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BUNCEFIELD ACCIDENT – HISTORY AND PROGRESS

Bassam Burgan[1], Graham.Atkinson [2], Renato F. Mendes[3]

Abstract

The Buncefield incident caught the attention of the oil industry for many reasons. Firstly, it showed up particular causes of overfilling incidents related to weaknesses in instrumentation testing, maintenance and fuel transfer procedures. Secondly, the incident drew attention to the fact that in calm conditions a gasoline overfill can be an extremely efficient mechanism for generating a flammable cloud. This can spread for many hundreds of meters without significant dispersion. Finally, the vapour cloud explosion that followed ignition was much more violent and widespread than would have been predicted.

On Dec 11th 2005, at 6.01AM a massive explosion and subsequent fire destroyed large parts of the Buncefield oil storage and transfer depot (mostly gasoline), Hemel Hempstead, and caused widespread damage to neighboring properties. The explosion set all of the 23 tanks surrounded by the flammable cloud alight and the resulting fires burned for five days. Fortunately the incident happened early in the morning and the flammable cloud did not engulf any occupied buildings- there were some injuries but no fatalities.

The Buncefield Major Incident Investigation Board (MIIB), headed by Health & Safety Executive (HSE), invited explosion experts from academia and industry to form an Advisory Group. The final report of the investigation was issued by the (HSE) in July 2008, and addresses several recommendations and a need for further research.

In parallel, one of the benefits to the industry of the incident was the work of the Process Safety Leadership Group (PSLG). This involved a dialogue between industry, trade unions and the COMAH Competent Authority (CA) to agree a framework of recommendations aimed at improving safety on tank farms.

Major players in the oil industry as well as the UK government also collaborated to set a Buncefield Explosion Mechanism Research Project. The first phase of this project is now complete and generated a wide range of improvements in the understanding of vapor cloud explosions. Subjects covered included:

- Overpressure indicators for forensic work at VCE sites
- Blast direction indicators in low lying VCEs
- Overpressure variation within and outside the Buncefield cloud
- Damage to structures at difference ranges
- Potential for flame acceleration in dense hedgerows
- Commonality with previous VCE incidents
- Potential for enhancement explosion severity through radiative ignition of debris ahead of the flame

Important uncertainties remained that could only be properly resolved by additional large-scale experimental work. Phase 2 of the work is currently underway – with Petrobras as one sponsor. This project will deliver fundamental understanding in the following areas:

- Generation and dispersion of flammable clouds during overfills
- Flame acceleration in dense vegetation
- Physical effects of detonations on enclosures and vehicles
- Blast wave characteristics of detonations
- Structural response of blast affected buildings

This paper examines the lessons to be learned from the Buncefield incident for the design, maintenance and operation of tank farms.

[1] Ph.D., Project Coordinator – Steel Consruction Institute
[2] Ph.D., Scientist – Health & Safety Laboratories
[3] M.Sc., Risk Expert, Petrobras/ Engineering

1. Introduction

Gasoline was being delivered through the UKOP South pipeline (550m^3/h) into Hertfordshire Terminal (HOSL) in the Tank 912 for about 11 hours. The tank, which had a capacity of 6,000 m^3, was fitted with an Automatic Tank Gauging System (ATG) which measured the rising level of fuel and displayed this on a screen in the control room. At 3:05 hrs on Sunday 11 December the ATG display 'flatlined', that is, it stopped registering the rising level of fuel in the tank although the tank continued to fill. Consequently the three ATG alarms, the 'user level', the 'high level' and the 'high-high level', could not operate as the tank reading was always below these alarm levels. Due to the practice of working to alarms in the control room, the control room supervisor was not alerted to the fact that the tank was at risk of overfilling. The level of gasoline in the tank continued to rise unchecked.
A second Independent High-Level Switch (IHLS) set at a higher level than the ATG alarms. This was intended to stop the filling process by automatically closing valves on any pipelines importing product, as well as sounding an audible alarm should the petrol in the tank reach an unintended high level. The IHLS also failed to register the rising level of petrol, so the 'final alarm' did not sound and the automatic shutdown was not activated. By Saturday, 5:37 hrs, 11 December, the level within the tank exceeded its ultimate capacity and petrol started to spill out of vents in the tank roof.

Over aperiod of 23 minutes 180 tonnes of gasoline were spilled , about 10% of which turned to vapor that mixed with the cold air, eventually reaching flammable concentrations capable of supporting combustion. The terminal CCTV cameras showed that soon after that a white vapor was seen to emanate from the bund around the tank. In the windless conditions (atmosphere stability F) this vapor cloud, which was likely to have been a mixture of hydrocarbons and ice crystals, gradually spread to a diameter of about 400 m, including outside areas of the terminal, see Fig.5.
The vapor cloud was noticed by several members of the public off site but they did not recognize that the terminal was the source of the mist spreading at low level. Eventually the flow of gasoline out of the tank top was spotted by a tanker driver on site waiting to fill his vehicle. He alerted site operators and the fire alarm button was pressed at 6:01 hrs, which sounded the alarm and started the firewater pump. A 'vapor cloud explosion' occurred almost immediately, probably ignited by a spark caused by the firewater pump starting. The severity of the explosion was far greater than could reasonably have been anticipated based on knowledge at the time and the conditions at the site. The devastation was enormous. Fortunately there were no fatalities but over 40 people were injured. The ensuing fire, the largest seen in peacetime UK, engulfed over 20 fuel tanks on the Hertfordshire Terminal and burnt for five days. The human effects may have been even greater had the event not occurred early on a Sunday morning when the adjacent industrial area was relatively quiet.

