIDDOR), and non-reportable injuries (sub-RIDDOR also referred to here as "minor") likely to arise from a major hazard site accident.

192. A value for each of these injuries and fatalities is derived from figures published by the Health and Safety Executive in the "Costs to Britain of workplace injuries and work related ill health" 2013 update publication (HSE website, k); this also includes a more comprehensive methodology report on Willingness to Pay approaches (HSE, 2011). The values are required to

be adjusted to year 2013 costs in order to reflect the changes in monetary value since their publication date.

193. Table 26 outlines the latest estimated appraisal values at time of writing, split into non-financial human costs and financial costs. The former are an estimate of the subjective value, expressed in monetary terms, that individuals would be willing to pay, over and above the direct financial consequences of such incidents, to avoid the adverse outcomes being realised and thereby avoiding the associated 'pain, grief and suffering' and loss of wellbeing to themselves, their friends and families. The 2013 values in Table 26 are based on 2011 prices that have been inflated using GDP deflators released by HM Treasury for March 2013.

**Table 26** Costs to society per case: Average appraisal value estimates based on three-year incidence data from 2010/11 to 2012/13 (£ in 2013 prices)

| Type of accident | Non-Financial Human Costs (£s) | Financial Costs (£s) | Total Costs (£s) |
|---|---|---|---|
| Workplace fatal accidents | 1,154,367 | 481,678 | 1,636,045 |
| Reportable injuries | 16,194 | 8,097 | 24,291 |
| Non-reportable injuries | 353 | 363 | 716 |
| *Source: Health and Safety Executive (2013)* | | | |

194. The HSE appraisal values were estimated specifically for worker injuries and fatalities. The values for injuries cover both men and women in employment, but the fatality value covers only men in employment as they are by far the most likely to suffer fatal injuries at work. However, these values are applied to workers and members of the public for the purposes of this study into the economic impacts of major hazard site accidents, as they are believed to also be a good approximation of the likely costs involved for the general population.

195. The non-financial human costs of the Health and Safety Executive appraisal values (the major proportion of total costs and accounting for around 70% of the cost of a workplace fatal accident) are similar to those from the Department for Transport values for the prevention of road accidents (Department for Transport, 2012a). The Department for Transport values are applicable to the general population rather than just workers. There are differences in the calculation of the financial costs between the two studies but, overall, these do not cause a large variation in the estimated values. It was therefore decided to use the Health and Safety Executive appraisal values for workers and non-workers for simplicity in modelling and in order to present a similar valuation on each person involved in the major hazard site incident.

### 5.2.2 Business disruption costs

196. The approach taken to estimating the cost of business disruption was to examine potential losses of industry value added, and then relate this through to employment. The preliminary analysis of sources of economic data at the spatial scale of defined zones around major hazard sites suggested that the key issue is to identify the direct economic activity that is supported within different zones, and that is thus potentially affected by an incident. An estimate of gross

value added (GVA)[1] supported by activity in the defined zones provides the first step in assessing the consequences of an incident.

197. For example, where a major incident might lead to the cessation of all economic activity within a defined zone for a calendar year then the GVA (and employment) information provided hints at the potential loss to the local economy were this activity not quickly relocated elsewhere. Furthermore, were activity to be lost in this way, the use of GVA and employment multipliers from UK input-output tables would provide insights into the indirect effects of loss of activity within the zone on other parts of the economy. Analytical input-output tables for the UK for 2005 are the latest available (Office of National Statistics, 2011). More problematic is where an incident results in temporary loss of activity within the affected 'zone'. Here there is the option of examining pro rata estimates of GVA losses. However, an issue here is that production losses are met by increased production later on, or that economic activity can be quickly displaced to other sites (e.g. in selected services sectors). Shorter term incidents may also have fewer indirect effects in the supply chain, and short term demands might be met from stocks. In the major hazard site case, the GVA and linked employment information is best used to highlight the economic activity in each zone (such that users of the impact model can review the potential effects of loss of activity in the zone, in comparison to the costs of accident mitigation).

**a) Losses in directly affected industries**

198. Data from the National Population Database on full-time equivalent (FTE) employment in the reference area by different zones (see Section 4.4.1) provides some inference on the likely production losses linked to accidents both at the major hazard site itself and for other employment locations affected in the vicinity.

199. To calculate the potential GVA loss (per year) the FTE employment numbers, by industry, are multiplied by average GVA per FTE worker in the corresponding industry in the UK.

200. To derive the gross value added per FTE, employee data from the ONS Annual Business Survey (ABS) (Office of National Statistics, 2013) was used. Data on GVA at basic prices broken down by industrial sector (Standard Industrial Classification (SIC) 2007) was sourced from the ABS and divided by the total number of FTE workers (derived from the ONS Business Register and Employment Survey) in the corresponding sector, to give an average per worker. Table 27 outlines the estimated GVA per full-time employee by industrial sector.

[1] Gross Value Added (GVA) measures the contribution to the economy of each individual producer, industry or sector in the United Kingdom.

**Table 27** Estimated Gross Value Added per full-time employee (£ in 2013 prices)

| Industry Classification (SIC 2007) | Approximate gross value added at basic prices (£ in 2013 prices) |
|---|---|
| Section A - Agriculture, forestry and fishing | 36,107 |
| Section B - Mining and quarrying | 335,061 |
| Section C - Manufacturing | 63,431 |
| Section D - Electricity, gas, steam and air conditioning supply | 202,737 |
| Section E - Water supply, sewerage, waste management and remediation activities | 109,059 |
| Section F - Construction | 61,311 |
| Section G - Wholesale and retail trade; repair of motor vehicles and motorcycles | 41,179 |
| Section H - Transport and storage | 63,842 |
| Section I - Accommodation and food service activities | 27,815 |
| Section J - Information and communication | 96,697 |
| Section K (Part) - Financial and Insurance activities | 304,567 |
| Section L - Real estate activities | 74,617 |
| Section M - Professional, scientific and technical activities | 69,342 |
| Section N - Administrative and support service activities | 48,675 |
| Section P (Part) - Education | 14,646 |
| Section Q (Part) - Human health and social work activities | 21,781 |
| Section R - Arts, entertainment and recreation | 33,882 |
| Section S - Other service activities | 38,275 |
| *Source: Annual Business Survey ABS), Business Register and Employment Survey (BRES), WERU calculations* | |

201. The impact model assumes GVA to be lost for the period a business is closed and that this will occur if the workforce is required to shelter, evacuate or relocate. It is assumed that businesses are not bankrupted and the workforce made redundant but, instead, that a business is disrupted and takes time to recover. The affected business may resume business or relocate.

202. In the former case they will be able to resume operations once any restrictions are lifted and any limiting building damages are repaired. In the latter case they may be operational much sooner but with the additional expense of leasing new premises.

203. The recovery time of business in an area is, with some constraint on the total time, assumed equal to the time taken to lift any countermeasure restrictions in the area. In practice countermeasure restrictions in major hazard site incidents would likely be of a relatively small scale compared to those allowed for in the work on COCO-2 (where potential radioactive

contamination had to be allowed for). The business facing closure for an extended period would review its options and the decision arrived at would depend on the market for its product, the age of the plant and the cost of new facilities. The details of such a decision are beyond the scope of this study which makes the assumption that the worldwide supply and demand for the products of the plant are in approximate balance and therefore the existing plant is likely to resume operation.

204. The direct economic loss of businesses in an area is assumed to be proportional to the length of time the businesses are out of action[2], which is in turn determined by the time taken to lift any countermeasures that halted production; repair any building damage; replace any damaged capital; and carry out any checks deemed necessary. The implicit assumption of this approximation, relating time to loss, is that GVA is uniformly produced throughout the year. Although this will not be true in many cases, it is a convenient assumption and unlikely to cause a gross distortion of the estimated costs (an exception to this is in agriculture, which has well defined seasonal outputs). It is further assumed for simplicity that a business is either working or not working. In practice, there may be considerable scope for businesses to maintain a reduced level of output while any damage is repaired.

**b) Multipliers estimating indirect effects**

205. Indirect losses are more difficult to value than direct losses but estimates are provided for those that are a tangible consequence of the disruption to businesses directly affected. These are generally associated with the disruption to the supply and sale of goods caused by the effects of the accident rippling through the economy. Indirect losses affect businesses because of the direct effect of the accident on their suppliers.

206. The indirect loss stemming from a direct effect to particular sectors of the economy in a particular location can be estimated using an Input-Output model. This is a static economic model designed to depict the mutual interdependence among the different parts of an economy. Input-Output modelling has been widely used and referenced in economic literature (see Miller and Blair, 2009). The model describes the economy as a system of interdependent activities that act on one another directly and indirectly. Thus, an Input-Output model describes how one industry uses the outputs of other industries as inputs, and how its own outputs are in turn used by other companies as inputs. An Input-Output model is a systematic deconstruction of the economy that describes the flow of goods and services necessary to produce finished products (goods and services).

207. The core assumption here is that a major hazard site accident would result in the loss of final demand for the goods and services produced by affected sectors, and that this causes ripple-through effects up through the supply chain. A further assumption here is that these losses are not made up through increased activity in other parts of the economy. Once again the approach provides an indication of the indirect economic activity that could be affected by an accident in the short term. Further details of the input-output analytical approach and the limits of it are found in Miller and Blair (2009). The latest Input-Output analytical tables for the UK from which indirect effects of changes in industrial activity can be derived are for 2005 (Office of National Statistics, 2011).

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[2] *The issue of temporary relocation is a potential issue: if a company relocates within a couple of months then only two months GVA will be lost (even if the original building takes nine months to rebuild).*

208. As impacts from major hazard site accidents would likely be at a much smaller geographical level than those for nuclear sites analysed under COCO-2 there are differences in analysis between the two when estimating indirect effects. Firstly, it is assumed in the case of major hazard site accidents that impacts to local tourism would be insignificant. Secondly, it is assumed unlikely that businesses supplying those businesses directly affected by a major hazard site accident are also directly affected. Consequently, there is no requirement to 'attenuate' the multiplier as in COCO-2 work.

**Table 28** Industry Gross Value Added (GVA) multipliers

| **Industry Classification (SIC 2007)** | **Multiplier** |
|---|---|
| Section A - Agriculture, forestry and fishing | 1.89 |
| Section B - Mining and quarrying | 1.42 |
| Section C - Manufacturing | 2.19 |
| Food, drink and tobacco [SIC Division 10-12] | 2.35 |
| Textiles, clothing, footwear [13-15] | 2.10 |
| Wood, paper, publishing [16-18] | 1.84 |
| Chemicals and pharmaceuticals [19-21] | 2.82 |
| Rubber and plastic [22] | 2.06 |
| Glass, ceramics, concrete [23] | 1.95 |
| Metals [24-25] | 2.14 |
| Machinery, electronics [26-30] | 2.19 |
| Furniture and other manufacturing [31-33] | 2.09 |
| Section D - Electricity, gas, steam and air conditioning supply, and Section E - Water supply, sewerage, waste management and remediation activities | 2.53 |
| Section F - Construction | 2.29 |
| Section G - Wholesale and retail trade; repair of motor vehicles and motorcycles | 1.71 |
| Section H - Transport and storage | 2.04 |
| Section I - Accommodation and food service activities | 1.89 |
| Section J - Information and communication | 1.48 |
| Section K - Financial and Insurance activities, Section L - Real estate activities, and Section M - Professional, scientific and technical activities | 1.51 |
| Section N - Administrative and support service activities | 1.91 |
| Section P - Education, and Section Q - Human health and social work activities | 1.46 |
| Section R - Arts, entertainment and recreation, and Section S - Other service activities | 1.56 |
| *Source: Analytical input-output tables for UK 2005 (ONS); WERU calculations* | |
| *Note - The demands that lead to the multiplier are calculated for the relevant industry supply chain using the UK IO Analytical Tables for 2005. The multiplier shown (Type 1) is the GVA weighted average multiplier of the multipliers for the component SIC divisions.* | |

### 5.2.3 Building damage costs

209. The approach to estimating the capital loss of buildings damaged or destroyed as a result of a major hazard site accident is to take a proportion of the property value. The proportion is dependent on the damage category estimated for each individual building.

210. The damage categories used in this study for both residential and non-residential (commercial etc.) properties are developed in Section 3.5.1.2. They are reproduced below for reference.

**Damage categories**

A - completely demolished

B - badly damaged and beyond repair

Cb - uninhabitable without extensive repairs

Ca - uninhabitable but repairable

211. In the real world properties differ in many ways, and consequently the total rebuilding costs for every dwelling or property will be different. 50% of property value appears to be a normal standard UK figure quoted as an average estimated figure for rebuilds. Rebuild costs include materials, labour, professionals' fees (surveyors/architects), demolition and site clearance but not the cost of the land itself which is still there. Rebuild costs are not the same as a property's market value which is (usually) higher because it (the market value) includes the land. A major factor in property price differentials across regions is the cost of land; however, differential wage rates across regions will to some extent counter-balance this, as wages tend to be higher in affluent areas (where property prices are higher).

212. The term structural repair is often used to refer to the actual reconstruction or renewal of a building and its key structural elements. It involves careful analysis of a building or premises in order to find areas of distress, and determining what is causing them. How to remove the damaged materials, and picking the right materials to use, is paramount to extending the structure's lifespan. The cost of structural repair depends on a variety of factors. On the whole, it is less expensive to repair a structure than to replace it.

### 5.2.4 Property Values

213. Individual property values were estimated for residential buildings based on Land Registry price-paid data averaged per postcode sector (e.g. SK17 9) for four types of house (detached, semi-detached, terraced and flat/maisonette). The Land Registry was sourced for a full year covering the period May 2012 to April 2013; this took advantage of the Land Registry's recent release of price paid data on an open licence.

214. The assumption explicit in this calculation is that the average value of a house type in an affected zone is the same as the average value of a house of that type in that postcode sector as a whole.

215. For commercial buildings the property value is estimated from the ratio of the rental value to the rental yield for each type of property classification. This follows the approach noted in the Health and Safety Executive report "Economic Costs of Land Use Restrictions around Major Hazard Sites- Assessing the Impact: A Methodology Note" by Nathaniel Litchfield and Partners (2010, unpublished).

216. Rateable values (an estimate of the annual rental value for a building) are published by the Valuation Office Agency (VOA) at low level geographic areas (Medium Super Output Areas) for England and Wales. These data are available for different premises classes (e.g. 'commercial offices'; 'other offices'; 'factories'; 'warehouses'; and 'other bulk premises') enabling matches to be made between the National Receptor Dataset building classifications and VOA premises

classes (see Section 4.3.2.2). It is therefore possible to derive geographic specific rateable values per metre squared for land-use-planning zones.

217. To convert pounds per square metre rental value into a pounds per metre capital value, a 'property yield' is required (a property yield provides a hypothetical yield for a freehold interest in a property, fully leased at current market rent). This will provide the present value of a rental income in perpetuity and therefore the capital value of the property as:

$$\text{Capital Value } (£) = \frac{1}{\% \text{ Yield}} \times \text{Rental } (£) \qquad \text{Equation } \{5\}$$

218. Research showing the latest estimated property yields for the UK as a whole, and its regions, are published by a number of organisations including CBRE (a well-known property brokerage and research firm[3]).

