CHEMICAL ENGINEERING TRANSACTIONS
VOL. 77, 2019
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216
DOI: 10.3303/CET1977143

An Analysis of Severe Vapour Cloud Explosions and Detonations in the Process Industries

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Not all accidental releases of flammable gases and vapours create explosions; most releases do not find an ignition source and of those that do ignite, most of them generate low or moderate overpressure only (deflagrative combustion). However, when certain conditions are satisfied, deflagration to detonation transition (DDT) can occur followed by stable detonation. A detonation is a rare event; however, it is a worst-case accidental event. Overpressures in detonation are much higher compared to deflagration. In addition, detonation does not stop at the edge of the congestion, as in case of deflagrations, but detonation continues through the entire flammable cloud. Items within the detonating cloud are destroyed or rendered unusable.
An intense vapour cloud explosion (VCE) occurred at the Buncefield fuel storage site in 2005. Extensive research into this incident revealed beyond doubt that detonation had taken place in the vapour cloud. Alternative mechanisms were considered and dismissed because they did not adequately explain the observed damage. Unique data were collected on the impact of blast on items of industrial plant, vegetation and vehicles. Combined with advances in fundamental knowledge of detonation science and large-scale tests on detonations, these new insights have allowed a comprehensive interpretation of the multitude of previous accidents involving intense vapour cloud explosions. The review identifies several past industrial accidents in which detonation was the cause of major destruction and loss of life. The new insight presented should help safety engineers to comprehend aspects of explosion hazards, to prepare and to optimise safety management procedures to minimise the detonation risk.

1. Introduction

The ignition of accidentally released flammable gases and vapour engulfing process plant leads to flame acceleration and the generation of a vapour cloud explosion (VCE). Numerous experiments over the last 40 years have shown that the presence of equipment and pipework act as obstacles that create turbulence ahead of the advancing flame which in turn causes flame wrinkling and increases in flame speeds. Overpressures are proportional to the square of the flame speed so significant blast can be created by large flammable clouds in densely packed process units. If flame acceleration is high enough the flame speed can become sonic, with the accompanying generation of shock waves. In extreme cases shocks and shock interactions create conditions in which a deflagration to detonation transition (DDT) might occur. Such conditions include reactive hot spots formed by shock compression, energy focussing by collision of shock waves and regions of intense turbulence. Detonations are the worst possible outcome following ignition of accidentally released flammable vapours. Flame speeds through the flammable vapours reach around 1800 m/s associated with overpressures of around 18 bar. People cannot survive these conditions and process equipment and buildings within the detonating cloud are totally destroyed or rendered unusable. Several recent projects show that a DDT may occur in conditions that are not as extreme as previously thought, given that certain critical requirements are met. Harris and Wickens (1989) first suggested that congestion by trees might induce a DDT. Initial investigation of the Buncefield explosion strongly hinted that such a situation might exist. In follow-up experiments (Burgan, 2014) a DDT was observed in a stoichiometric propane/air mixture engulfing a 4.5 m wide arrangement of deciduous trees. A 2 m wide arrangement of trees did not detonate even though the

Paper Received: 28 December 2018; Revised: 16 May 2019; Accepted: 20 June 2019

Please cite this article as: Chamberlain G., Oran E., Pekalski A., 2019, An Analysis of Severe Vapour Cloud Explosions and Detonations in the Process Industries, Chemical Engineering Transactions, 77, 853-858 DOI:10.3303/CET1977143

