REVIEW

Large vapour cloud explosions, with particular reference to that at Buncefield

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This paper first briefly surveys the energy releases in some major accidents. It then examines the analyses of the explosion at the Buncefield fuel storage site in the UK, one of the most intense accidental explosions in recent times. This followed the release of approximately 300 tonnes of winter-grade gasoline, when a 15m high storage tank was overfilled for about 40 min before ignition of the resulting flammable mixture. The ensuing explosion was of a severity that had not been identified previously in a major hazard assessment of this type of facility. It was therefore imperative to investigate the event thoroughly and develop an understanding of the underlying mechanisms to inform future prevention, mitigation and land-use planning issues. The investigation of the incident was overseen by the Buncefield Major Incident Investigation Board. A separate Explosion Mechanism Advisory Group examined the evidence and reported on the severity of the explosion. It concluded that additional work was necessary and recommended that a two-stage project be initiated, phase 1 of which has been completed. The analyses of the damage and the derivation of explosion over-pressures are described. Possible explosion mechanisms and the evidence for them at Buncefield are discussed, in the light of other major incidents. Mechanisms that are reviewed include high-speed turbulent combustion, quasi-detonations, fully developed detonations, the generation of fireballs, flame instabilities, radiative heat transfer and aspects of two-phase burning. Of particular importance is the acceleration of turbulent flames along the line of trees and hedgerows. A number of conclusions are drawn and suggestions made for further research.

Keywords: Buncefield; dispersion; deflagration; detonation; quasi-detonation; fireball

1. Introduction

Increasingly large amounts of fuel are being transported around the world and stored in ports, storage depots and manufacturing complexes, creating exceptionally high energy densities. Any uncontrolled loss of containment and

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One contribution of 12 to a Theme Issue ‘The physics, chemistry and dynamics of explosions’.
ignition of a flammable mixture could result in devastating consequences, including intense fires and explosions with an influence over several kilometres. Strong pressure waves could propagate beyond the immediate vicinity, and pollutants could disperse over even greater distances. The interaction of fire with the local atmosphere might affect the global atmosphere over many kilometres. Some examples of large flammable liquid and gas releases, together with one nuclear release, are given in Table 1. All the numerical values given in the table are uncertain owing to the difficulties of estimating spills and the proportion of them that was burned.

On Sunday 11 December 2005, at 06.01 h, two explosions in rapid succession were followed by fires that engulfed 23 large fuel storage tanks over a high proportion of the Buncefield oil storage and transfer depot at Hemel Hempstead in the UK. These caused widespread damage to neighbouring properties and injured 43 people. Fortunately, no one was seriously hurt and there were no fatalities. About 2000 people had to be evacuated from their homes and adjacent sections of the M1 motorway were closed. At the time of the explosion, Heathrow Airport was receiving half of its daily fuel supply from Buncefield. The fire burned for 5 days, destroying most of the site and emitting a large plume of smoke, 3 km high, into the atmosphere. This dispersed over southern England and beyond (Figure 1). Studies of this have involved the numerical generation of the plume structure, using large-eddy simulation, and measurements of the concentrations of particulates and gaseous pollutants within it [1,2]. The present paper discusses the possible mechanisms involved in the initial explosion.

An explosion event of such severity had not been identified previously in any major hazard assessment of this type of facility. It was therefore imperative to investigate the event thoroughly and develop an understanding of the underlying mechanisms to inform future prevention, mitigation and land-use planning issues.

### Table 1. Examples of large energy releases.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Event Description</th>
<th>Energy Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Port Hudson</td>
<td>Pipeline rupture due to over-pressure, releasing liquid propane at about 1°C</td>
<td>2.9 TJ total release, 0.12 TJ burn in ‘detonable zone’. Released cloud filled valley. Residual fuel burned in firestorm, creating localized wind damage.</td>
</tr>
<tr>
<td>1986</td>
<td>Chernobyl</td>
<td>Overheating of nuclear reactor, creating H₂ explosions</td>
<td>27 TJ graphite burning at mean rate of 20 MW. Widespread dispersion of radioactivity.</td>
</tr>
<tr>
<td>1988</td>
<td>Piper Alpha</td>
<td>Explosion and fire on oil platform</td>
<td>Burn rate 6.8 GW (17% of average UK electricity generation rate) at fractured riser pipes, diameter 0.9 m.</td>
</tr>
<tr>
<td>1989</td>
<td>Ufa, USSR</td>
<td>Fracture of 0.7 m diameter gas pipeline, releasing liquefied oil products</td>
<td>200 TJ release. Fuel–air cloud 2.5 km² surface area, 2 m high, finally exploded, releasing 20 TJ. Extensive firestorm damage.</td>
</tr>
<tr>
<td>2005</td>
<td>Buncefield</td>
<td>Release of winter-grade gasoline from over-filled tank</td>
<td>Total burn of 2500 TJ. 13.2 TJ in explosion. Fire burn rate of about 10 GW for 3–4 days from 23 storage tanks.</td>
</tr>
</tbody>
</table>
For the investigation of such incidents, two options are provided by the Health and Safety at Work Act 1974, which is the underpinning legislation for all health and safety regulations in Britain. These involve the setting up of either a major incident investigation, conducted by the Competent Authority, or a Public Inquiry. After some deliberations in Government, a Major Incident Investigation Board (MIIB) was established by the Health and Safety Commission, now the Health and Safety Executive (HSE), under the Chairmanship of Lord Newton. Its findings are presented in two volumes [3].