The investigation team, led by the UK's Major Incidents Investigation Board (MIIB), has since produced a series of reports (1,2,3,6) into issues such as safety management at storage sites for fuels and other hazardous substances, environmental impact and planning around industrial sites. There have also been the recent prosecutions of five companies ending to several fines.
A fully investigation on explosion mechanisms was developed named "Buncefield Explosion Mechanism – Phase 1" based on several evidences from the Buncefield site, explosion modeling and estimations. An ongoing Phase 2 research is developing experimental tests to prove some hypotheses for explosion mechanisms of Buncefield.

2. Major Root Causes

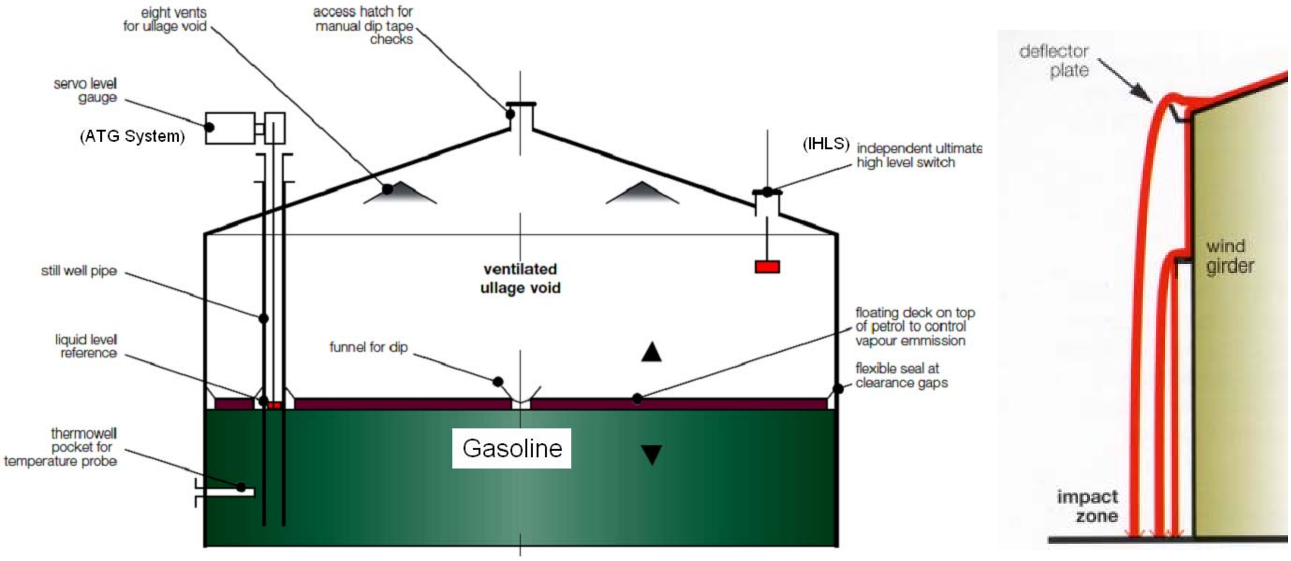
The immediate cause of this major incident was the failure of both the ATG and the IHLS to operate as the fuel level in Tank 912, see Fig.1. This was a loss of 'primary' containment (tank overfilling).

2.1. Control System at HOSL Terminal

The ATG system's servo-gauge had faulted (stuck) causing the level gauge to 'flatline' and not for the first time. In fact it had stuck 14 times between 31 August 2005 and 11 December 2005. Sometimes supervisors rectified the symptoms of sticking by raising the gauge to its highest position then letting it settle again, a practice known as 'stowing'. On other occasions a maintenance company was called in to rectify the matter, although the definitive cause of the sticking was never properly treated. Sometimes the sticking was logged as a fault by supervisors and other times it was not. The failure to have an effective fault logging process and the lack of a maintenance regime that could reliably respond to those faults were two of the most important 'root cause' managerial and organizational failures underlying the incident. Further, maintenance contractors never saw that the unreliable gauge should be investigated. They did not analyze why they had been called out so frequently nor raise questioned about the reliability of the system.

In July 2004, due to process safety concerns the Tank 912 received an Independent High-Level Switch (IHLS), see Fig.1a. The manufacturer had designed the switch so that some of its functionality could be routinely tested. Unfortunately, the way the switch was designed, installed and maintained gave a false sense of security. Because those who installed and operated the switch did not fully understand the way it worked, or the crucial role played by a safe padlock, the switch was left effectively inoperable after the test. The design fault could have been eradicated at an early stage if the design changes had been subjected to a rigorous review process. The manufacturer was aware that its switches were used in high-hazard installations and therefore were likely to be safety critical. Designers and suppliers should have adequate knowledge of the environments where their equipment will be used.
Failures by the installation and maintenance contractor were:

1. The process for specifying the requirements of switches they supplied and installed was not adequate;
2. They did not obtain the necessary data from the manufacturer and it follows that they did not provide such data to their customers;
3. They did not understand the vulnerabilities of the switch or the function of the safe padlock;
4. There was a reliance on the switch manufacturer, which was not justified given the lack of information provided and the critical role that the installation and maintenance company had in providing safety critical equipment.



a) ATG system and Independent High-Level Switch (IHLS) b) Tank Deflector

Fig.1 – Tank 912 (6,000 m^3 operational load)

On the night of incident, supervisors on the control room had just one computer to display data from the ATG system, no backup computer was available. The tank 912 window was on the back of four other tank display windows. Just with one computer was not possible to observe all tanks and was necessary to rely just on sound alarms and automatic shutdowns.

