Illustrative model of a risk based land use planning system around petroleum storage sites.

for

Buncefield Major Incident Investigation Board

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Summary:	Model for risk based planning advice in the vicinity of large petroleum storage facilities	
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Summary

The incident that occurred at the oil storage depot at Buncefield on 11 December 2005 caused significant damage both to the terminal itself and buildings in the vicinity. The Health and Safety Commission appointed a six person board (Buncefield Major Incident Investigation Board, MIIB) to oversee the incident investigation. The MIIB has issued a number of reports covering the investigation of the incident and also responses to two Consultation Documents issued by the Health and Safety Executive. In its response to CD211 MIIB indicated that (1) advice on land use planning (LUP) should be based more on a consideration of risk, (2) more attention should be paid to the population at risk and (3) it considered that LUP should be responsive to the levels of risk presented by each particular site. In its response to CD212 it gave a view that LUP and societal risk are inextricably linked and that the planning system around major hazard sites merited a review.

MIIB does not have an in depth knowledge of the quantified risk analysis process which is used to determine the risks posed by hazardous installations, particularly in relation to major petroleum storage facilities. MIIB therefore commissioned Det Norske Veritas (DNV) to carry out some preliminary risk analysis work on a site that had similar risks to the Buncefield site, primarily to gain a better understanding of the issues associated with the determination of the risk posed by such a site.

DNV developed a QRA methodology that could be applied to a site similar to the Buncefield site and determined predictions for both individual and societal risk. The method of analysis used in the Netherlands for LUP was also applied to the same site. Consideration was then given as to whether a methodology based on risk rather than a mixture of risk and hazard could be used in the UK for future land use policy around major hazard sites.

The methodology followed the classical approach to process QRA. The general approach was to make reasonable assumptions, neither overly conservative nor optimistic so that the analysis gives a realistic estimate of the risk, although it is recognised that the error band will be quite wide, and this would need to be taken into consideration should the predictions be used for decision making. Details are given in Section 3, and the predictions are given in contour, numerical and graphical format in the Appendices. The QRA demonstrated that different assumptions representing different site conditions or different levels of safety give different risk predictions. The examples given in this analysis show the effects of changing assumptions regarding (1) the frequency of overfilling a tank (which might be achieved by a more reliable overfill protection system) (2) the reduction in the duration of the overfill (which might be achieved by gas detection and remotely or automatically operated valves) and (3) the mitigation due to different building design as well as the effect of different base frequency data. Examples of two of the predictions in the form of contour plots are shown below, one showing the frequency of exceeding a ‘dangerous dose’ (used by the HSE) and one showing the individual risk of fatality (for people in typical brick construction housing). Societal risk plots and individual and societal risk predictions using the methodology in the Netherlands are also presented in the Appendices.

The work demonstrates that it is possible to carry out a QRA of a large petroleum storage facility and generate individual and societal risk predictions reasonably quickly and without significant expense despite the uncertainties.

Figure 1 Risk of Dangerous Dose or more

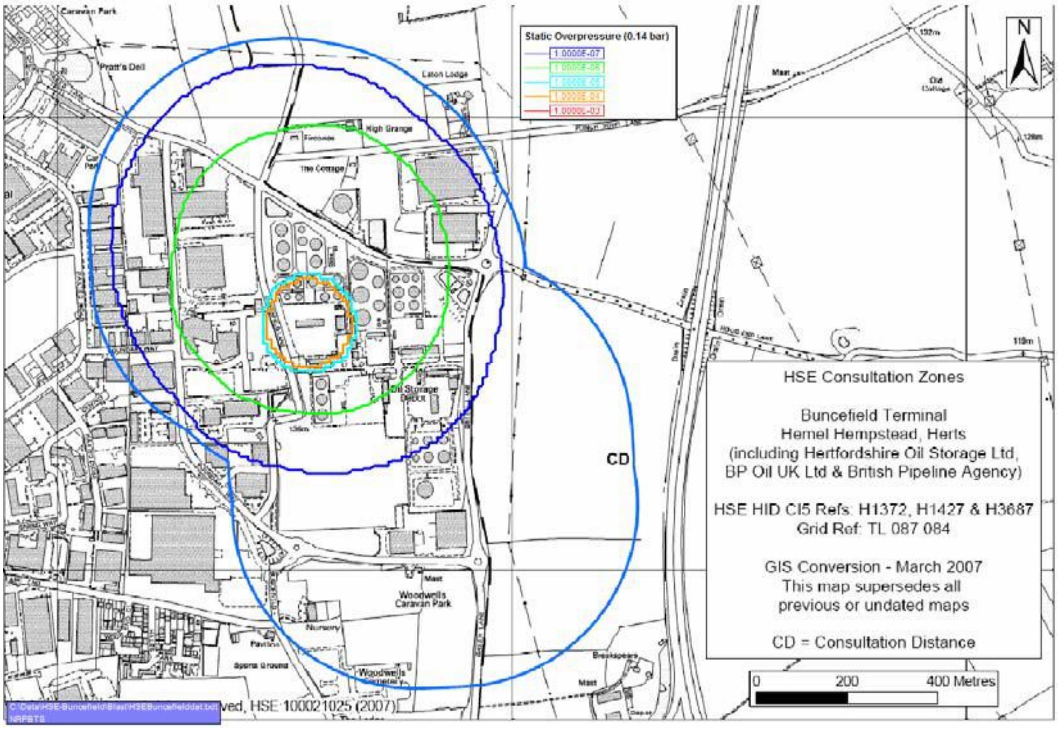

Figure 2 Individual risk of fatality.

The current system for LUP in the UK uses a combination of the protection concept (a hazard based system) and a system that uses the risk of a dangerous dose or more and derives essentially from a consultative document issued in 1989. Although a ground breaking system at that time it is now perceived to have a number of disadvantages such as (1) the differences in the two general bases used for the calculation of the LUP zone boundaries means that there is inconsistency in the definition of these boundaries which leads to inconsistencies in LUP decisions (2) as the risk of receiving a dangerous dose or more is different from the risk of fatality, which is the most common way for a QRA to express risk from process facilities, and which is used on the HSE ToR framework, there is considerable confusion when comparing numerical risk values, and when comparing LUP values based on dangerous dose with data on everyday risks (3) the risks from sites with different hazards cannot be cumulated (4) a risk calculation in the current system does not necessarily reflect the site risks as the particular operations and level of safeguards taken by the site operator are not included in the risk calculation (5) it does not easily lend itself to extension to the conventional way of displaying societal risk (either in numerical or graphical format) which is increasingly being used additionally to individual risk for decision making, especially for LUP purposes.

It would be reasonably easy to extend the type of analysis carried out for this work to all types of major hazard site and use such predictions as a platform for a LUP system totally based on risk (rather than the current system) which could remove the above disadvantages and bring the UK LUP system on a consistent basis and more in line with that in most other EU countries where a risk based approach to LUP is used. Although a move to an approach that was totally based on risk would have challenges, it could be achieved using a similar system to those in the Netherlands and Flanders where the methodology is defined by the regulator and the analysis is carried out by the site operator. The cost implications would not be excessive because much of the information required is known by the operator. Also the HSE has developed considerable expertise and state of the art models over the last 25 years which would underpin the defined methodology. There will be uncertainties associated with the frequencies to be used but these uncertainties already exist in the current system; the use of a risk based system should lead to better data becoming available, either voluntarily (as recommended by MIIB) or by regulation (as was the case for the offshore regime following the Piper Alpha disaster) which over time will improve further the robustness of the system. The predictions from the analysis could be based on the actual operations at an installation including the prevention measures, the extent and reliability of the control measures, and mitigation e.g. through building design, as these are in the site COMAH report so bringing offsite LUP decisions onto a consistent basis with the onsite decisions (to reduce risks ALARP). Further the outputs would be in terms of both individual and societal risk, which are considered necessary for the LPA to make robust and long term decisions on spatial planning.

It is recommended that the changes examined above should be given careful consideration in any review of the UK LUP system. Such changes, if implemented in the UK, would be a step towards a more consistent implementation of a small part of a single EU Directive meant to assure the safety of people living in the vicinity of major hazard sites.

Contents:

1.0 Introduction

The incident that occurred at the oil storage depot at Buncefield on 11 December 2005 caused significant damage both to the terminal itself and buildings in the vicinity. The Health and Safety Commission (HSC) appointed a six person board (Buncefield Major Incident Investigation Board, MIIB) to oversee the incident investigation. During the time since the incident the Health and Safety Executive (HSE) has issued two consultative documents (CD), one concerned with future land use policy around sites similar to Buncefield (CD211) and one associated with societal risk (CD212). These were supported by research reports (RR511, RR512). The MIIB has issued a number of reports covering the investigation of the incident and also responses to the CD's. In its response to CD211 MIIB indicated that (1) advice on land use planning (LUP) should be based more on a consideration of risk, (2) more attention should be paid to the population at risk and (3) it considered that LUP should be responsive to the levels of risk presented by each particular site. In its response to CD212 it gave a view that LUP and societal risk are inextricably linked and that the planning system around major hazard sites merited a review.

The HSE is responsible for providing advice to local planning authorities (LPA) on the hazards and risks associated with major hazard sites. The HSE is a statutory consultee for proposed major hazard sites and determines a consultation distance (CDi) for each major hazard site within which it recommends that development should be controlled by the LPA. In general the CDi is risk based for sites which handle toxic materials and hazard based (known as the protection concept) where sites handle flammable materials. Details of HSE's approach have been documented (HSE 1989, HSE LUP, RR511, ERM 2004). Following a Fundamental Review (FRLUP) the HSE has issued to all LPAs software referred to as PADHI, Planning Advice for Developments near Hazardous Installations). This enables the LPA to quickly determine whether a specific application for development within the CDi should or should not be granted permission given the type of development and its location with respect to the CDi and other planning zones (also determined by the HSE), based on HSE's experience over the last 15 years.

Following the review of responses to CD211, HSE has revised the consultation arrangements around major petroleum storage sites. Option 4 in CD211 is being implemented. Option 4 used societal risk information in RR512 to define a new inner zone (Development Proximity Zone) where development would be particularly restricted, and thus extended the use of QRA to sites handling flammable materials where previously only the protection concept had been used as the basis for determining LUP zones.

MIIB considers that in principle risk should be the basis of LUP around all major hazard sites, but did not have an in depth knowledge of the process, particularly in relation to major petroleum storage facilities. MIIB therefore commissioned Det Norske Veritas (DNV) to carry out some preliminary risk analysis work on a site that had similar risks to the Buncefield site, primarily to gain a better understanding of the issues associated with the quantification of the risk posed by such a site.

2.0 Scope of work

The scope of work defined by MIIB was as follows:

a. Provide an independent view on what a risk based approach to land use planning in the vicinity of large petroleum storage facilities might involve and show how this might be achieved in practical terms. This would include consideration of risk based options in place elsewhere, particularly in Europe, including their perceived limitations. It would take into account HSE published material, and previous reports of MIIB and the hierarchy of control of major hazard risks.
b. Establish the nature of data that need to be determined or assigned in order to produce a risk based model, and their source.
c. Show whether such a model can incorporate inherent risk reduction measures as called for in MIIB reports.
d. Show to what extent such a model could be used to determine societal risk and therefore provide an input into any decision making process.

2.1 Approach

The approach to this work was as follows:

- Develop a methodology that could be applied to a site similar to the Buncefield site that would enable a quantified risk analysis (QRA) to be carried out which would give predictions for both individual and societal risk, identifying the major uncertainties in the analysis.
- Apply the methodology used for risk assessment/development control in the Netherlands to the same site.
- Review the predictions and consider whether a methodology based on risk rather than a mixture of risk and hazard could be used in the UK for future land use policy around major hazard site.

3.0 Methodology

The methodology used analyses the potential impact of the defined system on people in the vicinity. It does not cover all the hazards and risks that would be experienced onsite nor does it address possible environmental effects. It follows the classical approach to process QRA:

- Define the system to be analysed
- Characterise the system with a representative set of scenarios
- Determine the consequences, frequencies and impact of the scenarios
- Combine these to give risk predictions

There is no comparison with criteria or assessment of the predictions.

For any QRA, it is necessary to define quantitatively all the consequence and frequency values that characterise each scenario. In most process QRAs, the numerical values can fall into the following categories:

- relatively sound and robust, e.g. discharge rates from the atmospheric tank, weather data.
- values that have been used in previous QRAs (and which have therefore developed reasonable acceptance by practitioners, e.g. generic failure frequencies, explosion overpressure decay)
- values that are based on relatively little knowledge or data and derived by extrapolation or ‘judgement’, e.g. ignition and explosion probabilities, gas dispersion

Many of the events included in this QRA (and in particular the events which generate overpressure) were, prior to the Buncefield incident, not considered foreseeable. However, after

Buncefield these events are foreseeable, but because of the rarity of this type of incident the approach for the determination or estimation of many values used has been to either develop methodology and assumptions specifically for the analysis (e.g explosion decay modelling) or to extrapolate from existing models (e.g. cloud formation).

The steps taken and assumptions made in the methodology are given below; further details are given in the Appendices.

3.1 The System

The system that has been analysed is shown in Figure 3. It comprises part of the Buncefield site, including the tanks in the vicinity of Tank 912 which was the source of leakage. The sources of hazard used to characterise the system are shown in Table 1.

Figure 3 Plan showing the Boundary of the Study

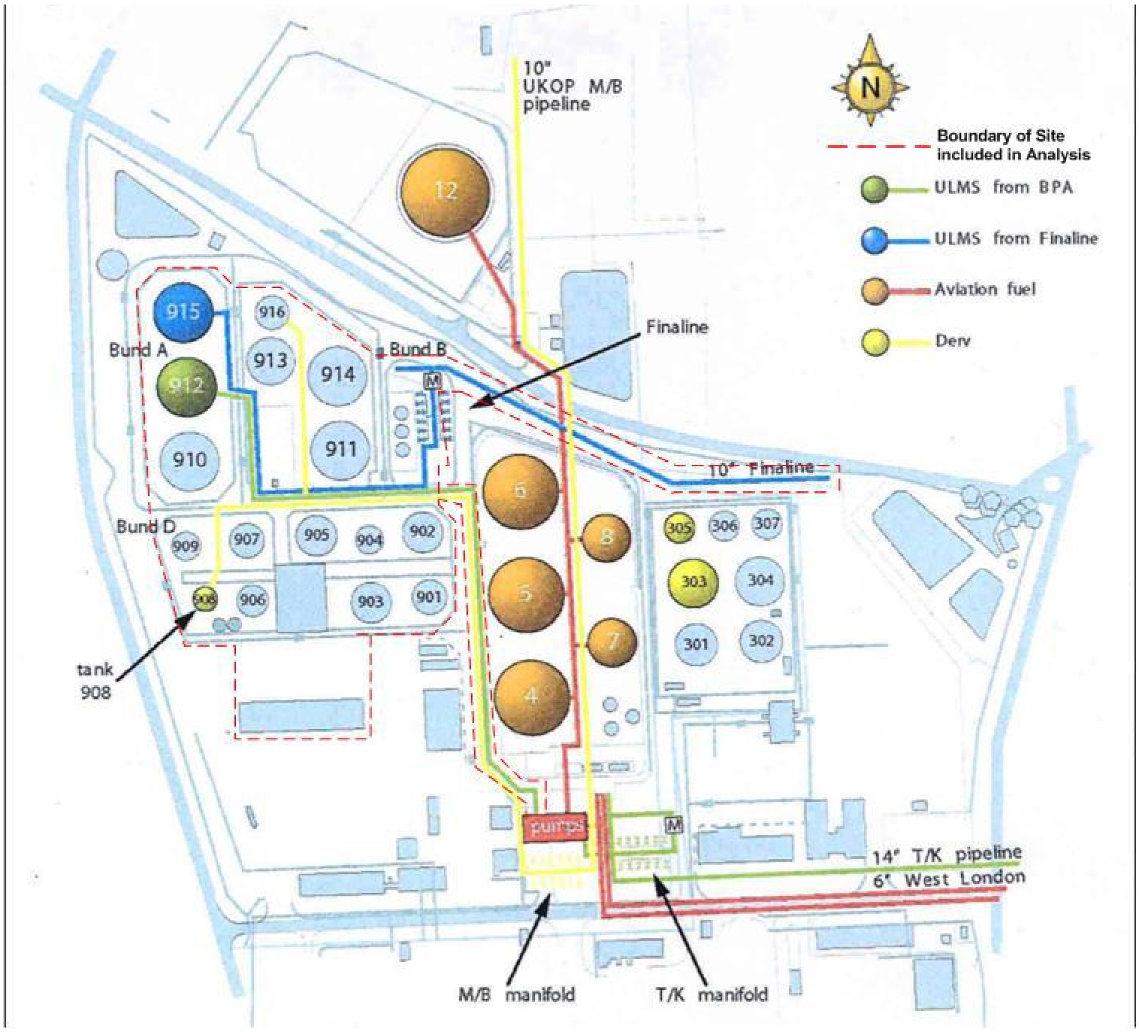

Table 1 Description of Hazard Sources

Bund	Tanks	Material	Feed Pipeline
A	910	Gasoline	T/K
	912	Gasoline	T/K
	915	Gasoline	Finaline
B	911	Gasoline	Finaline
	913	Diesel	
	914	Diesel	
	916	Diesel	
C	901	Gasoline	T/K
	902	Gasoline	T/K
	903	Gasoline	T/K
	904	Gasoline	T/K
	905	Gasoline	T/K
D	906	Gas Oil (1)	
	907	Gas Oil (1)	
	908	Diesel	
	909	Gas Oil (1)	
Piping	From/To		
T/K	Pumping area to tanks	Gasoline	
Finaline	East of site to tanks	Gasoline	
Tank	Tanks to pumps	Gasoline/ Diesel	
Loading	Pumps to loading rack	Gasoline/ Diesel	

(1) Neglected in the subsequent analysis as the contribution to the risk is very small.

3.2 The Scenarios

The scenarios used to characterise the system and determine the risk predictions have been derived by ‘breaking each part of the system’ to give loss of containment, together with an overfill scenario for each gasoline tank. A full scenario list is given in Appendix II. As the study is primarily concerned with offsite risks, only full bore failures or large holes have been included.

3.3 Consequence Analysis

The consequence analysis has used a blend of HSE and DNV methods. The hazard types analysed were:

- Pool fires
- Flash fires
- Vapour cloud explosions

Consequence analysis encompasses the determination of:

- Discharge rate
- Source term for the hazards above in terms of a pool or cloud size

x Relationships between the hazard and heat or overpressure levels which could affect people

3.3.1 Discharge Rate

Discharges were either from pumped sources or from tanks. The former were assumed to be at 110% of the normal flow rate and the latter were determined by conventional methods assuming a discharge coefficient of 0.8. Release rates used for each scenario are given in Appendix II.

3.3.2 Source Term for Fire and Explosion Hazards

The discharges of gasoline were assumed to give both a pool and a vapour/aerosol cloud. On ignition, the pool would give a pool fire and the cloud would give a flash fire, sometimes accompanied by overpressure and followed by a pool fire. The pool fire following the cloud ignition was not modelled.

The gasoline was assumed to contain 10% w/w of material that could potentially enter the cloud, and this material was assumed to be butane (C4). The Buncefield event showed that an overfilling event could generate significant vapour, but it was considered that other release types, e.g. from the feed or discharge piping, would not produce as much vapour given the same release rate as there would not be the same mechanisms for spray formation and liquid break up. A simple factoring relationship was used to allocate a vapour formation rate (either very high, high, medium, low or none) depending on the material (diesel was assumed not to give a significant spray under any release conditions) the rate of release and the height of the release. The fraction of the available C4 that was assumed to enter the cloud was 1, 0.75, 0.5 and 0.25 for these descriptions respectively. Only release rates above 300 m^3/h and from a height were assumed to be capable of giving the 'very high' vapour formation rates (when 10% of the release could enter the cloud). The release rates prior to the Buncefield incident were 550 m^3/h initially rising to 890 m^3/h. The allocation of the vapour formation type for each scenario is shown in Appendix II.