The Commission did not propose a Public Inquiry, in part because of the length of time that can elapse before any conclusions could be reached. The MIIB was able to make significant findings public as they emerged, subject to avoiding prejudice in any criminal investigation. The merits of different forms of Inquiry have been discussed by the key figures involved in the King’s Cross Fire Inquiry [4], the Piper Alpha Inquiry [5] and the Buncefield Investigation [6]. In the USA, such incidents are investigated by the Chemical Safety and Hazard Investigation Board. This is a permanent Federal Investigation Agency. Regulatory control is exercised by the Occupational Safety and Health Administration.

The second of the two Buncefield explosions measured 2.2 on the Richter scale, and was one of the most intense accidental explosions in recent times. At the time, it was thought to be a unique event for a gasoline release, but others have been reported, and two incidents of the Buncefield type have since occurred, both in October 2009. One involved a tank overflow at San Juan (http://www.cnn.com/2009/WORLD/americas/10/26/puerto.rico.fire), and the other a failure of a gasoline tank valve at Jaipur [7]. To meet all of the Board’s terms of reference, it was essential to develop an understanding of the mechanism of the explosion, which had led to such major and widespread destruction. Accordingly, an Explosion Mechanism Advisory Group (EMAG) was formed, composed of explosion specialists from the UK. They were given access to the

Figure 1. Early stages of the Buncefield smoke plume. London to the southeast, upper left, was covered by the plume. Sharply defined lower boundary of plume marks line of the temperature inversion. Low-lying mist over the ground indicates low temperature and still air [3]. (Online version in colour.)
results from earlier and continuing investigations of the HSE, and were required to report on whether the severity of the explosion could be explained in terms of existing scientific knowledge. The group made significant progress in the limited time available, but its report [8] concluded that further work was essential and recommended that a two-stage project be initiated. The first phase of this project has been completed [9] and work on the second phase is progressing. The events leading up to the explosion, the nature of the subsequent propagations of reaction fronts and the initiation of fires are presented in the Board’s report [3].

2. Spillage and dispersion of the vapour cloud

Authorization had been given for the storage of up to 194 ktonnes fuel on the three sites comprising the Buncefield depot. At the time of the explosion, fuel storage tanks held 82 ktonnes winter-grade unleaded gasoline, of which 57 ktonnes burned, releasing 2500 TJ. Approximately, 300 tonnes of this fuel were released when the 15 m high storage tank 912 (figure 2) was overfilled for about 40 min before the flammable mixture ignited. The formation of a large vapour cloud was the precursor to the first explosion. Of the two explosions, the second was the more severe. The liquid escaped through the roof vents and cascaded into the bund. The weather was calm and stable, with the air temperature close to 0°C,
with 99 per cent humidity. The development of a 400 m diameter pancake-shaped vapour cloud over the surrounding area can be seen in closed circuit television (CCTV) records by the formation of a white mist, assumed to consist of water droplets. The extent of the ultimately scorched region, also of approximately 400 m diameter, is shown in figure 3. Assuming that visible water mist marked the boundary of the vapour cloud, CCTV video records suggested that vapours were spreading from the bund during the final 23 min before ignition. It is possible that, close to the bund, micrometre-sized droplets of gasoline were also present in the cloud because of droplet splashing and mechanical break-up during the overfill cascade.

Complete appreciation of the mechanism of this cloud formation has proved difficult to achieve. As illustrated in figure 4, the flow of gasoline from the roof vents was interrupted by a circumferential water deflector plate that channelled part of the flow down the side of the tank to the height at which it impinged and sprayed off the wind girder. At roof level, the remaining flow overtopped the water deflector and cascaded down to collide with the spray from the wind girder. Mechanical break-up of the cascade into smaller droplets undoubtedly occurred: experiments with gasoline [10] suggested that this was complete after a fall of 6 m, approximately half way down the height of the fall, and that the characteristic droplet size was 2 mm.
The amount of air entrained into the cascade by momentum exchange is sensitive to the liquid mass density, which, in turn, requires knowledge of the width of the spray zone. A value of 1.5 m was derived from experiments with water cascades and was then used to calculate the average vapour concentration, and hence the propensity of the liquid to create a flammable cloud [10]. Further work with different liquids and tank geometries seems to be necessary to verify this calculation.

CCTV records show that 23 min before the first explosion, vapour first became visible, escaping from the northwest corner of Bund A. It reached a depth of about 2 m at 05.45 h as it continued to flow out of the bund. Although it would have been flowing in all directions [3], the general slope downwards in a northeasterly direction towards Cherry Tree Lane would have promoted flow along Three Cherry Trees Lane, via the lagoon (figure 2). This is consistent with both eyewitness accounts and CCTV records. Judging by the extent of the visible mist, the flammable cloud had spread to a radius of approximately 200 m, covering (*inter alia*) the car parks serving the Northgate and Fuji buildings by the time ignition occurred. Reliable models that predict the dispersion of low-momentum heavy vapours in still air remain to be developed. In this case, the event is further complicated by evaporation, air entrainment and dispersion from the gasoline in the cascade and inside the bund. Additionally, the topography of the surrounding

*Phil. Trans. R. Soc. A* (2012)
land and the blocking effect of the undergrowth (visible in figure 3), storage tanks and plant will also have affected the spreading. Thus, attempts to simulate the extensive spreading of flammable vapours have met with little success and it has not, so far, been possible to predict with any certainty the spatial and temporal composition of the cloud [11].

