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Vapour Cloud Explosions – The Evidence for Deflagration to Detonation Transition

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Approximately forty years ago, it was realised that the generation of high flame speeds would result in damaging pressures being produced in vapour cloud explosions (VCEs). At the time, however, it was not clear how high flame speeds could be generated in VCE. Research in the 1970s and 1980s showed that if a vapour cloud engulfed a region of congested process pipework, the flame could accelerate to levels where damaging pressures were produced. Since that time, the accepted basis for assessing VCE hazards has been to consider congested process regions as potential locations of deflagrations, with pressure reducing as the explosion propagated away from the region. However, this was not sufficient to explain the evidence found following the Buncefield explosion in the UK (2005). The research conducted following Buncefield, the most extensive for any VCE, led to the conclusion that the incident involved a transition from a deflagration to a detonation (DDT). In reaching this conclusion, several possibilities were considered and dismissed, including a speculative explosion mechanism not previously observed that involved ignition by radiation of dust particles ahead of the flame. Taken in combination with more recent experimental studies, they indicate that DDT was not just an explanation for Buncefield, but likely has a much wider relevance. The evidence obtained from Buncefield and subsequent research supporting DDT will be reviewed.

1. Introduction

That damaging overpressures can be generated following the ignition of a flammable cloud in a confined volume has been understood for some time. However, in the second half of the 20th century, it became clear that large vapour cloud explosions in more open environments were not fully understood.

It was known that high flame speeds could generate damaging overpressure (Kuhl, 1981), however the mechanism for producing these high flame speeds was not. Laboratory scale experiments at that time suggested flame speeds of only a few metres a second would be produced in the open, between one and two orders of magnitude less than was considered necessary to give damaging overpressures.

Subsequent experimental research, from laboratory (Abdel-Gayed, 1982) to large scale (Eyre 1987, Harris 1989), showed the importance of flame distortion and turbulence in flame acceleration. In a vapour cloud that engulfed unconfined congestion (e.g. process pipework), the flow produced by the expanding flame interacted with the congestion, resulting in flame distortion and turbulence. This intensified the combustion and accelerated the flame, potentially to high flame speeds and leading to significant overpressure.

In 2005, a VCE occurred at the Hertfordshire Oil Storage Ltd (HOSL) depot at Buncefield, UK. The HOSL site had little process congestion and had not been considered to have a VCE hazard. Given the severity of the explosion and the subsequent multiple tank fires, an independent investigation was carried out by the Buncefield Major Incident Investigation Board (BMIIB 2006). This investigation was wide ranging but included

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an initial review the evidence related to the VCE by a group of explosion experts, which identified that the incident did not appear to be consistent with the standard view that VCEs are restricted to regions of process congestion (BMIIB 2007).
This prompted a more detailed assessment in a Joint Industry Project (JIP) (HSE 2009) followed by large scale experimental studies (Burgan 2014). In relation to the explosion, the JIP had three main objectives:

- To determine if it was possible to explain the evidence with a 'deflagration only' scenario.
- To determine if DDT was consistent with both the evidence from the incident and the results from experimental studies.
- To assess other potential combustion mechanisms, particularly a speculative explosion mechanism not previously observed that involved ignition by radiation of dust particles ahead of the flame, a so called 'episodic explosion'.

Supported by experimental studies, it was concluded that the evidence from the incident was not consistent with the 'deflagration only' scenario but was consistent with a deflagration leading to a DDT. No evidence was found in experimental studies that supported the possibility of the episodic explosion mechanism.
In addition, the JIP research provided extensive data on the overpressure damage to items in and around a detonating cloud (Burgan 2014) giving a solid relationship between damage and strength of incident pressure waves. Such understanding, combined with developments in fundamental knowledge of detonation science has prompted re-investigation of previous intensive vapour cloud explosions accidents (Chamberlain et al, 2018). The damage evidence observed is consistent with the deflagrative and detonative combustion processes, indicating that most, if not all, large VCEs have involved DDT.

1.1 The problem

Recent UK HSE publications (Atkinson et al 2017a, 2017b) have suggested that neither deflagration in its 'standard' form nor DDT could explain Buncefield and some other VCE incidents. They conclude that a new explosion mechanism (the episodic mechanism mentioned above) was needed. In addition, another publication has proposed an alternative multi-stage explosion mechanism (Thomas, 2018).
This confusing message has the potential to misdirect the efforts of both researchers and operators of facilities in proper identification of locations where there is the potential for a severe VCE. The evidence for DDT is reviewed, showing the high level of consistency that has been found between the research and the observations from incidents. Comment is also provided on the recent contrary publications.