Conventional dispersion codes normally used to predict the size and shape of a vapour cloud, particularly the 'steady state' cloud, cannot be used with accuracy at low wind speeds, and the use of CFD techniques was beyond the scope of this analysis. The size of the steady state cloud and the time taken to reach this cloud was therefore derived by extrapolation of predictions for low wind speeds (1, 2 and 3 m/s) under inversion conditions (Pasquill F stability) in DNV's PHAST consequence model. When applied to the Buncefield release assuming a wind speed of 0.25 m/s, the steady state cloud for the initial release rate was predicted to be approximately 190,000 m^3 and reach steady state after 30 minutes, whereas the steady state cloud for the second release rate was predicted to be approximately 480,000 m^3 and reach steady state after 49 minutes. Using the burn area as the cloud area and a uniform depth of 2m, the cloud at Buncefield was estimated to have a volume of some 300,000 m^3. Further, it was observed (RR511) that the cloud was still spreading at the time of ignition, indicating that the cloud had probably not reached steady state for the second release rate. These data extrapolations were used to predict the time to achieve steady state and the volume of the steady state cloud for all the releases where there was vapour formation in wind speed conditions below that which gas dispersion codes used in QRAs may be less accurate (0.5 -1 m/s) (see Appendix II). The dispersion code in DNV PHAST was used to predict cloud dimensions in 2F conditions and the time to achieve steady state.

This technique was not applicable to large discharge short duration releases (from tank failures). The clouds generated by these failures would be very rich initially, and subsequently could give very large flammable clouds. It was not attempted to predict the size of these clouds; rather they were all assigned to one of the explosion clouds which then determined the consequences (see later).

For the subsequent analysis of flash fire and explosions, the steady state cloud was assigned to one of six cylindrical shaped clouds used for the overpressure analysis (see later section).

3.3.3 Pool Fires

These were analysed using a solid flame technique. The pool was assumed to be circular and at steady state (i.e. the rate of burning was taken to be equal to the rate at which material was discharged) with a pool depth at least 10mm thick. Releases from the tank (tank holes) were assumed to give a pool within the bund, whereas catastrophic tank releases were assumed to overtop the bund and to give a pool 100m diameter (as HSE assumption). The flame was assumed to be a cylinder. Flame height, flame drag and tilt angle were determined by recognised techniques (Thomas, Moorhouse, Johnson). The fraction of heat radiated was varied from 0.4 (for a pool of 5m diameter) to 0.05 (for pools with a diameter of 100m) so that the predicted distance to 1000tdu was similar to that predicted by the HSE. Two different methods were used to determine the surface emissive power (SEP) and the average value was used in the subsequent calculations. The SEP was then distributed over a two zone flame, with a lower section radiating at 140 kW/m^2 and an upper section radiating at 20 kW/m^2 so that the average SEP was equal to that calculated above (up to a maximum of 140 kW/m^2). View factors and transmissivity were calculated using standard techniques (Pietersen and Huaerta).

Examples of calculated values to thermal radiation levels downwind are given in Table 2. Both gasoline and diesel have been assumed to give the same thermal radiation effects, and a wind speed of 5m/s has been assumed. In order to develop a hazard area from the hazard distance, the offset ratio (from previous analyses) varies between 0.25 (10m diameter pools) and 0.33 (100m diameter pools). This was used to derive the ellipse dimension in the downwind direction and the crosswind dimension was made equal to the downwind dimension.

Table 2 Pool Fire Characteristics

Diameter m (1)	SEP kW/m^2	Distance (m) to 25 kW/m^2 (2)	Distance (m) to 1800tdu (2)(3)	Distance (m) to 14 kW/m^2 (2)	Distance (m) to 1000tdu (2)(3)
10	140	25	13	31	16
25	137	48	29	62	38
50	65	66	46	82	57
100	38	91	70	110	85

(1) Without drag
(2) Measured from pool centre
(3) tdu - thermal dose units (kW/m^2)$^{4/3}$ s. Distance from the fire from which a person can escape at a speed of 2.5 m/s to a location 75m from the start location and during this time accumulates the specified dose.

3.3.4 Vapour Cloud Explosions

A vapour cloud explosion (VCE) occurs when a flammable cloud is ignited and the flame is accelerated. Explosions can also occur if the ignition is within confinement, eg within a storage tank, but this type of explosion has not been considered in this analysis. The level of overpressure is a function of the flame speed achieved during combustion.

The mechanism of cloud formation and subsequent dispersion prior to ignition when the cloud is generated by droplets from a spillage of a material like gasoline is complex and cannot be predicted accurately by dispersion models that are traditionally used in process QRAs (Atkinson). It is often assumed that when a flammable cloud is ignited, the cloud is at steady state and the average composition in the cloud is stoichiometric. It appears likely that the cloud that was generated at Buncefield contacted an ignition source before reaching steady state for the second (larger) release rate as the cloud was still spreading at the time of ignition.

The observed effects from the Buncefield explosion (Table 14, RR511) were used to give a damage category. This was dependent on the type of building using either the world war II damage categories (A, B, Cb, Ca or D) or using damage categories from the BEAST program (see Appendix III). These were then associated with an overpressure and plotted with distance. This gave two decay curves, one representing the minimum distances and one representing the maximum distances. Coefficients that could be used with the Multi Energy model (Van den Berg) to predict overpressures at different distances from the cloud boundary were then derived (see Appendix III). An overpressure of 350mbar (category B damage) was assumed at the edge of the cloud.

It is likely that there is a minimum size of cloud that is necessary for the combustion to generate overpressure, but this threshold value is not known. It was assumed that this minimum volume was 12000 m^3 (approximately one tonne of flammable material). It was further assumed that the maximum cloud size was 400,000 m^3 (cloud sizes larger than this could probably be formed but ignition was assumed to prevent larger clouds). Five different cloud sizes were designated to represent exploding clouds within this range. Each was associated with a minimum and maximum overpressure decay curve. The minimum decay curves were the same for each cloud, but the maximum was increased using a ratio derived from the Multi Energy curve 5 (overpressure of 200 mbar at the cloud edge). The decay curves are shown in Appendix III, the allocation of the clouds determined above to a steady state exploding cloud, and distances to certain overpressure levels for these clouds are given in Table 3.

The volume of a clouds in 2F conditions predicted by PHAST was considerably smaller than those predicted for a wind speed of 0.25 m/s for the same cloud rate. Further, the cloud volume for the largest overspill rate was, in D5 conditions, predicted to be considerably smaller than the threshold cloud volume used for explosions. It was therefore assumed that clouds that were sufficiently large to cause an explosion only occurred in conditions when the wind speed was low (characterised by wind speeds of 0.25 and 2 m/s and inversion conditions).

Table 3 Relationship between Predicted Cloud Volume, the Volume of Cloud used for Overpressure Calculations and Distances to Specified Overpressure Levels

Cloud volume (m^3) from release rate and duration	Cloud Description	Distance (m) to 160mbar (1)	Distance (m) to 80mbar	Distance (m) to 30mbar
>350000	400000 Max	351	583	865
>350000	400000 Min	227	300	470
250000-350000	Buncefield Max	318	528	783
250000-350000	Buncefield Min	220	293	463
150000-250000	200000 Max	279	462	686
150000-250000	200000 Min	208	281	451
50000-150000	100000 Max	220	366	542
50000-150000	100000 Min	180	253	423
12000-50000	30000 Max	148	245	363
12000-50000	30000 Min	99	172	342
>12000	No VCE			

SummaryofDocs/MEM

(1) Measured from cloud centre.

It was assumed for the tank holes all of the above clouds could occur, but for catastrophic tank failures, only the two largest clouds were assumed.

3.3.5 Flash Fires

The size of the flash fire was assumed to be the same as the cloud used for the explosion calculation.

3.4 Impact

The impact of a flash fire is only relevant within the flash fire envelope; pool fires and explosions can affect people beyond the fire/burning cloud envelopes. For pool fires two levels were used to define the boundaries of envelopes outside the pool fire itself. The likelihood of fatality within the defined envelopes was assumed to be constant. For explosions a similar method was used except six envelopes were used rather than two. The assumed fatality probabilities for people indoors are shown in Table 4 for pool fires and in Table 5 for explosions.

Table 4 Fatality Probabilities for Immediate Ignitions - Pool Fires

	>25kW/m2	14-25kW/m2
All buildings	0.9	0.1

Buncefield Blast/Populations

Table 5 Fatality Probabilities for Delayed Ignitions - Explosions and Flash Fires

	30-70mbar	70-100mbar	100-140mbar	140-150mbar	150-350mbar	>350mbar	Flash fires
CIA2	0.0025	0.008	0.023	0.040	0.345	0.646	0.1
CIA3	0.0121	0.033	0.070	0.102	0.321	0.531	0.1
Beast1	0.00005	0.00005	0.00005	0.009	0.009	0.244	0.1
Beast1 Damage	2A	2A	2A	2B	2B	4	
Beast3	0.00005	0.00005	0.01	0.141	0.141	0.394	0.1
Beast3 Damage	2A	2A	2B	3	3	4	
Beast11	0.00004	0.0125	0.0125	0.161	0.161	0.494	0.1
Beast11 Damage	2A	2B	2B	3	3	4	

Buncefield Blast/Populations

The envelope for the flash fire and for >350mbar are the same, and it is assumed that the fatality probability within the ignited cloud is the sum of the overpressure and the flash fire probab when there is overpressure generation and just the flash fire probability if there is no overpressure generation

The assumed damage categories for the BEAST type buildings are together with the assumed fatality probability (50% the serious injury probability)

People outdoors are likely to be able to escape from pool fires and overpressure effects are considerably less serious than for people within conventional buildings. Although people would be expected to spend some time outdoors this has been neglected.

3.5 Frequency Analysis

3.5.1 Loss of Containment

The frequencies used for loss of containment events were taken from the data used by the HSE (using internal HSE documents dated 2005 obtainable under ‘Freedom of Information’). These are shown in Appendix I. These frequencies are assumed to cover all failure modes except for overfill. As the analysis is primarily concerned with major releases and offsite effects, only the largest failures have been included (except for two hole sizes in the feed pipelines and two hole sizes in the tank failures).

3.5.2 Overfill

Three data sources have been used to determine the frequency for tank overfill. These are shown in Table 6.

Table 6 Overfill Frequencies

Value	Unit	Source	Comment
4.00E-04	per tank per year	Lastfire Report (Table 7)	Average frequency value. Open top floating roof tanks only, spills outside tank shells
1.00E-03	per tank per year	Lastfire Report (Table 7)	Upper frequency value. Open top floating roof tanks only, spills outside tank shells
1.06E-04	per tank per year	Lastfire Group (1)	Preliminary value based on 16 overfills in 150000 tank years. All types of tank greater than 10m high
5.47E-03	per tank per year	Major Oil Company (2)	18 overfills in 3300 tank years
3.00E-04	per tank per filling operation	Major Oil Company	18 overfills in 60000 filling operations

(1) These data are considered to be the most rigorously collected data available. The overfilling incidents have not been broken down for different tank types. The figure is preliminary pending finalisation of Phase1 of the Lastfire Update study which is due at the end of 2008. The overfilling incidents represented approximately 14% of spills into the bund (which approximates to the findings in the earlier studies). The Lastfire Group currently consists of 16 members but it is intended to expand the Group with new members once the current phase has been completed.
(2) These data are from a major oil company (termed MOC) provided to DNV by MIIB.

The MOC data indicated that the probability of a major overfill (rather than a minor overfill) was 0.25. The derivation of a frequency for tank overfill is more complex than the simplistic product of the probability of an overfill per filling operation and the number of filling operations per year (which would typically be used to derive a generic frequency). However, this method has been used in this analysis with an assumed filling operation on each tank of 13 per year. This gives a frequency of a major overfill as 1E-03 per tank per year. This may be compared with a value of 2.65E-05 per tank per year from the Lastfire Group data (assuming the same probability of a major overfill). With nine gasoline tanks in the study system, the predicted frequency of a major overfill event on a gasoline tank would be once every 110 years (MOC) or once every 4200 years (Lastfire Group). The analysis has used both these values.

The frequencies used for each scenario (with MOC overfilling frequencies) including multiplying factors and usage factors for piping are shown in Appendix II.

3.5.3 Tank Events

The frequency of a large release of gasoline from a tank is predicted (HSE frequencies) to be once every 384 years (for catastrophic, major and minor failures). The Lastfire Group data do not record tank events in the format used by the HSE, nor is there a full record of hole size for the releases, but if corrosion, weld failures, roof instabilities and ‘not recorded’ are all assumed to give small releases, and two thirds of operator error are small (one third large), but all earthquake events are large and mixer releases and pipework releases are excluded, then the ratio of large tank release events to large overfill events is 1:1, i.e. the likelihood of a large release from overfill is approximately the same as a large release from the tank by other mechanisms (using the MOC probability of a large overfill). The ratio using the Lastfire Group frequency (once every 38000 tank years) and the HSE predicted frequency is approximately

100, i.e out of 100 major releases from a tank 99 will be from tank events and 1 will be from overfill. This seems to be inconsistent with experience.

Frequencies for tank events are defined in the Purple Book (which is used for QRA's in the Netherlands) and are shown in Appendix I. These are in terms of an instantaneous release, a release of the whole contents in 600s and a release from a hole with diameter 10mm. The tank to overfill ratios using these values and the Lastfire Group values are 4 tank releases per major overfill (with the 10mm hole included in the tank events) or 1:1 (with the 10mm tank event excluded). These ratios seem more in line with the experience of the Lastfire Group members.

3.6 Ignition Probabilities

Data on ignition probabilities for major releases of flammable materials onshore are virtually non existent. Hence for the purposes of the analysis a simple framework has been used. It was assumed that delayed ignition could occur after the following release durations: 120s, 300s, 600s, 1800s or 2700s. The framework allocated a probability of immediate ignition of 0.1 (i.e. pool fire consequences only, no flash fires or explosions) for all releases. It was further assumed that the largest cloud (diameter of 450m) which was in existence for the longest time (2700s) had a probability of non ignition of 0 (immediate ignition probability of 0.1 and delayed ignition probability of 0.9), i.e. the overall probability of ignition was unity. Smaller clouds and clouds in existence for a shorter time were allocated delayed ignition probabilities by interpolation with associated probabilities of non ignition. The delayed ignition probabilities for all the releases are given in Appendix I.

3.7 Explosion Probabilities

The probability of overpressure generation during the combustion of the flammable cloud is dependent on a number of factors (e.g size of cloud, number and size of features within the cloud that could cause flame acceleration). There are no data on which to base the probability of explosion given ignition of a large flammable cloud in and around atmospheric storage tanks. However, given Buncefield the probability is not zero. Again a simple relationship was used which assumed that the larger clouds were more likely to give explosion effects than the smaller clouds (more likely to cover the features that could cause flame acceleration), (see Appendix I). The overpressure outside the cloud was assumed to follow the overpressure decay curves described earlier with an equal probability for the maximum line and the minimum line.

The loading rack was assumed to be sufficiently congested that a leak from the rack could, on ignition give overpressure. The explosion frequency was assumed to be once every 10000 years, and the source overpressure was 1 bar (MEM line 7).

3.8 Meteorological Conditions

It has been determined that the cloud sizes were above the minimum volume considered for explosions only in low wind speed conditions. It was assumed that calm conditions (0.25 m/s wind) and low wind speed with inversion (2F) each occurred for 10% of the time. Although these conditions are unlikely to occur during the day, meteorological conditions for the day and the night were assumed to be the same.

3.9 Population

In order to calculate the societal risk, data on the population in the vicinity of the installation are required. Precise data were not available on the type of building in the vicinity of the Buncefield site and the number of occupants, so assumptions were made. These are shown in Table 7. The location of the buildings is shown in Appendix XIV.

3.10 Risk Determination

The risks associated with the defined scenarios were determined by combining the various consequences and frequencies in the BLAST program, a risk calculation program developed internally in DNV. The explosion calculations were carried out within BLAST, then the risks from the various hazards were determined on a coordinate grid system and for the defined population.

3.11 Analyses

A number of different analyses have been carried out with the following assumptions:

- The overfill frequency was as per the MOC data, with tank failure data as per the HSE.
- The overfill frequency was as per the Lastfire Group data, with tank failure data as per the HSE
- The overfill frequency was as per the Lastfire Group data, with tank failure data as per the Purple Book
- The overfill frequency was as per the Lastfire Group data, with tank failure data as per the Purple Book with mitigation measures to ensure that the release duration did not exceed 600s

A small sensitivity has also been carried out to examine the effects on the societal risk of moving the Northgate building 100m and 200m further away from the installation.

Table 7 Population Assumptions

Name	Type	Description	Number of People during day	Number of People during night
3 Com	Beast3	Steel framed structure with unreinforced masonry (CMU or brick) infill walls (non-load bearing) and a reinforced concrete or metal roof.	50	1
Andromeda	Beast1	Steel framed structure with metal panels for roof and wall cladding	25	1
Avica	Beast1	Steel framed structure with metal panels for roof and wall cladding	25	1
BOC	Beast1	Steel framed structure with metal panels for roof and wall cladding	25	1
Catherine House	CIA2	Concrete frame office building	25	1
Eaton Lodge	CIA3	Brick structure	8	1
Fuji	Beast11	Reinforced concrete frame structure with unreinforced masonry infill walls and a reinforced concrete roof	50	1
High Grange	CIA3	Brick structure	7	1
ISA	Beast1	Steel framed structure with metal panels for roof and wall cladding	25	1
Keystone	Beast1	Steel framed structure with metal panels for roof and wall cladding	50	1
Northgate	Beast11	Reinforced concrete frame structure with unreinforced masonry infill walls and a reinforced concrete roof	400	10
Ramsays	Beast1	Steel framed structure with metal panels for roof and wall cladding	10	1
RO	Beast3	Steel framed structure with unreinforced masonry (CMU or brick) infill walls (non-load bearing) and a reinforced concrete or metal roof.	10	1
The Cottage	CIA3	Brick structure	3	1
Warehouse (Empty)	Beast1	Steel framed structure with metal panels for roof and wall cladding	0	0
Waverley	Beast1	Steel framed structure with metal panels for roof and wall cladding	25	1

4.0 Predictions

The predictions are given in terms of:

- Hazard frequency and individual risk contour plots
- Individual risk at specified locations
- Societal risk.

The preliminary analyses showed that:

- Only the overfill events, the failure of the feed pipelines and the tank failures gave cloud formation rates that were sufficient to give a vapour cloud above the threshold explosion volume (ie the other scenarios gave only flash fires and pool fires).
- The contribution to the offsite risk from explosions following the failure of the feed pipeline was insignificant compared with the overfill and tank events.
- The pool fires do not give levels that are considered to give fatal injuries at any of the buildings.

Consequently neither the pool fires nor the explosions due to failure of the feed pipeline have been included in the predictions presented.

The explosions included in the analysis have the potential to cause significant knock on effects (failure of adjacent tanks and subsequent ignition of released liquids, as occurred during the incident). The effects of these secondary events have not been included in the risks presented in this report.

4.1 Hazard Frequencies

The predicted explosion frequencies for the various systems analysed are shown in Table 8. The frequency of exceeding 0.14 bar (HSE Dangerous Dose) and 0.07 bar (HSE Dangerous Dose for vulnerable population) are shown in contour format in Appendix IV to Appendix XIII for the four different assumptions (section 3.11).