However, it is known that the vapours would have spread as a gravity current, mixing with air at the leading edge and top surface of the cloud, while the lower part remained stratified and fuel rich. Once initiated, the flame would flash through the flammable regions, leaving the rich mixture to burn more slowly as diffusion flames. It seems reasonable to suggest that the centre of the cloud would be deeper and richer in fuel than the edges. The assertion that ‘the flammable limit corresponds closely to the top of the mist layer’ may not hold and needs to be justified by the thermodynamics of the local cloud composition and atmospheric humidity. This is unlikely to be achievable until more reliable models have been developed.

The exact chemical make-up of the gasoline is unknown, but a likely composition (by weight) for winter-grade gasoline is taken as [10]:

- *n*-butane (as surrogate for all C4) 9.6 per cent,
- *n*-pentane (as surrogate for all C5) 17.2 per cent,
- *n*-hexane (as surrogate for all C6) 16 per cent, and
- *n*-decane (as surrogate for all low volatility hydrocarbons) 57.2 per cent.

The reported loss of approximately 300 tonnes of gasoline in 40 min equates to a cascade of 550 m³ h⁻¹. In the analysis of Atkinson et al. [10], air is entrained at a rate of 96 m³ s⁻¹, while the final temperature at equilibrium is −8.6°C, assuming gasoline at an initial temperature of 15°C and air at 0°C. They showed that the composition of the vapour–air mixture (by weight) in equilibrium with the liquid at −8.6°C falling into the bund would be 6 per cent *n*-butane, 6.1 per cent *n*-pentane and 2.06 per cent *n*-hexane, giving 14.16% w/w in air (the vapour pressure of *n*-decane is negligible at this temperature).

For convenience, these figures can be converted into percentage by volume, thus becoming 3.2 per cent *n*-butane, 2.65 per cent *n*-pentane, 0.75 per cent *n*-hexane by volume in air, giving a total of 6.6% v/v in air. As the upper flammability limits of these three hydrocarbons lie between 8.4 and 7.4 per cent, it is clear that the vapour–air mixture derived from the gasoline cascade will be fuel rich, but below the upper flammability limit. It is reported [3] that the mixture would be falling at velocities of 4–6 m s⁻¹ on to liquid gasoline, through a rich vapour–air mixture arising from evaporation, with heat transfer from the bund floor. Thus, the source term for the vapour dispersion contains many uncertainties and inherent difficulties. Experiments and interpretations proposed in phase 2 [12] should resolve some of these unknowns.

3. Deduced over-pressures and directional indicators

Considerable independent effort—by BP, the Health and Safety Laboratory, GEXCON, Kingston University and the Ministry of Defence—was devoted in

*Phil. Trans. R. Soc. A* (2012)
Figure 5. View of the site after the incident, looking northwest towards Catherine House. Image reproduced with permission by the Health and Safety Laboratory [3]. (Online version in colour.)

the phase 1 programme to damage analysis and associated tests, in attempts to reproduce the effects of the explosion. Two views of the explosion and fire damage appear as figures 5 and 6 [3]. Various items, specially selected for their similarity to objects that suffered extensive damage within the flammable cloud, were exposed to static pressure tests, gas explosions and high-energy explosions. Relatively unambiguous pressure markers such as steel drums, switch boxes and oil filters revealed that, locally, over-pressures within the cloud, and indicated on figure 7, were greater than about 200 kPa [9].

Whereas the isobars of over-pressure in the EMAG report [8] showed a region slightly to the west of tanks 915, 912 and 910 (figure 2) where over-pressures in excess of 100 kPa were suggested, the more extensive studies in Buncefield Explosion Mechanism Phase 1 [9] suggested an extended zone in which over-pressures were in excess of 200 kPa, as indicated in figure 7. The testing could not be extensive enough to derive representative pressure–impulse iso-damage curves, but the approximate 200 kPa could be regarded as a lower limit, as most static tests seemed to be consistent with this level. There were no fatalities among the several personnel close to the cloud edge (e.g. near the loading gantry, see figure 2) and no one suffered any hearing loss (rupture of eardrums can occur at over-pressures above 35 kPa and there is a 50 per cent chance of eardrum rupture at 100 kPa [9]).

Damage to vehicles appears to be a less reliable marker of over-pressure and impulse because of its complexity. It is noteworthy that, despite the ubiquity of vehicles, damage to them is seldom used as an indicator of over-pressure. One complication is that windows shatter early in exposure to blast, thereby reducing

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the pressure difference between both sides. In cars, vapours can penetrate confined spaces under the bonnet and in the chassis, and when ignited can behave as vented explosions exhibiting a range of over-presures. Thus, the net force would be outward, away from the vehicle, rather than a crushing force. Short duration (10–12 ms) high-explosive tests required 1.0 MPa to reproduce the level of crushing damage observed at Buncefield, but these are not truly representative of vapour cloud deflagrations or detonations. It was noted that the damage from high explosives tended also to be asymmetric, unlike the responses seen at Buncefield. Nevertheless, these tests did indicate that, to reproduce the local damage at Buncefield, over-presures greater than 200 kPa would be required, consistent with other tests. A number of cars in the car parks exhibited ‘de-beading’, with complete loss of contact between tyre and wheel flange. Inflated tyre tests in a hydraulically driven test frame suggest that a sidewall surface pressure of about 800–870 kPa is necessary to de-bead a fully inflated tyre [13].