219. As indicated by the Litchfield (unpublished, internal Health and Safety Executive document) methodology note:

> "…Rateable values are not necessarily reflective of real world market dynamics and therefore are arbitrary in the actual value they assign to a property. However, market data on commercial property prices for different areas are not widely available and the Valuation Office Agency data provides a single consistent and comprehensive assessment of value…"

220. Rateable values per square metre for different building classes in Scotland were not readily available in a form that could be applied effectively for our approach, so England and Wales averages were used as a proxy here.

221. Table 29 outlines the estimated timings and valuation factors used for rebuild of destroyed or damaged properties. These aim to be conservative, 'ball-park' figures for summarising what are, in real life, widely varying numbers (due to the complexities and unique factors involved in each incident).

222. The figures in Table 29 were informed by web-based research looking for any industry norms. Websites for the insurance industry and construction (house-building related) sector were investigated in an attempt to arrive at typical 'average' figures[4]. Data here were challenging to source with figures, when given at all, tending to cover a range of times and costs, and being caveated with 'health warnings' noting that there was a wide degree of variability in completion times and costs due to the number of factors and processes involved in construction. As such the figures in Table 29 are speculative in nature, subject to uncertainty, and represent a potential area to focus resource on in future in order to confirm, or improve, their accuracy.

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[3] http://www.cbre.co.uk/uk-en

[4] http://www.homebuilding.co.uk/community/breaktime/how-fast-build-house
http://www.construction-online.co.uk/construction-professionals/how-to-get-the-best-structural-repair-for-your-home/
http://eyeonhousing.org/2013/10/21/how-long-does-it-take-to-build-a-house/
http://www.b4ubuild.com/resources/schedule/6kproj.shtml
http://abi.bcis.co.uk/checking_sum_insured/checkingSumInsured.aspx

223. Rebuilding times and costs do not include any additional specific allowances for making buildings ready for productive work (e.g. fitting out a factory with manufacturing equipment so that it can commence work again). Here, attempting to estimate the variability in re-tooling timescales and costs between (and within) the different types of industry involved was deemed a level of complexity too far for the purposes of this study.

224. Furthermore, the rebuild time estimates do not attempt to take into account possible scarcity in building resources resulting from having to repair not one but several buildings in a single location. Such estimates would vary over time and location depending on availability and delivery time of supply - with factors such as the number and extent of other building works taking place in the region, at the time of the accident, coming into the calculation. It was decided that the potential benefit of adding an estimate for this factor did not outweigh the difficulties in arriving at an accurate, timely estimate of potential scarcity of building resources.

225. However, despite these constraints, the values in Table 29 capture the major cost and time elements involved in rebuilding destroyed or damaged properties. They are based on industry expert advice and literature. As such they represent a reasonable estimation of the total costs and time involved in estimating the building damage component.

**Table 29** Suggested timings and valuation factors for rebuild of destroyed/damaged property

| **Category of damage** | **Estimated time to completion of works (months)** | **Cost of rebuild works as a percentage of total property value** |
|---|---|---|
| A – completely demolished | 9 | 50 |
| B – badly damaged and beyond repair | 9 | 50 |
| Cb – uninhabitable without extensive repairs | 4 | 20 |
| Ca – uninhabitable but repairable | 2 | 10 |

*Source: WERU estimates based on website review*

### 5.2.5 Business temporary re-location costs

226. One foundation for estimating the costs of business relocation in the case of more serious incidents is to use rateable value data for commercial property.

227. Valuation Office Agency data for England and Wales (as noted above in building damage cost estimations) is available at the geographic Medium Super Output Area level, giving a rateable value (for one year) per square metre for different premises classes. National Receptors Dataset building types have been matched (Section 4.3.2.2) to these premises classes enabling calculations to be made of the annual rateable value of premises required for re-location. A proportion of the annual rateable value can then be taken depending on how long the temporary re-location site is required (this is calculated through the damage repair time of the original property which is built into the model and is dependent on the amount of damage sustained in the accident).

228. As with the building damages, for Scotland, due to a lack of readily available data at a metre squared by premises class level, average rateable values from England and Wales have been used as a proxy.

### 5.2.6 Evacuation costs

229. The following section outlines a method to estimate the major cost components of a population evacuation from an area impacted by a major hazard site event. It suggests what major components would be important to include in such a measurement and gives examples of data sources that could be used to inform the estimations.

230. A literature review of previous calculations of evacuation costs was undertaken to provide examples of estimation methods. Research used to inform this paper was found from examples looking at natural disasters (e.g. hurricanes in the United States; UK (Environment Agency, 2010) and European flooding cases; and earthquakes across the globe) and accident/non-natural events (e.g. Buncefield). Typically estimates in prior research were derived from a sample survey, where data was collected via questionnaires sent out to people impacted by an event; or from insurance claims made by those affected.

231. The literature review highlighted a number of different methodologies with a number of differing elements being included in the measurement. Many studies concentrated mainly on 'household costs' (Whitehead, 2003) for the general population, here combining direct costs (such as lodging and food) with travel and time costs (with a value being given to people's time 'lost' as a result of the event, typically given a value of around 50% of the average wage rate per hour, Ronzaa et al., 2009). Estimates of more intangible costs of household evacuation, such as time costs due to traffic congestion in the risk–affected and surrounding areas were less commonly attempted, although estimates of these costs are typically used in transport studies based on an assumed cost of lost leisure time, or loss of working time.

232. Other studies included an investigation into the costs to the emergency services and local public authorities of evacuations (Shaw, 2012) including components such as personnel costs of any extra staff required to be brought in (e.g. studies into the staff costs of helping to evacuate holiday lodges in the event of an avalanche), and/or post-event clean-up (repairing infrastructure damage; clearing away rubble etc.). Public resources used to pay for such elements represent an opportunity cost to the economy (e.g. rather than being used to replace what was damaged/destroyed in the event the resources could have been used elsewhere).

233. There are difficulties in generalising costs pre-event for this work. Some components are relatively difficult to measure or maybe beyond the scope of this exercise (loss of possessions; damage to residents' vehicles; 'cost' of lost schooling time for pupils affected etc.). Instead the following example of a methodology provides a way of estimating evacuation costs that will give an indication of the magnitude of the costs involved, and constructively inform the estimation of overall incident impact.

#### *5.2.6.1 Evacuation costs – Implemented method*

234. In estimating the evacuation costs arising from an event it is suggested that a possible way forward would be to combine the major elements of costs accruing to households with an estimation of the costs to the emergency services and public authorities (see Figure 6). Household costs may be split into the major elements of 'immediate evacuation costs' and

‘long-term accommodation costs’. The former dealing with the immediate 24 hour period of evacuation, and the latter capturing a major cost element involved in the following months.

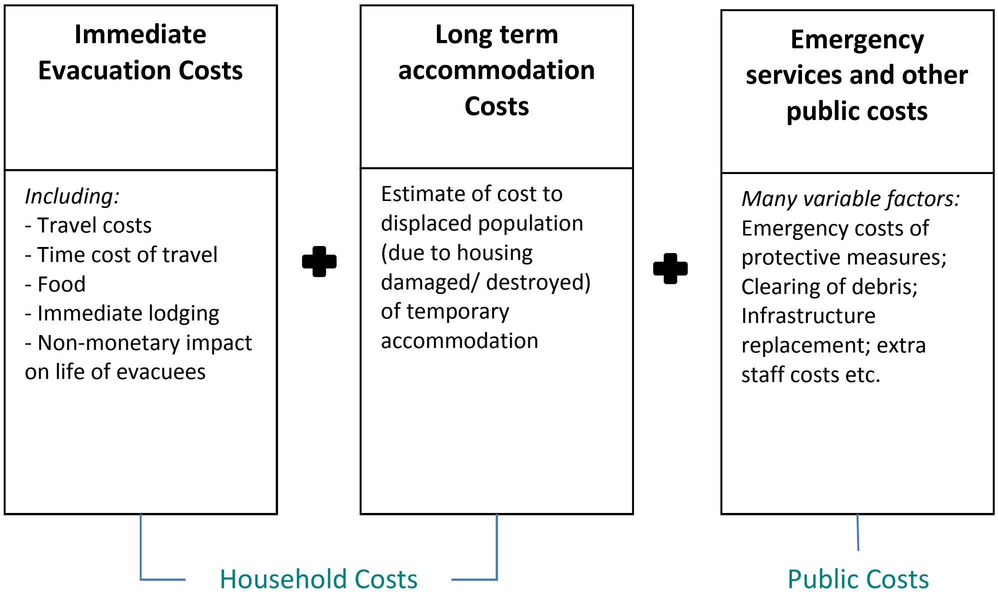



**Figure 6** Major Evacuation Cost Components Estimated

#### *5.2.6.2 Immediate evacuation costs*

**Travel distance costs**

235. Travel costs of the resident population require an estimate of the distance travelled to an evacuation area (here an assumption may have to be used in the absence of real world examples from the UK). This is multiplied by the cost of motoring per mile (which may be informed from an up to date survey such as the ‘AA Motoring Costs’, AA, 2013).

236. For example, the AA Motoring Costs 2013 indicated that, for a mid-range cost car, travel costs could be estimated at around £0.25 per mile.

237. Assuming an estimated travel distance to the evacuation site of 10 miles, a cost of travel per household would be estimated at £2.50 (or £1.09 per person using the average number of people per household in the UK, at 2.3, from the ONS Family Spending 2012 publication).

**Travel time costs**

238. An estimate for the ‘cost’ of the time taken for the resident population to travel away from the accident site may be included (this value being added to account for their lost leisure time). This may be calculated by estimating the time taken for the journey and applying Department for Transport information used in standard cost-benefit analyses (Department for Transport, 2012b).

239. Using an assumed travel distance of 10 miles and applying a 2.2 minutes per mile average weekday morning peak journey time (Department for Transport, Congestion Data; Table CGN0902b), an average journey time of: 10 x 2.2 = 22 minutes would be calculated.

240. Taking the value of lost time per hour per person from the Department of Transport *Values of Working Time, 2012* publication at £6.05 ('market price', 'other travelling' converted to 2013 prices) an estimate of the total time cost per person can be estimated at:

$$6.05 \times \frac{22}{60} = 6.05 \times 0.37 = £2.24 \qquad \text{Equation \{6\}}$$

**Evacuation impact costs**

241. Additionally, a cost can be added for the impact of the evacuation on the resident population for the initial 24 hour period after the event. This represents an estimate of the value of the lost leisure time, and hardship experienced, for the resident population in the immediate aftermath.

242. An estimate for the cost of lost leisure time per person for the initial 24 hour evacuation period can be derived by taking half the average daily wage rate.

243. Using the average UK weekly wage rate (taken from the ONS *Annual Survey of Hours and Earnings*, ASHE, 2013) of £517.50 an average daily wage rate is calculated by dividing by 5, and then dividing the result by 2. This is (517.5/5) / 2 = 103.5 /2 = £51.75.

244. From this has to be removed the cost of travel time (calculated above) in order to avoid double-counting. So that £51.75 - £2.24 = £49.51; the cost used for lost leisure time.

**Accommodation and food costs**

245. Estimates can also be added for any extra spending on food and drink that the evacuated population purchase on the day of evacuation (using data from the ONS *Family Spending* survey), and the cost of one night's lodging (taken from an average cost per night for a hotel/motel stay: organisations such as Trivago publish a hotel price index and average costs for a range of UK cities, Trivago, 2013).

246. People would have spent money on food and drink anyway during a normal day's activities so only additional purchases are required to be estimated here. These are likely to be minimal. The ONS *Family Spending 2012* survey estimates the average spend on food and non-alcoholic drink per person in the UK at £3.44 per day (year 2013 prices) so this value can be used as a proxy for additional food and drink expenditure for the immediate 24 hour period.

247. An average per person value for one night's accommodation (estimated from non-London, un-weighted, average UK data from Trivago, May to October 2013) was £37.83.

#### *5.2.6.3 Long term accommodation costs*

248. For those residents whose accommodation has been destroyed or damaged (category Cb/Ca), and are consequently staying in temporary accommodation, an estimate for the costs involved can be calculated by multiplying the number of people affected, by the length of time they are affected (here conservative average rebuild times have been suggested by the Cardiff Business

School research team for different categories of damage – see Table 29), and by the average cost per person per day of temporary accommodation (the latter may be derived from surveys of average rental costs for houses, e.g. organisations such as LSL Property Services (2013) currently publish average rental prices by region).

249. For example, using data published by LSL, the average rental price per calendar month for England and Wales for September 2013 was £757.

250. An indicative annual household cost of rental can therefore be calculated by multiplying the above monthly value by twelve = 12 x 757 = £9,084.

251. An indicative annual *per person* cost of rental can then be calculated by dividing the annual household cost of rental by the average number of people per household (sourced from the ONS *Family Spending 2012* publication, Table 2.2) = 9084/2.3 = £3,950.

### 5.2.7 Emergency services and other Public costs

252. The literature review of the costs to emergency services and other Public services resulting from an evacuation and its aftermath shows that the costs involved depend upon a number of factors (not least of which being the nature of the disaster) and include the number of people evacuated, number of rescue staff/ volunteers involved, whether infrastructure was damaged, etc. Examples found in the literature are mainly post-event estimations of natural disasters with elements involved in the calculations differing between studies. It is therefore generally challenging to develop an accurate understanding of the costs to authorities pre-event.

253. However, a possible way forward here is to assign a conservatively valued percentage of the total economic cost of the major hazard site event to the costs involved for emergency services and local authorities.

254. A study into the Paso Robles (San Simeon, California) earthquake (McEntire and Cope, 2004) of 2003 estimated the total financial losses at $226.5m, of which emergency service protective measures and debris removal was estimated at $2.92m (or 1.3% of all losses).

255. The Flood Mitigation on the Raritan River (Shaw, 2012) report (United States) highlighted estimates of the costs to public authorities of natural hazard events from several different studies (although stressing that it was difficult to fully assess the actual methodology behind many of the estimates). The report cites a study by Pfurtscheller and Schwarze that noted the approved government expenditure for emergency services during Hurricane Katrina was 3.7% of the total economic loss; as well as several other studies on different events which show a range of emergency costs as a percentage of the total economic loss from 2.2%, to 10.7% (a UK flooding example), to 14.7% (Magdeburg, Germany 2002).

256. Due to the relatively wide discrepancy in estimates of these costs it is therefore proposed that a conservative figure of 2.0% of the total economic cost is used as a proxy for the costs involved for emergency services and local authorities.

# 6 IMPLEMENTATION AND RESULTS

257. The previous chapters describe the background information and approach that were used to create the three components required for our impact model. Chapter 3 describes the approach required to produce the *hazard* data, including the associated direct effects of the hazard (describing the *vulnerability*). Chapter 4 details the background information and the approaches taken to create the database representing the exposure element of the *vulnerability* component. Chapter 5 documents the approach taken to assess the impacts in *economic* terms. With these components established, the next step in the process is the implementation of the model, combining these components and calculating the resultant outputs.

