The Potential for Vapor Cloud Explosions - Lessons from Buncefield

Mike Johnson, Principal Consultant, GL Noble Denton Safety and Risk Team
GL Noble Denton, Ashby Road, Loughborough, Leicestershire, LE11 3GR, UK

Abstract

As a storage site, the Buncefield terminal had very little pipework congestion and at first sight would not have been considered as having much potential for a vapor cloud explosion. As a consequence, one of the actions of the Buncefield Major Incident Investigation Board (BMIIB) was to initiate a review of the possible causes of the severe explosion on the site. This review was then extended to a Joint Industry Project, Phase 1 of which has offered an explanation of the cause of the explosion. The conclusions are summarized along with reference to relevant experimental studies, illustrating how the elements of the explanation were already known. The implications of the incident for the assessment of vapor cloud explosion hazards will be discussed, both in terms of understanding worst case consequences and the use of risk based approaches.

Introduction

At around 06.00 on Sunday 11th December 2005, a vapor cloud explosion occurred at Buncefield Oil Storage Depot, Hemel Hempstead, Hertfordshire, UK, generating significant blast pressures. The damage caused by this explosion resulted in further loss of containment and the subsequent fires involved a number of fuel storage tanks on the site. There were no fatalities, but 43 people were injured and significant damage occurred to both commercial and residential properties in the vicinity. Total damages were of the order of $1.5 billion.

The subsequent investigation by the Buncefield Major Incident Investigation Board (“BMIIB”) determined that the explosion was a consequence of the spillage of 300 tonnes of unleaded winter-grade gasoline following overfilling of one of the storage tanks on the site. The investigation by BMIIB covered many areas but identified the severity of the explosion as one of the important issue that required explanation.

The need for an explanation comes from the nature of the site. Having very little pipework congestion, there did not appear to be the conditions present that could lead to a vapor cloud explosion.

An initial review of the possible explanations was carried out for BMIIB by the Explosion Mechanism Advisory Group [1]. Subsequent to this, a more detailed examination of the evidence has been carried out by a Joint Industry Project. The UK Health & Safety Executive has recently published the findings of this project [2], indicating that the severity of the explosion was primarily due to a deflagration to detonation transition.

It will be seen that though each of the elements was already understood (and had already occurred in previous incident, though not necessarily together) there are implications for the assessment of vapor cloud explosion hazards.

The Vapor Cloud

The spillage of the gasoline occurred over a period of about 40 minutes prior to ignition. CCTV records show that a low lying vapor cloud developed over a wide area, extending significantly offsite. The total area of the cloud was of the order of 100,000m^2 with an estimated height of at least 2m over most of the area. Figure 1 shows the area of the site indicating the cloud boundary given in BMIIB reports. Also shown on the figure are:

- Tank 912, which was the tank that was overfilled
- The fire water pump house to the north of tank 912
- Buncefield Lane and Three Cherry Trees Lane
- The open car parks to the west (left) of tank 912.