Table 8 Explosion Frequencies

Description	MOC Overfill Data HSE Tank Data	Lastfire Group Overfill Data HSE Tank Data	Lastfire Group Overfill Data Purple Book Tank Data	Lastfire Group Overfill Data Purple Book Tank Data with reduced release of overfills
Explosion Frequency (per year)	2.39E-04	1.26E-04	1.06E-04	1.08E-04
Every x years (event return period)	4177	7931	9472	9261
Explosion Frequency (per year) excluding the loading rack explosion	1.39E-04	2.61E-05	5.57E-06	3.81E-06
Every x years (event return period)	7175	38326	179488	262385

These values may be compared with an explosion frequency on a typical refinery unit every 2300 years (API 752), so the predicted frequency of explosion on a refinery with 10 typical units would be once every 230 years.

4.2 Individual Risk

The predicted individual risks of fatality in contour format are shown in Appendix IV to Appendix VIII. Also shown on each plan is the CDi determined by the HSE following the incident. The fatality risks were calculated for people in typical brick dwellings occupied for 365 days per year. Comparable contour plots for people in steel frame brick infill buildings for an occupancy of 50 hours per week are shown in Appendix IX. The individual risks at the buildings are given numerically in Appendix X. These take into account the mitigation of the particular building type as well as the location of the building with respect to the installation (but not the population within the building). The individual risk of fatality due to tank events only are also shown together with the percentage of the individual risk due to tank events alone. The risk from the tank events represents, more or less, a baseline risk from the installation (although it is possible to reduce the risks from overfilling by control and mitigation measures it is difficult to incorporate risk reduction measures that can be represented numerically for tank events).

4.3 Societal Risk

Societal risk is normally presented graphically, where the frequency of killing N or more people (F) is plotted against N. The societal risks for the system analysed and the population assumptions given in Table 7 are shown in Appendix XI. The different curves show the overall risk and the risk due to tank and overfill events separately. The risks from the loading rack are shown (in the first curve in Appendix XI) to be very small so these are not included in the subsequent plots.

Societal risk can also be presented in terms of a single number. This is the sum of the product of the frequency of each of the outcomes from the analysis (f) and the number of fatalities associated with that outcome (N). In some cases the value of N is raised to a power, which gives relatively more weight to the events that kill large numbers of people, but when the power is unity the number is referred to as the potential loss of life (PLL) or Expectation Value (EV in

RR512). The predictions of PLL for the different assumptions analysed and showing a breakdown in terms of the various buildings included are presented in Appendix XI.

5.0 Approaches to Land Use Planning in the Netherlands and Flanders

The Seveso Directive requires that competent authorities within the EU exercise land use planning controls, but does not specify the method that should be used. The two main approaches used some 10 years ago were the 'consequence' based approach and the 'risk' based approach (Christou and Porter). The Netherlands has used a risk based approach to LUP for many years. In Belgium, offsite safety is a regional responsibility (whereas onsite safety is a Federal responsibility) and there are three regions; Brussels, Wallonia and Flanders. Most of the Belgian top tier Seveso sites are in Flanders, and this region uses a risk based approach to LUP. Most of the other Seveso sites are in Wallonia which uses a LUP system based on quantification of consequences with qualitative consideration of frequencies. The system in Brussels is not well defined (but the system in either Flanders or Wallonia may be used). The approaches in the Netherlands and Flanders have some common elements but are not identical. Some relevant features of the approaches are given below:

- In the Netherlands statutory legislation regulates the 'environmental quality' requirements for (a) offsite safety and land use planning in the vicinity of major hazards and (b) for new major hazard sites. Flanders has a similar regulatory system
- The methodology to determine the risk is defined by the competent authority. This includes the scenarios, the frequency for the scenarios and the determination of the consequences and impact. Most details for the Netherlands are given in the Purple Book (in English) and its successor 'Handboek Risicoberekeningen' (Manual for Risk Assessments) (only in Dutch). The Flanders guidance is in VR-richtlijnenboek (Guidebook for Safety Reporting)
- In the Netherlands the risks are now determined using specified software (SAFETI^{NL}). In Flanders the risks have to be determined by an approved company/person using validated software. In both cases the QRA is produced by the occupier of the hazardous installation
- In both countries the measures used for risk are the individual (location based) risk of fatality and societal risk

In the Netherlands, the location risk contour of importance is 1E-06 per year. The maximum tolerable location risk from new installations is 1E-06 per year (from existing installations it is currently 1E-05 per year but this relaxation will be phased out by 2010). From 2010 all 'vulnerable objects' should be beyond the 1E-06 per year contour for all installations. The risk values are binding on the Provincial authorities (and these authorities have a duty to explain decisions relating to the level of societal risk or when they accept individual risk above 1E-06 per year, only till 2010). The Provincial authorities are responsible for decision making in terms of granting permits for the hazardous installations and land use planning in the vicinity of the installations and hence for guaranteeing adequate safety in the vicinity of the major hazard sites.

The predicted individual and societal risks for the system defined in section 3.1 are shown in Appendix XII [1]. It can be seen that one of the offsite buildings is within the 1E-03 per year contour and other buildings are within the 1E-05, 1E-06 and 1E-07 per year contours. The predicted societal risk is above the upper criterion line (all people offsite who are not employed by companies with similar risks to those of the hazardous installation are considered in the

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[1] SAFETI ^{NL} is used for the determination of risks in the Netherlands. This software is based on DNV's SAFETI program. The analysis in this report used the current version of SAFETI with the same parameters as SAFETI ^{NL} so the predictions will be similar to but not necessarily the same as the predictions from SAFETI ^{NL} .

calculation). The implications of these risk predictions are not necessarily straightforward. Each hazardous installation in the Netherlands has a QRA that was carried out several years ago using the methodology that was approved by the authorities at that time, and was used as a basis to issue the required permit. For this type of site that methodology is likely to be similar to that at Buncefield prior to the explosion, i.e. based on pool fire hazards which would give contours much closer to the storage tanks than those shown in Appendix XII. If the hazardous installation has not changed since the time that the QRA was carried out, there is no requirement to update the QRA. If/when there is a change to the hazardous installation, e.g. one of the tanks is to be changed from diesel storage to gasoline storage, then there is a requirement to carry out a new QRA using SAFETI^{NL}. In addition, today the Dutch authorities request that new QRAs for all Seveso sites are performed with SAFETI^{NL}, even if no significant changes have occurred. If the Provincial authority was presented with these risk contours then the authority could either refuse to grant a change to the permit, or could discuss the risk predictions in more detail before coming to a decision regarding the acceptability of the risks. In some cases the national regulator (VROM/RIVM) would be asked to comment as to whether the risk analysis was sound, i.e. had been carried out in accordance with the current requirements for assumptions etc and sometimes the operators of the hazardous installation would be asked to interpret the risk predictions. Sometimes the operator would have a dialogue with the occupants of the buildings within the 1E-06 per year contours to investigate the possibility of relocation (but this dialogue would be separate from the discussions with the authorities). The Provincial authority would take into account advice from the various organisations, and other advice as it saw fit, prior to making a decision on the acceptability of the proposed change to the hazardous installation. The authority may well accept off site buildings within the 1E-06 per year contour (till 2010) but would be very unlikely to accept a situation where there were offsite occupied buildings within the 1E-04 or 1E-03 per year contours. The authority could also accept societal risks above the upper criterion line (also after 2010) provided they explain the reasons why a risk above the criterion line was accepted (i.e. the criteria are guidelines rather than mandatory). In the past, especially when the risk based system was introduced, finance has been made available from a federal foundation to pay for removal of ‘vulnerable objects’ from within the relevant contour.

In Flanders, the 1E-05, 1E-06 and 1E-07 per year contours and the societal risk criteria (see Figure 4) are important, with the latter three being ‘hard’ criteria, i.e. they are mandatory. The 1E-05 per year contour should be within the site boundary of the hazardous installation. If the 1E-05 per year extends beyond the boundary of the site and crosses the site boundary of an adjacent site, then a ‘safety information plan’ is required. This plan would provide information on the accidents which cause the risks at the adjacent site(s), the safety measures taken at the hazardous installation and appropriate cooperation in emergency planning. The 1E-06 per year contour defines the nearest location for groups of houses (five or more houses) and the 1E-07 per year contour defines the closest location for schools, old people’s homes and hospitals.

The responsibility for LUP in Flanders rests with either the Regional, the Provincial or the Municipal authority depending on the type and size of development (and consequently the system is quite complex). The Federal safety authority also has a role especially regarding the assumptions made in the QRA and whether they are appropriate for the specific plant. If the contours shown in Appendix XIII were from a hazardous installation in Flanders, then there could be discussion between the occupier of the hazardous installation and the authorities regarding the assumptions made in the QRA and whether they are appropriate for the specific plant. Should these discussions not lead to a change in the location of the contours in line with the above criteria, then there would be discussion between the occupier of the hazardous installation, the occupiers of the buildings that contravened the criteria and the authorities in order to resolve the situation. This could mean that extra safety measures would be required on the site (e.g. limiting amounts of the hazardous materials, or technical measures e.g. mounded or buried tanks). If this does not resolve the situation, the solution is not straightforward, but it is recognised that the existing situation is not acceptable and the aim would be to improve the situation in the long term. It may be that, for instance, if more than five houses are within the 1E-06 per year contour that these houses would not be permitted to be occupied by anyone other than the present occupiers, (so if or when the current occupiers decided to move out of the house it would be sold to the Federal authority rather than being sold to new occupiers, and the house would remain unoccupied).

The future development of land in Flanders takes into account Seveso sites. Different land uses are allocated different zones (e.g. red zones are housing, purple zones are commercial) and for future spatial planning the presence of a LUP zone within a 2km of a Seveso site would be identified by the federal safety authority. This distance would then be refined by reference to the current QRA (upper tier Seveso site). For a lower tier site, a relatively simple QRA would be required. A spatial safety report would be produced by the site occupier (paid for by the authority wishing to develop close to the hazardous installation) which would contain contours based on the projected risks from the hazardous installation in the next 10 years. These would then be used as the basis for discussion between the developer and the occupier of the installation to ensure that development did not breach the individual and societal risk criteria.

Figure 4 Societal Risk Criteria - Flanders

Location	Individual Risk (per year)
Fuji	2E-06
Northgate	9E-06

Unacceptable

Acceptable

6.0 Discussion

The meaning/potential implications of the predictions introduced in the above two sections is discussed below in terms of the scope of work in section 2.0. Then follows a consideration of some of the factors that would be involved in a risk based LUP system.

The methodology used in the determination of the risk from the petroleum storage facility has followed the classical approach. It has been demonstrated that the risks associated with such a facility can be determined and so a risk based approach to LUP around such sites would be viable. Within the generalities of this approach, however, there is considerable scope for differences in the details in the QRA, particularly the assumptions for frequencies and the analysis of consequences, and hence differences in the numerical risk values predicted. The methodology which was developed and used is presented in some detail so that it is transparent and may be understood and critically reviewed.

As with all process QRAs there are uncertainties in both the inputs and the calculation methods. Some of the more significant uncertainties in this analysis are given below:
- The different properties of gasoline, including seasonal variations
- The rate of formation of a vapour/aerosol cloud given a release of gasoline from piping or tank at different heights and with different potential mechanisms for the formation of both vapour and liquid droplets which remain airborne
- The dispersion of the vapour/droplet cloud, particularly in low wind speed conditions
- The size of the steady state cloud in different weather conditions
- The magnitude of overpressure given ignition of the cloud both within and outside the cloud
- The frequency of releases from piping and tanks
- The probability and timing of ignition
- The probability of an explosion given ignition for different weather conditions and sizes of cloud

Some of these uncertainties are independent of the particular installation, some are dependent on the installation and the surrounding environment, some are specific to the type of hazard at the installation others are general. All require assumptions to be made, many, as identified previously, on the basis of very scant information, in order to carry out the QRA, but not significantly more so than many other process QRAs. This analysis has attempted to make reasonable assumptions, neither overly conservative nor optimistic so that the analysis gives a realistic estimate of the risk, although it is recognised that the error band will be quite wide, and this will need to be taken into consideration should the predictions be used for decision making. With further investigation the values used for some of the assumptions could become more robust (e.g. overfill frequency, tank failure frequency), but some will require considerably more time and analysis, (e.g. likelihood of overpressure generation) and for consequence information possibly even experiments (e.g. gasoline dispersion in low wind speed conditions, magnitude of an explosion and what conditions would/would not cause overpressure).

The QRA demonstrated that different assumptions representing different site conditions or different levels of safety give different risk predictions. The examples given in this analysis show the effects of changing assumptions regarding (1) the frequency of overfilling a tank (which might be achieved by a more reliable overfill protection system) (2) the reduction in the duration of the overfill (which might be achieved by gas detection and remotely or automatically operated valves) and (3) the mitigation due to different building design as well as the effect of different base frequency data. The effect of other risk reduction measures could have been determined, such as ground level discharge from the overfill line, reduced rate of filling, but this was beyond the scope of the present study.

The QRA has used individual risk and societal risk as the main risk measures, as these are currently regarded by both industry and the regulators as being required for decision making. This type of analysis is used as a basis for onsite decisions (but with the inclusion of more scenarios) and its use could be extended to offsite decisions. It could therefore be used as a basis for LUP, but use for this purpose would require some changes to be made to the current UK system. Possible changes are discussed below.

The current system of LUP used in the UK derives essentially from a consultative document issued in 1989, and uses somewhat different risk measures as its basis. Instead of the individual risk of fatality a combination of hazard (the protection concept) and the risk of a 'dangerous dose or more'[2] are used. In short the protection concept quantifies the consequences for a single scenario and associates this with a qualitative estimate of frequency, whereas the risk based approach quantifies both the consequences and the frequencies of a number of different scenarios and cumulates them. The latter is therefore a far better characterisation of the 'risk' from an installation but both are different from the QRA in this report (the former in principle, the latter in detail) as the measure is fatality rather than dangerous dose or more. The reason for the use of dangerous dose or more is historical. At the time when the methodology was being developed there was much less knowledge, understanding or appreciation of 'risk', and the development of both the methodology and the associated criteria that was detailed in the 1989 document might be described as 'ground breaking'. The risk based approach was almost exclusively associated with toxic hazards, and it was appreciated that one of the greatest uncertainties associated with the methodology was the toxicology of the material. The establishment of a dose that produced the effects given in the definition of dangerous dose was considered to be more robust than the establishment of consensus for either LD50 or a continuous relationship between dose and fatality (e.g probit), and emphasised the broad nature of the potential effects rather than a perceived spurious accuracy associated with the probit approach. By using the dangerous dose as the measure, it was possible to transfer much of the uncertainty associated with the toxicology to the consequence part of the analysis. Although the main measure of risk was the dangerous dose, there was considerable background work examining the LD50 and fatality predictions to ensure that the methodology was robust and that the criteria proposed were reasonable in terms of the balance of land within the criterion lines and the numerical value of risk.

Over time as the use of QRA's developed and expanded, the risk measure almost universally used now (apart from the HSE in LUP) is risk of fatality. HSE has continued to use the dangerous dose for LUP in the vicinity of hazardous installations, but has given, in the 1989 document and more recently (Franks), approximate relationships between risk of death and risk of dangerous dose.

The general use of the technique of risk assessment has also increased considerably since 1989 and people are now much more familiar with the concept and the power of the approach. The development of risk assessment within the UK has been, however, more an evolution by separate groups rather than a consistent managed development (UK ILGRA). HSE's last significant publication on risk criteria was Reducing Risk Protecting People (generally known as

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[2] a dangerous dose of a toxic gas will give a range of effects because of different susceptibilities of different people, but will give all of the following - severe distress to almost everyone, with a substantial fraction requiring medical attention, serious injury with a requirement for prolonged treatment for some people and highly susceptible people might be killed

R2P2), published in 2001. It is primarily focussed on the regulatory framework for which HSE has responsibility and the interpretation of 'ALARP'. Numerical risk criteria are given for those risks which could entail fatalities either individually or in multiple fatality accidents and these criteria are given in terms of individual risk of fatality. The individual risk criteria follow the tolerability of risk (ToR) framework (three zones of risk) whereas the societal risk criterion is in terms of a point (but this has been extended by HSE to a three zone framework (SPC10)). R2P2 confirms that the criteria HSE uses for LUP are different from those on the ToR framework and they follow the criteria given in the 1989 consultative document.

Since the publication of R2P2, the HSE has issued guidance on the requirements for separation distances around explosives stores (explosives can give similar hazards to some hazardous installations but are subject to a different regulatory regime) (HSE 2002). The separation distance is the minimum distance between the store and a building inhabited by someone other than the 'storeholder' or site operator. As these stores are licensed, a separation distance is used (although various coloured lines specifying zones have been provided to LPAs around explosives stores there is no mention of a zone approach in the document). The separation distances are based on a calculation of the individual risk of fatality and societal risk (of fatality) but there is no distinction for vulnerable populations. Also the presence of some safety measures is incorporated in the distance calculations, which is now rare for the determination of the zones around hazardous installations (see below).

In 2002, the DfT issued guidance on the control of development in the vicinity of airports (DfT 1/2002). The two zones defined around airports are based on the individual risk of fatality (levels 1E-04 and 1E-05 per year). The main report used to derive the zones (Evans) shows the 1E-06 per year contour and also discusses the use of societal risk but on the basis of cost benefit analysis, the necessity for measures over and above those proposed within the 1E-05 per year contour were considered to be doubtful, although it is likely that there was a degree of pragmatism involved in not including the 1E-06 per year contours within the policy given the size and location of some of the contours.

As stated previously, the approaches taken for LUP in the vicinity of hazardous installations within the EU was (in 1990) either based on consequences or on risk (Christou and Porter). Since that time it is believed that the use of risk has become more widespread, and most countries use the risk of fatality. Although a move from risk of dangerous dose to fatality would be a shift in policy for the HSE, it would bring benefits as virtually all other risk assessments and data are in terms of risk of death, and the use of dangerous dose causes considerable confusion when comparing numerical values of risk with other everyday risks. Further, the use of risk of death allows the "or worse" part actually to be quantified and included in the presentation of risk.

Several years ago a fundamental review of the HSE LUP system was carried out (FRLUP). As part of FRLUP the HSE approaches for LUP (protection and risk) were reviewed (ERM 2004). The overall conclusion was that the HSE's risk assessment methodology was generally fit for purpose, but it was suggested that the criteria and methodology for setting LUP zones should be reviewed, if necessary revised and also published. The report made a number of recommendations to improve the system and identified that the methodology had a number of disadvantages. These included:

- If a site has both hazards that are analysed by the protection concept and hazards that are analysed by risk it is very difficult to add the two together to get an overall risk from the site
- If there are offsite populations subject to hazards from two sites, the same applies.

The use of the protection concept was HSE's original approach to LUP advice, however as the approach had been criticised in some planning inquiries (HSE advice 'should take account of the likelihood of injury to the public as well as the possible extent of injury effects') the risk approach detailed in the 1989 document was developed. The protection concept is still used for most LUP advice where the hazards are flammable, although risk methodology for flammables has been developed by the HSE and is used for some types of hazards (e.g pipelines) (Franks, IGE/TD/1 Supplement). The current policy is, however, that HSE advice to LPAs is only based on risk 'where it is considered beneficial to do so' (Circular 04/2000) although 'beneficial' is not defined. Even if the risks from flammable hazards were determined, because of the use of dangerous dose it is difficult to add such risks to those from toxic materials to produce an overall risk (as recognised in the 1989 document).