## 6.1 PRE-PROCESSING

258. The first step required for the implementation is to derive the data representing the hazard. This was based on two HSE sources: the consultation zone map library of major hazard site land-use-planning zones (CZL), and the hazardous substance sites database (HSSD).

1. CZL

The CZL stores information detailing the land use planning zones for all major hazard sites within Great Britain. The information is stored in GIS format, and includes spatial data for the zones (see Figure 1) as well as internal HSE hazard site reference numbers. The CZL is jointly maintained by HSE and HSL and provides a near up-to-date listing of major hazard sites which have been assessed for land use planning regulation. The extract of data for this work was taken on the 31st October 2012.

2. HSSD

The HSSD stores site-specific information for all major hazard sites within Great Britain including detail on the site owners and addresses, as well as an inventory of the substances (including types, amounts and methods of storage) that the site has registered consent for. It also includes a reference number that enables the records in the HSSD to be linked to the CZL. This extract was also taken on the 31st October 2012.

## 6.2 SITE CLASSIFICATION

259. The CZL and HSSD were joined based on the common hazard site reference number (hereafter referred to as the *H number*), with the CZL providing the definitive list of sites and the HSSD adding attribute information for each site.

260. The information on substances was used to classify each site into the classifications listed in Table 30, and matching those discussed in Chapter 3.

**Table 30** Site Classifications

| Classification | Site Count | Hazard Model Type |
|---|---|---|
| Aerosols | 41 | <not modelled> |
| Ammonium nitrate | 170 | Overpressure (Ammonium Nitrate) |
| B1 (very toxic) | 65 | Risk (Toxic) |
| B1 & B2 (very toxic and toxic) | 59 | Risk (Toxic) |
| B2 (toxic) | 80 | Risk (Toxic) |
| B3 (oxidising) | 14 | Overpressure (CPE) |
| B10 (dangerous to the environment) | 10 | <not modelled> |
| Chlorine | 74 | Risk (Toxic) |
| Ethylene oxide and propylene oxide (*not* stored under pressure) | 2 | Risk (Toxic) |
| Ethylene oxide and propylene oxide (stored under pressure) | 6 | Overpressure (VCE) |
| Large-scale petrol storage (Buncefield-type) | 38 | Overpressure (VCE) |
| LPG | 4 | Flammable |
| Liquefied Petroleum Gas (LPG): Bulk Storage | 427 | Flammable (Fireball/BLEVE) |
| Liquefied Petroleum Gas (LPG): Cylinder Storage | 110 | Flammable (LPG Cylinder) |
| Low Volatility Toxic (LVT) | 19 | Risk (Toxic) |
| Natural Gas: high pressure | 74 | Flammable (Jet fire/Pool fire) |
| Natural Gas: low pressure | 238 | Flammable (Fireball/BLEVE) |
| Liquid Oxygen | 15 | Flammable (Oxygen) |
| Refrigerated Flammable Liquids (RFLs) | 19 | Flammable (Flash fire) |
| Various flammable liquids | 204 | Flammable (Jet fire/Pool fire) |
| Various toxic | 4 | Risk (Toxic) |
| Complex/Mixed Substance Site | 103 | Mixed methodologies |

261. Complex/Mixed Substance sites were identified as those storing a variety of different substances, and thus might span multiple classifications and so require different types of substance methodologies. They can be small scale (for example a site storing one toxic and one flammable substance in containers in different locations on the site) but can be more complicated, with multiple substances in varying quantities and different methods of storage distributed across a large site.

262. The approach taken in assessing the hazard for complex sites was to consider them on a site-by-site basis, looking at the substance inventory information alongside maps of the land use planning zones. In the absence of readily available data detailing the exact nature of the hazards, the configuration, size and shape of the land use planning zones provide an indication of the locations and types of hazardous substances on site. This is an effective approach due to the method used to create the zones for complex sites, which creates zones for each substance and storage individually, before combining them into a single set of zones. The dominant substances and their configuration on site were assessed using this approach, working with experts in HSE. For the 103 complex sites, 3 main types of site emerged (with

further by combination); these are outlined below along with the approach taken in the model:

1. Sites with evidence of a geographical split of different hazard types (e.g. overpressure in the north, toxic in the south).

   The approach taken here was to split the site based on the geographical split, model the parts separately and then combine the results.

2. Sites with zones calculated by different models (e.g. overpressure for inner, toxic for middle and outer).

   The general approach here was to treat the zones independently and apply different models, and then combine the results. Due to the types of impact being modelled for the toxic sites (i.e. effects on population only – see Section 3.2), there were occasions where this approach had to be adapted. For example, where the toxic-type zones were identified *within* overpressure or flammable zones, the approach described will only evaluate population impacts in the innermost zones. For these situations, the non-population impacts in the innermost zones were calculated using the model for the outermost, (based on the overpressure or flammable model), zones.

3. Sites with no clear distinction of the constituent input zones

   The approach here was to run the sites through the models for the substance types on site, and use the worst case scenario.

263. The approaches implemented for complex sites were designed to be straightforward and are pragmatic given the potential complexity of the scenarios that might occur on site. If we consider that the registered consent assessments for each site are undertaken on an individual basis, then attempting to retrieve and analyse historical assessment records in order to interpret the land use planning zones and their derivation would have been too resource-intensive for this particular piece of work.

## 6.3 ADDITIONAL ZONES/CONTOURS

264. As discussed in Chapter 3, the risk (Section 3.2) and overpressure (Section 3.5.1.2) models required the derivation of zones delineating additional contours representing the hazard. The risk methodology requires an additional contour within the inner zone, while the overpressure methodologies require an extra contour between the inner and middle zones. GIS-based methodologies for deriving these new zones were developed as follows.

### 6.3.1 New Middle Zone

265. The specification for creating the new middle zones was defined as being 37% (equation 3) of the distance from the middle to the inner zone (see Section 3.5.1.2). With this in mind the contours marking the limits of the risk were attributed values of 1 and 2 respectively and a spatial linear interpolation was performed. Contours for the value of 1.63 (based on 100 - 37 = 63%) were extracted and converted to zones and were checked visually. Most sites processed adequately. Some sites had multiple inner zones which had to be processed individually and combined afterwards.

### 6.3.2 New Inner Zone

266. Based on the discussion in Section 3.2.1.2 to calculate LD50, the specification for the new inner zone was defined as 127% of the distance from the existing middle zone to the inner zone. Initially the interpolation that was used for the middle zones was considered. However this was found to be inadequate as the distance wasn't between two reference objects (i.e. the inner and middle zones) but an extrapolation beyond these objects. Therefore two new methods were devised. Figure 7 illustrates these two processes.

267. The first method started by converting the zone polygons into points. Then each point from the middle zone was joined by a straight construction line to the nearest point in the inner zone. The construction line was then extended by a further 27% of its length. The end points for each line were taken and a convex hull (a polygon that contained all the points, similar to putting a rubber band around them) was created as the new zone.

268. The convex hull process has a limitation regarding concavities in the zones, so an adapted second method was required for sites where this was an issue. The adapted method created another polygon by joining the construction line endpoints, or if lines intersected then using the intersection point. The output was then visually inspected. The majority of polygons processed well although some required extra lines (of length 127% the distance from middle to inner zone) to be created manually where the geometry was particularly changeable, and then the new inner zone was edited to include this new line. Sites with multiple inner zones were run separately for each inner zone and then combined.

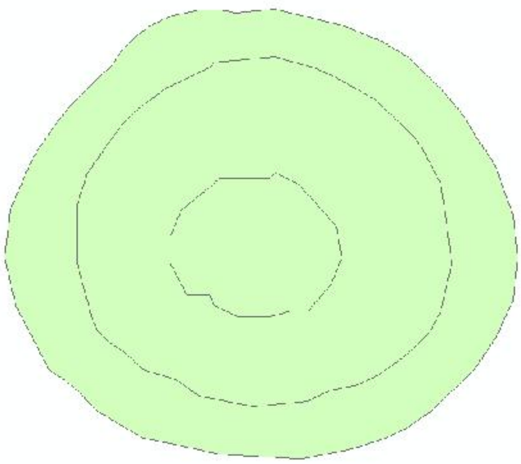
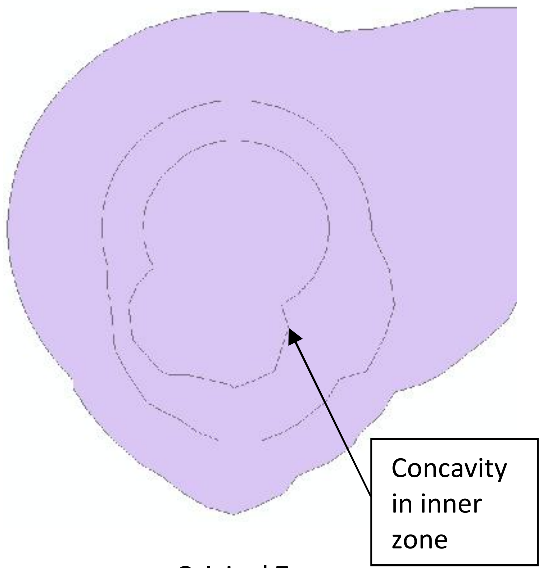
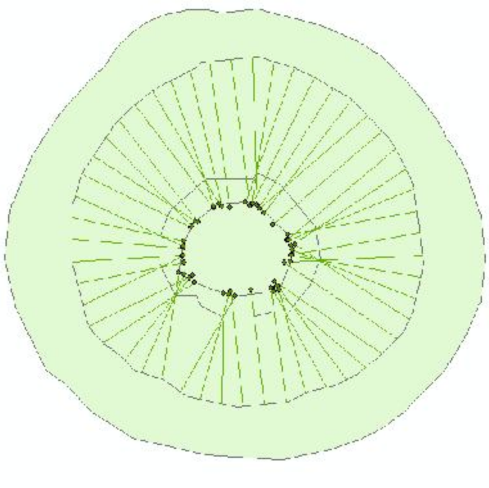
| **Additional Inner Zone method 1** | **Additional Inner Zone method 2** |
| --- | --- |
| <br>Original Zones | <br><br>Original Zones |
| <br>End points of construction lines joined by convex hull polygon to create new inner polygon | <br>Approach is similar to method 1. Concavities in inner zone accounted for using the innermost point of the concavity |

**Figure 7** Methods used to create additional inner zones in the model

### 6.4 ATTACHMENT OF ECONOMIC MULTIPLIERS

269. Chapter 3 outlines the method for creating the exposure and vulnerability data for the model. For the economic assessment of damage to buildings, the value of the building was also required. For non-residential buildings, the value was estimated as the multiplication product of the floorspace attribute and the relevant rateable value (per $m^2$). The rateable value is

available at MSOA and LA level and was determined for each buildings based on the corresponding VOA class (see Section 5.2.4) and the building's location within the MSOA or LA.

270. For Scotland, valuation data was not available at the MSOA level, and the national level valuation info was only available per asset rather than related to floorspace. This was not satisfactory for the approach being taken here, as the floorspace would not be taken into account. Hence, the average Rateable Value per $m^2$ values for England and Wales were applied instead.

271. Residential buildings in England were valued based on average (mean) house sale values sourced from the Land Registry at MSOA and LA level (Section 5.2.4). These values were attached to dwelling data based on the location. Scottish dwellings used equivalent data at local authority level.

## 6.5 IMPLEMENTATION OF MODEL

272. The initial model processing was implemented via GIS using ArcGIS and MapInfo software. This was automated to run for all sites within scope and combined the hazard data with the exposure data based on their corresponding spatial locations. The results were then imported into Microsoft Excel spreadsheet-based models using look-up tables which modelled the impact outcomes, and estimated the resulting costs for each site, and for each zone. The results were then aggregated and summarised according to the following criteria:

- Hazard type (Overpressure, Flammable or Toxic)
- Site Classification (Table 30)
- COMAH Classification (Top-tier, Lower Tier and Sub-COMAH)
- Government Office Region
- HSE Region

273. Headline statistics are included in Section 6.7.

## 6.6 SAMPLE CASE STUDIES

274. The following three case studies illustrate the model approach for three fictional major hazard sites, one for each hazard type. The costs are evaluated against the methodologies outlined above and used to calculate the results. Note that the zones are fictitious and may not be an accurate depiction of zones for that particular site type. Costs are rounded to two significant figures.

### 6.6.1 Site 1 – Hazard type: Overpressure (Ammonium Nitrate)

275. The overpressure methodology estimates the impacts on population in terms of the fatalities, major and minor injuries. This focuses on the indoor populations only. There is no distinction for vulnerable populations. Building damage is estimated based on gradings specific to each zone, and calculated as a percentage of the building value. Impacts on business are estimated based on relocation (rental) costs and the amount of GVA lost. Numbers are also estimated for immediate and long-term evacuation. Figure 8 and Table 31 detail the site and the costs for example site 1.

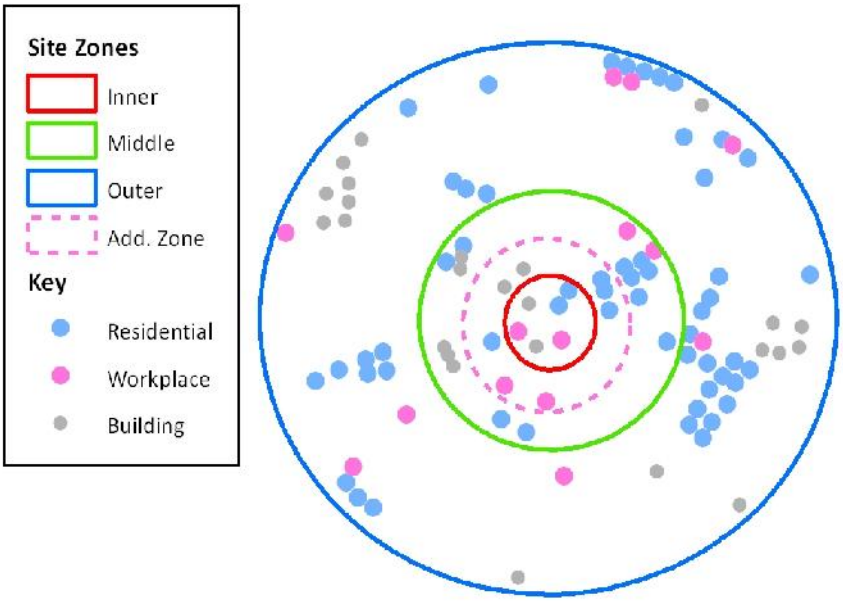



**Figure 8** Example scenario for an overpressure (ammonium nitrate) site

**Table 31** Example costs for an overpressure (ammonium nitrate) site

| **Component of Loss** | **Inner Zone** | **Additional Zone** | **Middle Zone** | **Outer Zone** |
|---|---|---|---|---|
| Population Impact | 4 fatalities<br>4 major injuries<br>0 minor injuries<br><br>£6,600,000 cost | 3 fatalities<br>7 major injuries<br>2 minor injuries<br><br>£5,100,000 cost | 6 fatalities<br>14 major injuries<br>4 minor injuries<br><br>£10,000,000 cost | 11 fatalities<br>26 major injuries<br>29 minor injuries<br><br>£19,000,000 cost |
| Business Disruptions | £250,000 lost GVA | £336,000 lost GVA | £93,000 lost GVA | £890,000 lost GVA |
| Business Temporary Location | £15,000 rental cost | £76,000 rental cost | £7,900 rental cost | £79,000 rental cost |
| Building Damage | £540,000 damage (capital cost) | £1,800,000 damage (capital cost) | £910,000 damage (capital cost) | £1,600,000 damage (capital cost) |
| Evacuation | 4 immediate<br>6 long-term<br>£18,000 cost | 13 immediate<br>18 long-term<br>£40,000 cost | 21 immediate<br>35 long-term<br>£77,000 cost | 102 immediate<br>117 long-term<br>£87,000 cost |
| Emergency Services | £950,000 | | | |
| **Total:** | £48,000,000 | | | |

**Note:** totals may not sum due to rounding

#### 6.6.2 Site 2 – Hazard type: Risk (Toxic)

276. The risk methodology estimates the loss in terms of the impact on people only. This includes a differentiation for vulnerable people. The costs for immediate evacuation are also calculated. No costs are estimated for damage to buildings, loss of business or long-term evacuation.