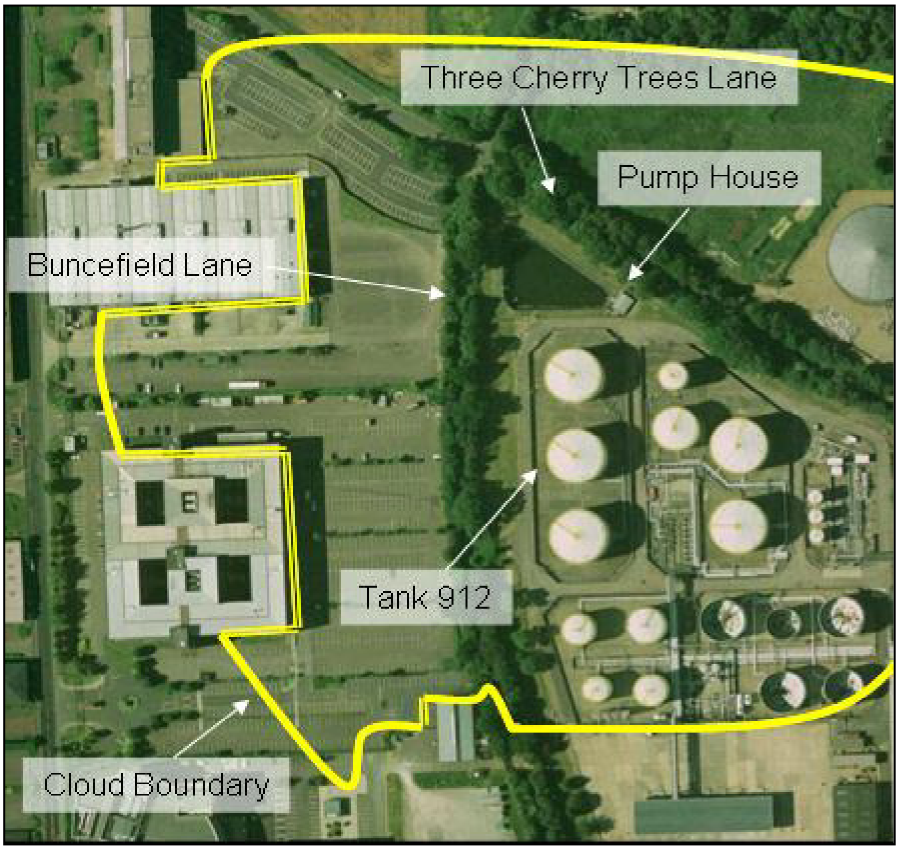

Figure 1: Buncefield Site Prior to Explosion Showing Approximate Cloud Boundary (Site picture from Google Earth)

The spillage occurred from the top of tank 912 and the design of the tank would have promoted the break-up of the liquid as it flowed off the top and down the side, which would have aided the formation of vapor. In addition, the gasoline was reported to be a 'winter mix' incorporating about 10% butane [3], which would also have increased the rate of vapor generation. The main components of the vapor cloud were probably butane and pentane [4].

Unusual Aspects of the Explosion

The key aspects of the explosion at Buncefield that were unusual were:

- The evidence of high overpressures throughout the vapor cloud despite the lack of any significant on-site pipework congestion that would normally be considered as a prerequisite for a vapor cloud explosion.
- Duration of positive (non-negative) phase – CCTV records show arrival of overpressure (in the form of moving objects and cameras) at a number of locations followed by a 'misting' of the atmosphere of the order of half a second later. This misting has been interpreted as being due to condensation of water vapor in the atmosphere in the 'negative phase' of the overpressure loading.
- Directional indicators – within the boundary of the vapor cloud, objects such as bent fence posts and camera towers were all bent towards the source of the explosion. Outside the cloud, such items pointed away from the cloud.
- Pressure Decay from the edge of the cloud – there was rapid decay in the degree of overpressure damage from the edge of the vapor cloud, with significant changes over distances of just a few meters.

The explanation of these characteristics was the primary objective of the Joint Industry Project.

Cause of the Vapor Cloud Explosion

The findings of the detailed review and analysis carried out within the recent Joint Industry Project were summarized in the report:

> "*From the work undertaken, the most likely scenario can be summarised as follows:*
>
> - *Dense vapour dispersion in very low wind speed conditions leading to a cloud build-up over an area of 120,000m*^{2}
> - *Ignition at the emergency pump house; failure of the pump house structure followed by a deflagration outside the pump house and flame propagation to the undergrowth and trees.*
> - *Flame acceleration in the undergrowth and trees along Three Cherry Trees Lane up to flame velocities to several hundred m/s, followed by a transition to detonation near the junction between Three Cherry Trees Lane and Buncefield Lane.*
> - *Detonation of part of the remaining gas cloud."*

The project showed that a deflagration in the trees could not explain the evidence on its own. In particular, a deflagration could not explain:

- The widespread pressure damage to vehicles, instrument boxes, drums, etc located within the vapor cloud. Most of which indicated that overpressures were in excess of 2bar, even in areas some distance from the congestion provided by the trees.
- The directional indicators, such as bent posts. Objects within the cloud but outside the areas of trees and bushes (where the deflagration would occur), would be pointing away from the explosion, not towards the explosion as was observed.
- The rapid decay in overpressure damage from the edge of the cloud.