The use of the protection concept to define zone boundaries for LUP leads to zone boundaries at which the risk is not determined and so is not known. The location of the zone boundaries would likely be different from those determined by a risk assessment (based on either dangerous dose or fatality), so the use of risk for flammable hazards would probably lead to different LUP zones. However, under the current PADHI system, once the location of a zone is established, from either the protection concept or a risk assessment, the advice on appropriate development in the zone is consistent (as an implicit assumption is made that the risks at a particular zone boundary are the same).

The location of the LUP zone boundary is dependent primarily on the type of material and the quantity stored at the site. Currently determined zone boundaries are likely to be based on the information in the HSC. Although this information is specific in terms of the size of the largest vessel, it may not be specific in terms of the material (because of generic material classes). Consequently the HSE bases its assessment on what could be stored under the terms of the HSC rather than what is actually stored on the site, so the risk at a zone boundary is based on a hypothetical risk. There is very limited account taken in these assessments of measures that are in place at the site to mitigate the risks. Zone boundaries determined before the consent regime, when it was possible for HSE to devote more time to the assessment of risk, would typically be based on what was stored and some account would be incorporated in the assessment for the presence of risk reduction measures, so these assessments were a more realistic measure of the risk from an installation than the assessments carried out now.

The Netherlands and Flanders use both individual and societal risk (of fatality) as inputs and determinants for LUP. The two approaches have some advantages and some disadvantages, such as:

- The methodology is set in the Netherlands so that two sites with the same design would pose the same individual risk. This may not be the case in Flanders.
- It is understood that the methodology in the Netherlands is fixed for a period of five years, and after this time changes can be made to update the methodology. This could impact on the location of the LUP zones. In Flanders the methodology is more flexible and so changes to methodology and experience (such as the Buncefield incident) can take place more quickly. Again, however, these can impact on existing LUP zones.
- The use of individual risk of fatality allows the effects of different types of hazards to be combined and also extended in a consistent way to societal risk.

As in the UK, the methodology for the analysis and the use of the risk predictions for LUP are determined by the regulator(s). The actual analysis, however, is carried out by the operator of the site. A similar system would be appropriate for the UK as control would still rest with the regulator, but the time and cost to carry out the analysis would fall on the occupier, but given that most occupiers of major hazard sites have carried out some QRA, the additional cost would be relatively small. Although QRA's were expensive when the methodology was being developed (some 30 years ago) since then there have been significant advances in the computer programs which aid the analysis and the cost of QRA's now is much less. Further much of the cost of a QRA is associated with the time for the definition of input data and assumptions rather than the analysis itself and most sites will already have these input data. There would however be a cost associated with defining the methodology. The HSE has invested considerable resources into the development of state of the art consequence models over the last 25 years and in 2004 there were approximately 80 models and over 20 methodologies in the HSE LUP portfolio (IFRLUP P5). HSE also has much data on most of the frequencies required for an analysis. Major companies have developed QRA methods also, using either commercially available or in house developed consequence models, and either generic or company specific frequency data and use these for decision making. Although the quality of frequency data used in QRAs is improving, there are still considerable uncertainties. A formal system where data are collected and shared (e.g. as developed offshore after the Piper Alpha accident, and as recommended by MIIB) would, in time, put frequencies on a far sounder footing. The development of standard methodology, from the experiences that HSE has in the determination of risk from major hazard installations, should therefore be reasonably straightforward. In carrying out such an exercise, the HSE could benefit also from the experiences of other EU countries, such as the Netherlands. One of the criticisms of the system used in that country is the rigidity of the methodology, but by examining the systems in use and combining this with its undoubted in-house expertise, the HSE could develop a slightly less rigid system that allows a better balance between consistency of predictions and appropriate modelling of the particular situation, which would be advantageous. The methodology would however need to include sufficient detail that all the information required by a LPA to decide on the appropriateness of a new hazardous installation or development in the vicinity of an existing installation was available. This would mean that the risk predictions would be based on the actual operations at an installation (e.g. as detailed in the COMAH report for top tier sites) including the prevention measures, the extent and reliability of the control measures, and mitigation e.g. through building design, and be expressed in terms of both individual and societal risk of fatality.

Societal risk has been used in LUP decisions in the UK for many years. In the early days it had an essentially qualitative structure, but over the last 10 years HSE has made a number of extensions to quantitative analysis (Carter, Hirst, ERM Risk). Societal risk was not specifically addressed in the methodology review carried out as part of FRLUP, but it is recognised that with the current UK approach the determination of societal risk in the standard F-N format is difficult.

The issue of CD212 and feedback indicated the level of interest in societal risk and the difference in both knowledge and expectations of stakeholders compared with that at the time the LUP risk criteria document was issued. The feedback indicated:

- There was considerable support for using societal risk to aid decisions regarding both on site control measures and LUP
- It was considered important that the assessment of the site operations and the LUP process could give tolerable levels of safety to people in the vicinity

For most QRAs where the individual risk of fatality is determined, the extension to societal risk is relatively minor. Methodologies typically in use currently are simple to implement and transparent. Given the availability of aerial photographs and the existing knowledge about the external population (by the number of people who could be affected by the activities at a site and the distribution of information to those within a specified distance of an installation) the data required should be readily available reasonably quickly yet be sufficiently detailed to be a suitable input for long term LUP decisions and individual applications. The extension from individual risk to societal risk would therefore have benefits for improving site safety as well as providing more information for LUP. Decisions about the safety of people in onsite buildings do not necessarily need to be based on a QRA, but the extent, severity and likelihood of harm do need to be considered (SPC/ENF/106) and this would, for most cases, be quantitative (as there is a numerical criterion for new buildings and an ALARP demonstration is required for existing buildings and HSE Guidance contains a quantified methodology). Hence the use of risk for decisions for offsite development will bring LUP in line with onsite decisions for safety of people in buildings.

Societal risk was used to determine the Development Proximity Zone for Option 4 in CD211. RR512 indicated that societal risk issues were important within 250m of the site boundary. The main contributor to the societal risk in this analysis is the Northgate building. This is partly because of its position close to the gasoline storage tanks and partly owing to the large number of occupants. The effect on the societal risk was investigated by moving the location of the Northgate building 100m and 200m further to the west (thereby increasing the distance between the nearest point of the Northgate building and the site boundary from approximately 100m to 200m (Northgate A) and 300m (Northgate B). The predicted FN curves are shown in Appendix XIII. It can be seen that increasing the distance by 100m reduces the frequency of large numbers of fatalities, but as the edge of the building is still within the assumed flammable cloud from some scenarios, the number of people who could be affected is not reduced (maximum approximately 200 people). By increasing the distance by 200m, the building would then be some distance outside the flammable cloud and therefore not subject to the highest overpressures, thereby reducing the maximum number of fatalities (to approximately 65). This gives support to the findings in RR512.

The overall societal risk from a single installation can be broken down to show the main contributors both in terms of the source of risk and the receptor of risk. This is indicated in Appendix XI which shows the contributors from the sources (which could be broken down much further if required). The breakdown in terms of receptors (Appendix XIII) indicates where mitigation would be most effective. The PLL can indicate the percentage reduction in risk that can be achieved, and, with a cost of life input, it can be determined whether risk reduction either at source or by mitigation is likely to be reasonably practicable. Societal risks can also be added, so the overall societal risk from all the major hazards within a local authority area could be determined and so the LPA would be able to see the effect on the societal risk over a period of time due to changes in both the hazardous installation and the population in the vicinity of the installation (for this to be effective the analysis would need to be ‘live’ and societal risk calculations would need regular updates in line with changes on the major hazard installation and in the population in the vicinity, probably as part of COMAH updates). This would enable better long term spatial planning than is possible on currently available information. The Netherlands is considering different graphical representations of societal risk that will also enable more transparent and better long term planning in the Netherlands (TNO).

Although a move by the UK to an approach that was totally based on risk (individual and societal risk of fatality) would still have some disadvantages, it could remove many of the undesirable features of the current system discussed above, enable LUP to be more soundly and consistently based and could represent the actual risks from an installation. In the development of such a system the main challenges would be technical (consensus on appropriate methodology), and management of the changes to some LUP zones as well as the costs, but it is recommended that such a change should be given careful consideration. Although it could not be expected that the predicted risk levels at an installation in the UK would correspond with the predicted risk levels at the same facility in a different EU country (even though they may be the same), which would be the ideal situation, a change to a system based on risk of fatality would at least mean that the risk measures are consistent. Further, it would enable a consistent methodology to be used for both onsite and offsite decisions, and could be devised to incorporate the best features of the current systems that have been developed for use in other EU countries (eg the Netherlands and Flanders) or by major companies and so would be a robust basis for decision making. A move to an approach based on the risk of fatality would also bring UK LUP in line with advice on airports, in line with R2P2 and remove current confusion and inconsistencies.

7.0 Conclusions

The main assumptions and some of the potential outputs (predictions) of a (quantified) risk model of a large petroleum storage facility have been presented, together with examples of risk based predictions that would be used for LUP in the Netherlands and in the Flanders region of Belgium. Risks have been presented both in terms of the individual risk of fatality, the risk of a dangerous dose or more and the societal risk (of fatality). The methodology followed the classical approach to process QRA and the predictions are given in contour, numerical and graphical format. The QRA demonstrated that different assumptions representing different site conditions or different levels of safety give different risk predictions. The examples given in this analysis show the effects of changing assumptions regarding (1) the frequency of overfilling a tank (which might be achieved by a more reliable overfill protection system) (2) the reduction in the duration of the overfill (which might be achieved by gas detection and remotely or automatically operated valves) and (3) the mitigation due to different building design, as well as the effect of different base frequency data.

The current system for LUP in the UK uses a combination of the protection concept and a system that uses the risk of a dangerous dose or more and derives essentially from a consultative document issued in 1989. Although a ground breaking system at that time it is now perceived to have a number of disadvantages such as (1) the differences in the two general bases used for the calculation of the LUP zone boundaries means that there is inconsistency in the definition of these boundaries which leads to inconsistencies in LUP decisions (2) as the risk of receiving a dangerous dose or more is different from the risk of fatality, which is the most common way for a QRA to express risk from process facilities, and which is used on the HSE ToR framework, there is considerable confusion when comparing numerical risk values, and when comparing LUP values based on dangerous dose with data on everyday risks (3) the risks from sites with different hazards cannot be cumulated (4) a risk calculation in the current system does not necessarily reflect the site risks as the particular operations and level of safeguards taken by the site operator are not included in the risk calculation (5) it does not easily lend itself to extension to the conventional way of displaying societal risk (either in numerical or graphical format) which is increasingly being used additionally to individual risk for decision making, especially for LUP purposes. It would be reasonably easy to extend the type of analysis carried out for this work to all types of major hazard site and use such predictions as a platform for a LUP system totally based on risk (rather than the current system) which could remove the above disadvantages and bring the UK LUP system on a consistent basis and more in line with that in most other EU countries where a risk based approach to LUP is used. Although a move to an approach that was totally based on risk would have challenges, it could be achieved using a similar system to those in the Netherlands and Flanders where the methodology is defined by the regulator and the analysis is carried out by the site operator. The cost implications would not be excessive because much of the information required is known by the operator. Also the HSE has developed considerable expertise and state of the art models over the last 25 years which would underpin the defined methodology. There will be uncertainties associated with the frequencies to be used but these uncertainties already exist in the current system; the use of a risk based system should lead to better data becoming available, either voluntarily (as recommended by MIIB) or by regulation (as was the case for the offshore regime following the Piper Alpha disaster) which over time will improve further the robustness of the system. The predictions from the analysis could be based on the actual operations at an installation including the prevention measures, the extent and reliability of the control measures, and mitigation e.g. through building design, as these are in the site COMAH report so bringing offsite LUP decisions onto a consistent basis with the onsite decisions (to reduce risks ALARP). Further the outputs would be in terms of both individual and societal risk, which are considered necessary for the LPA to make robust and long term decisions on spatial planning.

It is recommended that the changes examined above should be given careful consideration in any review of the UK LUP system. Such changes, if implemented in the UK, would be a step towards a more consistent implementation of a small part of a single EU Directive meant to assure the safety of people living in the vicinity of major hazard sites.

8.0 References

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Appendix I – Frequencies and Delayed Ignition Probabilities

Table 9 Loss of Containment Frequencies - HSE

Description	Value	Units
Tanks >12000m3		
Catastrophic tank failure	5.00E-06	per year
Major tank failure 1000mm	1.00E-04	per year
Minor tank failure 300mm	2.50E-03	per year
Tanks 4000-12000m3		
Catastrophic tank failure	5.00E-06	per year
Major tank failure 750mm	1.00E-04	per year
Minor tank failure 225mm	2.50E-03	per year
Tanks <4000m3		
Catastrophic tank failure	5.00E-06	per year
Major tank failure 500mm	1.00E-04	per year
Minor tank failure 150mm	2.50E-03	per year
Pump	3.00E-05	per year
Pipework		
Full Bore		
500-1000mm	4.00E-08	per m per year
300-499mm	7.00E-08	per m per year
150-299mm	2.00E-07	per m per year
50-149mm	5.00E-07	per m per year
One third dia		
500-1000mm	1.00E-07	per m per year
300-499mm	2.00E-07	per m per year
150-299mm	4.00E-07	per m per year
25mm		
500-1000mm	4.00E-07	per m per year
300-499mm	5.00E-07	per m per year
150-299mm	7.00E-07	per m per year
50-149mm	1.00E-06	per m per year

SummaryofDocs/HSEFrequencies

Table 10 Loss of Containment Frequencies - Purple Book

Equipment	Description	Frequency	Unit
Stationary tank atmospheric	Instantaneous release of the complete inventory to atmosphere	5.00E-06	per tank per year
	Continuous release of the complete inventory to atmosphere in 10 minutes	5.00E-06	
	Continuous release from a hole with an effective dia of 10mm to atmosphere	1.00E-04	
Pipes	Full bore rupture dia <75mm	1.00E-06	per m per yr
	Full bore rupture dia <=75mm to <=150mm	3.00E-07	
	Full bore rupture dia >150mm	1.00E-07	
	Leak, dia is 10% of nominal dia, up to max 50mm, nom dia <75mm	5.00E-06	
	Leak, dia is 10% of nominal dia, up to max 50mm, nom dia <=75mm to <=150mm dia	2.00E-06	
	Leak, dia is 10% of nominal dia, up to max 50mm, nom dia >150mm	5.00E-07	
Pumps	Catastrophic failure- failure of largest connecting pipe	1.00E-04	per year
	Leak, dia is 10% of nominal dia, up to max 50mm	5.00E-04	

SummaryofDocs/PBScenarios

Table 11 Delayed Ignition Probabilities

Description	Delayed Ignition Probability
Release duration <300s, cloud less than 12000m^3	0.05
Release duration <300s, 30000m^3 cloud	0.1
Release duration <300s, 100000m^3 cloud	0.2
Release duration <300s, 200000m^3 cloud	0.3
Release duration <300s, 300000m^3 cloud	0.4
Release duration <300s, 400000m^3 cloud	0.5
Release duration 300s, cloud less than 12000m^3	0.1
Release duration 300s, 30000m^3 cloud	0.2
Release duration 300s, 100000^3 cloud	0.3
Release duration 300s, 200000m^3 cloud	0.4
Release duration 300s, 300000m^3 cloud	0.5
Release duration 300s, 400000m^3 cloud	0.6
Release duration 600s, cloud less than 12000m^3	0.2
Release duration 600s, 30000m^3 cloud	0.3
Release duration 600s, 100000m^3 cloud	0.4
Release duration 600s, 200000m^3 cloud	0.5
Release duration 600s, 300000m^3 cloud	0.6
Release duration 600s, 400000m^3 cloud	0.7
Release duration 1800s, cloud less than 12000m^3	0.3
Release duration 1800s, 30000m^3 cloud	0.4
Release duration 1800s, 100000m^3 cloud	0.5
Release duration 1800s, 200000m^3 cloud	0.6
Release duration 1800s, 300000m^3 cloud	0.7
Release duration 1800s, 400000m^3 cloud	0.8
Release duration 2700s, cloud less than 12000m^3	0.4
Release duration 2700s, 30000m^3 cloud	0.5
Release duration 2700s, 100000m^3 cloud	0.6
Release duration 2700s, 200000m^3 cloud	0.7
Release duration 2700s, 300000m^3 cloud	0.8
Release duration 2700s, 400000m^3 cloud	0.9

Table 12 Explosion Probabilities

Cloud volume	Explosion Probability
m3	
30000	0.15
100000	0.2
200000	0.25
300000	0.25
400000	0.25

Appendix II – Scenario Details

Table 13 Scenario Details

Description	Material	Included in analysis	Location of release point for consequence analysis	Basis for release rate	Release Rate kg/s	Vapour production type	Frequencies	Cloud vol in time 1800s	Cloud vol in time 1800s
							per year	m3 2 m/s	m3 0.25 m/s
Above ground T/K pipeline	Gasoline	Yes	Along the pipeline at 25m intervals	Pump rate (890m3/h) x 1.1	200	Medium	2.64E-06	9810	148509
Above ground T/K pipeline	Gasoline	Yes	Along the pipeline at 25m intervals	Pump rate (890m3/h) x 1.1	104	Medium	7.55E-06	825	2269
Above ground Fina pipeline	Gasoline	Yes	Along the pipeline at 25m intervals	Pump rate (220m3/h) x 1.1	50	Low	1.12E-05	4502	39857
Above ground Fina pipeline	Gasoline	Yes	Along the pipeline at 25m intervals	Pump rate (220m3/h) x 1.1	50	Low	2.24E-05	825	2269
Overfill at T910	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (890m3/h) x 1.1	50	Very High	1.00E-03	22293	327705
Overfill at T912	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (890m3/h) x 1.1	104	Very High	1.00E-03	22293	327705
Overfill at T915	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (220m3/h) x 1.1	50	High	1.00E-03	3030	20417
T910 to A/B pump area (P910)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
T912 to A/B pump area (P912)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
T915 to A/B pump area (P915)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
P910	Gasoline	Yes	Pump area in Bund B to west of T-911	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P912	Gasoline	Yes	Pump area in Bund B to west of T-911	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P915	Gasoline	Yes	Pump area in Bund B to west of T-911	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P910 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	1.21E-05	0	0
P912 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	1.21E-05	0	0
P915 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	1.21E-05	0	0
P910 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P912 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P915 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
Overfill at T911	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (220m3/h) x 1.1	50	High	1.00E-03	3030	0
Overfill at T913	Diesel	Pool fires only	Bund wall to north, south east and west	Pump rate (220m3/h) x 1.1	56	None	1.00E-03	0	0
Overfill at T914	Diesel	Pool fires only	Bund wall to north, south east and west	Pump rate (220m3/h) x 1.1	56	None	1.00E-03	0	0
Overfill at T916	Diesel	Pool fires only	Bund wall to north, south east and west	Pump rate (220m3/h) x 1.1	56	None	1.00E-03	0	0
T911 to A/B pump area (P911)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	5.04E-06	753	0
T913 to A/B pump area (P913)	Diesel	Pool fires only	Half way between tank centre and pumps	5m head (100mm dia line)	52	None	5.04E-06	0	0
T914 to A/B pump area (P914)	Diesel	Pool fires only	Half way between tank centre and pumps	5m head (100mm dia line)	52	None	5.04E-06	0	0
T916 to A/B pump area (P916)	Diesel	Pool fires only	Half way between tank centre and pumps	5m head (100mm dia line)	52	None	5.04E-06	0	0
P911	Gasoline	Yes	Pump area in Bund B to west of T -911	5m head (100mm dia line)	46	Low	3.00E-05	753	0
P913	Diesel	Pool fires only	Pump area in Bund B to west of T -911	5m head (100mm dia line)	52	None	3.00E-05	0	0
P914	Diesel	Pool fires only	Pump area in Bund B to west of T -911	5m head (100mm dia line)	52	None	3.00E-05	0	0
P916	Diesel	Pool fires only	Pump area in Bund B to west of T -911	5m head (100mm dia line)	52	None	3.00E-05	0	0
P911 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	1.21E-05	0	0
P913 to loading	Diesel	Pool fires only	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	10	None	1.79E-05	0	0
P914 to loading	Diesel	Pool fires only	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	10	None	3.64E-05	0	0
P916 to loading	Diesel	Pool fires only	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	10	None	5.95E-06	0	0
P911 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P913 loading	Diesel	Pool fires only	Loading area	Pump rate (41m3/h) x 1.1	10	None	1.05E-04	0	0
P914 loading	Diesel	Pool fires only	Loading area	Pump rate (41m3/h) x 1.1	10	None	1.05E-04	0	0
P916 loading	Diesel	Pool fires only	Loading area	Pump rate (41m3/h) x 1.1	10	None	1.05E-04	0	0