intensity of congestion was increased. The venting of burnt gases from the congested region is a process which limits flame acceleration (Taylor and Bimson, 1988) and may have played an important part in the 2 m wide tests. Furthermore, explosion tests using a tapered rig demonstrated that detonation can continue to propagate into clouds as thin as 200 mm. The implication is that a detonation would be able to propagate through relatively thin detonable layers and paths in a large cloud. This makes a detonation much less susceptible to concentrations variations than a deflagration. Once a detonation has been initiated, it is likely it will propagate through the remainder of the cloud, bypassing any zones where concentrations are outside the detonable range. Pekalski et al. (2015) found that quiescent ethane/air underwent a DDT in a rig of 5.2 m square by 2.6 m high consisting of horizontal and vertical pipes each 0.076 m diameter with a pitch of 0.34 m. The DDT occurred towards the end of the congested region and the detonation propagated through an unconfined part of the rig and back through pockets of unburnt gas at the edges of the congestion. Johnson et al. (2015) reported a series of large-scale experiments involving the interaction of vented confined explosions with an external region of pipework congestion (jet ignition) that showed evidence of DDT and the continued propagation of the detonation through unobstructed vapor cloud. The DDT occurred in both ethylene/air and propane/air experiments. Davis et al. (2017) found that quiescent propane/air at slightly greater than stoichiometric in a “low congestion” rig transitioned to detonation after flame acceleration of about 22 m. The rig consisted of 3.7 m cubes each containing 5.8% volume blockage of uniformly distributed pipes. Lean (φ = 0.9) and rich (φ = 1.35) mixtures of propane/air also made the transition to detonation when the rig was changed to the “high congestion” of 10.9% volume blockage.

Extensive research into the Buncefield vapour cloud explosion over several years (Burgan, 2014) revealed that a gas detonation had taken place in the vapour cloud. A spin-off from this research was a collection of unique data on “damage markers” and “direction indicators” arising from the impact of blast on items of industrial plant, vegetation and vehicles. The relationship between damage and incident pressure waves from these and previous studies, combined with developments in fundamental knowledge of detonation science has prompted this re-investigation of many previous accidents involving intense vapour cloud explosions. The review has identified incidents in which detonations have occurred. The new insight can be used to guide plant layout and design, improve operational awareness, and prioritise maintenance procedures that would help to avoid, prevent, and mitigate the disastrous damage wrought by detonations. Implementation of such changes will save lives, maintain the company’s reputation and reduce consequential costs.

2. Data on detonation effects

Following the Buncefield incident, several detonation markers applicable to large-scale VCEs were determined (Burgan, 2014). These indicate specific forms of damage to property (here cars, oil drums, instrument boxes, oil filters, and posts shown in Figure 1, and tanks and iso-containers) in the path of a detonation. Calculations were also performed on the effect of overpressure and impulse on storage tanks and on the debeading of car tyres (Venart and Rogers, 2011, Haider et al. 2010). Tables 1 and 2 summarise the markers used in this review to identify evidence for detonation.

Figure 1: Damage to some of the items placed inside a propane detonation (Burgan, 2014). Damage created by overpressure > 10 bar. Note the dark markings on the post (extreme right) facing opposite to detonation propagation.

The tests also quantified the rapid overpressure decay from the edge of a detonating pancake shaped cloud. Simulations performed using the Fluid Gravity Engineering code, EDEN (Burgan, 2014), showed a correlation between the maximum overpressure outside a pancake shaped cloud P (bar) and the ratio of cloud height H (m) to distance from the edge of the cloud d (m). From this work, a simple expression $P = 7.8H/d$ was derived to estimate the maximum overpressure applicable to clouds with a radius ≥ 50 m. For smaller clouds (<50 m radius), it was found that either the Multi-Energy Method or TNT Equivalence was sufficiently accurate within the limitations of the tests and simulations performed. In addition, it was shown that the negative impulse within the large cloud is observed to be more intense than the positive pulse and causes items inside the cloud to be drawn in a direction opposite to that of detonation propagation. Outside the cloud the positive pulse dominates the impulse and items are displaced outward. Direction indicators, such as how poles and trees have been eroded or tumbled, indicate how the objects encountered the strong shock and subsequent waves that form.

Table 1. Damage markers used as evidence of detonations as shown in Figure 1.

Item	Overpressure Required
Vehicle damage	> 10 bar
Tyres debeaded	> 8 bar
Oil drums	> 3 bar
Switch boxes	> 5 bar
Oil filters	> 10 bar

Table 2. Additional damage criteria used as evidence of detonations in the review.