2. Review of Buncefield

2.1 Why not just deflagration?

The evidence from two incidents is used to illustrate why deflagration alone does not explain some VCEs. As already identified, the Buncefield incident provides a wealth of evidence. In addition, reference is made to evidence from a VCE at the Indian Oil Corporation's (IOC) Petroleum Oil Lubricants (POL) Terminal at Sanganer in Jaipur, India, which occurred on 29th October 2009 (Johnson, 2012). The evidence that led to the conclusion that deflagration, on its own, was insufficient to explain these incidents was the presence of severe overpressure damage and directional indicators throughout the vapour clouds.
Both the Buncefield and Jaipur incidents showed high levels of overpressure damage throughout the vapour cloud, including damage to vehicles, instrument boxes and oil drums, as illustrated in Figure 1.

Figure 1: Examples of pressure damage at Buncefield (left and centre) and Jaipur (right)

The experimental studies demonstrated that the damage could only be caused by overpressures well in excess of 2 bar. For example, the car damage observed inside the cloud at Buncefield required pressures in excess of 5 bar. In addition, the damage level to a car within a detonated propane-air cloud closely matched the damage observed at Buncefield and Jaipur.

Importantly, all the items at Buncefield and Jaipur were in open areas, well away from any congestion that might sustain a deflagration. Even if a very intense deflagration were postulated in those areas where there was congestion, the decay in the magnitude of the pressure wave would result in incident pressures on the items that would have been well below that required to cause the observed damage.

Directional indicators include such things as bent posts, scoured paintwork, fallen trees, trees scorched on one side and displacement of items laterally. Examples found within the vapour clouds are shown in Figure 2.

Figure 2: Examples of directional indicators from Buncefield (left and centre) and Jaipur

Prior to the involvement of the BMIIB expert group, the directional indicators were misinterpreted. For example, it was thought that the lamppost post bent over in Figure 2 indicated an explosion travelling from right to left. This led to the suggestion of at least three separate explosions in an early BMIIB report. However, modelling conducted by the JIP showed that fast deflagrations and detonations in shallow pancake type clouds imposed a net negative load on items in the cloud due to the long duration reverse flows behind the flame caused by expansion of the combustion products. With this reversal, the directional indicators all pointed to approximately the same location, confirming a consistent, single event explanation.

The indicators were widely spread through the vapour clouds at Buncefield and Jaipur and almost always in open areas without any congestion. This evidence is not consistent with a standard deflagration scenario where directional indicators would only be present in the congested regions.

The BMIIB expert group, and subsequently the JIP, therefore considered several alternatives for the VCE at Buncefield, including DDT, the episodic explosion mechanism and wind generated by buoyancy of fireball. The last of these was dismissed relatively quickly in the JIP as the inward velocities were insufficient to produce the deformation caused to the directional indicators. Additionally, any directional evidence would tend to point towards the centre of the cloud where the buoyancy would be greatest. However, in both Buncefield and Jaipur, the directional indicators pointed toward the corner or close to the edge of the cloud.

Attention in the JIP was focussed on deflagration leading to DDT, however, in case the DDT scenario turned out to be inconsistent with the evidence, the speculative episodic mechanism was also studied experimentally.

2.2 DDT

The DDT hypotheses was assessed against a wide range of evidence (Burgan 2014), including:

- The potential for DDT – experimental studies and review of previous experiments (Harris, 1989).
- Directional indicators within the cloud – assessed in both simulations and experiments.
- Severe damage throughout the vapour cloud – detonation experiments assessing damage.
- Timing of events – constraints on timing from CCTV records and witness statements.
- Duration of positive and negative pressure phases – as determined from Buncefield CCTV records.
- Overpressure Decay from the edge of the cloud – assessed using numerical simulation.

Given the consistency of the DDT scenario with the wide range of evidence, the JIP concluded that the DDT scenario provided the explanation for Buncefield. A similar conclusion was reached for Jaipur.

It is worth noting that since the JIP was completed, other experimental programs (Pekalski 2015, Davis 2017) have shown that DDT can occur soon after the speed of a flame approaches the speed of sound.

2.3 Postulated episodic mechanism

The concept underlying episodic combustion originates from publications in the 1980s (Moore, 1983, 1987), but did not progress due to the lack of experimental evidence. In the episodic form, it is postulated that thermal radiation ignites particulate matter within a zone ahead of the flame. The simultaneous ignition of the particles would then rapidly consume the fuel within a zone ahead of the flame. This then radiates further, repeating the process in an episodic manner, with each rapid combustion generating pressures of several bar.