Vehicle damage at Buncefield also pointed to a rapid decay in impulse beyond the edge of the cloud. This unexpected finding suggested that the over-pressure from a large pancake-shaped vapour cloud does indeed decay rapidly outwards, beyond its edge [9] and requires a re-examination of the rate of over-pressure decay outside such a geometry. The predicted decay in the vertical direction was less marked, but was not consistent with the evidence of low-level damage to cladding panels on the Northgate building, about 150 m west of the site boundary.
Assessments of structural damage suggested a peak over-pressure of 15–20 kPa to the Northgate building and of 20 kPa at the northeast corner of the RO building [9] (figure 2). It was found that back-calculating from these values over-estimated the trinitrotoluene (TNT) equivalents of the explosion. The damage inflicted on the reinforced concrete cladding panels of the Northgate building was subjected to a finite-element analysis with the aim of back-calculating the nature of the blast wave impinging upon them from the inflicted damage. The modelled panels were subjected to four different pairs of pressure and impulse loading curves. These included curves that simulated a vapour cloud deflagration and a detonation. Only the deflagration profiles produced damage comparable to that observed [9].

Initially, it was thought that the faces of trees and posts that were most pit-marked by particles would be the ones that faced the on-coming flame [3], but particle momentum considerations suggested that the cause was more likely to

*Phil. Trans. R. Soc. A* (2012)
be the particles entrained in expanding burned gases, moving in an opposite direction. Directional indicators are provided by abrasions on trees and posts and movements of skips, branches, lamp posts and cars. The direction of the net impulse on physical objects such as lamp posts and trees are shown by the arrows in figure 8. Within the cloud, the arrows are directed inwards towards an epicentre, unlike those for previous vapour cloud explosions, such as at Flixborough. Directional indicators outside the cloud pointed away from the site. The main explosion had long-duration positive and negative phases, as inferred from the responses of items exposed to the pressure pulses that were visible in CCTV footage.

4. Ignition

In the earlier EMAG analyses [8], the emergency generator cabin to the south of the Northgate building (figure 2) was considered as a possible ignition source, as it showed evidence of suffering an internal explosion. A flamefront created by the explosion venting from this building would have to travel some 120 m over the open car park before reaching significant congestion. An initially fast
flame from a vented explosion would have slowed significantly, to perhaps 10–20 m s\(^{-1}\), over this distance. This proved to be inconsistent with eye witnesses, CCTV and directional evidence. Consequently, the emergency generator cabin was eliminated as the location of a potential ignition source, in favour of the emergency pump house [9] (figure 2).

This was within the vapour cloud from an early stage. A flammable mixture would have built up inside it. It had clearly suffered an internal explosion after the fire water pumps started automatically, upon activation of the emergency fire alarm. It was, however, the only area where uncrushed boxes and tanks were found. After a relatively modest start in the pump house, the explosion intensity clearly must have increased [9]. The flame speed could have been enhanced by the aerosol fuel mist [14] and also by the turbulence generated in the gas ahead of the flame as it propagated through confining trees and undergrowth [15,16]. In contrast to some other large explosions, there was no significant pipework congestion for turbulence generation. There was considerably less damage close to the pump house than in both directions further along Cherry Tree Lane and down Buncefield Lane. Here, along the lines of trees and hedges, flame speeds and associated over-pressures would have been significantly greater.

5. Deflagration

The turbulence created by obstacles and confining boundaries accelerates the flame by accelerating the gas flow ahead of it. This further increases the r.m.s. turbulent velocity, which, in turn, increases the turbulent burning velocity, further accelerating the flame. This run-away feedback mechanism eventually is countered by partial quenching of the flame, because of the increasing flame stretch rate, and a volume packing limit to the flame surface density. As a result, there is a maximum value of the ratio of turbulent to laminar burning velocity, \(u_t/u_l\). This ratio is a function of the Markstein number for strain rate and the dimensionless group, \(u_lL/\nu\), where \(L\) is the turbulent integral length scale and \(\nu\) is the kinematic viscosity [17]. Many stoichiometric mixtures, initially under atmospheric conditions, can attain turbulent flame speeds that are comparable to Chapman–Jouguet (CJ) detonation speeds. Chao & Lee [18] have measured such turbulent flame speeds in ducts that are closed at one end and packed with cylindrical rods to accelerate the flame. These flame speeds also depended upon the blockage ratio.

Flame speeds and over-pressures in the Buncefield vapour cloud were modelled employing the Explosion Simulator (EXSIM) code [19,20]. The porosity-distributed resistance approach [19] was used to model the progress of an averaged flamefront interacting with averaged turbulence. Initially, this was carried out with a stoichiometric propane–air mixture with a depth of 3 m. Simulations assumed ignition to occur in the region of the emergency pump house (figure 2), with subsequent flame propagation through the hedgerows along Cherry Tree Lane and Buncefield Lane; these are also visible in figure 3. EXSIM does not allow for pressure wave/flamefront interactions that generally increase the combustion rate. Nor does it allow for any shock waves generated by the gas flow ahead of the flame or deflagration-to-detonation transitions (DDTs). The code does not allow for flame quenching, which diminishes the combustion rate and over-pressures.
However, it has been calibrated and validated against rigid pipework obstacles of the type found in process plant, but not against flexible objects such as leaves and branches, which would be expected partially to accommodate the flows [20].

The build-up of pressure at the accelerating flamefront was shown by pressure–time plots for the propane flame propagating along Cherry Tree Lane from the emergency pump house. The maximum computed flame speed was 714 m s\(^{-1}\), and the maximum transient flamefront pressure was 400 kPa. Because it was not possible to resolve the detailed influence of obstacles, such as the myriad of small branches and leaves smaller than the computational grid, the associated small-scale turbulence was simulated by using ethylene, a fuel with a higher burning velocity than propane. Maximum over-pressures were computed in the region of the junction of the two lanes. Not surprisingly, the highest pressure peaks associated with the flame propagation lay along the lines of the trees and undergrowth, and were of the order of 200 kPa [9], with a peak value of over-pressure of 290 kPa at the junction of the lanes. Free-field over-pressures over most of the car park were no more than 100 kPa. As the flame accelerated through the hedgerows down Buncefield Lane, the peak over-pressure of the wave travelling across the car park dropped to approximately 50 kPa at the far side, adjacent to the Fuji building [20] (figure 2). On the more congested east side of Buncefield Lane, the steady-state pressure was about 75 kPa.