The supervisors' main duty was operating and monitoring the control systems relating to movement and storage of fuel. A key role was the filling and emptying of tanks at HOSL Terminal. The ATG system was capable of providing supervisors with readings of a number of parameters. For level measurement the system was designed with a series of sound and visual alarms to alert the supervisor to the need to take action at various product levels within the tank.
Essentially there were three 'high level' alarms. These were:

1. user level - set by the supervisor to indicate that intervention was required;
2. high level - set at a level in the tank below its maximum working level;
3. high-high level - set below the level at which the IHLS was intended to operate.

However each of the eight supervisors used these alarm levels in their own way.

The supervisors written procedures relating to the filling process were weak on details. They gave no guidance as to how to choose the tanks which had to be filled or in what circumstances, if any, it was appropriate to deliberately fill a tank above the high or the high-high level. If such a procedure was deemed by management to be appropriate, there was no guidance to support this. Considering that this was the single most important process control system to prevent loss of containment of fuel, this was a serious management failure in the control of a major accident hazard.

The control of incoming fuel from UKOP pipelines were done from elsewhere for historical reasons, and the supervisors did not have access to the UKOP's SCADA monitoring system to tell them incoming flow rates and other transfer variables. Advance planning of deliveries from the UKOP pipelines would have been difficult and sometimes impossible. Significantly, no suitable advance planning system was in place. Changes in flow rates were significant and sometimes the HOSL supervisors were not informed. For example, shortly before the explosion, the flow rate in the UKOP South pipeline changed from 550 m^3/h to 900 m^3/h without the knowledge of the supervisors.

2.2. Cascade Effect

The tank 912 was fitted with a deflector plate, installed to direct water from sprinklers on the tank's roof to its side walls to provide cooling in the event of fire. Tests by the UK Health and Safety Executive demonstrated that the deflector plate channeled some of the escaped fuel onto the tank wall, but the rest ran over the top of the plate, fragmenting into droplets that cascaded through the air. Most of the fuel running down the wall hit a wind girder (a structural stiffening ring) and detached from the tank wall, creating a second cascade of droplets, see Fig.1b.

This gasoline cascade promoted the evaporation of the lighter components, i.e. butanes, pentanes and hexanes. The free-fall of droplets leads to entrainment of air and mixing between the air and fuel vapor, and the formation of a rich fuel/air mixture. Cooling of the surrounding air, already saturated with water vapor by the evaporation, would cause some of the water content to precipitate as an ice mist, which is consistent with the cloud of mist visible on CCTV cameras. The fuel/air mixture and its accompanying ice mist were heavier than air and dilution of the vapour current was reduced for this reason. Build up of a deep layer of vapour in and around the bund further reduced the rate at which fresh air could be mixed into the early high speed parts of the vapour flow. Eventually a slow moving stable vapour current was established that flowed away form the tank with very limited dilution and flammable concentrations extended over a very wide area. Further work to simulate the overflow of liquid from the full height of Tank 912 has been carried out to improve understanding of fuel dispersal and vaporization (7).

3. Phase 1: Explosion Mechanism

The Phase 1 Project was undertaken on the recommendation of the Explosion Mechanism Advisory Group, part of Buncefield Major Incident Investigation Board (MIIB). Its main objectives was to provide an understanding of the explosion mechanism in the Buncefield incident, to provide interim guidance where this proves possible and to define the scope of further work for a second phase (Phase 2), if necessary.
A vast amount of data in the form of witness statements (using extracts from anonymised witness statements), photographs, CCTV and video footage were studied and catalogued. Careful examination of this data enabled the explosion source terms and characteristics to be inferred.

3.1. Overpressure Findings

Based on anonymised witness statements, there was the initial drag described as a "strong wind" and the arrival of the most intense blast wave was characterised by destruction of buildings and witnesses being thrown around. All the witnesses within a few tens of metres of the cloud describe sustained pressure effects and/or sounds prior to the most violent phase of the blast. There was a sole witness mentioning "a flash" but might misrepresent a description of an extended process of flame advance:

"I clasped my hands over my ears and kept an eye on the mirror, seeing the flame coming towards me. I continued to look, to see whether the flames went past me, being concerned due to the fact my window was still down……..There was a flash, the flames came towards me; I could see the flame engulfing cars in the lane …….it lasted for two seconds."

The explosion was registered by a number of CCTV cameras records and this helped confirm the location of the ignition point. The cameras also provided information on illumination from the explosion, the arrival of shock waves generated by the event, the possible appearance of condensation of water vapour (evidencing the arrival of rarefaction) and the end of the rarefaction phase. In particular the timing of the arrival of the first shockwaves was very well defined by the onset of camera shake. The average speed of the blast wave can be calculated by comparing the time of first light and shockwave detection at a range of cameras outside the cloud – assuming ignition in the pump house. In all cases the average shock speed is within a few percent of the speed of sound.

There were a number of objects (*e.g*. oil drums, switch boxes, cars) distributed across the site and immediate surrounding areas. The condition of these objects after the explosion provided an indication of the overpressure magnitude at the location of these objects.



a) Crushed electrical connection box b) Crushed oil drum c) Crushed car


d) Diesel tank in pump house e) Post in car park f) Deflected lamp post

Fig. 2 – Damaged objects due to overpressure inside flammable cloud

Damaged lightweight steel junction boxes, Fig.2a, on the site located within the area covered by the gas cloud were compared with similar boxes tested under a range of different loading conditions using hydrostatic pressure, gas explosions and High Explosive charges (HE). Analysis of these results has shown that the minimum magnitude of overpressure required to cause damage comparable to that sustained by junction boxes on the Buncefield site is of the order of 2 bar with duration ~ 50 ms. At shorter durations that are more representative of overpressure within a detonating gas cloud (~10ms), an overpressure of 5 bar would be required.