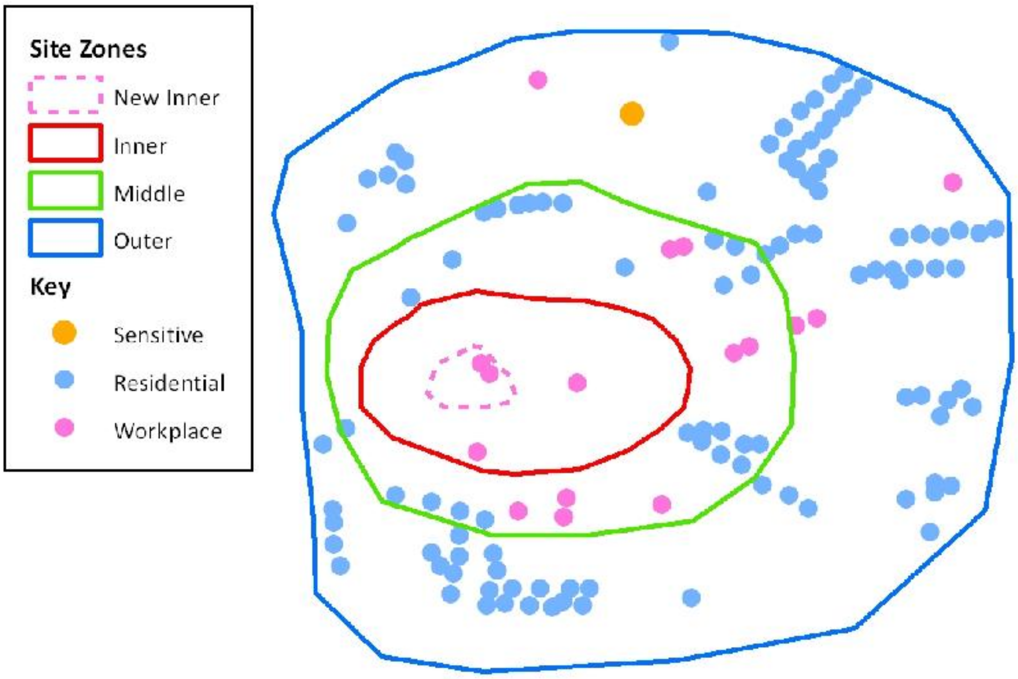



**Figure 9** Example scenario for a risk (toxic) type site

**Table 32** Example costs for a risk (toxic) type site

| Component of Loss | New Inner Zone | Inner Zone | Middle Zone | Outer Zone |
|---|---|---|---|---|
| Population Impact | 4 fatalities<br>4 major injuries<br>0 minor injuries<br>£6,600,000 cost | 1 fatalities<br>7 major injuries<br>0 minor injuries<br>£1,800,000 cost | 4 fatalities<br>52 major injuries<br>32 minor injuries<br>£7,800,000 cost | 0 fatalities<br>0 major injuries<br>8 minor injuries<br>£5,700 cost |
| Evacuation | 0 immediate<br>£0 cost | 0 immediate<br>£0 cost | 62 immediate<br>£5,800 cost | 190 immediate<br>£18,000 cost |
| Emergency Services | £330,000 | | | |
| **Total:** | £17,000,000 | | | |

**Note:** totals may not sum due to rounding

### 6.6.3 Site 3 –Hazard type: Flammable (Natural Gas – Low Pressure)

277. The flammable methodologies vary in terms of the impacts that they model. The method for *natural gas – low pressure* models a fireball/BLEVE. The population impacts are calculated as loss of life, and major and minor injuries. These differentiate working, normal, sensitive and immobile populations, and indoor and outdoor. Damage to buildings (and the associated effects on business and long-term evacuation) is modelled against *superficial* and *extensive* damage categories.

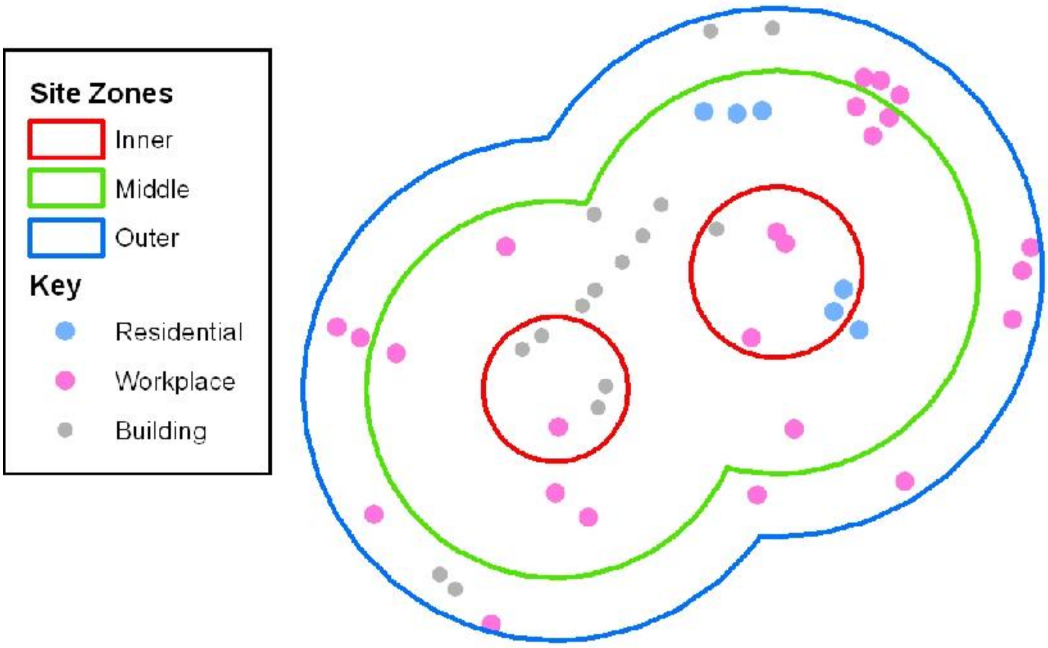



**Figure 10** Example scenario for a flammable (natural gas – low pressure) type site

**Table 33** Example costs for a flammable (natural gas – low pressure) type site

| Component of Loss | Inner Zone | Middle Zone | Outer Zone |
|---|---|---|---|
| Population Impact | 20 fatalities<br>6 major injuries<br>0 minor injuries<br>£33,000,000 cost | 4 fatalities<br>11 major injuries<br>6 minor injuries<br>£6,800,000 cost | 0 fatalities<br>0 major injuries<br>0 minor injuries<br>£0 cost |
| Business Disruptions | £370,000 lost GVA | £410,000 lost GVA | £0 lost GVA |
| Business Temporary Location | £110,000 rental cost | £79,000 rental cost | £0 rental cost |
| Building Damage | £960,000 *extensive* +<br>£190,000 *superficial* damage (capital cost) | £670,000 *extensive* +<br>£140,000 *superficial* damage (capital cost) | £0 *extensive* +<br>£0 *superficial* damage (capital cost) |
| Evacuation | 5 immediate<br>6 long-term<br>£11,000 cost | 10 immediate<br>10 long-term<br>£4,600 cost | 0 immediate<br>0 long-term<br>£0 cost |
| Emergency Services | £850,000 | | |
| **Total:** | £44,000,000 | | |

**Note:** totals may not sum due to rounding

## 6.7 RESULTS AND DISCUSSION

278. The full results for the work were produced as a spreadsheet with statistics and costs for each site. The statistics include the total cost and a breakdown for each site, including the following:

- Harm to people (Non-financial human costs and financial costs)
- Evacuation (immediate and long-term)
- Building damage (residential and non-residential)
- Business disruption (loss of business and relocation)
- Emergency services

Classifications are also included against each site for:

- Site classification (based on substance – see Table 30)
- Model type (see Table 30)
- COMAH site status (top tier, lower tier or sub-COMAH)
- Government Office Region
- HSE Region

279. The combination of this information creates great potential for analysis. The information is also held in a GIS database which includes spatial referencing, which means that further information could be added based on the sites' geographical locations (e.g. urban/rural

contexts or alternative administration boundaries). Although costs have been estimated for individual sites, they are most effective when considered as an aggregate as the methodologies used are sensitive at the local level. Furthermore, estimates for individual sites are not presented in this report due to the potential sensitivities associated with accidents of this nature, such as loss of life, business, or site reputation. This should also be considered in any work taken forward using this information.

280. The results presented here focus on the reporting of aggregate statistics against some of the different site classifications. Costs have been rounded to two significant figures. Table 34 includes the mean and median costs for all sites, broken into the different components of loss. Figure 11 illustrates the contribution of the different components of loss. The biggest contributor across all of the sites is the non-financial human costs, making up 60.8% of the total cost.

**Table 34** Average costs per site for all sites

| | **Mean per site** | **Median per site** |
|---|---|---|
| Site count | 1,725 | |
| **Population Impact** | | |
| Non-financial human costs | £68,000,000 | £14,000,000 |
| Financial costs | £29,000,000 | £6,000,000 |
| **Total population impact** | **£97,000,000** | **£20,000,000** |
| Evacuation | £170,000 | £6,300 |
| Building damage | £4,700,000 | £1,300,000 |
| Business disruption | £5,100,000 | £520,000 |
| Business temporary relocation | £340,000 | £96,000 |
| Emergency services | £2,100,000 | £520,000 |
| **Total cost** | **£110,000,000** | **£26,000,000** |

**Note:** totals may not sum due to rounding. The median cost components and the total cost are all independent so will not sum.

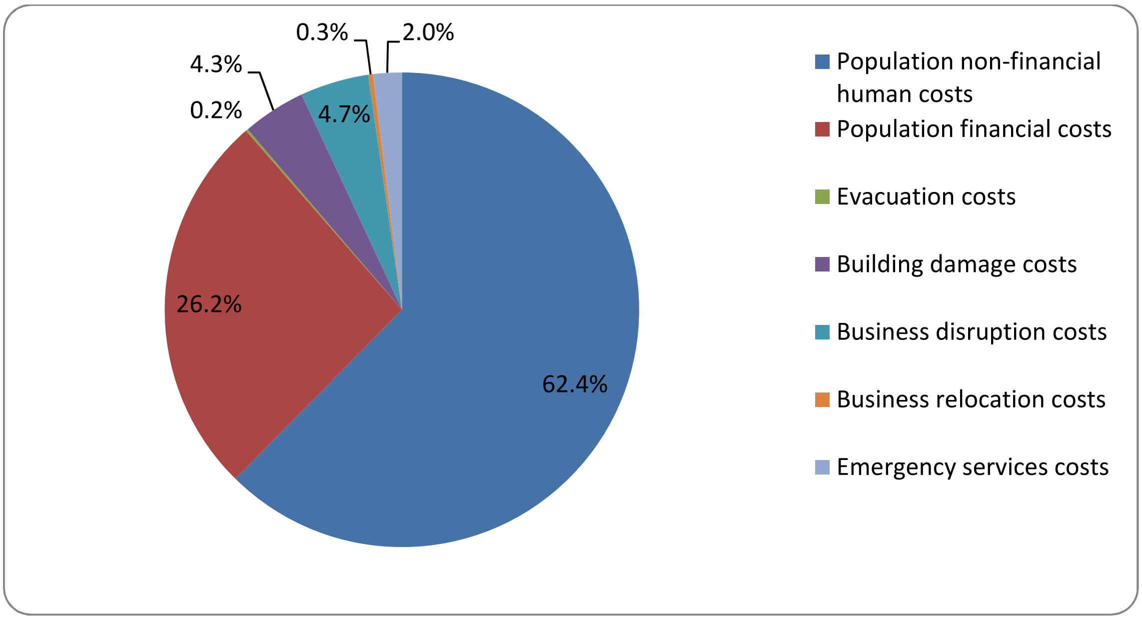



**Figure 11** Breakdown of average (mean) costs for all sites

281. Table 35 and Table 36 provide a geographical breakdown of the mean costs, by HSE Region and Government Office Region. Sites in the Southern region are estimated to have the greatest cost. The London Government Office Region (within the Southern region) has the greatest average cost – at £200,000,000 this is £40m greater than the South East, which has the second highest cost.