The computed results suggested that the net impulse created by the large flows in the vegetation was in the reverse direction relative to the flame propagation, whereas in the uncongested part of the flammable cloud, the net flows were in the direction of flame propagation. The former observation is consistent with the evidence of bent trees along the lines of trees, but the latter is not (figure 8).

6. Deflagration-to-detonation transition

A critical condition for a DDT in a duct is that the maximum attainable turbulent burning velocity should be high enough for the gas velocity ahead of the flame to generate a shock wave sufficiently strong for the increased pressure and temperature behind it to cause autoignition of the compressed reactants between the shock wave and the flame [21]. Without a sufficient maximum turbulent burning velocity, autoignition and hence detonation cannot occur. However, because of heterogeneity in the vapour cloud, autoignition will first occur at the most reactive hot spot, within a localized reactivity gradient. This might generate a localized shock wave that triggers earlier autoignition throughout the remaining reactants. The condition for the coupling of an acoustic wave and a chemical reaction front, essential for the development of a detonation, is that the localized reactivity gradient generates an autoignition velocity that is close to the acoustic speed [22].

In the presence of the transverse obstacles that generate localized flow recirculations in ducts [18], high values of \(u_t\) are accompanied by flamelet extinctions and regenerations, as well as transverse and reflected shocks, which enhance autoignition. The reacting flow field is far more complex than that in a duct without obstacles, or in the one-dimensional analysis for a flame and
planar shock wave [21]. A quasi-detonation regime lies between those of high-speed deflagration and developed CJ detonation. It has elements of both, with flame quenching and re-ignition, shock waves, and the initiation and decay of localized detonations. The detonations continually turn on and off. On the other hand, once started, a true detonation is self-sustaining and, provided the fuel concentration stays within the detonable limits, no further obstacles are needed to sustain it. The complexity of the localized changes that ultimately give birth to an established detonation can be seen in the numerical simulations of Oran [23]. If the turbulent flame speed is high enough, localized autoignitions can occur, increasing the flame speed still further, even though it is less than the CJ speed and would decline in the absence of obstacles.

It was found in the study of Chao & Lee [18] that for a stoichiometric methane–air mixture, originally under atmospheric conditions, a high average turbulent deflagration speed of about 1000 m s$^{-1}$ with huge fluctuations could be attained in the duct, at a pressure ratio of about 7 and with fluctuation amplitudes of about 0.1 MPa. The deflagration speed declined sharply as the flame moved into a region without obstacles. A similar sharp decline was observed for natural gas–air, beyond the end of pipework obstacles, by Harris & Wickens [24]. Localized autoignitions became more probable with stoichiometric propane–air and a more stable quasi-detonation regime was observed in [18]. The measured quasi-detonation speed was 1400 m s$^{-1}$ at a blockage ratio of 0.41, less than the theoretical CJ speed of 1802 m s$^{-1}$, and the pressure ratio was just over 8.

Harris & Wickens [24] reported the development of a propane–air flame speed of 300 m s$^{-1}$ in an initial confined 9 m length of a 45 m duct, fitted with repeated obstacles for the first 24 m. The flame accelerated further into the 15 m length also with obstacles, but with open-sided walls for a length of 36 m. The flame acceleration continued through the first 6 m of the 15 m length, reaching a flame speed of 600 m s$^{-1}$, just prior to a transition to a detonation. The detonation continued to propagate at nearly 1800 m s$^{-1}$, close to the CJ speed, through the remaining unobstructed length of 21 m. Photographs show venting of burned gas to atmosphere, after failure of the light-weight enclosing material.

In ducts without obstacles, the fluid dynamics are less complex. It is also possible to observe in detail the onset of autoignition at a hot spot, the subsequent transition to a fully developed detonation and the instant at which the CJ speed is attained. In the work of Bradley [17], it is suggested that, in such cases, the time interval between the first hot spot autoignition and the attainment of the equilibrium CJ detonation speed is about 0.1 ms. An equi-mole mixture of hydrogen and oxygen first autoignited at a flame speed of 1930 m s$^{-1}$ (CJ speed 2237 m s$^{-1}$) at a pressure ratio of 14.14. A stoichiometric ethylene–oxygen mixture autoignited at 1600 m s$^{-1}$ (CJ speed 2379 m s$^{-1}$) [17].

To complete the discussion of DDT, as reported in the EMAG report [8], the methodology in Bradley et al. [21], for a duct closed at one end, gave a maximum computed turbulent flame speed for butane–air, originally at atmospheric pressure, of about 1200 m s$^{-1}$. This could generate a shock wave ahead of the flame giving a pressure of 1.17 MPa and a temperature of 825 K. Based upon the autoignition delay times at this pressure and temperature, this was sufficient to induce autoignition. Similar computations for a pentane–air mixture showed that it was unlikely to autoignite.
In summary, the various over-pressures reviewed here are: (i) up to 400 kPa, computed for a propagating turbulent flamefront, (ii) 700 and 800 kPa, measured, close to the constant volume combustion values, for near-quasi and quasi-detonations, (iii) 1414 kPa, measured for autoignition prior to a detonation, and (iv) 1170 kPa, calculated for autoignition after the leading shock. All values are for an initial atmospheric pressure. The computational fluid dynamics modelling employed for (i) would not include the generation of shock waves. Apart from this over-pressure, all these listed values are significantly higher than those on figure 7. Importantly, they also indicate that damaging over-pressures are not unique to detonations, but can occur also with fast deflagrations and quasi-detonations. It has been known for some time that deflagration velocities can be quite high and can lead to extensive blast wave damage [25].