Additional data from incident investigation	Criterion
Windows broken	>3 km
Richter Scale	> 2
TNT equivalence	> 10 tonnes
Broken reinforced concrete	-
Crushed storage tanks	> 8 bar

3. The incidents

Reviews of historical VCEs (Slater 1978a, Lenoir and Davenport 1993, Marsh 2014) involving major losses and damage were chosen for further investigation based on the reported level of damage, the type of fuel (the more reactive hydrocarbons) and availability of reliable information. A thorough review to search for combinations of several damage effects consistent with those in Figure 1 and Tables 1 and 2 was taken as direct evidence that a detonation had taken place. The release conditions of identified incidents are shown in Table 3. The results are summarised in Tables 4 and 5. A summary of the incidents is given in Chamberlain et al. (2018) and references therein. Sadly, information on old accidents is often insufficient. However, damage to items characteristic of detonation and directional indicators in open areas suggested that detonation had occurred in accidents at Ludwigshafen 1948, Linden New Jersey 1970, Baton Rouge 1971, East St Louis 1972, Climax Texas 1974, Petal Mississippi 1974, Englewood Yard Houston 1974, Baton Rouge 1989, and La Mede France 1992. In earlier years a surprising number of these VCEs arose from railcar punctures. This is not the case in the later years. It is tempting to believe that a valuable lesson has been learnt.

4. Recommendations

An understanding of the root causes of an accidental VCE always leads to valuable lessons for future improvements in process safety.

4.1 Design and layout of facilities

The layout of occupied buildings as specified in API RP752 (2009) and API RP753 (2007) should be adhered to as a first requirement. However, these Standards assume deflagrations in congested areas of plants and the rapid decay of flame speed as the flame front emerges from the congestion into an external cloud. They do not consider detonations. The overpressure decay associated with deflagrations is defined by the size of the congested area engulfed by a potential flammable cloud, and not solely by the size of the flammable cloud. We know that if a DDT or detonation occurs, then there is a high possibility that the detonation will propagate through the remaining cloud and into open uncongested areas of industrial plant. Since the degree of spread of the cloud is dependent on the size and duration of the release before ignition, the local topography, and weather conditions, the cloud extent cannot be predicted with any certainty.

However, a vapour fence may contain the cloud and may have advantages in limiting the spread of heavier than air pancake-shaped clouds. At Buncefield, for example, gasoline vapours remained inside the bund for a considerable time before spilling over into the surroundings. At Jaipur, the vapour cloud was contained by a surrounding wall.The decay of overpressure from the edge of a pancake shaped detonating cloud is rapid. One sure way of protecting occupied buildings from destruction is to locate the buildings far away from congested units and areas of potential vapour cloud accumulation. Where this is not practical, some degree of blast proofing is required, in particular to control rooms.

Where environmental screening is required around sites, the use of trees and vegetation should be carefully considered. Current information (Burgan, 2014) shows that a width of vegetation no more than 2 m wide has been shown to lead to flame acceleration but not to DDT. Any further increase in width cannot be guaranteed to prevent DDT of an engulfing cloud. One common feature of vapour clouds of the heavier hydrocarbons is that the flammable cloud height is below about 3-4 m. Thus, elevated vegetation, such as large tree branches, would play little or no part in flame acceleration whereas ground level vegetation should be cleared away or limited in width to less than 2 m.CCTV coverage of the entire site is highly recommended. This would enable a more rapid and effective response to unusual behaviour, such as the sudden development of a misty cloud. One further advantage is the great assistance CCTV records offer to accident investigators. In this regard, it is helpful if clocks on the CCTV cameras are synchronized with each other.

Drainage systems should be equipped with water traps to prevent the migration of flammable vapours.

The use and quantity of the more reactive combustibles such as olefins and acetylene should be minimized where possible. Efforts should be made to research the elimination of olefins in mixed refrigerants in LNG plants.New plants should consider separating process units into smaller sections with at least 10 m separation between each section to limit flame acceleration.Unoccupied buildings near or within process units should have at least one collapsible wall, which withstands wind forces, but which would prevent the build-up of high over-pressures inside the building. This would prevent high velocity jet ignition of an external flammable cloud and the possible transition to detonation.Occupied buildings, such as control rooms, should be designed to avoid ingress of flammable vapours where there is a risk of exposure to flammable gas.

The use of active mitigation systems should be considered. The use of solid powders (Davis et al. 2017) and water sprays (Allason et al. 2018) have shown considerable promise in this area.