Overall, the evidence indicated that conditions changed significantly at the cloud boundary, not outside the ‘congested’ areas of trees and bushes. A transition to detonation provides an explanation, as it provides high overpressures throughout the cloud. Venting of the combustion products behind the detonation front also results in a net force in the direction opposite to the direction of the detonation front, explaining the directional indicators. Finally, the detonation will provide high pressures within the cloud, but as the cloud was probably no more than 2 meters high at its edge, rapid decay would occur beyond the cloud edge.

Deflagrations and Detonations

In order to assess the implications of the findings, it is worthwhile to consider briefly the differences between deflagrations and detonations in relation to the generation of damaging overpressures.

Deflagrations

The primary characteristics of a vapor cloud explosion involving a deflagration are:

- Pressure is generated by the flame travelling at high speeds, typically over 200ms^{-1} (for comparison the ambient speed of sound is about 340ms^{-1}). The flame generates pressure because of the inertia of the unburnt mixture in front of the flame, in a manner similar to the way any object moving at high speed through the air generates a pressure wave in front of it.
- Large scale experimental work showed that, if the flammable cloud engulfs a region of repeated pipework obstacles, then flame acceleration occurs and that under certain conditions, the flame will achieve the high speeds required to generate damaging pressures.
- The flame acceleration is a consequence of the flow field generated by the expansion of the combustion products behind the flame front. As the flame front encounters obstacles and follows the flow around the obstacle, the flame distorts, increasing its area and the rate at which combustion products are generated. This increases the flow speeds ahead of the flame and can lead to the generation of turbulence in the wake of obstacles. When the flame enters the turbulence, the local burning velocity will increase. This can produce a positive feedback mechanism in repeated obstacles, producing successively higher flame speeds and increasing overpressures. Under certain conditions, this can lead to continuous flame acceleration.

An important aspect of deflagrations is that the high flame speeds are dependent on the continued presence of obstacles. Once the flame passes into an open area it rapidly decelerates. Pressure generation is therefore limited to regions of repeated obstacles with the magnitude of the pressure wave produced by the explosion decreasing as it propagates away from the congested region. The rate at which the observed pressure decays will depend to an extent on the nature of the actual explosion.

Detonations

The key properties of a detonation, as compared to a deflagration are :

- The detonation front (analogous to the flame front in a deflagration) has an initial sudden rise in pressure, which then decays. This sudden rise in pressure is known as a shock front and the whole pressure wave as a shock wave.

- The shock front compresses the fuel/air mixture and in doing so, raises its temperature. In a detonation, the temperature rise is sufficient to initiate combustion as it exceeds the autoignition temperature of the mixture.
- Energy released from the combustion process maintains the magnitude of the shock front.
- This coupling of the shock wave and combustion process is self sustaining and is not dependent upon the presence of obstacles.
- In an unconfined vapor cloud, the volume of the cloud that contributes to pressure generation is determined by the extent of cloud within the concentration limits that can sustain a detonation. Compared to a deflagration, this can be a significant increase if the cloud extends well outside areas of congestion.

The initial shock front typically has a magnitude in excess of 20 bar for hydrocarbon/air mixtures initially at atmospheric pressure. The detonation front travels at speeds of the order of 1800ms^{-1}. The ability of a detonation to be sustained depends on the fuel type and its concentration in air. The influence of both fuel type and concentration is indicated in in publications such as Bull [5] and it is notable that that this shows that the detonability of fuels such as propane, butane and pentane are similar (the relevance of this becomes clear when experimental data is considered).