**Table 35** Average (mean) costs per site by HSE Region

| | **Region** | | |
|---|---|---|---|
| | **Central** | **Scotland and North East** | **Southern** |
| Site count | 492 | 807 | 426 |
| **Population Impact** | | | |
| Non-financial human costs | £60,000,000 | £65,000,000 | £83,000,000 |
| Financial costs | £25,000,000 | £27,000,000 | £35,000,000 |
| **Total Population Impact** | **£85,000,000** | **£93,000,000** | **£120,000,000** |
| Evacuation | £190,000 | £130,000 | £240,000 |
| Building Damage | £4,000,000 | £3,900,000 | £6,900,000 |
| Business Disruption | £4,800,000 | £5,000,000 | £5,700,000 |
| Business Temporary Location | £290,000 | £360,000 | £370,000 |
| Emergency Services | £1,900,000 | £2,000,000 | £2,600,000 |
| **Total cost** | **£96,000,000** | **£100,000,000** | **£130,000,000** |

**Note:** totals may not sum due to rounding

**Table 36** Average (mean) costs per site by Government Office Region

| | Government Office Region | | | | | |
|---|---|---|---|---|---|---|
| | **East Midlands** | **Eastern** | **London** | **North East** | **North West** | **Scotland** |
| Site count | 123 | 182 | 63 | 113 | 245 | 248 |
| **Population Impact** | | | | | | |
| Non-financial human costs | £50,000,000 | £52,000,000 | £120,000,000 | £59,000,000 | £75,000,000 | £64,000,000 |
| Financial costs | £21,000,000 | £22,000,000 | £51,000,000 | £25,000,000 | £31,000,000 | £27,000,000 |
| **Total population impact** | **£71,000,000** | **£74,000,000** | **£170,000,000** | **£83,000,000** | **£110,000,000** | **£91,000,000** |
| Evacuation | £160,000 | £140,000 | £460,000 | £170,000 | £120,000 | £150,000 |
| Building damage | £3,500,000 | £4,700,000 | £12,000,000 | £3,300,000 | £2,700,000 | £6,200,000 |
| Business disruption | £4,300,000 | £4,700,000 | £7,300,000 | £3,800,000 | £3,700,000 | £7,800,000 |
| Business temporary relocation | £270,000 | £380,000 | £330,000 | £310,000 | £210,000 | £610,000 |
| Emergency services | £1,600,000 | £1,700,000 | £3,900,000 | £1,800,000 | £2,300,000 | £2,100,000 |
| **Total cost** | **£81,000,000** | **£85,000,000** | **£200,000,000** | **£92,000,000** | **£120,000,000** | **£110,000,000** |

| | Government Office Region | | | | |
|---|---|---|---|---|---|
| | **South East** | **South West** | **Wales** | **West Midlands** | **Yorks & Humber** |
| Site count | 181 | 153 | 98 | 118 | 201 |
| **Population Impact** | | | | | |
| Non-financial human costs | £100,000,000 | £61,000,000 | £63,000,000 | £65,000,000 | £59,000,000 |
| Financial costs | £42,000,000 | £26,000,000 | £26,000,000 | £27,000,000 | £25,000,000 |
| **Total population impact** | **£140,000,000** | **£87,000,000** | **£89,000,000** | **£93,000,000** | **£83,000,000** |
| Evacuation | £250,000 | £320,000 | £100,000 | £120,000 | £86,000 |
| Building damage | £7,500,000 | £5,500,000 | £2,500,000 | £4,100,000 | £2,900,000 |
| Business disruption | £6,100,000 | £6,200,000 | £3,600,000 | £4,500,000 | £3,600,000 |
| Business temporary relocation | £370,000 | £320,000 | £210,000 | £340,000 | £280,000 |
| Emergency services | £3,200,000 | £2,000,000 | £1,900,000 | £2,000,000 | £1,800,000 |
| **Total cost** | **£160,000,000** | **£100,000,000** | **£97,000,000** | **£100,000,000** | **£92,000,000** |

**Note:** totals may not sum due to rounding

282. Table 37 details the mean costs by COMAH status. As expected the greatest average costs are associated with the top tier sites, followed by lower tier, and sub-COMAH.

**Table 37** Average (mean) costs per site by COMAH Status

| | COMAH Top Tier | COMAH Lower Tier | Sub-COMAH |
|---|---|---|---|
| Site count | 332 | 655 | 652 |
| **Population Impact** | | | |
| Non-financial human costs | £130,000,000 | £60,000,000 | £42,000,000 |
| Financial costs | £55,000,000 | £25,000,000 | £18,000,000 |
| **Total Population Impact** | **£190,000,000** | **£86,000,000** | **£60,000,000** |
| Evacuation | £220,000 | £140,000 | £160,000 |
| Building damage | £8,400,000 | £3,500,000 | £3,600,000 |
| Business disruption | £7,600,000 | £4,700,000 | £3,900,000 |
| Business temporary relocation | £690,000 | £270,000 | £220,000 |
| Emergency services | £4,100,000 | £1,900,000 | £1,400,000 |
| **Total cost** | **£210,000,000** | **£96,000,000** | **£69,000,000** |
| *COMAH statuses were sourced for 1,639 (95%) of the 1,725 major hazard sites. The remaining 5% of sites are excluded from the table.* | | | |

**Note:** totals may not sum due to rounding

283. Table 38 and Table 39 detail the average cost by the model type and site classification respectively. The model type with the highest average (mean) cost is Overpressure (VCE). The majority of the sites included here are large-scale petrol storage sites (Buncefield-type), which have the greatest estimate of cost of all the site classifications in Table 39.

**Table 38** Average (mean) costs per site by model type

| | Model | | | | |
|---|---|---|---|---|---|
| | **Overpressure (Ammonium Nitrate)** | **Risk (Toxic)** | **Overpressure (VCE)** | **Overpressure (CPE)** | **Flammable (Fireball/ BLEVE)** |
| Site count | 173 | 341 | 43 | 22 | 684 |
| **Population Impact** | | | | | |
| Non-financial human costs | £59,000,000 | £100,000,000 | £260,000,000 | £130,000,000 | £67,000,000 |
| Financial costs | £25,000,000 | £44,000,000 | £110,000,000 | £55,000,000 | £28,000,000 |
| **Total population impact** | **£84,000,000** | **£150,000,000** | **£360,000,000** | **£190,000,000** | **£95,000,000** |
| Evacuation | £700,000 | £40,000 | £710,000 | £720,000 | £120,000 |
| Building damage | £9,500,000 | £0 | £25,000,000 | £14,000,000 | £3,300,000 |
| Business disruption | £8,200,000 | £0 | £34,000,000 | £18,000,000 | £4,300,000 |
| Business temporary relocation | £610,000 | £0 | £2,000,000 | £1,000,000 | £200,000 |
| Emergency services | £2,100,000 | £3,000,000 | £8,500,000 | £4,400,000 | £2,100,000 |
| **Total cost** | **£100,000,000** | **£150,000,000** | **£430,000,000** | **£220,000,000** | **£100,000,000** |

| | Model | | | | |
|---|---|---|---|---|---|
| | **Flammable (Jet fire/ Pool fire)** | **Flammable (Flash fire)** | **Flammable (Oxygen)** | **Flammable (LPG Cylinder)** | **Mixed Substance and Refinery** |
| Site count | 287 | 21 | 15 | 111 | 28 |
| **Population Impact** | | | | | |
| Non-financial human costs | £13,000,000 | £56,000,000 | £11,000,000 | £11,000 | £250,000,000 |
| Financial costs | £5,500,000 | £24,000,000 | £4,800,000 | £4,500 | £100,000,000 |
| **Total population impact** | **£19,000,000** | **£80,000,000** | **£16,000,000** | **£15,000** | **£350,000,000** |
| Evacuation | £74,000 | £130,000 | £12,000 | £41,000 | £270,000 |
| Building damage | £5,200,000 | £560,000 | £0 | £5,500,000 | £25,000,000 |
| Business disruption | £4,500,000 | £520,000 | £0 | £7,500,000 | £17,000,000 |
| Business temporary relocation | £500,000 | £49,000 | £0 | £370,000 | £1,800,000 |
| Emergency services | £580,000 | £1,600,000 | £330,000 | £270,000 | £7,900,000 |
| **Total cost** | **£30,000,000** | **£82,000,000** | **£17,000,000** | **£14,000,000** | **£400,000,000** |

**Note:** totals may not sum due to rounding

**Table 39** Average (mean) costs by site type

| Site type | Count | Total cost | | Site type | Count | Total cost |
|---|---|---|---|---|---|---|
| Ammonium Nitrate | 170 | £100,000,000 | | LPG Cylinder Storage | 110 | £12,000,000 |
| B1 - very toxic | 65 | £120,000,000 | | LVT | 19 | £38,000,000 |
| B1 & B2 | 59 | £180,000,000 | | Mixed Substance | 106 | £190,000,000 |
| B2 - Toxic | 80 | £93,000,000 | | Natural Gas - High Pressure | 74 | £33,000,000 |
| B3 | 14 | £290,000,000 | | Natural Gas - Low Pressure | 238 | £130,000,000 |
| Chlorine | 74 | £280,000,000 | | Oxygen | 15 | £17,000,000 |
| EO/PO | 8 | £59,000,000 | | RFLs | 19 | £91,000,000 |
| Large-scale petrol storage (Buncefield-type) | 38 | £480,000,000 | | Various Flammables | 204 | £29,000,000 |
| LPG Bulk Storage | 428 | £86,000,000 | | Various Toxic | 4 | £34,000,000 |

# 7 CONCLUSIONS/RECOMMENDATIONS

284. This report has documented the approach taken to develop and implement a model for estimating the potential costs of an accident at major hazard sites within Great Britain. The model developed uses a 'catastrophe-modelling'-type approach, which breaks down the model into three components of *hazard*, *vulnerability* and *economic cost*, which are then combined to provide the final estimates of the cost. This proved to be an effective method of breaking down the work. The clear distinction of components enabled the different partners on the project to focus on their respective scientific areas.

285. Due to the rarity of the kinds of reasonable worst-case scenario accidents being modelled, it is difficult to test the effectiveness of the model. Buncefield does however provide some kind of precedent. If we compare the estimated economic cost of that incident (£980m) with modelled sites of that type (large-scale petrol storage), the Buncefield estimate corresponds approximately with the 80$^{th}$ percentile result from our model.

286. The aim when creating the model was to make best use of the methodologies available, building on existing datasets and approaches. The use of land use planning zones as a representation of the hazard, with the associated vulnerability multipliers has limitations for some sites and methodologies, but is a pragmatic choice given the scope of the work. The work has also demonstrated that large-scale analysis of major hazard sites is possible using GIS. It has also highlighted the value in this application of some of the data available within government or on open data licences, such as the National Population Database, National Receptors Dataset, and valuation data.

287. Further statistical analysis of the data could yield further insights and could clarify the sensitivities in the methodologies.

## 7.1 UPDATES

288. There is potential to develop the data and model structure used in this work. There are different options for doing this, with increasing levels of complication.

1. Update of economic multipliers

   The economic multipliers used to estimate the population impact, GVA (business disruptions), and evacuation have been implemented using live lookup tables in the spreadsheet-based model. Updating these with up-to-date or more accurate figures (or projections) is possible without the need for re-running any of the spatial analysis, and should be a relatively straightforward task for these criteria. Economic updates against the other criteria (building damage and business relocation) could be implemented via annual multipliers applied across the whole results set.

2. Update of non-economic multipliers

   Similar to the economic multipliers, the non-economic multipliers for population impact (loss of life and injury probabilities), building damage (percentage) and evacuation time use live lookup tables in the results spreadsheets. These could be updated using more up-to-date information in the model.

3. Site classifications

   The addition or update of information about the site could also be added into the model, if further breakdowns of statistics were required. This might include information on site ownership, responsible authority, or size. Further to this, aggregate statistics for specific lists of sites could also be incorporated. This does not include changes to site land use planning zones regarding their spatial distribution.

4. Update of GIS information

   The GIS data used to represent the hazard and the exposure and relate them in a spatial context have been developed per site or for individual geographical locations such as buildings. This includes building valuations, population estimates, and workplaces which are all based on information specific to each individual building (e.g. its floorspace and type). Updating these would be a more complicated exercise, requiring greater effort.

5. Additional sources of loss

   The model structure leaves an option open to add further estimates of loss against each site, or type of site. For example, estimates of the loss associated with environmental impacts could be added. Replacement of methodologies for the existing sources of loss is also possible, if improved methods are identified in the future.

# 8 APPENDICES

## 8.1 APPENDIX 1: DERIVATION OF GENERIC AMMONIUM NITRATE ZONES

289. Land-use-planning zones for generic ammonium nitrate sites were calculated using the new consequence-based assessment methodology, as implemented in ANENOME v1.0 (HSE website, e). Two types of generic site were modelled:

- Coastal or estuary sites, which take deliveries of ammonium nitrate from ships and bag them up, prior to transfer of the ammonium nitrate to customers or storage sites. The throughput at such sites is very high.
- Inland sites, which provide local storage of bagged ammonium nitrate prior to the growing season (it is commonly used as a fertiliser). The throughput at these sites is much lower than at coastal or estuary sites.

290. The ANENOME inputs used for the calculation of the generic zone boundaries are shown in Table 40. The generic zone boundaries calculated in ANENOME for coastal or estuary sites and inland sites are given in Table 41.

**Table 40** ANENOME inputs used for the calculation of the generic zone boundaries

| | **Coastal or estuary sites** | **Inland sites** |
|---|---|---|
| Building throughput (tonnes/year) | 12,000 | 5,000 |
| Heaps or bagged | Heaps | Bagged |
| If bagged, is it stored on pallets? | N/A | Yes |
| Indoor or outdoor storage | Indoor | Indoor |
| Stack size (tonnes) | 1,000 | 300 |
| Urea? | Yes | No |
| Bagging plant? | Yes | No |
| Months per year | 6 | 12 |
| Site conditions | Average | Average |
| Truck load (tonnes) | 25 | 25 |
| Are trucks loaded / unloaded inside? | Yes | Yes |

**Table 41** Generic zone boundaries for ammonium nitrate sites

| Zone | Generic zone boundaries for ammonium nitrate sites (m) | |
|---|---|---|
| | **Coastal or estuary sites** | **Inland sites** |
| Inner zone | 65 | 65 |
| Middle zone | 216 | 157 |
| Outer zone | 538 | 360 |

## 8.2 APPENDIX 2: OS-VOA CLASS MAPPINGS

291. Table 42 and Table 43 detail the class mappings for the VOA valuation information for non-residential buildings for the NRD property points data (England and Wales) and the equivalent data created for Scotland based on OS Addressbase and MasterMap. Section 4.3.2.2 in the main report details the methodology used. The *Workplace Flag* column (0 or 1) indicates whether the building was identified as a potential workplace and assigned a multiplier for the estimation of workplace populations. The *AOI Count* details the number of building records for each classification that were located in the area of interest (i.e. postcode areas overlapping major hazard site zones). Additional classifications exist in the data but are not associated with buildings in the area of interest. The VOA Class allows the attachment of economic multipliers.