An empty oil drum, Fig.2b, sustained inward plastic deformation (crushing) to its walls, Fig.2a, and buckling of the drum end. A similar damage pattern was caused in a hydrostatic pressure test at pressures of between 1.5 and 2 bar. A gas explosion with a maximum overpressure of 1.8 bar on an empty drum produced a smaller magnitude but similar deformation pattern in the end plate of the drum.

Over 20 cars were in the area covered by the gas cloud and all were badly crushed. Comparative tests using HE have shown that overpressures of the order of 10 bar were required to cause the level of damage observed at Buncefield (see Fig.2c). Comparative gas explosion tests in a strong steel enclosure in which cars were subjected to overpressures of 1bar resulted in significantly less damage that observed at Buncefield. It is concluded from examining all the data available that the overpressures experienced by cars at Buncefield exceeded 2 bar for durations ~ 50 ms.

On the emergency pump house, where the explosion is thought to have started, contained a number of lightweight metal objects that sustained minimal damage (Fig. 2d). This suggests that in its initial phase, the explosion overpressure was modest.

A number of objects on site were susceptible to drag forces (e.g. lamp posts, fence posts, camera masts, trees). An example can be seen in Fig.2f. The deformation exhibited by such objects provided information on the net drag impulse sustained by these objects. Other directional evidence was provided by the directional abrasion found on one side or one part of painted surfaces of post in car parks, as in Fig.2e. There was also evidence of large objects such as cars and skips being displaced in a particular direction.

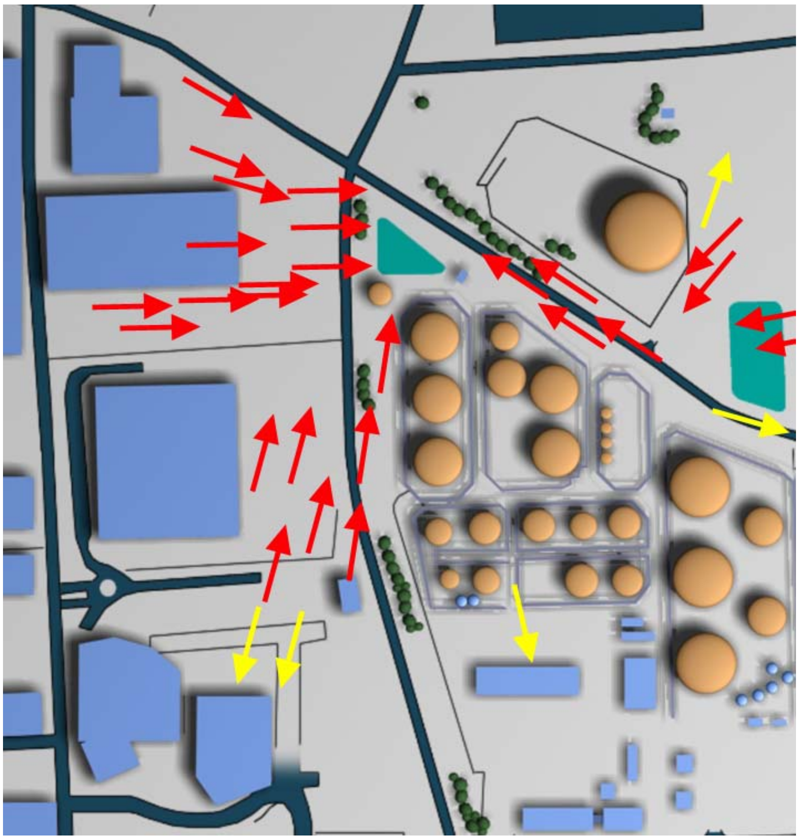


Fig.3 – Net drag impulse direction across the site

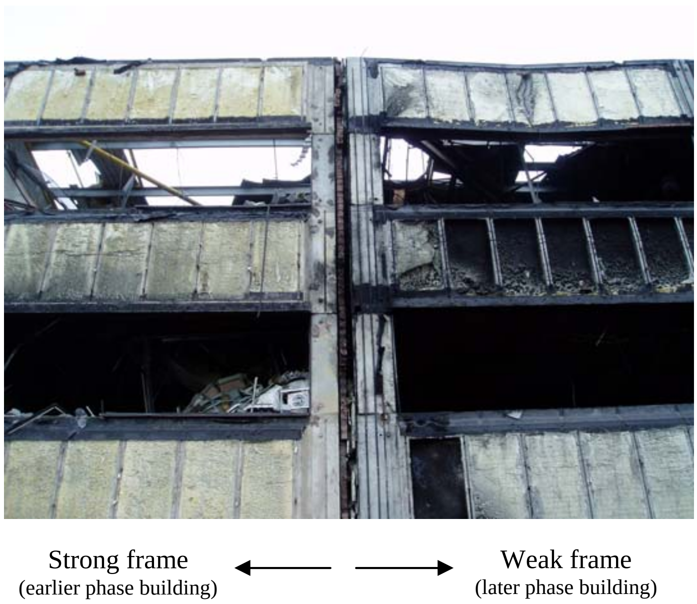
3.2. Assessment of Building Damage

Based on overpressures estimated from findings, it was calculated the amount of TNT charge near the centre of the gas cloud which would be expected to cause the observed damage to a number of buildings within a 0.5km radius of the emergency pump house. The charge size near the centre of the cloud found to give these overpressure values is 7500kg of TNT. Although derived from conventional military explosives scaling, the overpressures are reasonably consistent with the observed damage.