Description	Material	Included in analysis	Location of release point for consequence analysis	Basis for release rate	Release Rate kg/s	Vapour production type	Frequencies	Cloud vol in time 1800s	Cloud vol in time 1800s
								m3	m3
							per year	2 m/s	0.25 m/s
Overfill at T901	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (890m3/h) x 1.1	200	Very High	1.00E-03	22293	0
Overfill at T902	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (890m3/h) x 1.1	200	Very High	1.00E-03	22293	0
Overfill at T903	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (890m3/h) x 1.1	200	Very High	1.00E-03	22293	0
Overfill at T904	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (890m3/h) x 1.1	200	Very High	1.00E-03	22293	0
Overfill at T905	Gasoline	Yes	Bund wall to north, south east and west	Pump rate (890m3/h) x 1.1	200	Very High	1.00E-03	22293	0
Overfill at T908	Diesel	Pool fires only	Bund wall to north, south east and west	Pump rate (220m3/h) x 1.1	56	None	1.00E-03	0	0
T901 to D pump area (P901)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
T902 to D pump area (P902)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
T903 to D pump area (P903)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
T904 to D pump area (P904)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
T905 to D pump area (P905)	Gasoline	Yes	Half way between tank centre and pumps	5m head (100mm dia line)	46	Low	1.01E-05	753	1944
T908 to D pump area (P908)	Diesel	Pool fires only	Half way between tank centre and pumps	5m head (100mm dia line)	52	None	1.01E-05	0	0
P901	Gasoline	Yes	Pump area in Bund C/D to west of T-903	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P902	Gasoline	Yes	Pump area in Bund C/D to west of T-903	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P903	Gasoline	Yes	Pump area in Bund C/D to west of T-903	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P904	Gasoline	Yes	Pump area in Bund C/D to west of T-903	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P905	Gasoline	Yes	Pump area in Bund C/D to west of T-903	5m head (100mm dia line)	46	Low	3.00E-05	753	1944
P908	Diesel	Pool fires only	Pump area in Bund C/D to west of T-903	5m head (100mm dia line)	52	None	3.00E-05	0	0
P901 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	9.53E-07	0	0
P902 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	1.30E-06	0	0
P903 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	1.30E-06	0	0
P904 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	5.36E-07	0	0
P905 to loading	Gasoline	Yes	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	9	None	1.73E-06	0	0
P908 to loading	Diesel	Pool fires only	Half way between pumps and loading area	Pump rate (41m3/h) x 1.1	10	None	1.99E-06	0	0
P901 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P902 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P903 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P904 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P905 loading	Gasoline	Yes	Loading area	Pump rate (41m3/h) x 1.1	9	None	1.05E-04	0	0
P908 loading	Diesel	Pool fires only	Loading area	Pump rate (41m3/h) x 1.1	10	None	1.05E-04	0	0
Bund A	Gasoline	Yes	Centre of bund	5m head (1000mm dia hole)	4587	Medium	1.00E-04	300000	300000
Bund B	Gasoline	Yes	Centre of bund	5m head (1000mm dia hole)	4587	Medium	1.00E-04	300000	300000
Bund C	Gasoline	Yes	Centre of bund	5m head (750mm dia hole)	2580	Medium	1.00E-04	300000	300000
Bund D	Diesel	Pool fires only	Centre of bund	5m head (750mm dia hole)	2905	None	1.00E-04	0	0
Overtop Bund A	Gasoline	Yes	Bund wall to north, south east and west	Tank contents (11400m3) ove	28005	Medium	5.00E-06	400000	400000
Overtop Bund B	Gasoline	Yes	Bund wall to north, south east and west	Tank contents (11400m3) ove	28005	Medium	5.00E-06	400000	400000
Overtop Bund C	Gasoline	Yes	Bund wall to north, south east and west	Tank contents (3800m3) over	6858	Medium	5.00E-06	400000	400000
Overtop Bund D	Diesel	Pool fires only	Bund wall to north, south east and west	Tank contents (3720m3) over	10299	None	5.00E-06	400000	400000

Appendix III Derivati on of Overpressures

Table 14 Damage Level Descriptions and associated overpressures (Scilly and High)

Damage Level	Description	Overpressure (mbar)
A	Houses completely demolished - ie with over 75% of external brickwork demolished	
B	Houses so badly damaged that they are beyond repair and must be demolished. 50-75% of external brickwork is destroyed, or in the case of less severe destruction, the remaining walls have gaping cracks rendering them unsafe.	350
Cb	House rendered uninhabitable by serious damage, needing extensive repairs, eg partial or total collapse of the roof structure, partial demolition of 1 or 2 external walls up to 25% of the whole, severe damage to load bearing partitions necessitating demolition and replacement.	160
Ca	House rendered uninhabitable but reasonably quickly repairable, damage sustained not to exceed minor structural damage and partitions and joinery wrenched from fixings	80
D	House requiring repairs to remedy serious inconveniences, but remaining habitable eg. Damage to ceilings and tiling, battens of roof covering, minor fragmentation effects on walls, broken glass (but excludes cases with <10% window breakage)	30

Table 15 Damage Level Descriptions and associated overpressures (BEAST)

BEAST Type	Damage Level	Description	Upper Overpressure for Damage (mbar)
12	1	Damage will consist of minor cracking in the masonry wall panels on the reflected face. Other walls should not sustain permanent damage. Building can be reused but will require repair of wall panels.	35
	2A	Damage is characterized by major damage to the masonry wall on the reflected face and minor damage to walls on other faces. Roof slabs and beams will receive moderate damage. The building will require substantial repair before reuse.	100
	2B	Damage includes collapse of wall panels on the reflected face. Wall panels on the other faces will sustain moderate damage. Roof damage will be moderate. Main framing will receive major damage on the reflected face and moderate damage on other faces.	175
	3	Building has lost structural integrity and may collapse due to environmental conditions, (i.e., wind, snow, or rain). Building blast protection is impaired. Total cost of repairs exceeds replacement cost of building.	320
	4	All components will receive major damage, up to and including	>320

		collapse. Reinforced concrete framing will remain standing but will not be repairable. Some connections failures may occur at columns on the reflected face.	
11	1	Damage will consist of minor cracking in the masonry wall panels on the reflected face. Other walls should not sustain permanent damage. Building can be reused but will require repair of wall panels."	35
	2A	Damage is characterized by major damage to the masonry wall on the reflected face and minor damage to walls on other faces. Roof slabs and beams will receive moderate damage. The building will require substantial repair before reuse.	60
	2B	Damage includes collapse of wall panels on the reflected face. Wall panels on the other faces will sustain moderate damage. Roof damage will be moderate. Main framing will receive major damage on the reflected face and moderate damage on other faces.	115
	3	Damage will consist of collapse of all wall panels and roof deck. Roof beams will sustain major damage. Frames will sustain major damage to all members. Replacement of the entire structure will be required. Building entry should be restricted prior to demolition due to collapse hazards.	320
	4	All components will receive major damage, up to and including collapse. Reinforced concrete framing will remain standing but will not be repairable. Some connections failures may occur at columns on the reflected face.	>320
3	1	Damage will consist of minor cracking in the masonry wall panels on the reflected face. Other walls should not sustain permanent damage. Wall columns and frames will also receive minor damage. Girts on the reflected faces will sustain moderate damage. Building can be reused but will require replacement of girts and wall panels.	30
	2A	Localized building damage. Building performs function and can be used; however, major repairs are required to restore integrity of structure envelope. Total cost of repairs is moderate.	65
	2B	Damage includes collapse of wall panels on the reflected face. Wall panels on the other faces will sustain moderate damage. Roof damage will be moderate. Main framing will receive major damage on the reflected face and moderate damage on other faces.	120
	3	Damage will consist of collapse of all wall panels and roof deck. Roof beams will sustain major damage. Columns and frames will sustain major damage to all members. Replacement of the entire structure will be required. Building entry should be restricted prior to demolition due to collapse hazards.	240
	4	All components will receive major damage, up to and including collapse. Main framing will likely remain standing but will not be repairable. Some connections failures may occur at columns on the reflected face.	>240

The overpressures associated with the damage levels are dependent on the building size and the impulse as well as the overpressure; the above are for a building 100 x 40 x 10 ft and an impulse of 100ms.

Figure 5 Overpressure v Distance for the Explosion at Buncefield

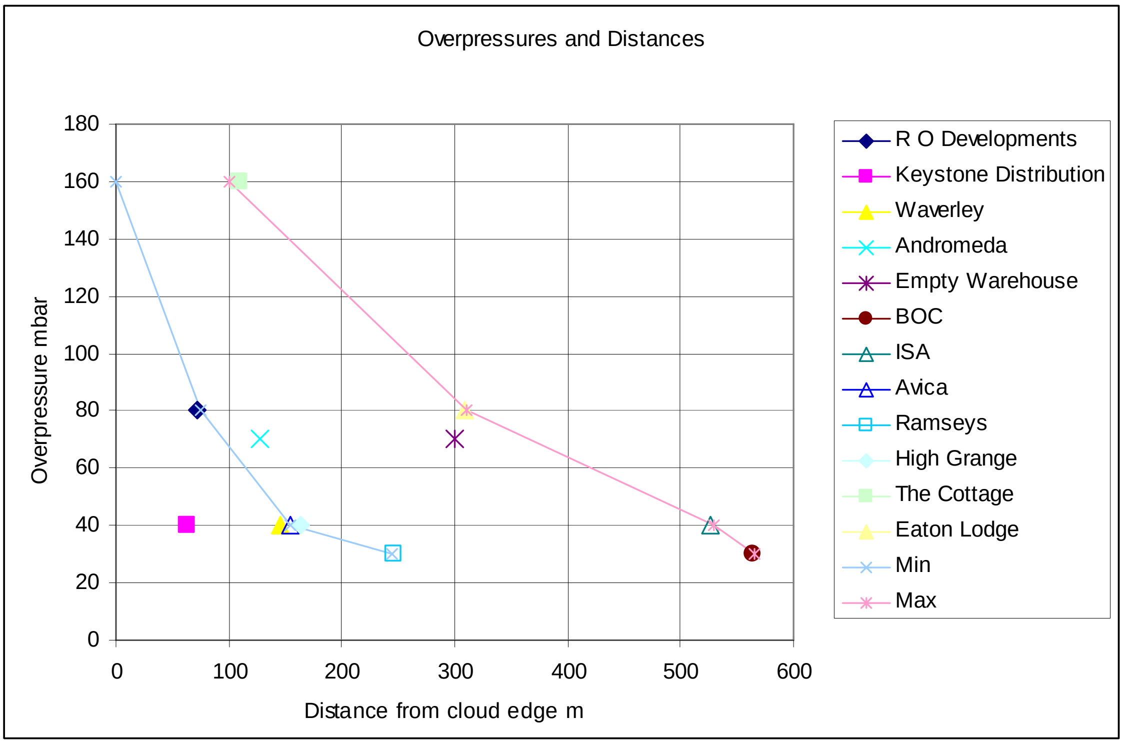
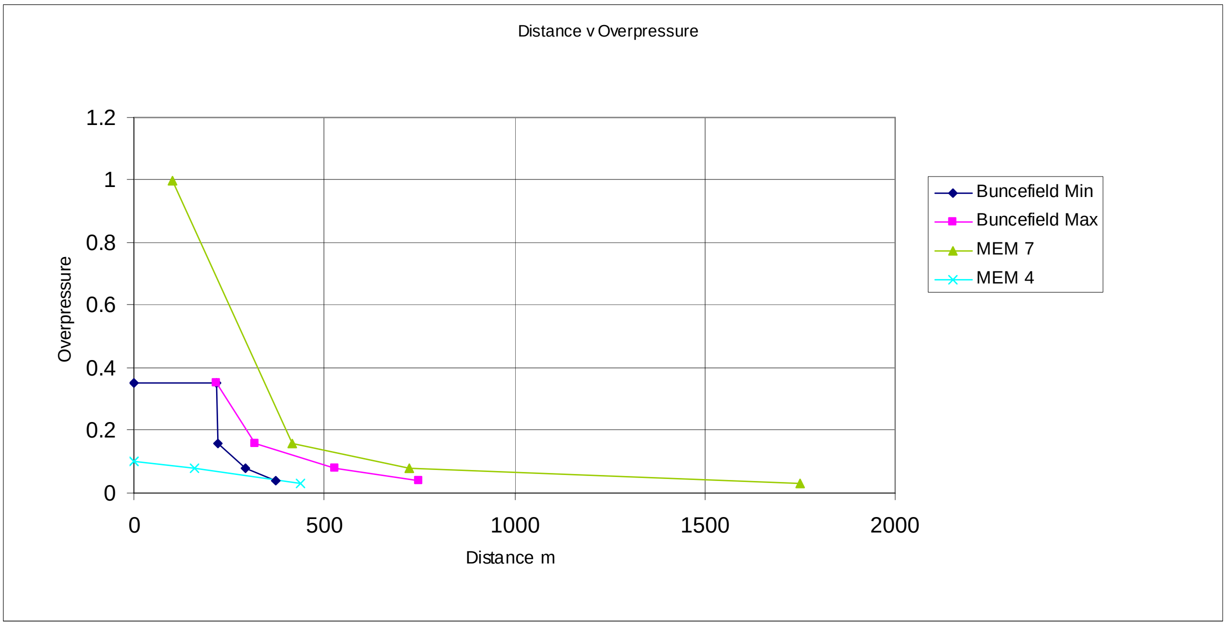
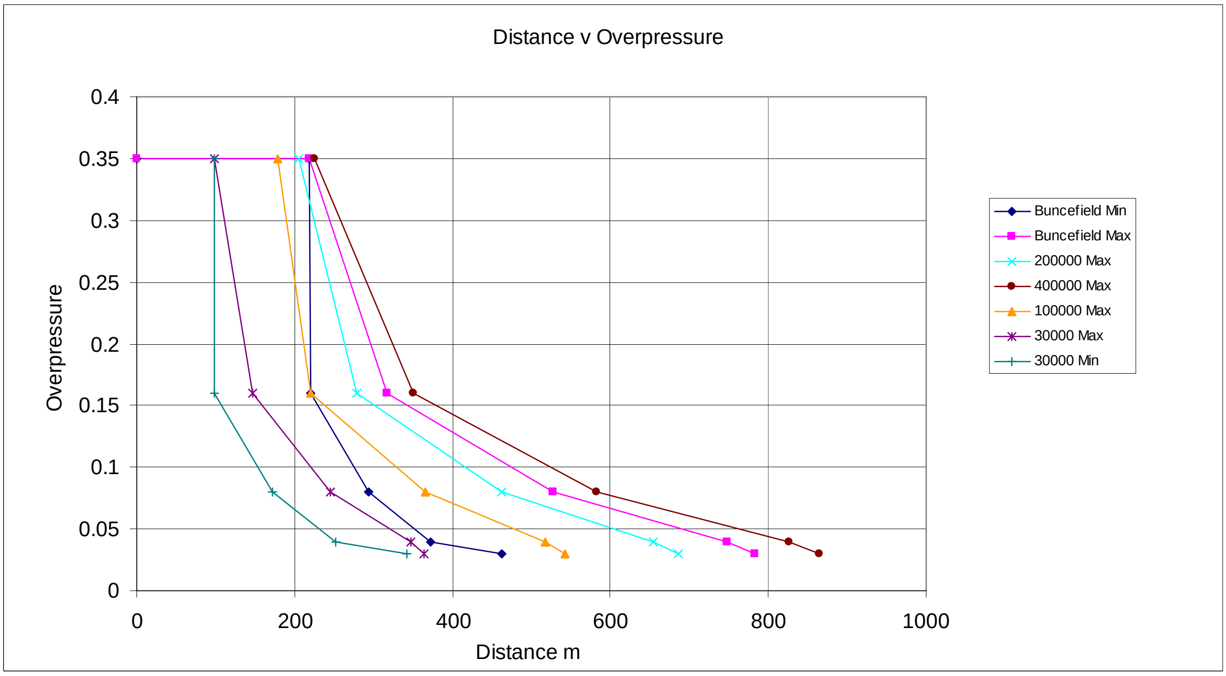


Figure 6 Overpressure Decay Curves



It was assumed that the overpressure inside the cloud was 0.35bar, and the decay curves are shown in Figure 5 and Figure 6. Also shown in Figure 6 are the decay curves using Lines 7 and 4 of the Multi Energy method for VCE decay prediction assuming a hemispherical cloud of similar volume.

Figure 7 Selection of Overpressure Decay Curves used in the Analysis



8.1 References

Scilly NF and High WG. The Blast Effects of Explosions. Int Symp on Loss Prevention and Safety promotion in Process Industries, Cannes, 1987.

BEAST. Building Evaluation And Screening Tool. Developed for 2000 Petrochemical Industry Technology Cooperative. Wilfred Baker Engineering Inc.