**Table 42** OS-VOA class mappings (England and Wales)

| OS class | VOA Class | AOI Count | Workplace Flag | | OS class | VOA Class | AOI Count | Workplace Flag |
|---|---|---|---|---|---|---|---|---|
| Adult education | All Bulk | 2 | 1 | | Insurance broker | Offices | 9 | 1 |
| Air force site | All Bulk | 3 | 1 | | Job centre | Offices | 47 | 1 |
| Airport | All Bulk | 2 | 1 | | Local government office | Offices | 416 | 1 |
| Arena | All Bulk | 3 | 1 | | Magistrates court | Offices | 6 | 1 |
| Art centre | All Bulk | 11 | 1 | | Mental health centre | Offices | 3 | 1 |
| Art studies | All Bulk | 2 | 1 | | Office | Offices | 4967 | 1 |
| Barracks | All Bulk | 3 | 1 | | Police headquarters | Offices | 4 | 1 |
| Child day care | All Bulk | 5 | 1 | | Police house | Offices | 3 | 1 |
| Children’s home | All Bulk | 1 | 1 | | Police services | Offices | 66 | 1 |
| Children’s nursery | All Bulk | 22 | 1 | | Police station | Offices | 11 | 1 |
| Cleaning | All Bulk | 4 | 1 | | Social services | Offices | 14 | 1 |
| Contractors yard | All Bulk | 1 | 1 | | Sorting office | Offices | 3 | 1 |
| Day care | All Bulk | 37 | 1 | | Surgery | Offices | 62 | 1 |
| Disinfecting | All Bulk | 1 | 1 | | Taxi business | Offices | 70 | 1 |
| Education | All Bulk | 28 | 1 | | Veterinary surgery | Offices | 44 | 1 |
| Ferry terminal | All Bulk | 6 | 1 | | Visitor information | Offices | 16 | 1 |
| Field studies | All Bulk | 1 | 1 | | Welfare services | Offices | 38 | 1 |
| First school | All Bulk | 6 | 1 | | Activity centre | Other bulk | 5 | 1 |
| Further education | All Bulk | 1 | 1 | | Adventure playground | Other bulk | 3 | 0 |
| Further education college | All Bulk | 49 | 1 | | Allotment | Other bulk | 437 | 0 |
| Guest house | All Bulk | 43 | 1 | | Almshouse | Other bulk | 2 | 1 |
| High school | All Bulk | 11 | 1 | | Arboretum | Other bulk | 3 | 0 |
| Higher education | All Bulk | 35 | 1 | | Art gallery | Other bulk | 31 | 1 |
| HM coastguard rescue | All Bulk | 14 | 1 | | Basketball | Other bulk | 1 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| HM coastguard services | All Bulk | 1 | 1 | | Bingo hall | Other bulk | 11 | 1 |
| HM naval base | All Bulk | 1 | 1 | | BMX racing | Other bulk | 2 | 1 |
| HM prison | All Bulk | 10 | 1 | | Boat house | Other bulk | 38 | 0 |
| HM young offenders institution | All Bulk | 2 | 1 | | Boat yard | Other bulk | 25 | 1 |
| Holiday camp | All Bulk | 1 | 1 | | Bowling | Other bulk | 10 | 1 |
| Holiday park | All Bulk | 1 | 1 | | Bowls | Other bulk | 3 | 1 |
| Hospice | All Bulk | 7 | 1 | | British legion club | Other bulk | 87 | 1 |
| Hospital | All Bulk | 18 | 1 | | Burial ground | Other bulk | 29 | 0 |
| Hostel | All Bulk | 6 | 1 | | Camping | Other Bulk | 3 | 1 |
| Hotel | All Bulk | 298 | 1 | | Caravanning | Other bulk | 104 | 1 |
| Infant school | All Bulk | 42 | 1 | | Casino | Other bulk | 7 | 1 |
| Inshore rescue | All Bulk | 1 | 1 | | Cats home | Other bulk | 1 | 1 |
| Junior school | All Bulk | 17 | 1 | | Cattery | Other bulk | 11 | 1 |
| Language studies | All Bulk | 1 | 1 | | Cemetery | Other bulk | 130 | 0 |
| Library | All Bulk | 18 | 1 | | Chapel | Other bulk | 68 | 1 |
| Lifeboat services | All Bulk | 3 | 1 | | Chapel of rest | Other bulk | 2 | 1 |
| Lighthouse | All Bulk | 4 | 1 | | Church | Other bulk | 527 | 1 |
| Married quarters | All Bulk | 1 | 1 | | Circus | Other bulk | 1 | 1 |
| Medical services | All Bulk | 2 | 1 | | Club | Other bulk | 280 | 1 |
| Middle school | All Bulk | 5 | 1 | | Club house | Other bulk | 15 | 1 |
| Music studies | All Bulk | 1 | 1 | | Community centre | Other bulk | 122 | 1 |
| Nursery | All Bulk | 48 | 1 | | Community hall | Other bulk | 6 | 1 |
| Nurses home | All Bulk | 2 | 1 | | Concert hall | Other bulk | 1 | 1 |
| Nursing home | All Bulk | 90 | 1 | | Conference centre | Other bulk | 23 | 1 |
| Passenger ferry terminal | All Bulk | 1 | 1 | | Convent | Other bulk | 3 | 1 |
| Performing arts studies | All Bulk | 1 | 1 | | Country club | Other bulk | 5 | 1 |
| Pre-school education | All Bulk | 107 | 1 | | Crazy golf | Other bulk | 5 | 1 |
| Private primary school | All Bulk | 1 | 1 | | Crematorium | Other bulk | 7 | 1 |
| Probation centre | All Bulk | 14 | 1 | | Cricket | Other bulk | 60 | 1 |
| Railway station | All Bulk | 15 | 1 | | Dancing | Other bulk | 2 | 1 |
| Research | All Bulk | 82 | 1 | | Dockyard | Other bulk | 1 | 1 |
| Rest home | All Bulk | 16 | 1 | | Dog pound | Other bulk | 2 | 1 |
| Retirement home | All Bulk | 1 | 1 | | Dogs home | Other bulk | 2 | 1 |
| School | All Bulk | 133 | 1 | | Equestrian | Other bulk | 2 | 1 |
| Secondary school | All Bulk | 8 | 1 | | Equestrian training | Other bulk | 15 | 1 |
| Sixth form college | All Bulk | 3 | 1 | | Exhibition centre | Other bulk | 2 | 1 |
| Studio | All Bulk | 4 | 1 | | Fitness club | Other bulk | 36 | 1 |
| Sunday school | All Bulk | 20 | 1 | | Football | Other bulk | 137 | 1 |
| Technology studies | All Bulk | 1 | 1 | | Garden centre | Other bulk | 39 | 1 |
| Television studio | All Bulk | 9 | 1 | | Garden of rest | Other bulk | 2 | 0 |
| Testing | All Bulk | 13 | 1 | | Golf | Other bulk | 213 | 1 |
| Training | All Bulk | 102 | 1 | | Golf range | Other bulk | 11 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| University | All Bulk | 11 | 1 | | Guides meeting place | Other bulk | 2 | 1 |
| Vehicle driver training | All Bulk | 4 | 1 | | Gymnasium | Other bulk | 33 | 1 |
| Vineyard | All Bulk | 2 | 1 | | Hall | Other bulk | 321 | 1 |
| Abattoir | Factory | 6 | 1 | | Health club | Other bulk | 5 | 1 |
| Aeration | Factory | 1 | 0 | | Heritage centre | Other bulk | 3 | 1 |
| Ambulance station | Factory | 35 | 1 | | Hide | Other bulk | 3 | 0 |
| Animal feed factory | Factory | 18 | 1 | | Hockey | Other bulk | 2 | 1 |
| Ash disposal | Factory | 1 | 1 | | Horse racing | Other bulk | 1 | 1 |
| Bakery | Factory | 25 | 1 | | Kennels | Other bulk | 38 | 1 |
| Boat building | Factory | 1 | 1 | | Kingdom hall | Other bulk | 23 | 1 |
| Boat repair | Factory | 1 | 1 | | Leisure centre | Other bulk | 107 | 1 |
| Brewery | Factory | 27 | 1 | | Marina | Other bulk | 33 | 1 |
| Brick works | Factory | 10 | 1 | | Mausoleum | Other bulk | 1 | 0 |
| Builders | Factory | 16 | 1 | | Maze | Other bulk | 1 | 1 |
| Catering | Factory | 1 | 1 | | Meeting room | Other bulk | 3 | 1 |
| Cement works | Factory | 10 | 1 | | Military youth club | Other bulk | 8 | 1 |
| Chalk extraction | Factory | 2 | 1 | | Mortuary | Other bulk | 3 | 1 |
| Chandlery | Factory | 4 | 1 | | Mosque | Other bulk | 8 | 1 |
| Chemical works | Factory | 197 | 1 | | Motor racing | Other bulk | 7 | 1 |
| China clay works | Factory | 12 | 1 | | Museum | Other bulk | 25 | 1 |
| Clay extraction | Factory | 53 | 1 | | Nature reserve | Other bulk | 3 | 1 |
| Coach builders | Factory | 3 | 1 | | Netball | Other bulk | 1 | 1 |
| Coal extraction | Factory | 1 | 1 | | Nonconformist meeting house | Other bulk | 4 | 1 |
| Concrete works | Factory | 87 | 1 | | Parish hall | Other bulk | 10 | 1 |
| Cooling | Factory | 182 | 0 | | Parish room | Other bulk | 1 | 1 |
| Dairy | Factory | 68 | 1 | | Park | Other bulk | 579 | 0 |
| Distillery | Factory | 1 | 1 | | Pitch and putt | Other bulk | 4 | 1 |
| Electricity generating | Factory | 109 | 1 | | Place of worship | Other bulk | 22 | 1 |
| Engineering works | Factory | 782 | 1 | | Play area | Other bulk | 564 | 0 |
| Factory | Factory | 1342 | 1 | | Playing field | Other bulk | 364 | 0 |
| Farming | Factory | 75 | 1 | | Presbytery | Other bulk | 5 | 1 |
| Fire station | Factory | 66 | 1 | | Public baths | Other bulk | 1 | 1 |
| Fire tower | Factory | 1 | 0 | | Public car parking | Other Bulk | 683 | 0 |
| Fish farming | Factory | 3 | 1 | | Public convenience | Other bulk | 247 | 1 |
| Fish hatchery | Factory | 2 | 1 | | Public park and ride | Other Bulk | 1 | 1 |
| Fishery | Factory | 36 | 1 | | Putting | Other bulk | 10 | 1 |
| Fishing | Factory | 1 | 1 | | Radar | Other bulk | 4 | 1 |
| Flare stack | Factory | 72 | 0 | | Radio communications | Other bulk | 17 | 1 |
| Food and drink manufacture | Factory | 38 | 1 | | Radio station | Other bulk | 1 | 1 |
| Food processing | Factory | 1 | 1 | | Reading room | Other bulk | 2 | 1 |
| Forge | Factory | 21 | 1 | | Recording studio | Other bulk | 4 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Foundry | Factory | 38 | 1 | | Recreation ground | Other bulk | 148 | 0 |
| Garage | Factory | 556 | 1 | | Rifle range | Other bulk | 19 | 1 |
| Gas monitoring | Factory | 18 | 1 | | Roller skating | Other bulk | 1 | 1 |
| Gas production and distribution | Factory | 120 | 1 | | Rowing | Other bulk | 6 | 1 |
| Gas regulating | Factory | 128 | 1 | | Rugby football | Other bulk | 22 | 1 |
| Granite extraction | Factory | 1 | 1 | | Sailing | Other bulk | 23 | 1 |
| Gravel extraction | Factory | 33 | 1 | | Scouts meeting place | Other bulk | 7 | 1 |
| Gravel works | Factory | 1 | 1 | | Shieling | Other bulk | 2 | 1 |
| Heating | Factory | 1 | 0 | | Shooting range | Other bulk | 1 | 1 |
| Hopper | Factory | 273 | 0 | | Shooting training | Other bulk | 4 | 1 |
| Horticultural nursery | Factory | 22 | 1 | | Skateboarding | Other bulk | 5 | 1 |
| Horticulture | Factory | 4 | 1 | | Skiing | Other bulk | 7 | 1 |
| Hydraulic power | Factory | 1 | 1 | | Snooker | Other bulk | 13 | 1 |
| Industry and business services | Factory | 35 | 1 | | Social club | Other bulk | 36 | 1 |
| Iron works | Factory | 54 | 1 | | Sports | Other bulk | 134 | 1 |
| Kiln | Factory | 6 | 1 | | Sports club | Other bulk | 14 | 1 |
| Kitchen | Factory | 1 | 1 | | Sports pavilion | Other bulk | 214 | 1 |
| Landfill | Factory | 2 | 1 | | Sports viewing | Other bulk | 54 | 1 |
| Lime kiln | Factory | 3 | 0 | | Stables | Other bulk | 46 | 1 |
| Limestone extraction | Factory | 1 | 1 | | Stud farming | Other bulk | 4 | 1 |
| Manufacturing | Factory | 8 | 1 | | Swimming | Other bulk | 33 | 1 |
| Mill | Factory | 84 | 1 | | Tabernacle | Other bulk | 1 | 1 |
| Mineral and fuel extraction | Factory | 347 | 1 | | Telecommunications | Other Bulk | 752 | 1 |
| Mushroom farming | Factory | 2 | 1 | | Telephone exchange | Other Bulk | 39 | 1 |
| Mussel bed | Factory | 1 | 0 | | Television communications | Other bulk | 3 | 1 |
| Oil extraction | Factory | 1 | 1 | | Temple | Other bulk | 7 | 1 |
| Oil refining | Factory | 46 | 1 | | Tennis | Other bulk | 259 | 1 |
| Ore distribution | Factory | 1 | 1 | | Territorial army | Other bulk | 16 | 1 |
| Paper mill | Factory | 2 | 1 | | Theatre | Other bulk | 12 | 1 |
| Piggery | Factory | 16 | 1 | | Trout farming | Other bulk | 1 | 1 |
| Pottery | Factory | 1 | 1 | | Water sports | Other bulk | 1 | 1 |
| Poultry farming | Factory | 19 | 1 | | Weapons range | Other bulk | 4 | 1 |
| Primary school | Factory | 167 | 1 | | Youth centre | Other bulk | 29 | 1 |
| Public recycling | Factory | 70 | 1 | | Zoo | Other bulk | 1 | 1 |
| Public waste disposal | Factory | 3 | 1 | | Agricultural merchants | Retail | 2 | 1 |
| Pump house | Factory | 179 | 0 | | Amusement arcade | Retail | 8 | 1 |
| Quarry | Factory | 1 | 1 | | Auction house | Retail | 4 | 1 |
| Recycling | Factory | 70 | 1 | | Bank | Retail | 140 | 1 |
| Repair centre | Factory | 159 | 1 | | Bar | Retail | 51 | 1 |
| Sand extraction | Factory | 25 | 1 | | Betting office | Retail | 96 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Scrap metal handling | Factory | 20 | 1 | | Builders merchant | Retail | 135 | 1 |
| Sewage pumping | Factory | 35 | 1 | | Building society | Retail | 26 | 1 |
| Sewage treatment | Factory | 261 | 1 | | Café | Retail | 250 | 1 |
| Ship repair yard | Factory | 4 | 1 | | Canteen | Retail | 2 | 1 |
| Smallholding | Factory | 5 | 1 | | Car dealer | Retail | 1031 | 1 |
| Smithy | Factory | 2 | 1 | | Car hire | Retail | 101 | 1 |
| Steel works | Factory | 67 | 1 | | Car wash | Retail | 33 | 1 |
| Stone extraction | Factory | 2 | 1 | | Cash and carry | Retail | 51 | 1 |
| Stonemasons | Factory | 13 | 1 | | Chemist | Retail | 137 | 1 |
| Sugar refinery | Factory | 3 | 1 | | Cinema | Retail | 19 | 1 |
| Tar distillery | Factory | 2 | 1 | | Department store | Retail | 22 | 1 |
| Timber mill | Factory | 2 | 1 | | Dry cleaners | Retail | 53 | 1 |
| Tower | Factory | 3564 | 1 | | Employment agency | Retail | 63 | 1 |
| Valve house | Factory | 15 | 1 | | Entertainment centre | Retail | 4 | 1 |
| Vapour stack | Factory | 2 | 0 | | Estate agency | Retail | 70 | 1 |
| Vehicle breakers | Factory | 10 | 1 | | Filling station | Retail | 42 | 1 |
| Vehicle inspection centre | Factory | 2 | 1 | | Fish market | Retail | 1 | 1 |
| Vehicle testing | Factory | 37 | 1 | | General commercial | Retail | 31792 | 1 |
| Ventilating | Factory | 38 | 0 | | Hairdresser | Retail | 276 | 1 |
| Waste disposal | Factory | 65 | 1 | | Hire shop | Retail | 416 | 1 |
| Waste distribution | Factory | 12 | 1 | | Inn | Retail | 210 | 1 |
| Waste incineration | Factory | 4 | 1 | | Internet cafe | Retail | 1 | 1 |
| Waste pulverisation | Factory | 3 | 1 | | Joinery | Retail | 11 | 1 |
| Water distribution | Factory | 136 | 1 | | Kiosk | Retail | 1 | 1 |
| Water filtration | Factory | 78 | 1 | | Launderette | Retail | 38 | 1 |
| Water regulating | Factory | 121 | 1 | | Laundry | Retail | 1 | 1 |
| Water settling | Factory | 63 | 1 | | Market | Retail | 5 | 1 |
| Water treatment | Factory | 45 | 1 | | Metal merchant | Retail | 6 | 1 |
| Waterwheel | Factory | 4 | 0 | | Motor cycle dealer | Retail | 13 | 1 |
| Windmill | Factory | 6 | 1 | | Nightclub | Retail | 4 | 1 |
| Works | Factory | 2246 | 1 | | Post office | Retail | 218 | 1 |
| Airfield | No Value | 14 | 0 | | Printing works | Retail | 114 | 1 |
| Airstrip | No Value | 3 | 0 | | Public house | Retail | 413 | 1 |
| Aqueduct | No Value | 22 | 0 | | Restaurant | Retail | 289 | 1 |
| Bandstand | No Value | 5 | 0 | | Retail park | Retail | 58 | 1 |
| Basin | No Value | 64 | 0 | | Sandwich bar | Retail | 79 | 1 |
| Bothy | No Value | 1 | 0 | | Service station | Retail | 102 | 1 |
| Brine reservoir | No Value | 2 | 0 | | Shopping | Retail | 7264 | 1 |
| Chimney | No Value | 840 | 0 | | Shopping centre | Retail | 2 | 1 |
| Citadel | No Value | 1 | 0 | | Supermarket | Retail | 208 | 1 |
| Crane | No Value | 649 | 0 | | Superstore | Retail | 8 | 1 |
| Dock basin | No Value | 2 | 0 | | Take away | Retail | 267 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dry dock | No Value | 16 | 1 | | Tourist information | Retail | 5 | 1 |
| Electricity sub station | No Value | 7995 | 0 | | Travel agency | Retail | 116 | 1 |
| First aid post | No Value | | 0 | | Tyre depot | Retail | 263 | 1 |
| Graving dock | No Value | 9 | 1 | | Undertakers | Retail | 19 | 1 |
| Harbour | No Value | 28 | 0 | | Vehicle auction | Retail | 1 | 1 |
| Jetty | No Value | 410 | 0 | | Wholesale market | Retail | 4 | 1 |
| Landing stage | No Value | 173 | 0 | | Aircraft works | Warehouse | 2 | 1 |
| Lock | No Value | 110 | 0 | | Boat storage | Warehouse | 1 | 0 |
| Memorial gardens | No Value | 2 | 0 | | Bus depot | Warehouse | 14 | 1 |
| Mine | No Value | 4 | 1 | | Bus station | Warehouse | 9 | 1 |
| Mooring | No Value | 434 | 0 | | Cattle market | Warehouse | 1 | 1 |
| Paddling | No Value | 10 | 1 | | Cement storage | Warehouse | 1 | 1 |
| Pier | No Value | 67 | 0 | | Coach station | Warehouse | 2 | 1 |
| Police emergency telephone | No Value | 3 | 0 | | Coal storage | Warehouse | 4 | 1 |
| Pond | No Value | 9362 | 0 | | Container storage | Warehouse | 23 | 1 |
| Pontoon | No Value | 86 | 0 | | Council depot | Warehouse | 25 | 1 |
| Post box | No Value | 1555 | 0 | | Depot | Warehouse | 2066 | 1 |
| Public telephone | No Value | 1332 | 0 | | Dinghy storage | Warehouse | 1 | 1 |
| Pumping | No Value | 430 | 0 | | Distribution | Warehouse | 156 | 1 |
| Quay | No Value | 111 | 0 | | Docks | Warehouse | 54 | 1 |
| Reservoir | No Value | 284 | 0 | | Engine housing | Warehouse | 10 | 1 |
| Shaft | No Value | 56 | 0 | | Freight air terminal | Warehouse | 3 | 1 |
| Shelter | No Value | 839 | 0 | | Fuel depot | Warehouse | 56 | 1 |
| Slag heap | No Value | 44 | 0 | | Gas storage | Warehouse | 248 | 1 |
| Spoil heap | No Value | 30 | 0 | | Grain storage | Warehouse | 2 | 1 |
| Vicarage | No Value | 7 | 1 | | Oil distribution | Warehouse | 1 | 1 |
| Watercress bed | No Value | 8 | 1 | | Oil storage | Warehouse | 34 | 1 |
| Weighbridge | No Value | 378 | 0 | | Oil terminal | Warehouse | 14 | 1 |
| Animal welfare | Offices | 3 | 1 | | Packing | Warehouse | 106 | 1 |
| Central government office | Offices | 47 | 1 | | Postal distribution | Warehouse | 19 | 1 |
| Civic hall | Offices | 1 | 1 | | Pound | Warehouse | 3 | 1 |
| Clinic | Offices | 102 | 1 | | Retail warehouse | Warehouse | 133 | 1 |
| Community office | Offices | 3 | 1 | | Road haulier | Warehouse | 283 | 1 |
| County court | Offices | 2 | 1 | | Sand storage | Warehouse | 1 | 1 |
| Crown court | Offices | 1 | 1 | | Sewage storage | Warehouse | 1 | 1 |
| Customs inspection | Offices | 2 | 1 | | Ship freight | Warehouse | 56 | 1 |
| Dental surgery | Offices | 86 | 1 | | Shipyard | Warehouse | 9 | 1 |
| Disabled persons service | Offices | 1 | 1 | | Sludge storage | Warehouse | 4 | 0 |
| Dock office | Offices | 1 | 1 | | Slurry storage | Warehouse | 1 | 0 |
| Drugs clinic | Offices | 2 | 1 | | Steel storage | Warehouse | 2 | 1 |
| Estate management | Offices | 1 | 1 | | Storage | Warehouse | 422 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Family service | Offices | 12 | 1 | | Tank | Warehouse | 9895 | 0 |
| Financial and professional services | Offices | 85 | 1 | | Timber storage | Warehouse | 84 | 1 |
| Government office | Offices | 25 | 1 | | Trade distribution | Warehouse | 129 | 1 |
| Health centre | Offices | 149 | 1 | | Water storage | Warehouse | 35 | 1 |