In Buncefield Explosion Mechanism Phase 1 [9], it is suggested that a deflagration accelerated along the line of trees and hedgerow on Cherry Tree Lane and translated to a detonation, the more severe explosion, near the junction with Buncefield Lane. This propagated through a substantial proportion of the charge, although its path is not suggested. On the other hand, neither a DDT nor a deflagration mechanism were inconsistent with witness evidence and CCTV camera evidence relating to the first shock wave or luminosity [9]. Furthermore, the mean propagation velocity across the cloud with a maximum radius of 240 m was 150 m s$^{-1}$ [9] and could only be detonative, or perhaps quasi-detonative, in parts. While these figures suggest that the flame would have propagated through the cloud in 1.6 s, there are camera records that show bright flame luminosity lasting up to 3.0 s [9].

7. Birth and death of a detonation

The crucial question emerges of how a sufficient degree of confinement/congestion could be provided by the hedgerows at Buncefield to initiate a DDT and, if so, whether the detonation could be sustained outside that confinement/congestion. Unlike the situation at the Port Hudson explosion, where there was good evidence that the initial explosion occurred in a concrete warehouse [15], it is not easy to explain how the requisite pressures and temperatures for autoignition, followed by a fully developed detonation, could have been attained, bearing in mind the venting along the line of trees and undergrowth and the relatively low over-pressures from the computational modeling.

In the study of Harrison & Eyre [26], experiments are reported, in which a ‘bang-box’ explosion vented into an unconfined natural gas–air cloud without obstacles. This generated an over-pressure in the cloud of about twice that with no external flammable mixture. The most severe test condition generated a maximum over-pressure of 22 kPa about 4 m from the vent and a maximum flame speed of 145 m s$^{-1}$ about 7 m from the vent. This decayed roughly linearly to about 15–20 m s$^{-1}$ at 30 m from the vent. In the absence of turbulence-generating obstacles in the external reactive mixture, the highly turbulent flame generated by the venting process decays and, with it, the flame speed.

The nearest possible ‘bang-box’ for the generation of a detonation close to the Cherry Tree Lane junction with Buncefield Lane is the emergency pump house. However, the damage was rather minimal in that region [9]. The explosion there
would vent through the roof and the south wall. However, the nearest hedgerow was some distance away. As in Harrison & Eyre [26], the vented flame gases would decelerate significantly before entering the vegetation, while providing the ignition source for further flame propagation.

In addition to problems of identifying the birth of a detonation, there are problems of identifying whether it might survive or perish. There have been few studies on whether an established detonation can survive sideways and upwards venting, as in a hedgerow. In one of the few studies of this, Radulescu & Lee [27] rapidly established sustained detonations in a duct, using a Schelkin spiral. This was followed by a length of the duct in which the walls were porous. On reaching this region, the propagation velocity of the detonation decreased. Transverse waves that were stabilizing were unable to overcome the losses owing to the mass divergence into the wall, leading to a curved shock front. It was found that unstable detonations propagated a shorter distance than stable ones, before the detonation eventually failed. Of course, the higher the maximum turbulent burning velocity, the more potential compensation there can be for loss through the walls. Another important practical issue requiring further work is the extent to which a fully developed confined detonation might continue to propagate through the same mixture, but outside the confinement.

8. Fireballs and firestorms

These have received rather less attention in Buncefield studies than turbulent deflagrations and detonations; yet, firestorms were the important aspects of the Port Hudson and Ufa vapour cloud explosions, events that have been classed as very similar to that at Buncefield [9]. A photograph of a fireball appears in figure 9. It is to be anticipated that the strength of a buoyant fireball and the induced radially inward velocities at ground level will be related to the mass of fuel entrained in the fireball. This, in turn, will be related to the initial mass of the fuel spill [28]. Although they are difficult to estimate, the fuel spills at the times of initiations of the explosions are very approximately: Port Hudson 62 tonnes [15], Ufa 4500 tonnes [28] and Buncefield 300 tonnes.

At Port Hudson, the firestorm seemed to develop after the main explosion. Winds appeared to rush in from the northeast and southeast towards a focal point, and were carried aloft by buoyant forces, consuming the residual propane. The area of wind damage, composed of broken tree limbs and uprooted small trees, also displayed scorching. The damage was rather localized and the area where it occurred ‘did not look as though it had been swept by any hurricane-strength wind’ [15]. In contrast, at Ufa, the firestorm generated by the rising fireball led to the breaking and blowing down of trees over an area of 2.5 km² [28].

Computations of fireballs show flows into and out of the combustion zone, generating short-duration hurricanes and shock waves strong enough to uproot trees [28,29]. The computations suggested that the destruction observed at Ufa involved the combustion of at least 300 tonnes of fuel. The topography, comprising localized steep slopes and dense vegetation, also contributed to the intensity of the firestorms at these locations. Vapour clouds from flashing liquids formed in small valleys. In contrast, in 1978 at Donnellson, after a pipeline rupture, the combustion of about 300 tonnes of spillage of liquefied petroleum gas over a flat
cornfield was more benign. Makhviladze & Yakush [28] have quoted approximate height scales, in metres, for topographic undulations as: Port Hudson 12–15, Ufa 30–40 and Donnellson 1–1.5.