Appendix IV Hazard Frequency and Individual Risk Contours - MOC Overfilling Frequency and HSE Tank Failure Frequencies

Figure 8 Frequency of Overpressure Exceeding 70 mbar (HSE Dangerous Dose for Vulnerable Population)

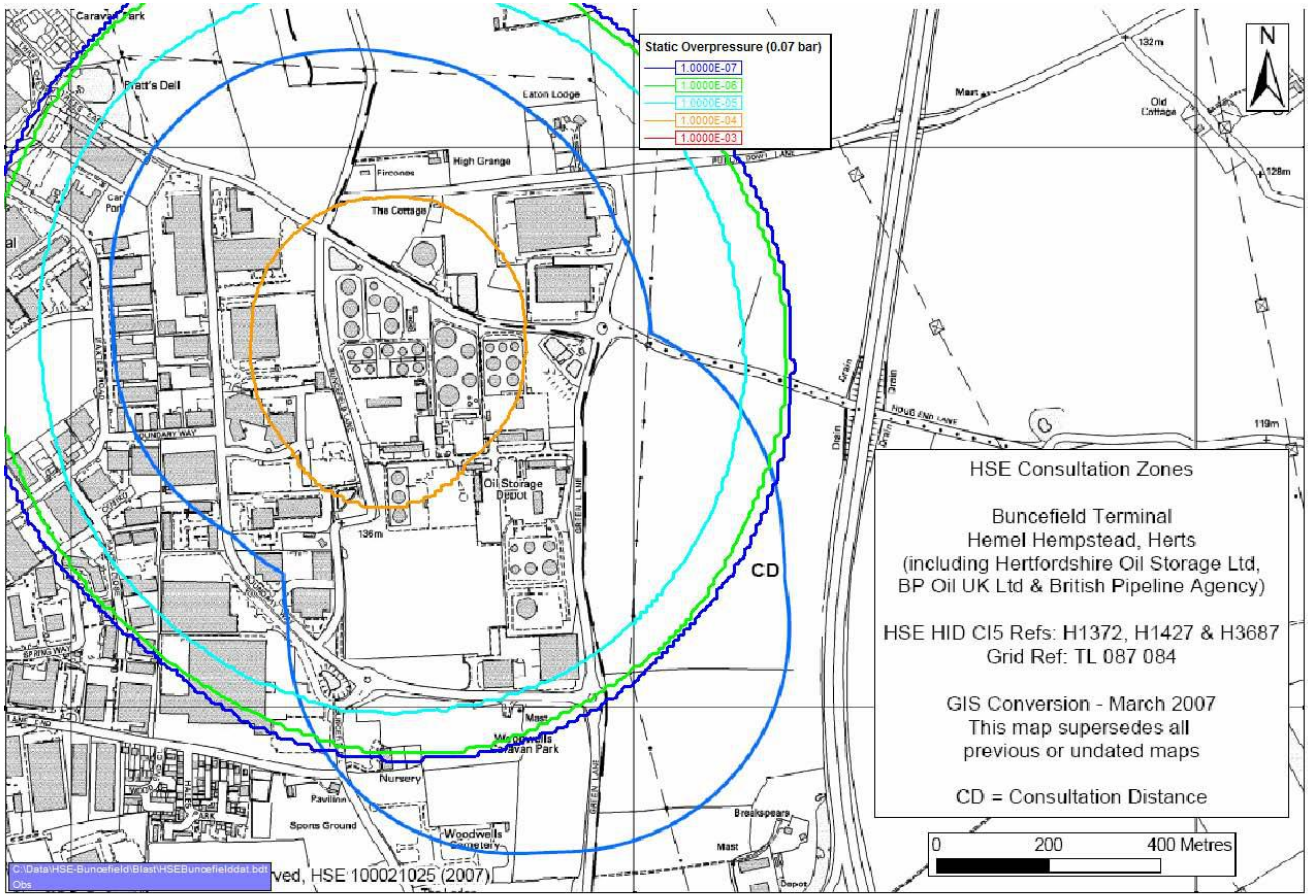


Figure 9 Frequency of Overpressure Exceeding 140 mbar (HSE Dangerous Dose)

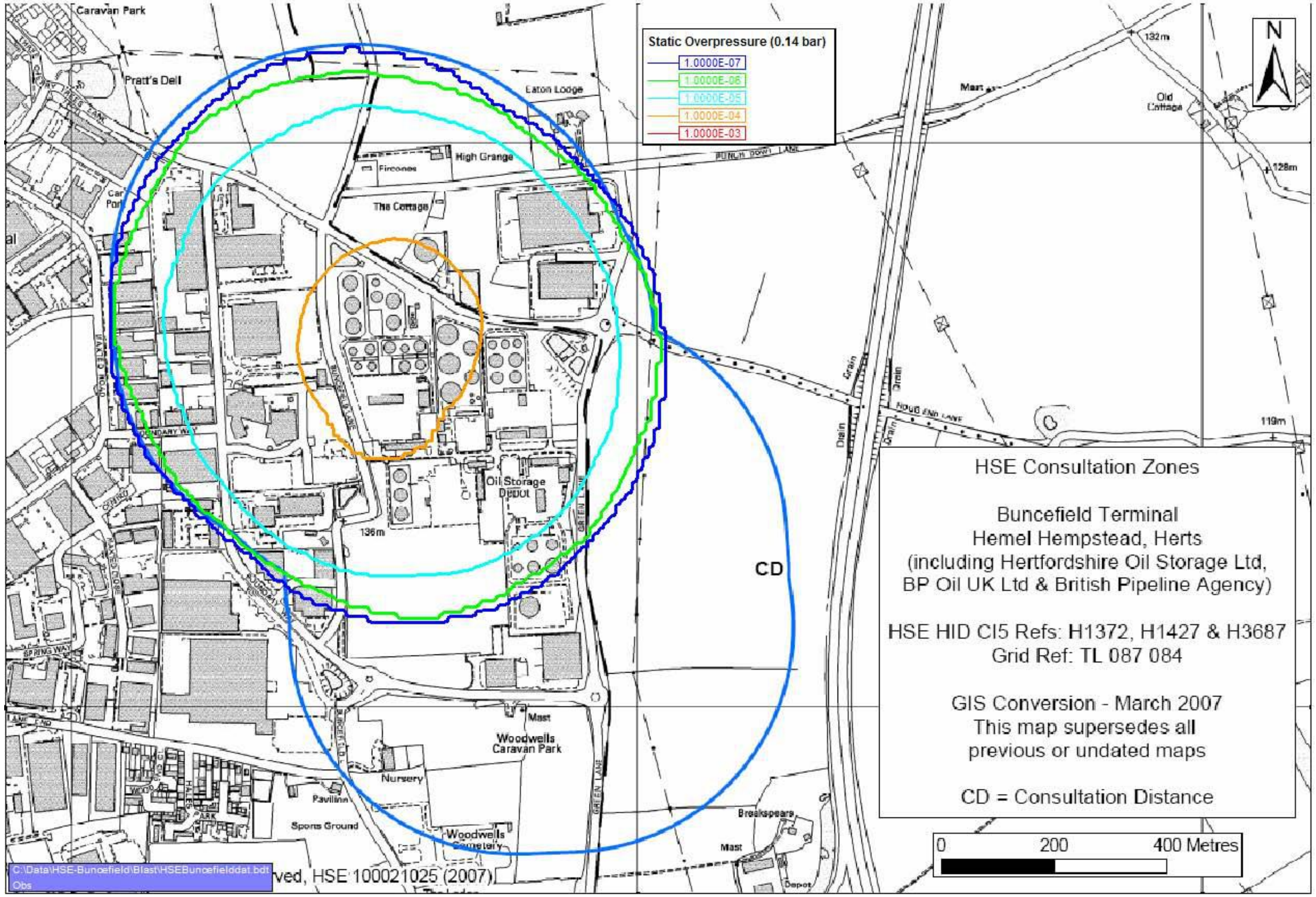
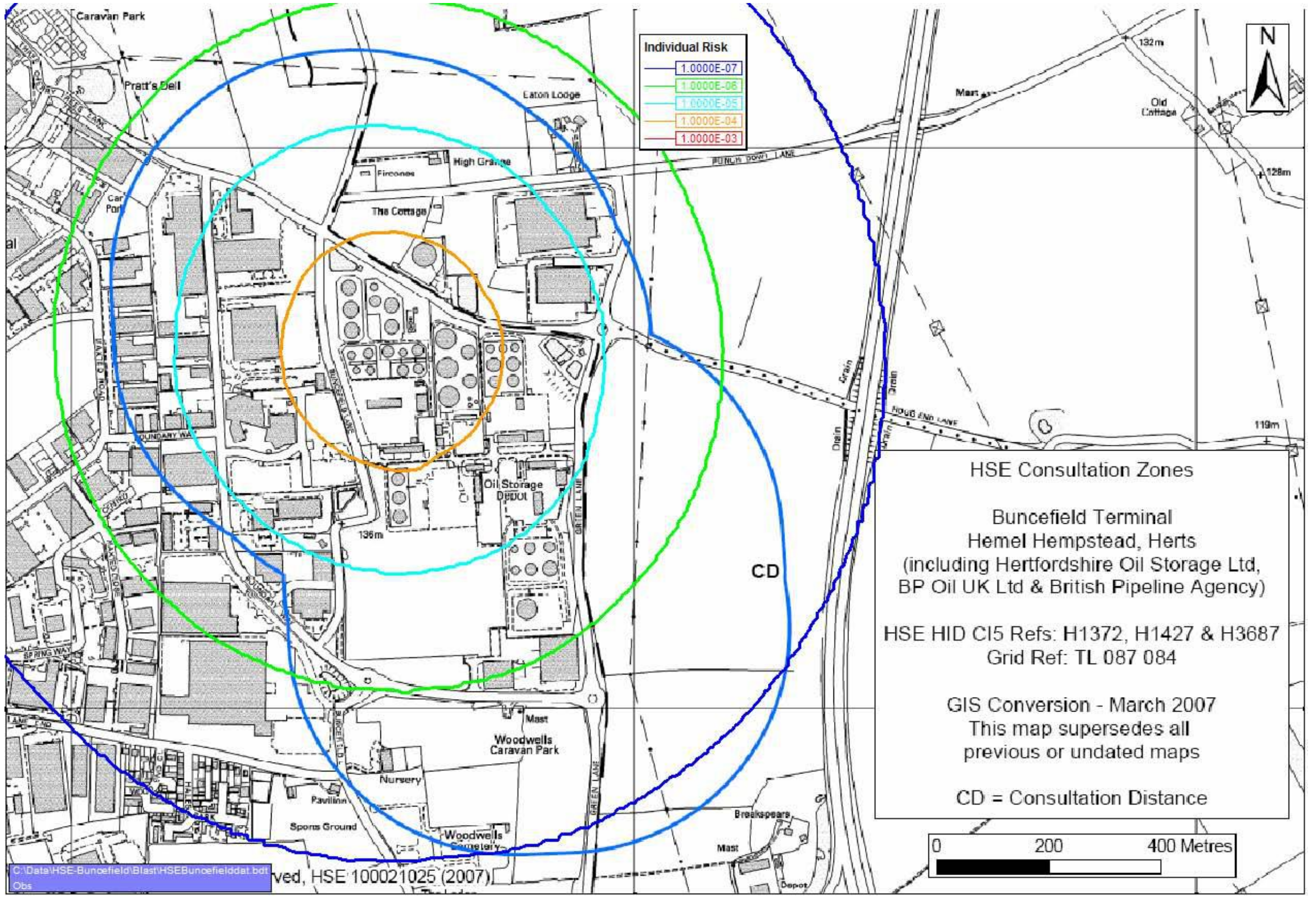


Figure 10 Individual Risk of Fatality to a Person in a Typical Brick House (assuming full time occupancy)



Appendix V Hazard Frequency and Individual Risk Contours - Lastfire Group Overfilling Frequency and HSE Tank Failure Frequencies

Figure 11 Frequency of Overpressure Exceeding 70 mbar (HSE Dangerous Dose for Vulnerable Population)

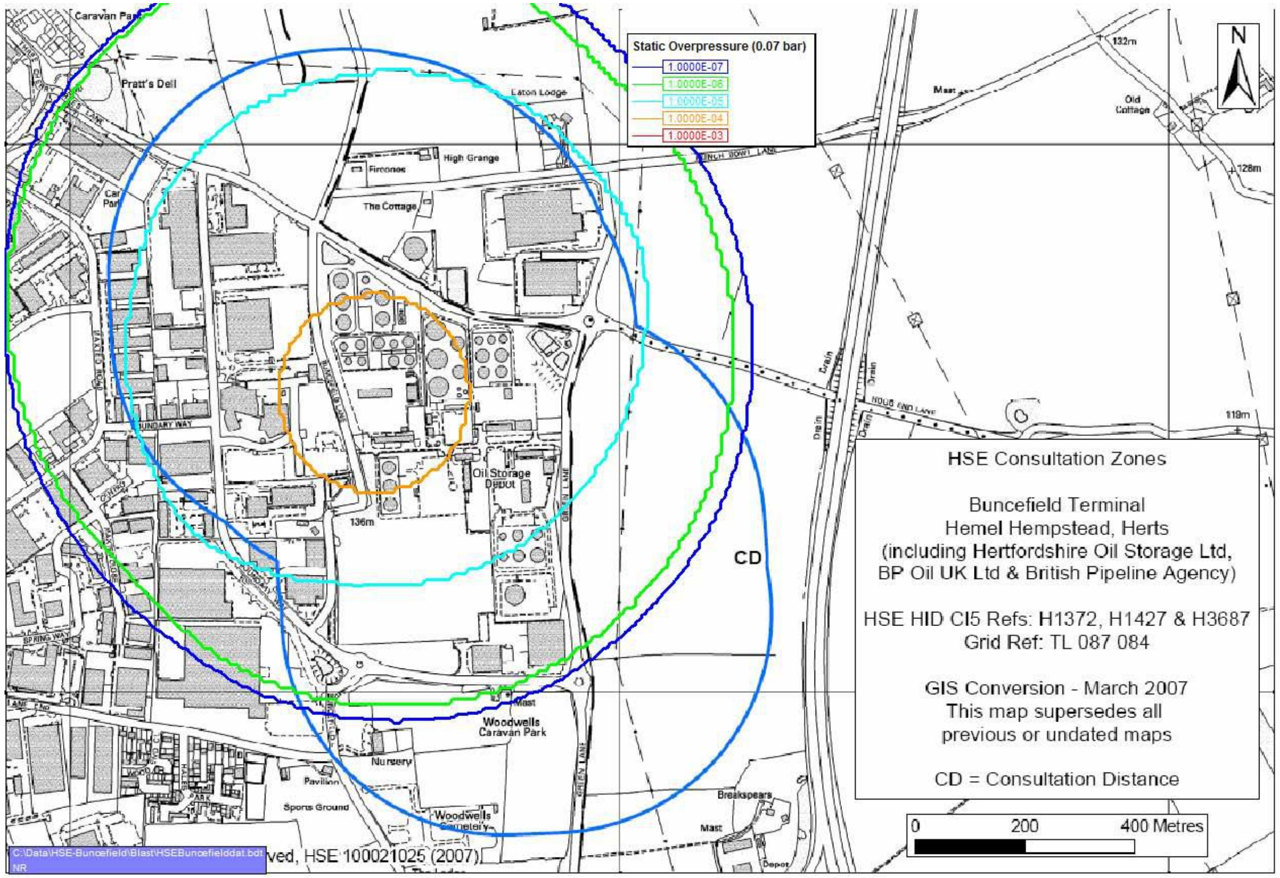


Figure 12 Frequency of Overpressure Exceeding 140 mbar (HSE Dangerous Dose)

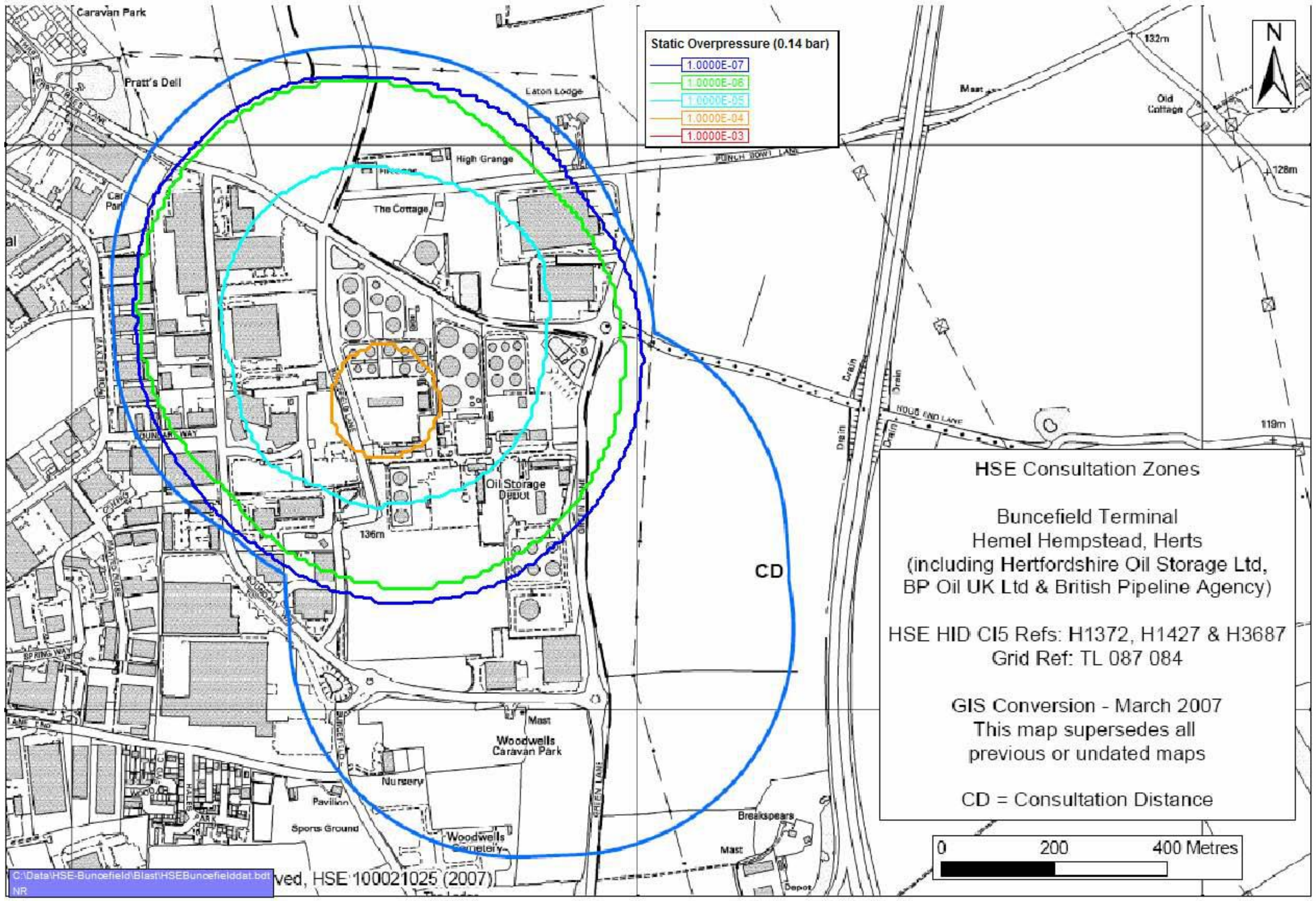
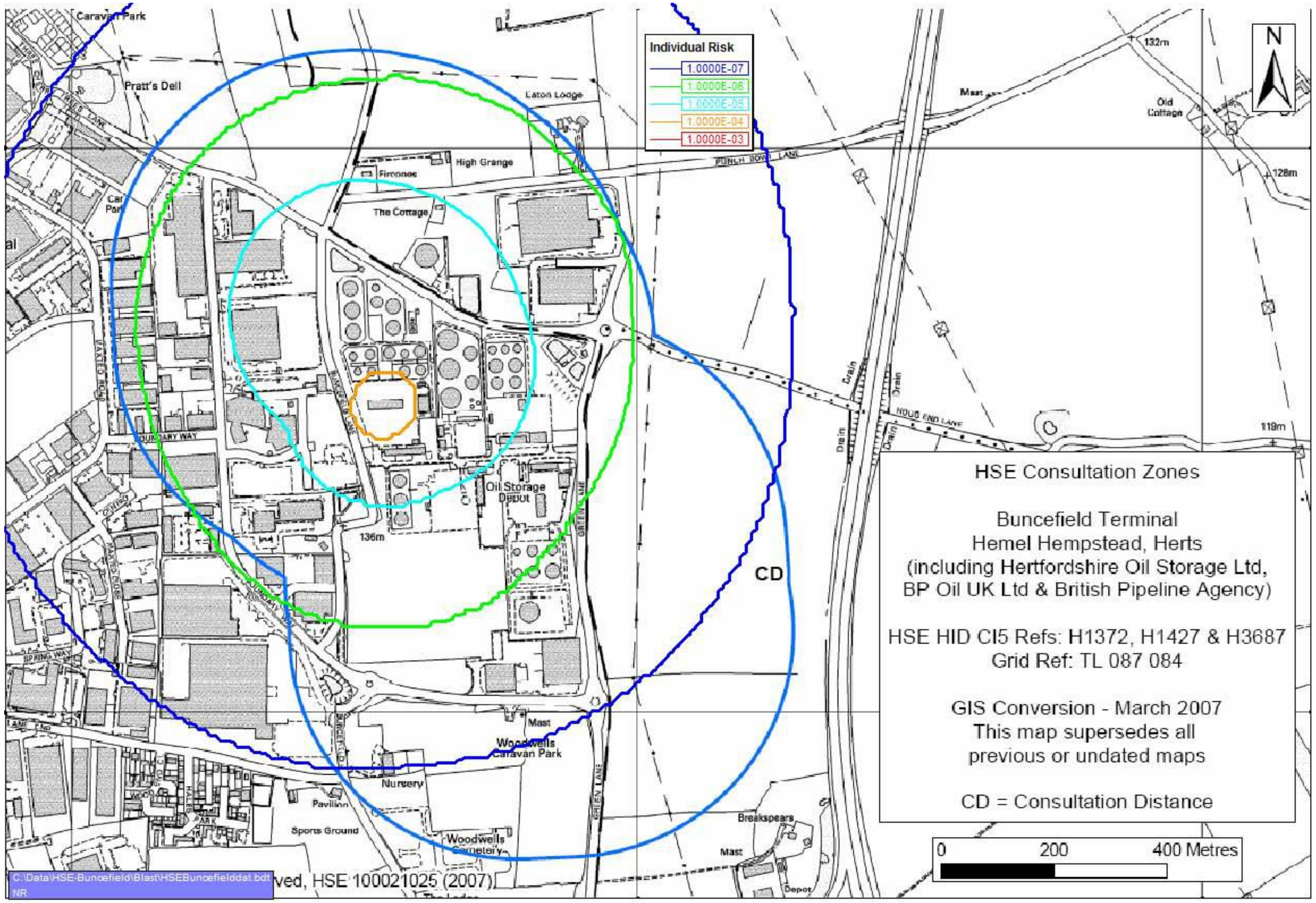