Was the Buncefield Explosion Foreseeable?

Assessment of major accident hazards requires the consideration of low likelihood events that can have major consequences. Though previous incidents can provide a guide to what is possible, they not sufficiently precise to allow prediction of the major accident risks for a particular facility.

The assessment of the major accident hazards is usually achieved by considering the likelihood and outcome of each step of the event sequence that can lead to the realization of the major accident. The event sequences considered should at the very least include the sequences of events observed in relevant previous incidents.

The Buncefield explosion can be compared with previous incidents and the elements that were involved can be examined to see if there was sufficient knowledge to foresee the possibility of the explosion. There are four main steps in the event sequence:

- Spillage of gasoline
- Development of a vapor cloud
- Ignition
- Vapor cloud explosion

Of these, the spillage of gasoline and ignition of a vapor cloud that extended over such a wide area were clearly foreseeable. The development of the vapor cloud and the occurrence of the explosion need to be considered further.

Previous Incidents

Buncefield is not the first incident where overfilling of a gasoline storage tank has resulted in a drifting vapor cloud and vapor cloud explosion. Four incidents are summarized below:

- Newark, New Jersey, 1983, in which overfilling of a storage tank resulted in a spillage of up to 265 tonnes of gasoline into a bund. A vapor cloud 450m to 600m long and 60 to 90m wide was formed. The explosion caused significant damage on site, including damage to storage tanks 100’s of meters from the point of release, and glass breakage out to a distance of 5.6km [6][7].
- Naples, Italy, 1985, in which overfilling of a gasoline storage tank resulted in spillage of about 700 tonnes into a bunded area. The explosion resulted in serious damage to structures within 100m and glass breakage out to 1km [8].
- Saint Herblain, France, 1991, in which a release of gasoline from a section of pipe inside a bund produced a vapor cloud. Ignition of the vapor cloud produced extensive damage [9].
- Sri Racha, Laem Chabang, Thailand, 1999, in which overfilling of a gasoline storage tank resulted in an explosion causing damage to nearby buildings [10].

This potential for a spillage of ‘cold’ gasoline to lead to a vapor cloud explosion was also recognized by Kletz in 1986 [11].

Buncefield is also not the first vapor cloud explosion to occur in an area where there was little or no pipework congestion. Two incidents are notable:

- Port Hudson, Missouri, 1970, in which a propane cloud was ignited in a rural area, generating severe explosion damage [12]. No pipework congestion was present; however, the cloud engulfed buildings and wooded areas.
- Brenham, Texas, 1992, in which the ignition of a vapor cloud comprising a mixture of hydrocarbons in a rural area resulted in significant damage to nearby buildings [13]. No pipework congestion was present but the cloud engulfed wooded areas.

The Port Hudson incident was reported to involve a detonation of the propane vapor cloud and shared many characteristics with the Buncefield explosion, including the same pattern of directional indicators within the cloud. In their analysis of the Port Hudson incident, Burgess & Zabetakis [14] stated in relation to the damage inside the Port Hudson cloud, “*We think that it is significant that the wind direction was everywhere opposite to the postulated direction of the detonation*”. (‘Wind direction’ in this case is taken to be the implied direction of the gas flow associated with the propagating detonation.)

A common factor to all of these incidents is that they took place at a time when the wind speed was low, allowing a widespread low lying vapor cloud to be developed.

Experimental Evidence

The lines of trees and bushes along the lanes at Buncefield had a length that was much greater than their width or the height of the cloud. This high aspect ratio is a problem when attempting comparison with experimental studies, as most have involved relatively low aspect ratio congested regions (that is the length width and height are all similar) such as that shown in Figure 2, which was used in the MERGE/EMERGE EU Co-funded project [15].

Figure 2: Congestion Used in MERGE/EMERGE Projects

A series of experiments were however carried out in the 1980s by British Gas Research & Technology (now GL (UK)) at the Spadeadam test site in the UK [16]. These experiments were conducted in a 45m long test rig with a 3m square cross section, shown in Figure 3. The typical obstacle arrangement used in these experiments was formed by arrays of 0.18m diameter pipes spaced at 1.5m intervals, as shown in Figure 4. The volume blockage used in these experiments was approximately 4%.