Table 3: Release conditions for incidents identified as detonations.

Event	Date	Fuel	Release	Release from	Wind, m/s	Cloud size	Ignition delay from release, minutes
Buncefield, UK	11/12/2005	gasoline	300 tonnes	Tank overfill	calm	120,000 m^2	40
Jaipur, India	29/10/2009	gasoline	1000 tonnes	Valve failure on tank	calm	350 m radius	75
CAPECO, Puerto Rico	23/10/2009	gasoline	600 tonnes	Tank overfill	calm	370 m radius	26
Amuay, Venezuela	5/8/2012	olefins	4 tonnes/min	Pump failure	Calm SE drift	300 m radius	>3000
Skikda, Algeria	19/1/2004	Paraffins C2-C4 plus ethylene	16 kg/s estimated	Pipe failure	calm	80 m radius	2-3
Brenham, Texas	7/4/1992	Paraffins mainly C2-C4	500-1600 m^3	Outflow from cavern storage	calm	500 m radius 700,000 m^2 1500 m range	30
Ufa, Russia	4/6/1989	LPG	2000-10000 tonnes	Pipeline rupture	calm	2.5 km^2 900 m radius	70
Port Hudson, USA	9/12/1970	propane	80 l/s, 70 tonnes	Pipeline rupture	Light wind	100,000 m^2 500 m radius	24
Newark, USA	7/1/1983	gasoline	100 l/s 114-379 m^3	Tank overfill	1.5 m/s	50,000 m^2 450-600 m radius	20
Flixborough, UK	1/6/1974	c-hexane	2500-5000 kg/s 30 tonnes	Pipeline rupture	2.5 m/s	60,000 m^2	0.3-0.6
Pasadena, USA	23/10/1989	Ethylene i-butane	37.8 tonnes	Reactor failure	?	100,000 m^2	1-1.5
Decatur, Illinois	19/7/1974	i-butane	176 kg/s	Rail car puncture	Light breeze	1200x800 m	8-10
Beek, Netherlands	7/11/1975	C2-C4 olefins	40 kg/s tonnes	5.540 mm pipe break	2 m/s	30-90 m from source	2

Table 4: Damage effects revealed by accident reports and published data. N/A = data not available/applicable, ? = unknown or undecided, Y =a yes result.

Event	Vehicle damage	Car tyres debeaded	Switch boxes	Oil drums	Oil filters	Directional indicators		Storage tanks crimped
						Radially inwards	Scouring one side	
Buncefield	Y	Y	Y	Y	Y	Y		Y
Jaipur	Y	Y	Y	Y	Y	Y	Y	Y
CAPECO	N/A	N/A	Y	Y	Y	Y	Y	Y
Amuay	Y	Y	?	Y	?	Y	?	Y
Skikda	Y	Y	?	Y	?	Y	?	N/A
Brenham	Y	Y	N/A	N/A	N/A	?	?	N/A
Ufa	Y	N/A	N/A	N/A	N/A	Y	?	N/A
Port Hudson	N/A	N/A	N/A	N/A	N/A	Y	?	N/A
Newark	Y	N/A	N/A	?	?	?	?	Y
Flixborough	Y	Y	?	?	?	?	?	?
Pasadena	N/A	N/A	N/A	N/A	N/A	N/A	?	Y
Decatur	Y	?	N/A	N/A	N/A	?	?	N/A
Beek	N/A	N/A	?	?	?	?	?	Y

Table 5. Supplementary information on damage effects for the events listed in

Event	Building severe damage	Reinforced concrete severed	Windows broken	Richter Scale	Detonation	Condition for detonation
Buncefield	Y	Y	Y	2.4	Y	DDT by tree and undergrowth
Jaipur	Y	Y	?	?	Y	Jet ignition from building?
CAPECO	N/A	N/A	Y	2.9	Y	Jet ignition from drain?
Amuay	Y	Y	Y	?	Y	Jet ignition from building?
Skikda	Y	Y	Y	?	Y	DDT by equipment in unit
Brenham	Y	N/A	Y	3.4-4	Y?	DDT by tree congestion or by jet ignition from drain
Ufa	N/A	N/A	Y	?	Y	DDD by tree congestion
Port Hudson	Y	?	Y	3	Y	Jet ignition from building
Newark	?	N/A	Y	?	Y?	Jet ignition from building?
Flixborough	Y	Y	Y	2.7	Y	DDT by equipment in unit
Pasadena	Y	Y	Y	3.5-4	Y	DDT by equipment in unit
Decatur	Y	N/A	Y	?	Y?	?
Beek	Y	Y	Y	?	Y?	?