Figure 13 Individual Risk of Fatality to a Person in a Typical Brick House (assuming full time occupancy)



Appendix VI Hazard Frequency and Individual Risk Contours - Lastfire Group Overfilling Frequency and Purple Book Tank Failure Frequencies

Figure 14 Frequency of Overpressure Exceeding 70 mbar (HSE Dangerous Dose for Vulnerable Population)

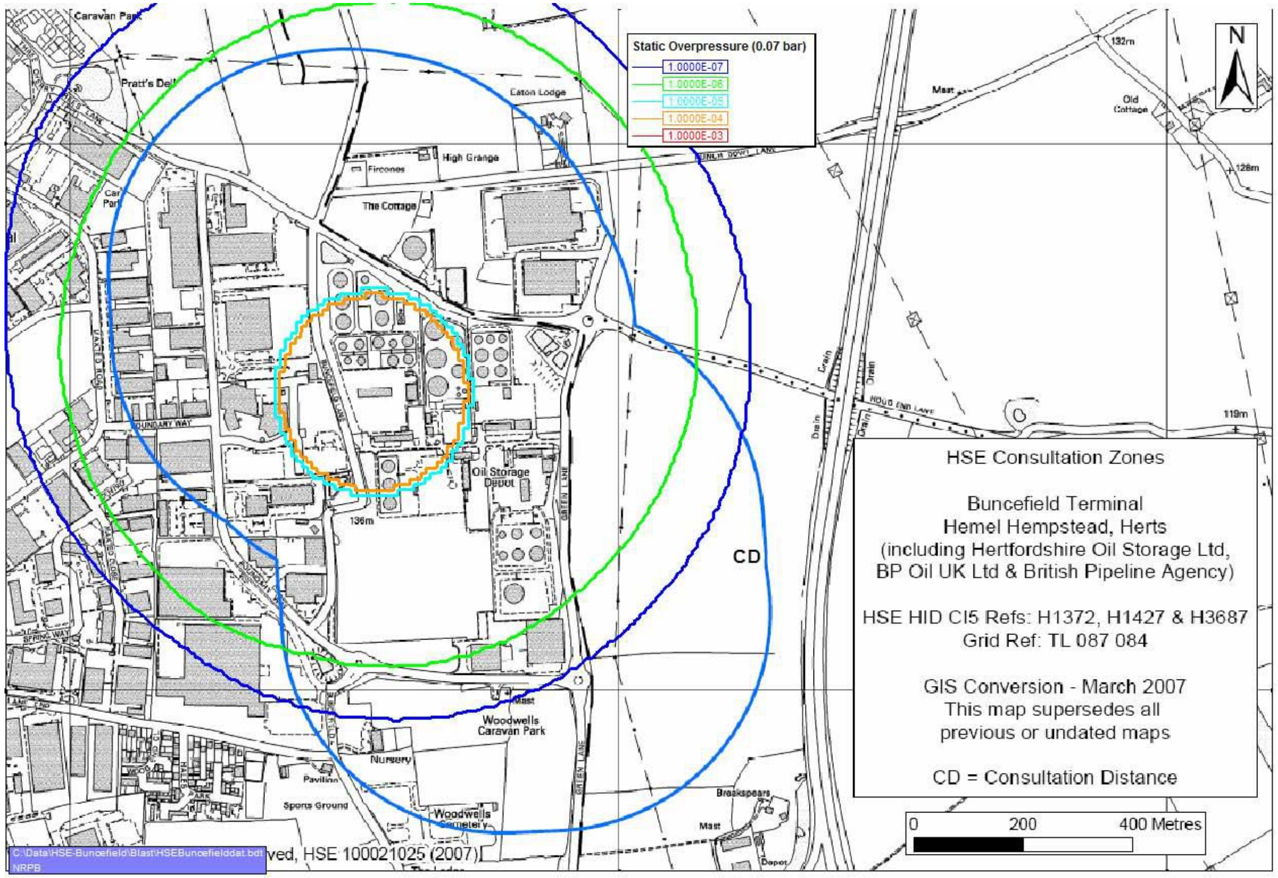


Figure 15 Frequency of Overpressure Exceeding 140 mbar (HSE Dangerous Dose)

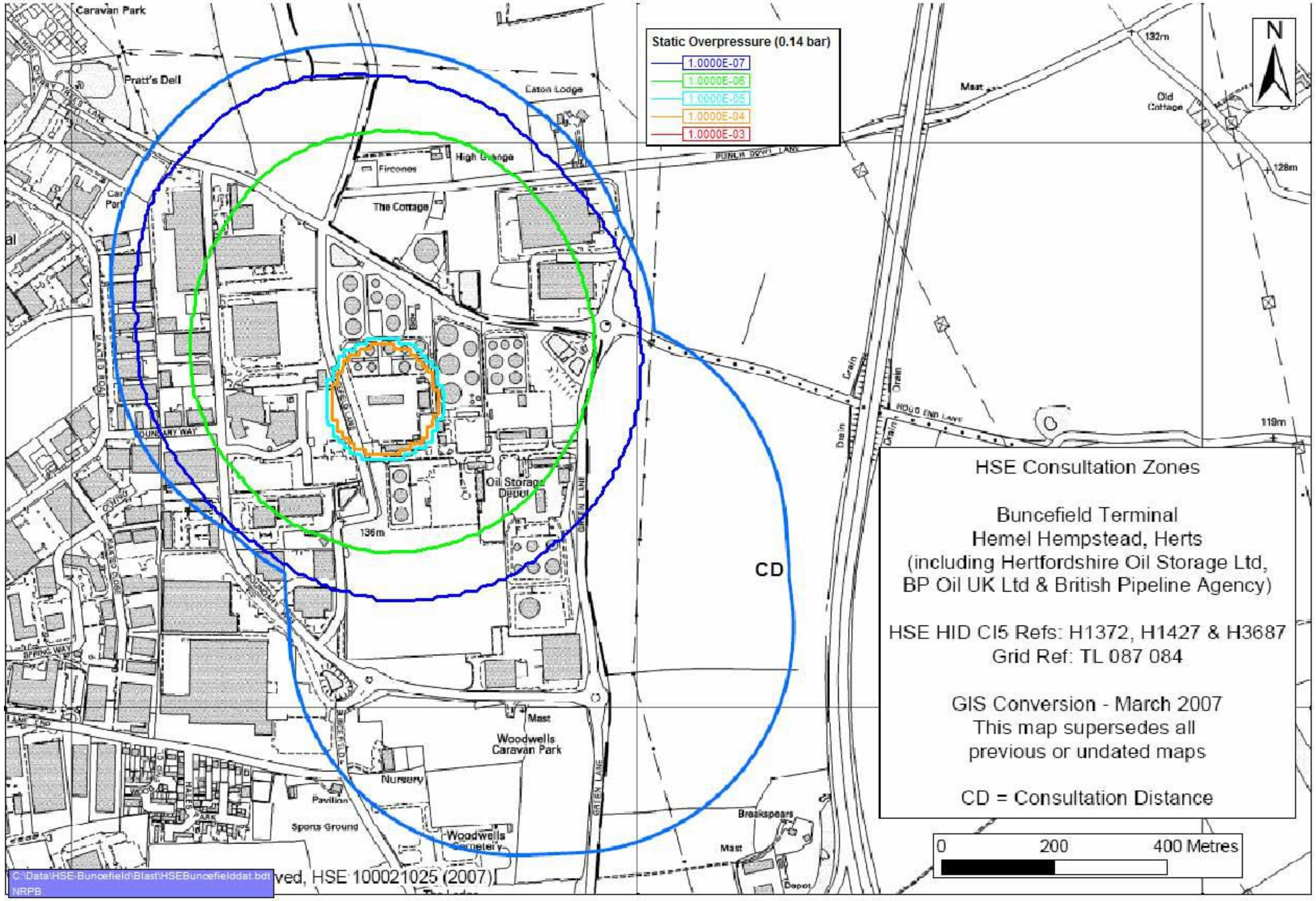
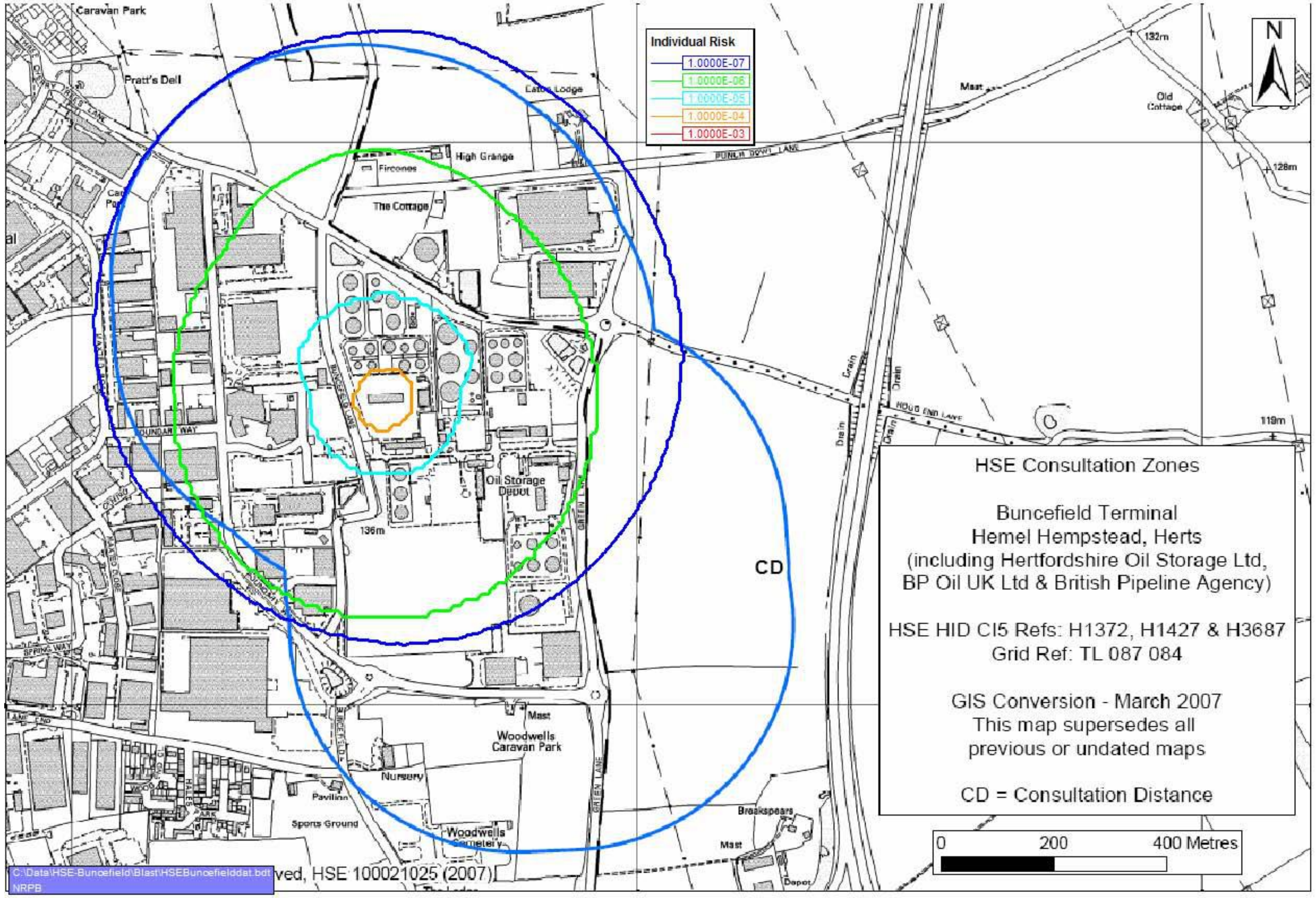


Figure 16 Individual Risk of Fatality to a Person in a Typical Brick House (assuming full time occupancy)



Appendix VII Hazard Frequency and Individual Risk Contours - Lastfire Group Overfilling Frequency, Purple Book Tank Failure Frequencies with measures to reduce likely release duration

Figure 17 Frequency of Overpressure Exceeding 70 mbar (HSE Dangerous Dose for Vulnerable Population)

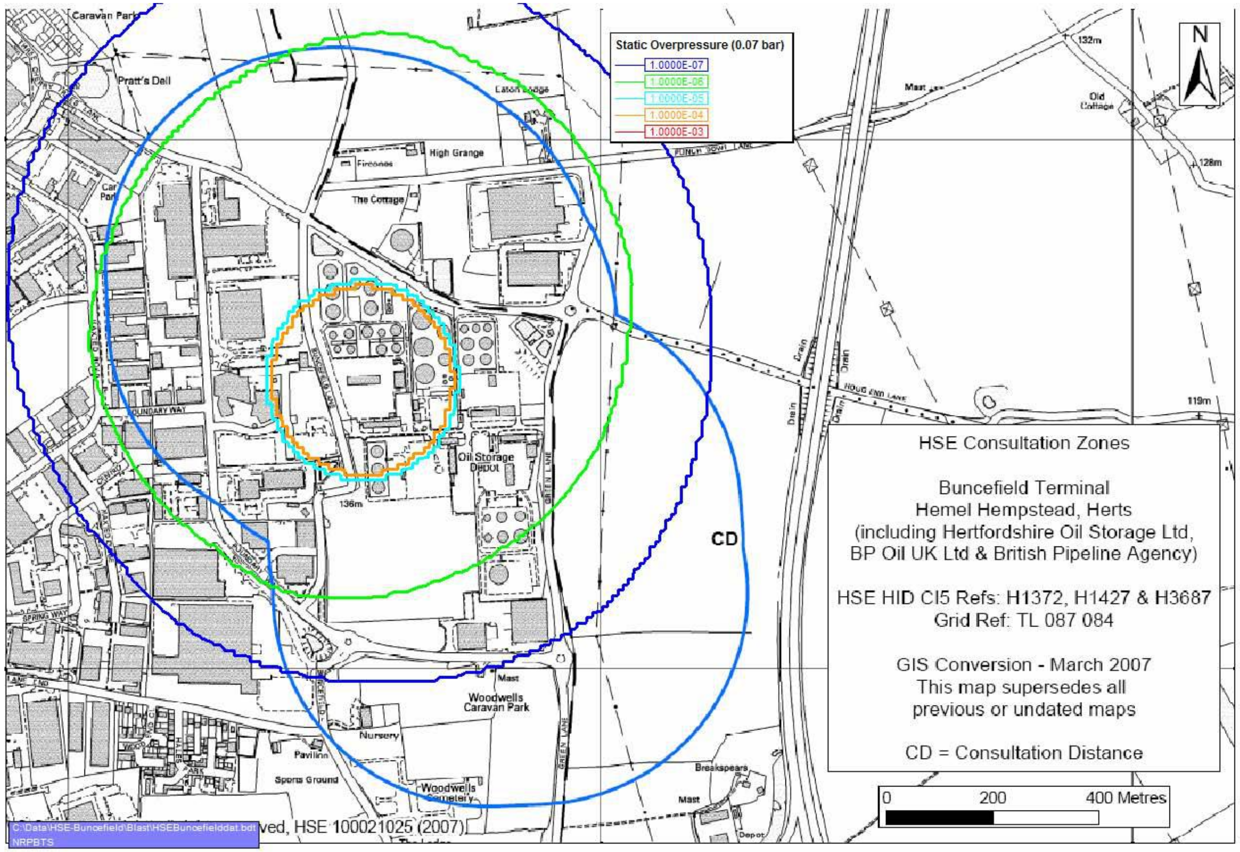


Figure 18 Frequency of Overpressure Exceeding 140 mbar (HSE Dangerous Dose)

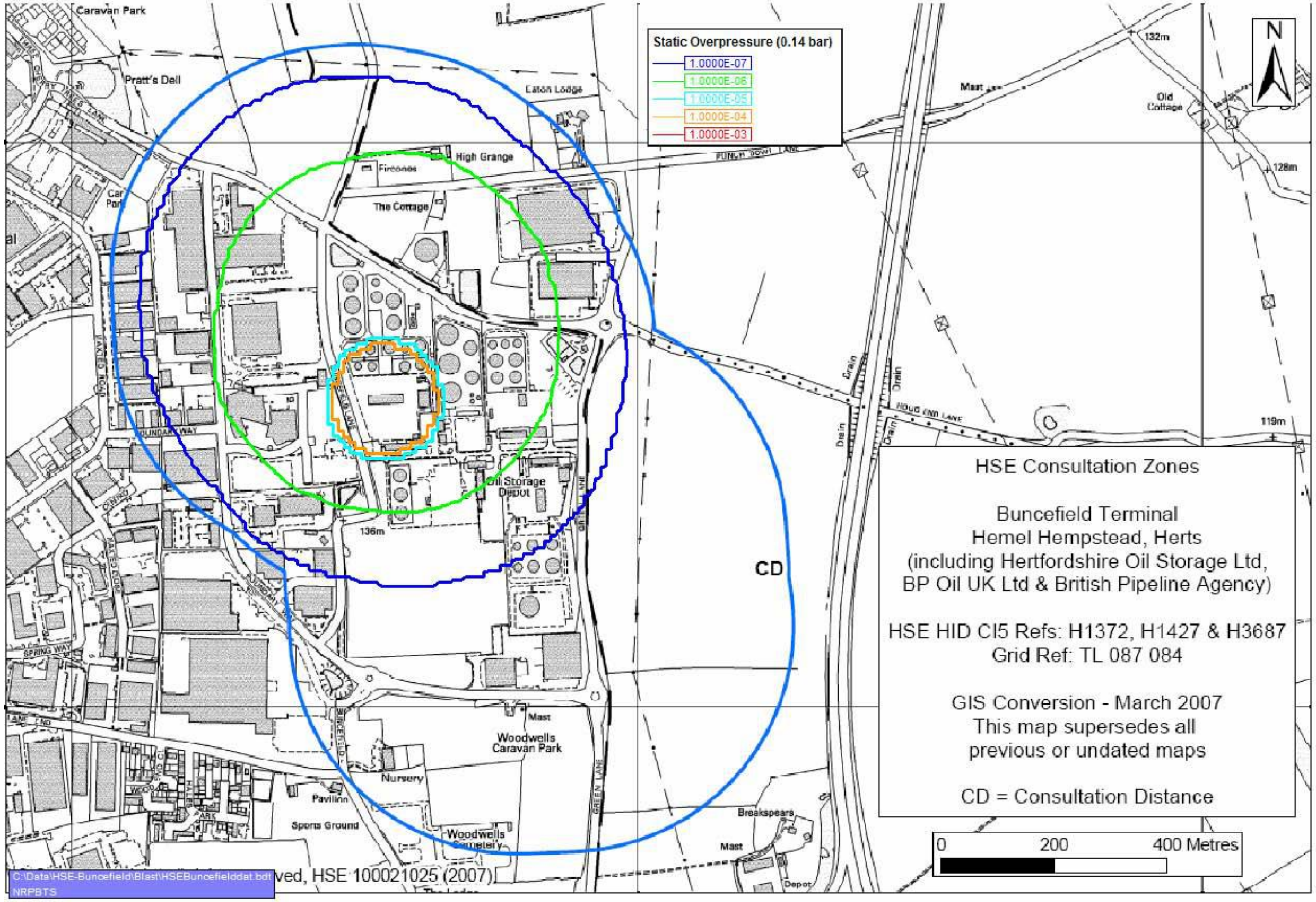


Figure 19 Individual Risk of Fatality to a Person in a Typical Brick House (assuming full time occupancy)