Experiments were conducted with natural gas, cyclohexane and propane, with similar results obtained in the cyclohexane and propane experiments. Ignition was by a single spark at one end of the test rig and in some of the tests the initial 9m was confined on the outer faces (this initial confined region can be seen in Figure 3.

In a cyclohexane air experiment without the initial confinement, the flame accelerated from a spark ignition to a speed of over 200ms^{-1} at the end of the test rig. It should be noted that the acceleration of the flame increased as the speed increased, thus, though it took 45m to reach over 200ms^{-1}, flame speeds in excess of the speed of sound would probably been achieved had the test rig been 10m or so longer.

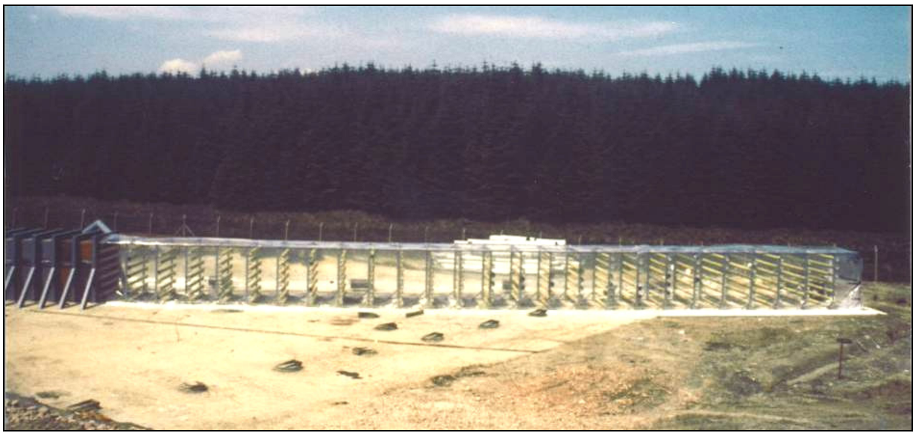

Figure 3: 45m Long Test Rig Used in Spadeadam Tests

Figure 4: Obstacle Configuration Used in 45m Long Test Rig

In propane and cyclohexane experiments using the initial confinement, rapid acceleration took place inside the confinement and the speed of the flame as it exited from the initial confinement was about 250ms^{-1}, comparable with the speed that was achieved at the end of the test rig in the earlier experiment. Within 15m of further flame propagation the flame had accelerated to a speed of over 600ms^{-1} and the deflagration underwent a transition to detonation, with flame speeds of about 1800ms^{-1} that continued through the full length of the rig, including a completely unobstructed region.

Though it is generally accepted that deflagration to detonation transition is possible with highly reactive fuels such as hydrogen, acetylene and ethylene, the experimental program clearly showed that flame acceleration up to a point where transition from deflagration to detonation occurred was possible with propane and cyclohexane, which have very similar properties to the main elements of the cloud in the Buncefield explosion, namely butane and pentane.
Figure 5 shows areas of trees and bushes along Buncefield Lane that were unaffected by the explosion and subsequent fires. Although much less regular, if anything the region is more congested that that used in the experiments. The length of the regions of trees and bushes at Buncefield was also greater than that used in the experiments, giving greater potential for flame acceleration. It is noteworthy that the paper describing the British Gas tests at Spadeadam identifies trees as potential congestion, largely due to consideration of the Port Hudson incident. The only remaining factor therefore that could have prevented the development of high flame speeds (with the potential for transition to detonation) in the trees and bushes was the fuel concentration, as this has a considerable effect on the rate of flame acceleration. CFD simulations carried out by Shell for the Joint Industry Project showed that representations of the trees could result in flame acceleration to supersonic speeds with a stoichiometric cloud.
The calculations suggest that the concentration of the vapor cloud in the tree line near to the pump house was likely to have been somewhere near stoichiometric.