Domestic housing estates exist to the North, West and South of the industrial area surrounding the Buncefield site. Based on information from insurance claims, the damage was frequent within a distance of 2 km from the site and sporadic building damage extended to a distance of more than 4km. There was a higher concentration of damage to the North and South of the site compared to the West.
Apart form weakened glazing the most vulnerable structures surrounding the terminal were a large number of steel clad portal frame sheds. These suffer significant damage at pressures of around 1 kPa (0.01 Bar) which would roughly correspond to the wind forces in a 90 mph gale. Such buildings were significantly damaged to a range of about 1 km so it can be concluded that pressures fell below 1 kPa at roughly this range
Using military scaling rules, the charge size at the ignition source that would be required to cause such damage at these distances is estimated to be approximately 5000 kg TNT. Such a charge size would have caused significantly greater damage in the near and mid-field than that observed. However, it is well known that a single value of TNT equivalence will not predict both the far field and near field damage for a vapor cloud explosion.

An assessment of damage to the RO Building (a minimum of 50 m from the edge of the cloud), see Fig.4a, concluded that there was:
1. Severe (80-100%) loss of glass windows to the east and north elevations with frame damage on the north elevation;
2. Minimal damage to the perimeter of exterior walls;
3. Minimal or no damage to the building structural frame.
The assessment concluded that an overpressure of 0.2 bar at the North East corner of the building was capable of generating the observed levels of damage.

a) Main buildings nearby terminal



b) Cladding panels at east face of Northgate building

Fig.4 – Damage to nearby buildings

The Northgate Building had been built in two phases at different times. The cladding panels used in the two phases were architecturally identical. However, examination of failed panels revealed that the earlier phase panels contained less reinforcement than those used in the second phase. This difference manifested itself in the response of these panels to the explosion. Two adjacent panels at the top floor level – one on the earlier phase and the other on the later phase were found to have deflected by 200mm and circa 30mm respectively, see Fig.4b.

A finite element structural analysis of these two panels was carried out to derive the single load profile that is consistent with the levels of damage to the two panels. A range of generic load profiles (typical of gas deflagrations, detonations and combinations of deflagration and detonation) were examined. The peak overpressure and the impulse were also varied. In total, some 160,000 analysis were performed and this enabled iso-damage diagrams to be constructed for both panels.

The load profile found to cause damage consistent with that observed in both panels has a rise time equal to 30% of the overall duration and a decay equal to 70% of the overall duration. Assessment of the sensitivity of the response to variation in the properties of the reinforcing bar yielded a peak pressure of 0.16 bar when using design values for the steel strength and 0.3 bar when using measured steel strength (from samples taken from site after the accident). The associated load durations were 1.6s and 0.6s respectively. Furthermore, it was found that the damage caused is very sensitive to the magnitude of peak pressure but much less sensitive to the magnitude of the impulse.

3.3. Characterization of the vapor cloud in the Buncefield Explosion

Burning of vegetation caused by the combustion of the vapour cloud enabled the cloud's location to be estimated, see Fig.5. The area covered by the cloud is approximately 120,000 m^2 (flammable cloud with average radius of 196m). CCTV images enabled the average depth of the cloud to be estimated as 2 m (assuming that the flammable limit corresponds closely to the top of the mist). The volume of the cloud with a concentration above the lower flammable limit (LFL) is therefore in the region of 240,000m^3. Based on tank inventory information, the chemical composition of the cloud is similar to butane or propane in terms of reactivity.

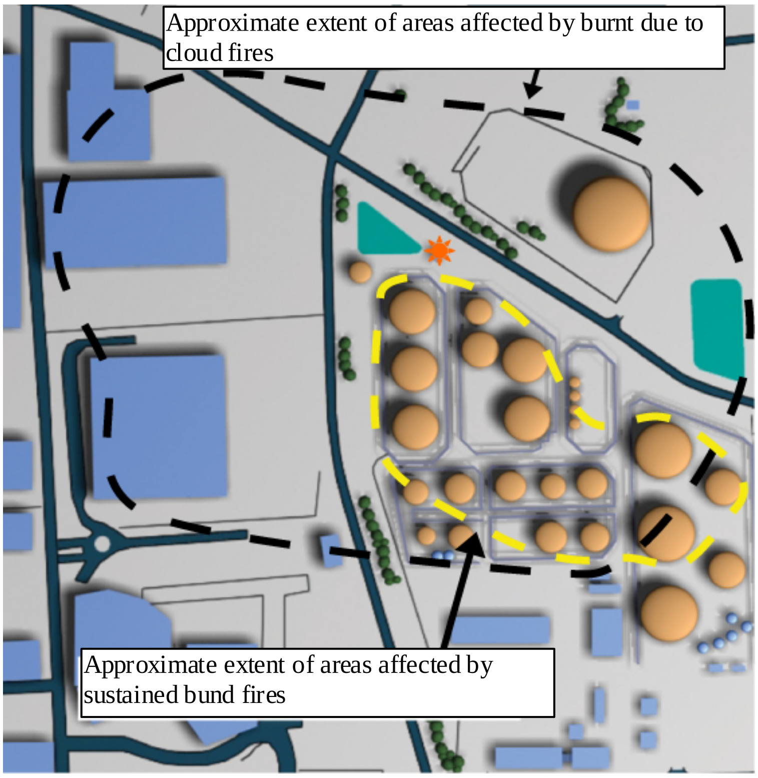


Fig.5 - Extent of flammable cloud (ignition location denoted by ✸)

3.3. How Buncefield compares with previous accidents

A search was developed for reported explosions on industrial sites for which detailed data were reviewed to assess whether key features of the Buncefield explosion have been reported in those incidents. On the basis of directional evidence and evidence of overpressure distribution over the area covered by the vapour cloud it is concluded that both Port Hudson (propane pipeline, US, 1970) and Ufa (LPG pipeline, Soviet Union, 1989) are very similar to Buncefield in terms of the characteristics of the explosion, whereas Flixborough, Texas City and Beek are very different.