The generation of an energetic fireball is associated with a relatively slow, yet prolonged, rate of combustion that is enhanced by localized surface roughening with high fuel concentrations in localized valleys. Laboratory experiments on rising flame kernels in explosions also suggest that appreciable buoyant lift requires a slow flame speed over a relatively large time scale [30]. The larger the mass of the localized accelerating buoyant plume of burned and burning mixture, the larger is the induced mass flow rate at its base, and the stronger is any potential firestorm. The development of a firestorm represents a transition to a more intense mode of burning, arising from the high induced air velocities. At Buncefield, along the gentle downward slope along Cherry Tree Lane, the height scale of the topographic undulation was about 2 m [3]. As at Donnellson, this is relatively small. Both the absence of highly localized pockets to prolong the combustion and the high mean flame speed of 150 m s\(^{-1}\) militate against highly accelerating buoyant plumes and the generation of firestorms.
If the mixture were of infinite extent and ignited at a point source, to create a near spherical explosion flame, the expressions of Andrews & Bradley [30] enable the rise due to buoyancy to be estimated. For the observed mean flame speed of $150 \text{ m s}^{-1}$, an overall explosion time of 1.6 s, as at Buncefield, and an assumed ratio of unburned to burned gas density of 6, the expressions suggest buoyancy would increase the topmost height of the fireball by no more than 7%. While this gives a very approximate confirmation that buoyancy effects will be small, these assumed conditions are rather different in detail from those at Buncefield. There may be some further slight buoyant lift at the upper boundary of the cloud where the mixture is close to the lean flammability limit and is consequently slow burning. In addition, the natural upward venting process, particularly of the gas that is burned first, would tend to increase the height of the burned gas cloud close to the source of ignition.

It was estimated in Buncefield Explosion Mechanism Phase 1 [9] that the area of the original flammable cloud was 120 000 m$^2$ and its depth was 2 m. This area is approximately equal to that of the scorched area in figure 3, from which measurements give a mean radius of 198 m and a scorched area of 123 160 m$^2$. The closeness of these two areas implies that the gaseous expansion was predominantly vertically upwards. If there were no change in the diameter of the initial 2 m deep pancake cloud, then—with a gas density ratio of 6—its height would increase uniformly to 12 m.

However, to allow for a greater lift at the centre of the burned cloud and to provide an approximate estimate of the maximum height of the burned gas at atmospheric pressure, it was assumed that this cloud was in the form of a spherical cusp. With an assumed gas density ratio of 6, the volume of burned gas would be 120 000 $\times$ 2 $\times$ 6 m$^3$. The dimensions of a spherical cusp with this volume and a ground radius of 210 m were found. This radius was assumed to be slightly greater than the scorched mean radius, in order to allow for some mixture extending just beyond the boundary of the scorching. The explosion was initiated close to the centre of this area. From the geometrical expression for the volume of the cusp and the ground radius, it was found that the height of the burned gas was 20.2 m at the centre of the cusp and 15.6 m at a radius of 105 m, falling to zero at a radius of 210 m.

With regard to any supportive evidence about the extent of any fireball from witness statements or cameras, the statements in Buncefield Explosion Mechanism Phase 1 [9] concentrate more on what was heard than what was seen. It is possible that the generation of a fireball contributed to the sound of the second more intense explosion. As to where such a sound came from, most of the cameras were directed downwards. However, the increasing light levels registered by camera YL might have corresponded to the flame rising above the building line [9]. This camera was relatively remote, situated in the Furnell yard, west of Boundary Lane (figure 2). On figure 7, it is located some short distance off the figure in a westerly direction, along the road running from the RO building. This, combined with the long-lasting 3.0 s of bright flame luminosity, referred to in §6, could be commensurate with the onset of the generation of a fireball. In addition, the inwards directional arrows on figure 8 are suggestive of a surface gas flow into the base of a rising fireball in this region.

The flame propagation along the lines of trees and hedgerows would create an appreciable amount of buoyant gas. However, at Buncefield, as the flammable...
mixture was fairly uniformly spread over the terrain, the rate of combustion could not be sustained locally for sufficient time to establish any appreciable buoyant upward flow of burned gas, still less to develop a firestorm. Although an appreciable spill is necessary to create a fireball, there must also be a sufficient localized concentration of fuel to sustain localized burning for a sufficiently sustained period of time. The absence of high localized concentrations at Donnellson and Buncefield could explain the absence of firestorms, even though the spillage mass, in both cases, was greater than at Port Hudson.

Venart & Rogers [31] also have suggested that a deflagration at the emergency pump house lagoon (figure 2) led to a fireball that promptly rose. This created a pressure wave ‘whoosh’ from its lift-off, that moved across the car parks. This activated the remote keyless entry anti-theft alarms in cars at the western edges. These caused ignition and vented deflagrations from the cars, with transitions to detonations between the Fuji and Northgate buildings and the south Northgate wall (figure 2). These eventually jetted eastward into the car parks. This suggests that it would be prudent to test the propensity, or otherwise, for activated anti-theft alarms to ignite a flammable mixture.

9. Two-phase flows and radiative preheating

Combustion of liquid fuel aerosols can occur with an enhanced flame speed, as a result of flame instabilities that wrinkle the flamefront, and this is particularly so with rich mixtures [14]. In addition, the flame speed can be increased as a result of a sufficient radiative transfer from the burned gas to the reactants, particularly if the mixture contains fine particulates. In medium-sized flames, even those with finely pulverized coal, the radiative transfer has a relatively small effect [32]. The situation might be different with much larger flames, such as those in vapour cloud explosions.