**Table 43** OS-VOA class mappings (Scotland)

| OS Class | VOA Class | AOI Count | Workplace Flag | | OS Class | VOA Class | AOI Count | Workplace Flag |
|---|---|---|---|---|---|---|---|---|
| Activity / Leisure / Sports Centre | Other Bulk | 11 | 1 | | Hotel / Motel / Boarding / Guest House | All Bulk | 5 | 1 |
| Advertising Hoarding | Other Bulk | 11 | 0 | | Hotel/Motel | All Bulk | 47 | 1 |
| Agricultural | Factory / Warehouse | 4 | 1 | | Indoor / Outdoor Leisure / Sporting Activity / Centre | Other Bulk | 45 | 1 |
| Air Force | All Bulk | 2 | 1 | | Industrial Applicable to manufacturing, engineering, maintenance, storage / wholesale distribution and extraction sites | Factory / Warehouse | 774 | 1 |
| Air Force Site | All Bulk | 1 | 1 | | Industrial Support | Factory / Warehouse | 10 | 0 |
| Airfield / Airstrip / Airport / Air Transport Infrastructure Facility | Factory / Offices | 2 | 1 | | Infant School | All Bulk | 1 | 1 |
| Allocated Parking | Other Bulk | 6 | 0 | | Job Centre | Factory / Offices | 2 | 1 |
| Ambulance Station | Factory / Offices | 6 | 1 | | Junior School | All Bulk | 1 | 1 |
| Amusements | Other Bulk | 3 | 1 | | Kingdom Hall | Other Bulk | 1 | 1 |
| Animal / Bird / Marine Sanctuary | All Bulk | 4 | 1 | | Leisure - Applicable to recreational sites and enterprises | Other Bulk | 22 | 1 |
| Animal Centre | All Bulk | 3 | 1 | | Library | Other Bulk | 2 | 1 |
| Animal Services | All Bulk | 4 | 1 | | Licensed Private Members’ Club | Other Bulk | 2 | 1 |
| Army | All Bulk | 3 | 1 | | Lifeboat Services / Station | Factory / Offices | 1 | 1 |
| Army Site | All Bulk | 1 | 1 | | Local Government Service | Offices | 37 | 1 |
| Art Centre / Gallery | Other Bulk | 2 | 1 | | Maintenance Depot | Retail | 1 | 1 |
| Bank / Financial Service | Offices | 47 | 1 | | Manufacturing | Factory / Warehouse | 51 | 1 |
| Bingo Hall / Cinema / Conference / Exhibition Centre / Theatre / Concert Hall | Other Bulk | 6 | 1 | | Marina | Other Bulk | 3 | 1 |
| Boarding / Guest House / Bed And Breakfast / Youth Hostel | All Bulk | 29 | 1 | | Market (Indoor / Outdoor) | Other Bulk | 2 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Brewery | Factory / Warehouse | 1 | 1 | | Medical | Offices | 10 | 1 |
| Broadcasting (TV / Radio) | Offices | 5 | 1 | | Medical / Testing / Research Laboratory | Offices | 6 | 1 |
| Car / Coach / Commercial Vehicle / Taxi Parking / Park And Ride Site | Other Bulk | 7 | 1 | | Middle School | All Bulk | 3 | 1 |
| Caravanning | Other Bulk | 2 | 1 | | Mineral / Ore Working / Quarry / Mine | Factory | 5 | 1 |
| Care / Nursing Home | Offices | 31 | 1 | | Mineral Quarrying / Open Extraction / Active | Factory | 1 | 1 |
| Cattery / Kennel | All Bulk | 4 | 1 | | Museum / Gallery | Other Bulk | 9 | 1 |
| Cemetery | Other Bulk | 2 | 0 | | Object of Interest | All Bulk | 21 | 0 |
| Cemetery / Crematorium / Graveyard. In Current Use. | Other Bulk | 4 | 0 | | Office | Offices | 230 | 1 |
| Central Government Service | Offices | 14 | 1 | | Office / Work Studio | Offices | 717 | 1 |
| Channel / Conveyor / Conduit / Pipe | Factory / Warehouse | 1 | 0 | | Oil / Gas Extraction / Active | Factory | 7 | 1 |
| Chemical Works | Factory / Warehouse | 6 | 1 | | Oil Refining | Factory | 7 | 1 |
| Children’s Nursery / Crèche | All Bulk | 28 | 1 | | Other Educational Establishment | All Bulk | 16 | 1 |
| Chimney / Flue | Factory / Warehouse | 9 | 0 | | Other Licensed Premise / Vendor | Retail | 22 | 1 |
| Church | Other Bulk | 24 | 1 | | Petrol Filling Station | Retail | 33 | 1 |
| Church Hall / Religious Meeting Place / Hall | Other Bulk | 13 | 1 | | Place Of Worship | Other Bulk | 26 | 1 |
| Coastguard Rescue / Lookout / Station | Factory / Offices | 3 | 1 | | Police Training | All Bulk | 9 | 1 |
| College | All Bulk | 1 | 1 | | Post Office | Retail | 18 | 1 |
| Commercial | All Bulk | 1525 | 1 | | Postal Sorting / Distribution | Factory / Warehouse | 1 | 1 |
| Community Service Centre / Office | Factory / Offices | 1 | 1 | | Power Station / Energy Production | Factory | 7 | 1 |
| Community Services | Factory / Offices | 21 | 1 | | Preparatory / First / Primary / Infant / Junior / Middle School | All Bulk | 9 | 1 |
| Conference / Exhibition Centre | Other Bulk | 2 | 1 | | Primary School | All Bulk | 26 | 1 |
| Container Freight | Factory / Warehouse | 1 | 1 | | Printing Works | Factory / Warehouse | 3 | 1 |
| Crane / Hoist / Winch / Material Elevator | Factory / Warehouse | 3 | 0 | | Public / Village Hall / Other Community Facility | Factory / Offices | 59 | 1 |
| Crematorium | Other Bulk | 1 | 0 | | Public Convenience | Other Bulk | 12 | 1 |
| Dairy Processing | Factory / Warehouse | 3 | 1 | | Public House / Bar / Nightclub | Retail | 62 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dentist | Offices | 12 | 1 | | Public Household Waste Recycling Centre (HWRC) | Factory / Warehouse | 5 | 1 |
| Distillery | Factory / Warehouse | 29 | 1 | | Pump House / Pumping Station / Water Tower | Factory | 7 | 0 |
| Diving / Swimming Facility | Other Bulk | 1 | 1 | | Rail Infrastructure Services | Factory | 4 | 1 |
| Dual Use | All Bulk | 11 | 0 | | Railway Asset | Factory | 2 | 1 |
| Education | All Bulk | 6 | 1 | | Recreational / Social Club | Other Bulk | 32 | 1 |
| Electricity Production Facility | Factory | 1 | 1 | | Restaurant / Cafeteria | Retail | 78 | 1 |
| Electricity Sub-Station | Factory | 545 | 0 | | Retail | Retail | 432 | 1 |
| Emergency / Rescue Service | Factory / Offices | 9 | 1 | | Retail Service Agent | Retail | 47 | 1 |
| Entertainment Complex | Other Bulk | 1 | 1 | | Road Freight Transport | Factory / Warehouse | 3 | 1 |
| Equestrian | Other Bulk | 2 | 1 | | Rugby Facility | Other Bulk | 4 | 1 |
| Factory/Manufacturing | Factory / Warehouse | 553 | 1 | | Secondary / High School | All Bulk | 6 | 1 |
| Farm / Non-Residential Associated Building | Factory / Warehouse | 14 | 1 | | Secondary School | All Bulk | 6 | 1 |
| Fast Food Outlet / Takeaway (Hot / Cold) | Retail | 30 | 1 | | Servicing Garage | Factory / Warehouse | 35 | 1 |
| Fire Station | Factory / Offices | 10 | 1 | | Shop / Showroom | Retail | 189 5 | 1 |
| First School | All Bulk | 2 | 1 | | Station / Interchange / Terminal / Halt | Factory | 5 | 1 |
| Fish Farming | Factory / Warehouse | 1 | 1 | | Steel Works | Factory / Warehouse | 1 | 1 |
| Food Processing | Factory / Warehouse | 3 | 1 | | Storage Land | Factory / Warehouse | 1 | 1 |
| Football Facility | Other Bulk | 4 | 1 | | Telecommunication | Other Bulk | 24 | 0 |
| Further Education | All Bulk | 8 | 1 | | Telephone Exchange | Other Bulk | 1 | 0 |
| Garden Centre | Retail | 2 | 1 | | Tenpin Bowling Facility | Other Bulk | 3 | 1 |
| Gas / Oil Storage / Distribution | Factory | 4 | 1 | | Theatre | Other Bulk | 2 | 1 |
| General Practice Surgery / Clinic | Offices | 15 | 1 | | Tourist Information Signage | Other Bulk | 3 | 0 |
| General Storage Land | Factory / Warehouse | 1 | 1 | | Transport | Factory / Offices | 7 | 1 |
| Golf Facility | Other Bulk | 14 | 1 | | Transport Related Infrastructure | Factory | 2 | 1 |
| Goods Freight Handling / Terminal | Factory / Warehouse | 6 | 1 | | Transport Track / Way | Factory | 1 | 1 |
| Grab / Skip / Other Industrial Waste Machinery / Discharging | Factory / Warehouse | 1 | 0 | | University | All Bulk | 1 | 1 |
| Health Care Services | Offices | 20 | 1 | | Utility | Factory | 10 | 1 |
| Health Centre | Offices | 11 | 1 | | Vehicle Storage | Factory / Warehouse | 36 | 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Heritage Centre | Other Bulk | 1 | 1 | | Vet / Animal Medical Treatment | Offices | 10 | 1 |
| Higher Education | All Bulk | 3 | 1 | | Warehouse / Store / Storage Depot | Factory / Warehouse | 378 | 1 |
| HM Prison Service | Factory / Offices | 2 | 1 | | Waste Water Treatment | Factory | 1 | 1 |
| Holiday / Campsite | Other Bulk | 2 | 1 | | Water / Waste Water / Sewage Treatment Works | Factory | 7 | 1 |
| Holiday Let/Accommodation/Short-Term Let other than the above | All Bulk | 79 | 1 | | Water Controlling / Pumping | Factory | 1 | 0 |
| Hopper / Silo / Cistern / Tank | Factory / Warehouse | 1358 | 0 | | Water Distribution / Pumping | Factory | 3 | 0 |
| Horticulture | Factory / Warehouse | 2 | 1 | | Water Sports Facility | Other Bulk | 2 | 1 |
| Hospice | Offices | 3 | 1 | | Water Treatment | Factory | 1 | 1 |
| Hospital | Offices | 2 | 1 | | Wholesale Distribution | Factory / Warehouse | 29 | 1 |
| Hospital / Hospice | Offices | 1 | 1 | | Workshop / Light Industrial | Factory / Warehouse | 732 | 1 |