Both Port Hudson and Ufa resulted from ignition of a gas release whereas Buncefield resulted from a liquid release but all three occurred following extended releases. Dispersion of the heavy vapours over most of the area would have been by slow gravity currents in low wind conditions. Flow speeds would have been low with the potential for very low (or zero) entrainment rates. Substantial volumes of gas would have been created with low concentration gradients in at least two-dimensions. It is possible that a high level of homogeneity in the cloud is a prerequisite for a Buncefield type explosion.

Buncefield, Ufa and Port Hudson also covered a wide range of terrain types; they included dense forest, lightly wooded areas, arable land, tarmac parking, rough grassland, hedging/roads, tank farm. At Buncefield, in particular, it was possible to show that the severity of the explosion was maintained over at least the last four types of terrain. Another common feature is the cloud size; Buncefield, Port Hudson and Ufa all involved vapour clouds with a maximum dimension >300m.

There is good evidence that the initial explosion at Port Hudson occurred in a storage building made from concrete blocks. The initial explosion would have been confined, with a corresponding increase in the pressure. The original investigation report for the Port Hudson incident identified this as a potential mechanism of triggering detonation. The Buncefield explosion started in the emergency pump house; it was therefore confined and with some congestion. However, the evidence suggests that the overpressure associated with the explosion within the emergency pump house was low (see Fig.1d). The high overpressure at Buncefield is thought to be a result of flame acceleration outside the pump house.

3.4. Inferring Potential Scenarios for Buncefield Explosion

Several potential scenarios were examined. They differed primarily in the mechanism by which overpressure is generated. Each was tested against evidence from the Buncefield explosion and the explosion characteristics derived from that evidence to demonstrate the likelihood or otherwise of each of these scenarios. None of these scenarios were found to be inconsistent with either the witness evidence or the CCTV camera evidence relating to arrival of first shock wave or luminosity. This is due to the fact that there is sufficient uncertainty in this evidence and the assumptions that may be made about the different stages of each scenario.

3.4.1. Deflagration Scenario

The deflagration scenarios were modelled using the Computer Fluid Dynamics code EXSIM (by Shell). Modelling simplifications had to be made to the congestion offered by tree branches and undergrowth, these were modelled as rigid pipe elements and blockage ratios had to be estimated.

In order to consider the effect of small obstacles that are more representative of the form of congestion presented by the trees and shrubs in Three Cherry Trees Lane, a smaller geometric domain that included the emergency pump house (acting as the ignition location) and parts of Three Cherry Trees Lane adjacent to it was modelled.

The overpressure predicted close to the junction with Buncefield Lane was around 4 bar and the flame speed was 714 m/s. There is experimental evidence to show that a Deflagration to Detonation Transition (DDT) can occur at flame speeds of around 600 m/s for fuels with a similar reactivity to that at Buncefield. There is therefore a possibility that DDT occurred close to the junction with Buncefield Lane. The analysis estimated that this would have happened some 230ms after initial ignition.

3.4.2. Detonation Scenario

The detonation scenario examined comprises the following sequence of events:

1. Ignition in the emergency pump house resulting in a confined explosion venting into the external cloud;
2. Flame propagation into the tree line to the north of the emergency pump house along Three Cherry Trees Lane;
3. Flame acceleration in the tree line in the same manner as described in the deflagration scenario (Section 3.4.1);
4. Transition to detonation somewhere near the junction of Buncefield Lane and Three Cherry Trees Lane.

In the detonation case the flame and shock travel at around 2000 m/s through the cloud so the observation that overall the shock travels at the speed of sound (~331 m/s) to all cameras, implies that the delay before DDT exactly compensates for the extra speed in the cloud. In the detonation scenario this has to be explained as a coincidence.

The extended period of luminosity from the explosion recorded by cameras has to be explained as a result of afterburning – no detonation flash was captured on any camera. The slow build up and rapid cut-off in illumination are however not what would be expected during the post detonation burning of fuel rich parts of a cloud.

Similarly the images recorded before and after the time of the supposed detonation are closely similar in brightness and balance. Again this is not what would be expected given the huge increase in flame height and extent in the wake of detonation.

Work on analysis of the Buncefield data and building damage continues but it has not yet been possible to completely eliminate the possibility that the explosion was a detonation and further work to characterise such events is underway.

Large scale simulations of axisymmetric pancake shaped clouds of 400m diameter and 2m height were performed. They enabled the overpressure decay from the edge of the cloud and the net impulse (both outside and within the cloud) to be calculated. Additionally, an obstructed scenario was simulated by placing a solid object at the edge of the cloud. This was used to estimate the overpressure that might have acted at the face of the Northgate Building if the cloud detonated up to face of the building.

Overpressures within the cloud comprised a short duration (10 – 20 ms) shock wave with an overpressure in excess of 10 bar followed by a positive duration phase that lasted > 100 ms. A similar phenomenon is observed outside the cloud. At 30 m from the edge of the cloud, a short duration of shock wave of around 0.7 bar is followed by a long duration low overpressure phase that lasts over 300 ms.