Here, the radiative flux into the reactants is much enhanced by the increased emissivity of the large volume of burned gas. The burn rate is also increased as a result of the flame wrinkling being extended to ever-greater length scales [33]. The simulations of the Buncefield fire plume in Devenish & Edwards [1] involved radiative interactions with the aerosol in the plume and a reduction in the solar radiation reaching the ground.

Moore & Weinberg [34] have demonstrated how anomalously high rates of propagation of unconfined vapour cloud explosions could be caused (or aggravated) by radiation-induced, multi-point ignition due to fibrous particles ahead of the main flamefront. They showed that the presence of Kaowool, a silica–alumina-based refractory, could result in the ignition and enhanced burning of ethylene–air, under a radiative flux of about 80 kW m$^{-2}$. At the upper limit of size, at stoichiometric flame temperatures, the black-body radiative flux would be of the order 1 MW m$^{-2}$ [35]. Owing to air entrainment during combustion, the radiative flux falls below this limit. A propane fireball of 10 m diameter, based on the experimental correlations in Roberts [36], would have a radiative flux at its surface of about 125 kW m$^{-2}$. Atkinson & Cusco [37] have expressed the view that the difficulty of reconciling the high over-pressures in excess of 200 kPa at Buncefield with the relatively low average flame speed of 150 m s$^{-1}$ could be overcome if the rate of flame advance were episodic, with periods of
rapid combustion punctuated by pauses with very slow flame advance. This would be consistent with the radiative heating mechanism, with fragments of dry brittle leaves able to provide a sufficient concentration of particles for periodic fast burning, under heat fluxes of about 300 kW m\(^{-2}\) for 35 ms.

Although not directly applied to the Buncefield circumstances, or the presence of particles, the numerical investigation of Karlin [38] explored the possible effects of radiative preheating of unburned gas entering a wrinkled flame. Numerical simulations showed that as the wrinkled flame grew, at a certain rate of localized radiative absorption, a critical reactivity gradient, in the form of a temperature gradient, could develop at the side of the flame surface wrinkles. At this location, the chemical reaction might couple with an acoustic wave to initiate a localized detonation.

10. Conclusions

A number of mechanisms for the propagation of combustion have been discussed, without reaching any definite conclusions as to what precisely happened at Buncefield. Of particular importance was the acceleration of turbulent flames along the line of trees and hedgerows. There was no unequivocal evidence that a principal mode of reaction was a fully developed detonation sweeping across the site. There was, however, evidence that the observed damage and various camera records could be explained in terms of high-speed deflagrations and quasi-detonations. The former could generate localized flamefront over-pressures of 400 kPa and, with sufficient confinement, shock pressures of 1 MPa. Quasi-detonations, the details of which are complex, can create constant volume combustion over-pressures of about 0.7–0.8 MPa, while a detonation would give a pressure spike of about 1.75 MPa.

The maximum attainable burning velocity for a given mixture is an important parameter that governs flame and shock wave over-pressures. Some values of this have been measured at high r.m.s. turbulent velocities in laboratory experiments, but in the absence of strong shock waves. As autoignition is approached, such shock waves can develop. This suggests the necessity for fundamental studies of turbulent propagation in the presence of shock waves. There is also a need for further study of the role of radiation in the propagation rate of large explosions of aerosols, including droplets.

The generation of fireballs and firestorms is complex and has been rather neglected in Buncefield studies. An initial foray into this area has been attempted, and it seems that the initiation of a fireball would by no means have been impossible, although there would be no associated firestorm at the level of that at Port Hudson, still less that at Ufa.

Other areas for further study emerge, some of which are included in the Buncefield Explosion Mechanism Phase 2 programme. The most significant should include the following.

(i) Analysis of the complexities of multi-component gasoline spillage, involving droplet break-up, air entrainment and vapour production, followed by dispersion in still air over uneven terrain. Dispersion under almost still conditions provides significant modelling challenges.
(ii) The mathematical modelling of explosions through densely packed, small-scale, flexible obstacles and the question of whether reactant temperatures and pressures can become high enough for a DDT. The modelling of transitions to detonation and the conditions for their continuing propagation are particularly challenging, in terms of both the underlying science and the required computational power.

(iii) A related experimental investigation of flame acceleration, with and without ‘bang-box’ initiation, along hedgerows and lines of trees to ascertain the probability of a DDT and its continuing propagation into an uncongested cloud. Further investigations are also needed of direct jet flame ‘bang-box’ ignition of external vapour clouds, to define the conditions that can lead to detonation of the cloud.

(iv) The generation of necessary fundamental experimental and theoretical data on autoignition delay times, laminar burning velocities, and the effects of flame stretch on high turbulent burning velocities, including extinctions, all over the relevant ranges of temperature and pressure. The combination of (ii), (iii) and (iv) could provide retrospective guidance on the relative contributions of high-speed deflagrations, quasi-detonations and detonations to the damage at Buncefield.

(v) As a general rule, for effective practical incident investigation, immediate access to the site by specialist investigators is essential, before any disturbance of the site. Even the nature of broken glass can provide important evidence. Forensic tests of damaged items should be extended to build up a library of pressure–impulse damage curves for use in future studies. Full CCTV and recording of key events at sites containing large quantities of flammable materials will continue to be invaluable.

References


8 Buncefield Major Incident Investigation Board. 2007 Explosion Mechanism Advisory Group report.