Appendix VIII Hazard Frequency and Individual Risk Contours - Lastfire Group Overfilling Frequency, Purple Book Tank Failure Frequencies with measures to reduce likely release duration with no loading rack explosion

Figure 20 Frequency of Overpressure Exceeding 70 mbar (HSE Dangerous Dose for Vulnerable Population)

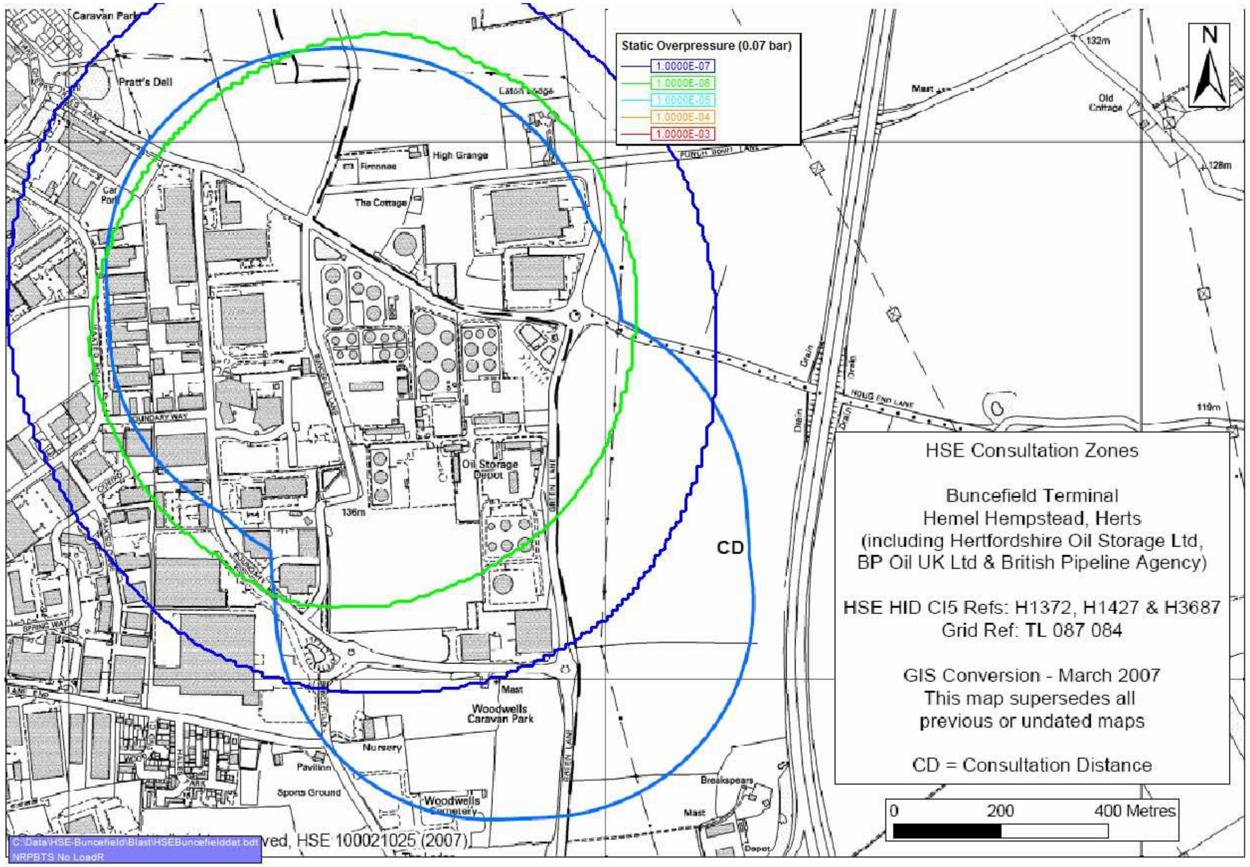


Figure 21 Frequency of Overpressure Exceeding 140 mbar (HSE Dangerous Dose)

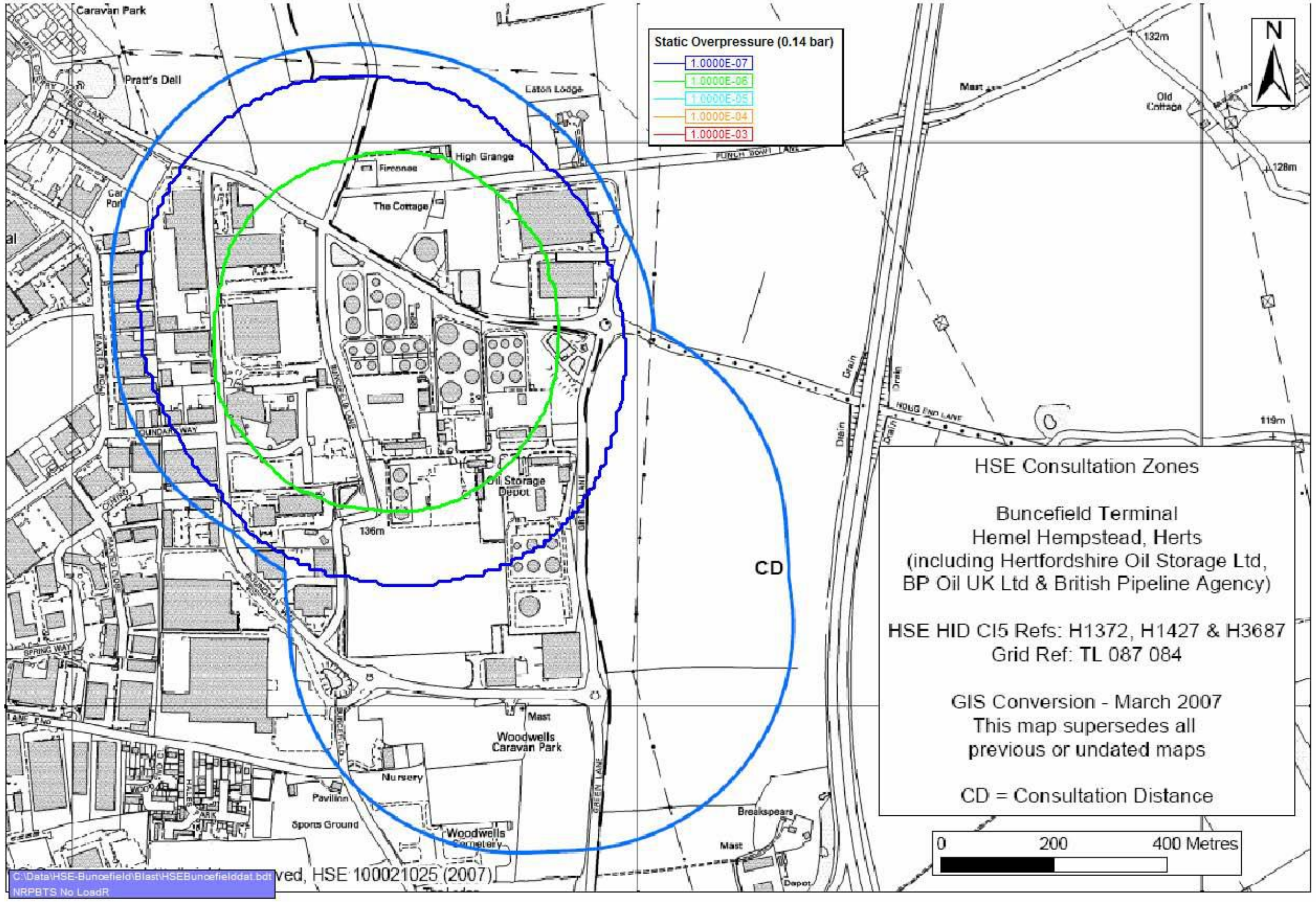
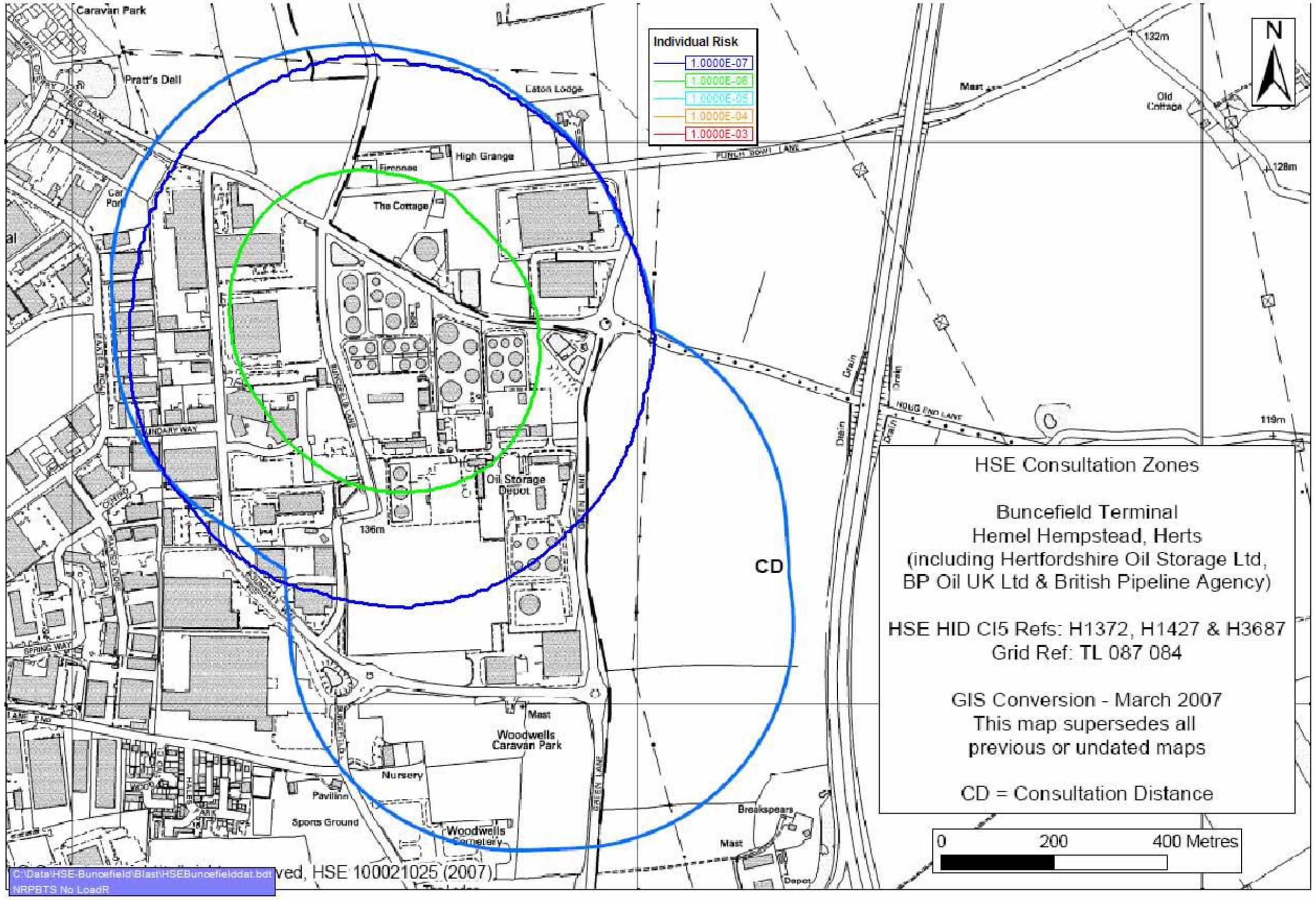
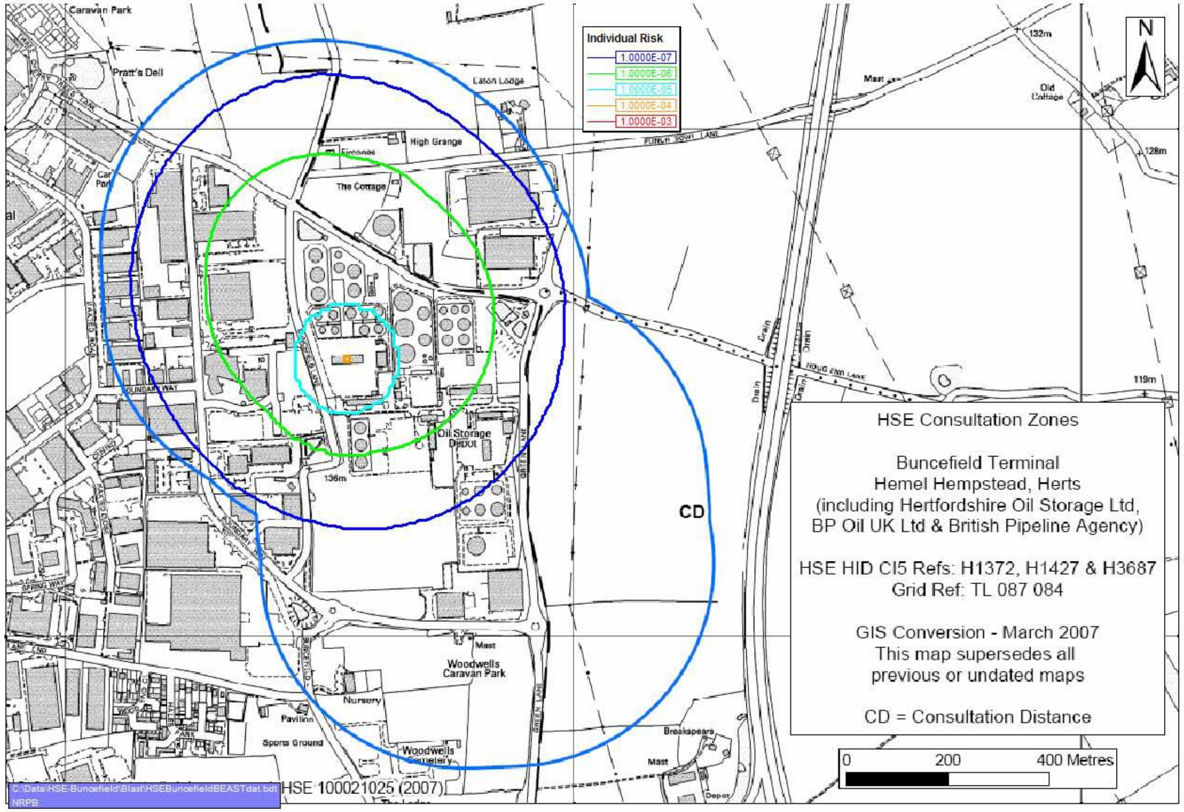


Figure 22 Individual Risk of Fatality to a Person in a Typical Brick House (assuming full time occupancy)



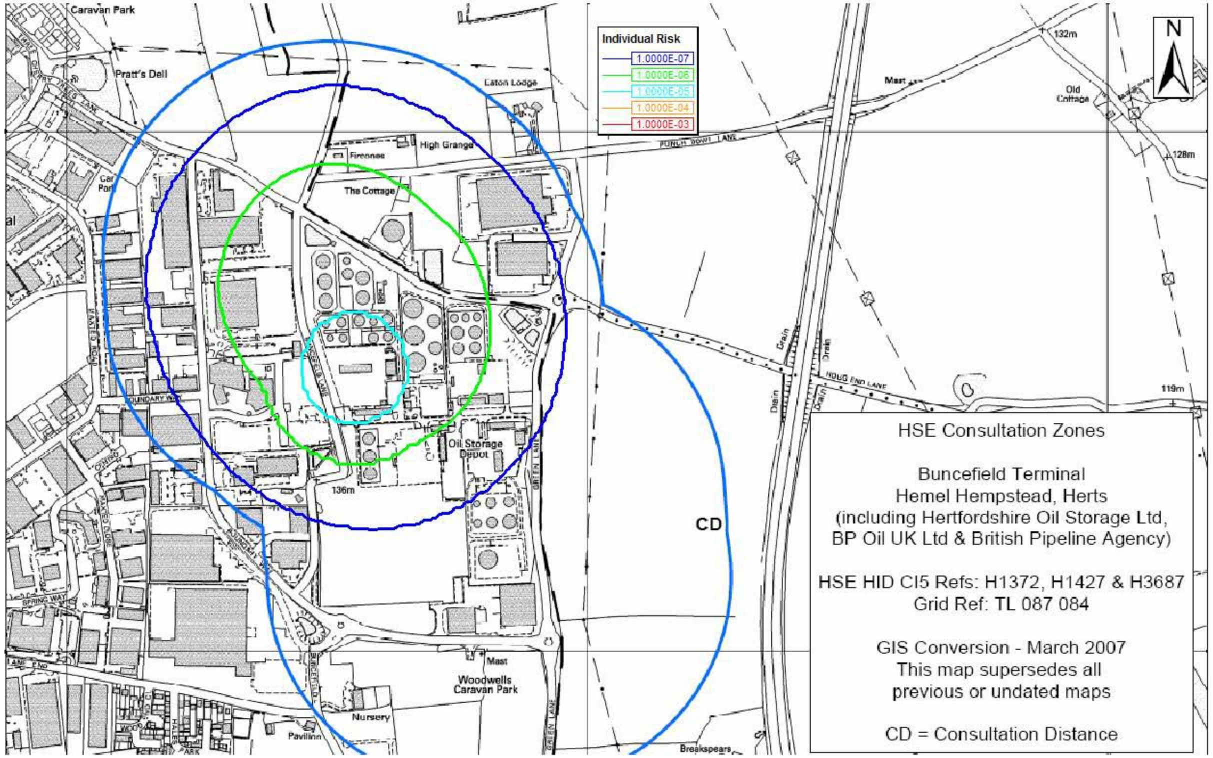
Appendix IX Individual Risk Contours for People Inside a Steel frame Brick Infill Building for 50 hours per week

Figure 23 Lastfire Group Overfilling Frequency and Purple Book Tank Failure Frequencies



This contour plot should be compared with Figure 16.

Figure 24 Lastfire Group Overfilling Frequency and Purple Book Tank Failure Frequencies with reduced durations of release



This contour plot should be compared with Figure 19.

DNV ENERGY

Illustrative model of a risk based land use planning system around petroleum storage sites:

Buncefield Major Incident Investigation Board
Rev 0, June 2008

MANAGING RISK