The simulations showed a net impulse in the opposite direction to the propagation of the explosion within the cloud and in the direction of the explosion outside the edge of the cloud- which is consistent with damage to objects and structures

For Far-field damage, the volume of the vapour cloud at Buncefield was estimated to be around 250,000 m^3. A simple Multi-Energy method was used to estimate the relationship between the cloud volume and the overpressures produced at distance from a detonating vapour cloud. If a cloud volume of 100,000 m3 had detonated, this would have resulted in overpressures of 0.04 bar and 0.02 bar at about 900m and 1700m respectively. These distances are dependent on the cube root of the cloud volume, thus a doubling or halving of the cloud volume will alter these distances by approximately 25%. The observed far field damage suggests somewhat lower overpressures but it is hard to correctly allow for the effects of shock refraction and scattering by ground level objects.

Within the cloud the level of damage to items such as cars and boxes is broadly consistent with the detonation scenario. In the case of Northfield Building, a load profile comprising a slow rise time was found to provide a solution that was consistent with the damage to the cladding panels (see Section 3.2). This is clearly not consistent with the detonation scenario, which would generate high shock loadings on the building if the detonation reached the building. On the other hand, a detonation that involved a thinner section of the cloud than that modelled might be consistent with the damage. Additional detonation simulations are therefore required to explore the loading regimes that might be generated at the face of the Northgate Building.

The damage to the RO building is consistent with an incident overpressure of 0.2 bar (see Section 3.2). This building was about 50-80m from the cloud edge. The small scale simulations indicate that a 20m x 2m high cloud would give overpressures of 0.21-0.14 bar at these distances from the cloud edge whereas the large scale simulations indicate an overpressure of about 0.3 bar at these distances. There is therefore reasonable agreement between the level of overpressure estimated from the observed damage and those obtained from the detonation simulations. On the other hand a warehouse building around 40m form the north-east edge of the cloud had substantially intact roof and sidewalls. Detonation pressures at this range would have been expected to be of order 0.5 bar which is around 50 times greater than that which would be expected to cause wall and roof failure.

3.4.3. Other Possible Explosion Mechanisms

There are a number of alternative mechanisms beyond deflagration and detonation and at least one warrants further research. The episodic deflagration mechanism is an unsteady deflagration accelerated by forward radiation from the flame front.

Registered from CCTV cameras, structural analysis and eye witness, the total duration of the explosion may be interpreted to last 1600 ms. Given the maximum radius of the cloud was 240m this indicates an average velocity of 150 m/s. Since this average flame speed is less than the speed of sound the initial shock runs ahead of the flame and always travels at a speed close to the speed of sound – which is consistent with the observations.

The sub-sonic average flame speed mechanism also explains the gradual build up of pressure recorded by witnesses and camera deflection. A gradual increase in pressure also explains how it is possible that all warehouses between 40 and 300m from the cloud edge suffered complete disruption of the front face whilst sidewalls and roof survived – the slow build up of pressure allows internal pressurisation when the front “bursts” and this reduces the load on other building faces (8).

If flame propagation is episodic, i.e. comprises short periods of intense combustion (which generate the high overpressures) punctuated by pauses, then the apparent the low average flame speed can be reconciled with the high overpressures within the cloud.

Such a variation in burning rate may arise through a combination of thermal radiation and adiabatic compression. If forward radiation initiates combustion in suspended particulates the pressure will rise close to the flame front. If the particle density is sufficient, the resulting compression will initiate further ignition (in preheated particulates) further away from the flame front. This results in the initiation of ignition in an extended range. Still further out from the flame front particulates and gas are not pre-heated sufficiently to be ignited by adiabatic compression. When the pressure subsides gas associated with these more distant particles simply cools and is left at a temperature well below that required for spontaneous ignition. There is an extended delay until forward radiation brings gas and particles to the temperature required for ignition and the next cycle of rapid combustion can start. The distance scale over, which the flame progresses in each cycle is determined by the range of thermal radiation i.e. the length scale of the burned cloud.

The episodic character of the explosion also explains how appropriate particulates could be numerous and suspended in the gas cloud. Since the average speed is sub-sonic, relatively strong shock waves progress ahead of the flame and these can disperse and fragment dust and objects such as dried leaves.

4. Phase 2: Experimental Work on development

The Phase 1 identified a number of areas that require further research to gain a greater understanding of explosions involving large unconfined vapour clouds and the associated structural response. The aim of the work of Phase 2 is to provide a better understanding of vapour cloud development following large losses of primary containment, the characteristics of explosions involving large flat flammable vapour clouds and the key explosion mechanisms that can give rise to very high overpressures over a large area as observed in Buncefield. To achieve this aim, Phase 2 comprises four work packages described in the following sections.

4.1. Modelling of Large Flat Vapor Cloud Explosions

Since the conclusion of Phase 1, additional analysis was commissioned by the HSE to extend the limited numerical study of vapour cloud detonation undertaken in Phase 1. This covered a wider range of cloud geometries by varying the depth and radius of the cloud, the effect of a taper in cloud height, variation in cloud stoichiometry and the interaction of the detonation with objects of different shapes located at the edge of the cloud. This work has provided a wide range of pressure time profiles associated with the different scenarios studied. However, one limitation which remains due to the 2 dimensional nature of the analysis is the effect of ignition away from the centre of the cloud and the effect of non-circular cloud shape. Phase 2 is therefore focusing on studying the pressure profile associated with non-symmetric detonations so that its effect on the surroundings (building structures and other objects) can be considered. This is being undertaken using three-dimensional analysis in order to properly model the asymmetry.

4.2. Flammable Cloud Formation

There is a need to characterise the behaviour of different substances in overfill situations and to understand the effect of the bund on vapour cloud formation. The effect of bund walls may be to deflect vapour flow upwards allowing it to be drawn back into the cascade. This re-entrainment process may greatly increase the risk of forming heavy slow vapour currents that can travel for hundreds of metres without significant dilution.