4.2 Operation and Maintenance

Operators and maintenance engineers should be made fully aware of the hazards created by detonations by process safety training courses that include such topics.

Plant audits, HAZID, HAZOP and LOPA studies could consider the possibility of detonation.

Maintenance procedures should be produced to increase the surveillance of parts of the plant containing the more reactive flammable liquids and vapours. A suggested priority list, in order of decreasing propensity to detonate is: acetylenes, olefins, paraffins (propane and higher homologues), ethane, hydrogen (in open spaces), natural gas, and least reactive: methane.

After accidental VCEs, investigators should be engaged before clearance of the site has begun. Photographs should be taken of all damage as soon as possible after the event, and the location of damaged items and major debris should be logged.

5. Conclusions

A striking feature common to most of these events was release of heavier than air fuel vapour in calm or low wind conditions combined with several minutes delay before an ignition. In such conditions a pancake shaped vapour cloud developed by gravity-driven dispersion over a large area. These incidents are Buncefield, Jaipur, CAPECO, Amuay, Brenham, Ufa, Port Hudson, Newark and Decatur. Large releases of short duration before ignition, on the other hand, remain largely momentum dominated and tend to relate better to turbulent hemispherical clouds. These incidents are Flixborough, Pasadena and Beek. The incident at Skikda appears to be a combination of initial turbulent momentum driven dispersion followed in the far field by passive dispersion. The incidents at Decatur and Beek were powerful events but there is some doubt over whether a DDT occurred due to lack of key information.The incidents can also be classified by the general mechanism of DDT. Buncefield, Brenham and UFA underwent DDT by flame acceleration in dense vegetation. Skikda, Flixborough, and possibly Pasadena and Beek suffered from DDT by industrial plant congestion. The incidents at Jaipur, CAPECO, Port Hudson, Amuay, Newark and possibly Decatur are likely to have undergone DDT by jet ignition from confined volumes into the external flammable cloud. While it is difficult, if not impossible, to assign the fundamental mechanism of DDT to each incident, it is likely that a combination of hot spot formation, energy focussing by coincidence of shock waves and intense turbulence has played its role.Further classification can be derived from the type of fuel that was released. Saturated hydrocarbons were involved in incidents at Buncefield, Jaipur, CAPECO, Brenham, UFA, Port Hudson, Newark, Flixborough and Decatur. The gasoline released at Buncefield, Jaipur and CAPECO also contained aromatics which are of similar reactivity to paraffinic hydrocarbons. The remaining incidents at Amuay, Skikda, Pasadena and Beek involved releases containing olefins.The survey of accidents identified no detonations involving methane or natural gas and very few VCEs involving hydrogen. It seems that the natural buoyancy of these gases does not favour the development of sufficiently large flammable clouds engulfing congested space. Nevertheless, release of these gases in confined surroundings can create the right conditions for powerful explosions. The nuclear power plant at Fukushima is one case in point because evidence points towards at least one detonation having occurred in the build-up of hydrogen/air cloud inside the reactor buildings.

A further 16 incidents of intense VCEs were identified where the evidence of detonation as the overpressure generating phenomenon is suggestive but not definitive. The available evidence is not comprehensive enough. Of these it is tentatively suggested that 9 more events may have involved transition to detonation.

The incident at Buncefield was shown by many follow-up field tests to be consistent with a DDT. Alternative mechanisms were considered and researched but none could adequately explain the combined effects of levels of damage, directional effects and rapid decay of overpressure from the cloud edge (Johnson et al., 2018).

Acknowledgments

The authors wish to thank Shell Research Ltd for financial support and permission to publish.

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