Figure 5: Bushes and Trees on Buncefield Lane (Unaffected by the Incident)

Assessment of Vapor Cloud Explosion Hazards

There are a number of aspects of the Buncefield explosion that stand out as important issues for the assessment of vapor cloud explosions:

- There is a need to consider all objects that can interact with a vapor cloud, including those off-site.
- Trees and bushes can represent congestion which, if engulfed by a vapor cloud, can lead to significant flame acceleration. Likewise any other objects that can form congested regions should be included; the analysis should not be restricted to process units.
- The low wind speed at the time of the incident and the nature of the spillage resulted in a large vapor cloud. In the case of Buncefield this allowed a significant length of trees and bushes to be engulfed, giving the potential for very high flame speeds to be generated. Determining the potential vapor dispersion from a release is therefore important, particularly for cases where there are low wind speeds.
- Transition from deflagration to detonation is possible with fuels such as propane, butane and pentane when high flame speeds are generated. The issue here is that not that detonation is possible, just that it was not widely accepted that this could occur with these fuels in practical situations.

The Joint Industry Project has proposed experimental work to characterize the flame acceleration generated by trees and bushes. This would be comparable to the work carried out to investigate the effects of process congestion and provide guidance on what types of environmental screening would be appropriate for sites. However, in the interim, regions of tree should be treated as congestion, just as any pipework region.

In this respect it should be noted that it was probably the bushes at low level (2m and less) that were most important for flame acceleration at Buncefield. Had only widely spaced tree trunks been present with the branches at higher levels, the flame acceleration probably would not have occurred with the low lying cloud at Buncefield. However, it is not uncommon for such low lying bushes to be used to screen a site. As initial guidance, it can be stated that the potential for flame acceleration would be reduced if:

- The horizontal depth of the screening bushes should is kept to a minimum
- Gaps are placed along the length of the screening to prevent continued flame acceleration.

The key aspect of accepting detonation as a possibility is that the worst case consequences of a vapor cloud explosion can be significantly greater than would be possible with a deflagration. For example, if an occupied building has a reasonable separation from a congested process area, then it is possible to design the building to withstand the pressure incident on the building from a deflagration. However, if the cloud that engulfs the congested region also extends towards the building, then a detonation would generate high overpressures much closer to the building and it would be much more difficult to design to withstand this much higher loading. Similarly, a detonation is more likely to cause further loss of containment (as happened at Buncefield) and escalation of the incident.

The inclusion of detonation can significantly alter the basis of any VCE hazard analysis based on consequences alone (taking no account of the likelihood of the event) and would most likely be impracticable. GL has, for some time, routinely incorporated the possibility of detonation into risk based explosion assessments. (Largely due to our background in conducting large scale experiments and having observed deflagration to detonation transition.)

The methodology employed by GL is:

- Model the vapor dispersion for a range of release scenarios.
- Use our explosion model to estimate the flame speeds and pressures generated in any congested region the vapor cloud overlaps.
- If the predicted flame speed is close to the speed of sound (the actual value used depends on the fuel type), then it is assumed that detonation is possible. In the detonating cases, the flammable cloud is used as the region of pressure generation. (It is worth noting that when the GL explosion models were applied to the bushes and trees at Buncefield, flame speeds were predicted that would have required detonation to be included.)
- Using a wide range of scenarios, overpressure exceedance curves can be generated and design targets can be selected on a risk basis.

Within a risk based approach, because the potential for detonation is relatively remote, its inclusion does not necessarily have any impact on design targets for on-site structures. However, due to the low tolerability of risk to offsite personnel (the public) and detonation may have implications for facilities located in areas with significant off-site populations as it can lead to severe pressure damage to off-site buildings.

Conclusion

The severity of the Buncefield explosion may have been surprising given the lack of on-site congestion but it can clearly be explained using current knowledge of vapor cloud explosions.