Several key processes remain beyond computational methods. They include primary aerodynamic break-up of dense liquid cascades and impacts of liquid streams on a wind girder and/or the ground, as well as the effect of and design of bunds.

To understand the underlying phenomena affecting the dispersion mechanism, Phase 2 is examining at full scale the effect of the following parameters on the formation and characteristics of vapour clouds:

i) fuel/substance type
ii) bund filling
iii) height of cascade

The release height in the tests is in the range 10 –15 m. Releases are adjacent to a wall that provides a suitable model of the side of a bulk storage tank. The liquid release rates are up to 30 kg/s - lasting at least 100 seconds to allow stabilisation of the vapour current. Tests are carried out in still conditions without strong solar heating of the impact surface or “tank wall”.

The tests determine the spreading rate of the cascade as it falls and provide simultaneous measurement of both liquid and vapour phase temperatures in transects across the cascade. Near field (<10m) dispersion of the resulting vapour currents on an open flat surface are also be measured.

Three substances are used in the tests:

- a 0.25 mol/mol of Industrial butane/decane mixture with RVP between 11 and 12 to represent a nominal live crude
- cyclohexane (or another important solvent prone to freezing)
- toluene (or another important material with a marginal capacity to produce a flammable cloud)

The tests are intended to provide evidence on:

- The propensity of different substances to form large vapour clouds (i.e. which substances or classes of substances do/do not have the ability to form large vapour clouds and under what conditions?). Cyclohexane and toluene are examples of such substances.
- The cloud characteristics once a vapour cloud is formed.

In addition, a series of large-scale experiments with different bund profiles and tank/bund distances are being carried out to provide the data necessary to guide design of new bunds and risk assessment at existing installations. In particular, these focus on extreme bund/tank distances used in practice to provide comparative results for the effect of different layouts. The tests compare the vapour concentration upstream and downstream of the bund in comparable conditions.

4.2. Effect of Congestion Caused by Vegetation

Phase 1 showed that there was much uncertainty in the quantification of the effect of congestion in the form of vegetation. This extends down to extensive small-scale twigs and leaves, whereas process plant tends to have much less fine detail. Both the volume blockage presented by the congestion and the number density of obstacles are important in the generation of overpressure. The latter is higher in the vegetation than in process plant. Vegetation also moves to accommodate airflow, whereas process plant is stiff. Such compliant objects would generate less turbulence than stiff one, but may still have a significant influence in flame area generation. These aspects make the reliable prediction of the effects of the vegetation using current modelling techniques (designed and validated for explosions in typical process plant) very difficult.

Two test series are being undertaken in Phase 2. The first at medium scale (in an open ended enclosure of dimensions 2m x 2m x 8m) is looking at the following aspects:

i) The effect of removal of branches below a certain diameter
ii) The effect of different varieties of vegetation
iii) The difference between smooth pipes (for which models have been validated) and rough tree trunks and branches.

A series of around 6 large scale tests is being undertaken to study the effect of congestion caused by vegetation on the characteristics of a vapour cloud explosions. Variation in width of undergrowth, hedgerow length and type of vegetation are being studied in a test program that covers the following parameters and ranges:
i) Fuel type: propane (to provide a link to earlier experimental work).
ii) Vegetation type: volume blockage similar to that at Buncefield and down by 50% and up to 150% times.
iii) Length of vegetation: 60m to 100m
iv) Width of vegetation: 1m to 4m
v) Height of vegetation: 1m to 3m

4.4. Explosion Characteristics of Large Flat Vapour Clouds

This work package is studying experimentally at large scale the pressure fields associated with low-lying vapour cloud explosions in the open or when they impinge on objects. Initially, episodic deflagration trials are being carried out to demonstrate at a realistic scale the feasibility or otherwise of this mechanism. Depending on the outcome of those initial tests, either further episodic deflagration tests will be carried out or the focus of the work package will shift to large scale detonation tests.

5. Conclusion

Since the incident, the Competent Authority (COMAH), industry and trade unions have worked together to drive forward high standards at fuel storage sites. This has resulted in improved standards of safety and environmental protection for all UK sites storing large volumes of gasoline and to systematically upgrade sites to meet these standards, with progress monitored by the Competent Authority as part of its regulatory programs.

A key lesson from Buncefield is that at site level process safety must be secured by automatic systems, without reliance on human intervention. Moreover, senior management should be responsible for delivering and maintaining site safety regimes, based on systems that minimize the impact of human error and make its occurrence less likely.

The investigation board (MIIB) recommendations included a mandatory requirement that overfill must be prevented by independent and automatic means so that operators cannot rely on human intervention, for example in responding to an alarm and then taking executive action.
The Process Safety Leadership Group (PSLG) has provided minimum safety standards for gasoline tank farming where functional safety as set out by the IEC61508 (Functional safety of electrical/electronic/programmable electronic safety-related systems) and 61511 (Functional safety–Safety instrumented systems for the process industry sector) standards. This has led to some significant improvement in risk analysis and risk classification (SIL 1).

Human interface remains a difficult issue worldwide. Some companies have a corporate safety strategy, philosophy or operational procedures where human interaction is still acceptable as part of the procedures, while other companies exclude this entirely. Both are correct within the corporate philosophy and their interpretation of the safety bible. However, we must remember that more than 90% of issues are caused by human errors; if we solve that, we will get a good solution.

With the increased standards installed as recommended by authorities, the risks of another ‘Buncefield accident’ will undoubtedly be reduced. Very reliable prevention of overfilling of tanks can only be achieved with a number of layers of protection; all aspects of the design and operation have to be carefully considered
The Buncefield explosion mechanisms are still under investigation to give reliable guidance to design engineers and operators.

7. References

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