## 8.3 APPENDIX 3: MAIN GIS DATA SOURCES

**Table 44** Main GIS data sources used in the vulnerability component

| **Dataset** | **Source** |
|---|---|
| National Receptors Dataset | Environment Agency (2010) |
| National Population Database | HSL (2013) |
| AddressBase Premium | Ordnance Survey (2013) |
| MasterMap Topography | Ordnance Survey (2013) |
| Codepoint with Polygons | Ordnance Survey (2013) |
| BoundaryLine | Ordnance Survey (2013) |

# 9 REFERENCES

AA (2013). *Car running costs 2013/2014*, http://www.theaa.com/motoring_advice/running_costs/ (accessed January 2014)

Aldridge T, Balmforth H, Jones C, Roche N and Munday M (2011). *Economic Model for COMAH site accidents – Scoping study* HSL Report MSU/2011/01

ASH (2014). *Smoking statistics.* http://www.ash.org.uk/files/documents/ASH_93.pdf (accessed June 2014)

Ashe BSW and Rew PJ (2003). *Effects of flashfires on building occupants*, prepared by W S Atkins Consultants Ltd. for the HSE, Research Report No. 084

Burrell G and Hare J (2006). *Review of HSE Building Ignition Criteria, prepared by the Health and Safety Laboratory for the HSE, HSL/2006/33*. Available on the HSE website at http://www.hse.gov.uk/researcH/hsl_pdf/2006/hsl0633.pdf (accessed June 2014)

Cole SJ, Moore RJ, Aldridge T, Lane A and Laeger S (2013). *Real-time hazard impact modelling of surface water flooding: some UK developments,* International Conference on Flood Resilience: Experiences in Asia and Europe.

The Council of the European Union (1996). *Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances* http://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:31996L0082

Daycock JH and Rew PJ (2000). *Thermal radiation criteria for vulnerable populations*, prepared by W S Atkins Consultants Ltd. for the HSE, Contract Research Report 285/2000

Department for Transport (2012a). *Reported Road Casualties in Great Britain: 2012 Annual Report* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/244913/rrcgb2012-02.pdf

Department for Transport (2012b). *Values of Time and Operating Costs',* http://www.dft.gov.uk/webtag/documents/expert/unit3.5.6.php (accessed January 2014)

Environment Agency (2010). *The costs of the summer 2007 floods in England,* http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCRM/Project.aspx?ProjectID=A6AFBE42-51BC-4848-99C6-6F943F1687E8

European Commission (2000). *Explosion in Enschede (Netherlands): President Romano Prodi visits the scene of disaster* http://europa.eu/rapid/press-release_IP-00-489_en.htm (accessed 15th November 2013)

European Commission (2001). *Toulouse Accident – Memorandum from the French Delegation* http://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vi7jgsu8xiyc#p2 (accessed 15th November 2013)

European Commission (a). *Chemical Accidents (Seveso I, II & III) – Prevention, Preparedness and Response* http://ec.europa.eu/environment/seveso/ (accessed 15th November 2013)

The European Parliament and the Council of the European Union (2012). *Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC* http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0001:0037:EN:PDF (accessed June 2014)

Franks A (2004). *A review of HSE's risk analysis and protection-based analysis approaches for land-use planning, prepared by ERM for the HSE, Reference 0016072.* Available on the HSE website at http://www.hse.gov.uk/landuseplanning/hseriskanalysis.pdf (accessed June 2014)

Franks AP, Harper PJ and Bilo M (1996). *The relationship between risk of death and risk of dangerous dose for toxic substances*, J. Hazard. Mater., Vol. 51(1): 11 – 34

HSE website (a). *HSE's current approach to land use planning (LUP)*, http://www.hse.gov.uk/landuseplanning/lupcurrent.pdf (accessed June 2014)

HSE website (b). *PADHI: HSE's land use planning methodology*, http://www.hse.gov.uk/landuseplanning/padhi.pdf (accessed June 2014)

HSE website (c). *Toxicity levels for chemicals*, http://www.hse.gov.uk/chemicals/haztox.htm (accessed June 2014)

HSE website (d). *Failure rate and event data for use within risk assessments*, http://www.hse.gov.uk/landuseplanning/failure-rates.pdf (accessed June 2014)

HSE website (e). *Explosion based LUP siting policy for ammonium nitrate sites*, http://www.hse.gov.uk/landuseplanning/explosion-siting-policy-for-ammonium-nitrate-sites.pdf (accessed June 2014) (accessed June 2014)

HSE website (f). *Land use planning advice around large scale petrol storage sites*, http://www.hse.gov.uk/foi/internalops/hid_circs/technical_general/spc_tech_gen_43/ (accessed June 2014)

HSE website (g). *PADHI – HSE's current methodology,* http://www.hse.gov.uk/landuseplanning/methodology.htm (accessed November 2013)

HSE website (h). *PADHI+ User Guide Protecting the Public,* http://www.hse.gov.uk/landuseplanning/padhi/protecting-public/index.htm (accessed June 2014)

HSE website (i). *Control of Major Accident Hazards (COMAH)* http://www.hse.gov.uk/comah/ (accessed June 2014)

HSE website (j). *Introduction to the Seveso III directive*, http://www.hse.gov.uk/seveso/introduction.htm (accessed June 2014)

HSE website (k). *Economics of health and safety – appraisal values or 'unit costs'*, http://www.hse.gov.uk/economics/eauappraisal.htm (accessed June 2014)

HSE (2005). *A National population data base for major accident hazard modelling*, HSE Research Report: RR297.

HSE (2007). *Proposals for revised policies for HSE advice on development control around large-scale petrol storage depots and land use planning objectives and principles.* Responses to an HSC/E Consultation Document, http://www.hse.gov.uk/consult/condocs/cd211response.pdf (accessed June 2014)

HSE (2008). *Updating and improving the National Population Database to National Population Database 2*, HSE Research Report: RR678.

HSE (2011). *The costs to Britain of workplace injuries and work-related ill health in 2006/07 – workplace fatalities and self reports*, HSE Research Report: RR897.

HSE (2013) *Costs to Britain of workplace fatalities and self-reported injuries and ill health, 2010/11* http://www.hse.gov.uk/statistics/pdf/cost-to-britain.pdf (accessed 16th July 2014)

Higgins N, Jones C, Munday M, Balmforth H, Holmes W, Pfuderer S, Mountford L, Harvey M and Charnock T (2008). *COCO-2: A Model to Assess the Economic Impact of an Accident*, HPA Report HPA-RPD-046 http://www.hpa.org.uk/webw/HPAweb&HPAwebStandard/HPAweb_C/1228894710715?p=1197637096018

HMSO (2009). *The Planning (Hazardous Substances) (Amendment) (England) Regulations 2009.* Available from: http://www.legislation.gov.uk/uksi/2009/1901/body/made (accessed June 2014)

Hockey SM and Rew PJ (1996). *Review of human response to thermal radiation*, prepared by W S Atkins Safety and Reliability for the HSE, Contract Research Report No. 97/1996

Hurst NW, Nussey C and Pape RP (1989). *Development and application of a risk assessment tool (RISKAT) in the Health and Safety Executive,* Chem. Eng. Res. Des. Vol. 67(4): 362

Irx WPM and van den Berg AC (2005). *Vapour cloud explosion in Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases) 'Yellow Book'*. van den Bosch CJH, Weterings RAPM (ed), CPR 14E, TNO (The Netherlands Organization of Applied Scientific Research), Third edition, Second revised print

Jávor B and Hargitai M (2011). *The Kolontár Report: Causes and Lessons from the Red Mud Disaster* http://lehetmas.hu/wp-content/uploads/2011/05/Kolontar-report.pdf (accessed 15th November 2013)

Jones DA (1983). *A method for assessing the off-site risks from bulk storage of liquid oxygen*, 4th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Harrogate

LSL Property Services (2013). *LSL property services plc*, http://www.lslps.co.uk/ (Accessed October 2013)

McEntire D and Cope J (2004). *Damage assessment after the Paso Robles (San Simeon, California) earthquake: Lessons for emergency management*, Quick Response Research report #166, Natural Hazards Center at the University of Colorado. http://www.colorado.edu/IBS/hazards/research/qr/qr166/qr166.pdf

Miller RE and Blair PD (2009). Input-Output Analysis: Foundations and Extensions, Cambridge University Press

Lawson DI and Simms DL (1952). *The ignition of wood by radiation*, Brit. J. Appl. Phys., Vol. 3: 288

MIIB (2010). *Buncefield Investigation*, http://www.buncefieldinvestigation.gov.uk/index.htm (accessed 15th November 2013)

Office of National Statistics (2011). *Input-Output Analytical Tables, 2005 Edition*, http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-237341

Office of National Statistics (2013). *Annual Business Survey,* http://www.ons.gov.uk/ons/rel/abs/annual-business-survey/index.html

Office of National Statistics (2014). *UK Standard Industrial Classification 2007*, http://www.ons.gov.uk/ons/guide-method/classifications/current-standard-classifications/standard-industrial-classification/index.html (accessed 9th July 2014)

Petts JI, Withers RMJ and Lees FP (1987). *The assessment of major hazards: the density and other characteristics of the exposed population around a hazard source*, J. Hazard. Mater., Vol. 14: 337 – 363

Quinn DJ and Davies PA (2004). *Development of an intermediate societal risk methodology: an investigation of FN curve representation*, prepared by ERM Risk Ltd. for the HSE, Research Report No. 283. Available on the HSE website at: http://www.hse.gov.uk/research/rrhtm/rr283.htm (accessed June 2014)

Rew PJ (1997). *The LD50 equivalent for the effect of thermal radiation on humans*, prepared by WS Atkins Safety and Reliability for the HSE, Contract Research Report 129/1997

Ronzaa A, Lázaro-Touzab L, Carola S and Casala J (2009). *Economic valuation of damages originated by major accidents in port areas*, Journal of Loss Prevention in the Process Industries, Vol. 22:5: 639–648

Rushton AG and Carter DA (2009). *'Total risk of death' – towards a common and usable basis for consequence assessment*. Process Saf. Environ., Vol. 87: 21 – 25

Rushton AG and Glossop M (2005). *Study of the ratio of injuries to deaths for single incidents in the process industries*, Process Saf. Environ., Vol. 83(B4): 338 – 342

Shaw J (2012). *Flood Mitigation on the Raritan River*, prepared by Rutgers, The State University of New Jersey for the Department of Homeland Security. Available at: http://eac.rutgers.edu/wp-content/uploads/FEMAProjectReport3.pdf

Scilly NF and High WG (1986). *The blast effects of explosions, Fifth international symposium on loss prevention and safety promotion in the process industries*, Cannes, 15-19 September 1986, volume 1, paper 39, Société de Chimie Industrielle (Paris)

Trivago (2013). *Trivago hotel price index*, http://www.trivago.co.uk/hotelprices (Accessed October 2013)

Valuation Office Agency (2008). *Commercial and Industrial Floorspace and Rateable Value Statistics (2005 Revaluation), 2008 – H27 metadata*

Whitehead J (2003). *One Million Dollars Per Mile? The Opportunity Cost of Hurricane Evacuation*. Ocean and Coastal Management, Vol. 46: 1069-1083

Woo G (2011). *Calculating Catastrophe*, Imperial College Press

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# Modelling the economic impacts of an accident at major hazard sites


This report documents the development, implementation and results of a model to estimate the economic costs of accidents at major hazard sites in Great Britain, focusing on the impacts of the accident, and taking into consideration a broad spectrum of losses. A catastrophe-modelling type approach was used to structure the work, based around model components for hazard, vulnerability and economic cost. The model was developed by the Health and Safety Laboratory in Buxton (HSL) with further input from the Welsh Economic Research Unit at Cardiff Business School and HSE, and used the COCO-2 model developed by Public Health England for nuclear site accidents as a starting point of reference.

Hazard models were developed to take advantage of existing information regarding the risk around major hazard sites that is used to inform HSE's land-use planning advice. The model also took advantage of national geographic datasets on the types and locations of buildings and population, including HSE's National Population Database. The costs considered included casualty impact costs, business disruptions, business temporary locations, building damage and evacuation costs.

The model was applied to all major hazard sites in Great Britain, with average costs estimated across all sites, and for subsets based on the expected hazard, type of site, Control Of Major Accident Hazards (COMAH) classification and geographical administrative regions.



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