The incident has implications for the assessment of vapor cloud explosions, particularly in that it has shown that transition to detonation can occur with fuels such as propane and butane in realistic conditions. This can be accommodated within a risk based approach to explosion assessment due to the low probability of the event.

Finally, it should be noted that in the case of Buncefield, the detonation would not have occurred if very high flame speeds had not been generated in the deflagration. Reducing the likelihood and severity of deflagration will therefore reduce the potential for detonation to occur.

Acknowledgement

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References

[1] Explosion Mechanism Advisory Group report, Buncefield Major Incident Investigation Board, August 2007

[2] Buncefield Explosion Mechanism Phase 1, http://www.hse.gov.uk/research/rrpdf/rr718.pdf, 2009

[3] BUNCEFIELD MAJOR INCIDENT INVESTIGATION, 'Initial Report to the Health and Safety Commission and the Environment Agency of the investigation into the explosions and fires at the Buncefield oil storage and transfer depot, Hemel Hempstead, on 11th December 2005 Buncefield Major Incident Investigation Board', 13th July 2006

[4] Liquid dispersal and vapour production during overfilling incidents, G Atkinson, S Gant, D Painter, L Shirvill and A Ungut, Hazards XX University of Manchester, UK, 14–17 April 2008 in IChemE Symposium Series 154

[5] Initiation of unconfined gas detonations in hydrocarbon-air mixtures by a sympathetic mechanism. Bull DC, Elsworth JE, McLeod MA, Hughes D, Progress in Astronautics and Aeronautics, Volume 75, Gas Dynamics of Detonations and Explosions, Pages 61-72, 1981

[6] Bouchard JK Gasoline Storage Tank Explosion and Fire: Newark NJ January 7, 1983. National Fire Protection Association (NFPA) Summary Investigation Report (in cooperation with Federal Emergency Management Agency/United States Fire Administration and National Bureau of Standards/Center for Fire Research) (referenced in BMIIB Initial report).

[7] A survey of vapour cloud explosions second update by Eric M. Lenoir & John A. Davenport, Industrial Risk Insurers, Hartford, Connecticut, Paper No. 74d, 26th Annual Loss Prevention Symposium, AIChemE, New Orleans, 1992..

[8] Maremonti M, Russo G, Salzano E et al 'Postaccident Analysis of Vapour Cloud Explosions In Fuel Storage Areas' Trans IChemE 1999 77 (B) 360365.

[9] Lechaudel JF and Mouilleau Y 'Assessment of an accidental vapour cloud explosion. A case study: Saint Herblain, October the 7th 1991, FRANCE' Loss Prevention and Safety Promotion in the Process Industries 1995 1 377388.

[10] The 100 Largest Losses 1972-2001, Large Property Damage Losses in the Hydrocarbon-Chemical Industries, 20th Edition: February 2003, A publication of Marsh's Risk consulting Practice.

[11] Will cold petrol explode in the open air, T Kletz (The Chemical Engineer, June 1986, IChemE)

[12] Pipeline accident report, Phillips Pipeline Co., Propane gas explosion, US National Transportation Safety Board, Report No. NTSB-PAR-72-1, March 1971.

[13] Pipeline accident report, Highly volatile liquids release from underground storage cavern and explosion, MAPCO natural gas liquids, Inc. Brenham, Texas April 7 1992, NTSB-PAR-93-01

[14] Detonation of a flammable cloud following a propane pipeline break, DS Burgess and MG Zabetakis, US Bureau of Mines, Report of investigation 7752, US Department of the Interior, 1973.

[15] Validation of Scaling Techniques for Experimental Vapour Cloud Explosion Investigations, W.P.M. Mercx, D.M. Johnson and J. Puttock, April 1995, Process Safety Progress, 14, No. 2, 120-130.

[16] Understanding vapour cloud explosions – an experimental study, RJ Harris and MJ Wickens, IGE comm. 1408, 1989.