Attempts have been made to produce explosions by forward thermal radiation in 'open' environments but without success. Dust and hybrid (dust with flammable gas) explosions do occur in different contexts (all involving experiments in confined spaces) and numerous publications are available. However, none discuss the episodic combustion concept.

In addition to the requirement for forward radiation from an explosion flame to ignite particulate matter in a zone ahead of it, critically the explosion mechanism also needs to lift sufficient particulate matter into the atmosphere ahead of the flame across large tracts of widely ranging ground types, including; concrete, asphalt, gravel and soil.

Atkinson et al (2017a) show two images of flame propagation through clean pipes and those contaminated with soot. It is implied that these support the episodic mechanism, but no evidence of ignition ahead of the flame is demonstrated, only increased radiation by the soot after flame arrival.

The Buncefield JIP conducted independent large scale experiments to investigate the episodic mechanism (Burgan 2014). They involved introduction carbon black into a flame venting from a confined explosion, giving the explosion flame a high emissivity. This flame vented into a pre-mixed flammable 10x3x30m vapour cloud with carbon black covering the floor and resting on elevated receptacles which dropped the carbon black into the atmosphere ahead of the flame. The particulate matter was therefore introduced in a manner and a quantity much more favourable to the proposed episodic mechanism than would occur in any real situation.

Despite having favourable conditions, an episodic explosion mechanism was not observed and no ignition ahead of the flame front was occurred. The experiments are not referenced in Atkinson et al (2017a, 2017b).

In addition, investigations have been carried out at laboratory scale to define the conditions required to ignite particulate matter ahead of a flame (Beyrau et al 2013, 2015, Li 2017). The experiments explored the relationship between radiation intensity and material properties using a continuous wave laser. Possible ignition was shown for a range of materials including different carbon blacks and non-reactive powders such as iron and copper oxides. However, the required thermal radiation levels were well above the maximum measured in the JIP large scale tests, even where carbon black was used to increase the flame emissivity.

In summary, there is no experimental evidence that any of the key elements of the mechanism would be present in a real VCE. This lack of empirical evidence makes the proposition speculative at best. Suggesting that it might be the cause of any VCE incident would only be justified if there were sound technical arguments and, critically, if the existing understanding of explosions fails to explain the evidence. However, as already shown, the well-defined and understood process of DDT is consistent with the evidence.

2.4 Recent alternative postulations

Thomas, 2018, proposes that the mechanism for generating pressures in the open car parks at Buncefield involved interaction of shock waves with the combustion front. Whilst such interactions are known to intensify combustion and play a part in the process of DDT, the suggested mechanism is not consistent with the evidence for several reasons, including:

- The publication makes no reference to the Buncefield JIP experimental studies (Burgan 2014). Consequently, it states that the best estimate of the overpressures in the open car parks and within the cloud are 700-1000 mbar. As already discussed, this is incorrect.
- The mechanism would not explain the homogeneous level of damage throughout the vapour cloud.
- The mechanism would not reproduce the directional indicators observed at Buncefield.

It is surprising that the author was not aware of key experimental evidence developed by the JIP. Once this evidence is added, the proposed mechanism fails the test of consistency with the evidence.

3. Evidence used to reject DDT

Atkinson et al 2017a, 2017b make a clear statement that there is evidence that some VCE incidents, including Buncefield and Jaipur, did not involve a DDT or 'standard' deflagrations, justifying the episodic mechanism.

The 'evidence' that leads to the rejection of DDT mostly relates to the damage caused to items within a detonating vapour cloud. For example, it is stated "Light weight steel elements in detonation tests showed characteristic continuously curved shapes" when exposed to detonation pressures. It shows pictures of curved steel angles that had formed theuprights of polythene support frameworks in detonation tests at DNV GL Spadeadam Research and Testing. However, the picture shown was not typical of the damage; in most cases there is no bending of the steel uprights (Johnson et al, 2018). Consequently, the lack of such deformation cannot be used to exclude the possibility of a detonation.

Atkinson et al (2017a) show damage to oil drums from a detonation test, the Jaipur incident and a 2 bar static test. The oil drum from Jaipur is shown on the right of Figure 1. The damage from the detonation test is taken as representative of evidence of a detonation. Comparison is then made between the drum from Jaipur with that from the static test, concluding that the Jaipur drum matched that from the static test, indicative of a strong deflagration, not a detonation. However, a wider view of the area around the Jaipur drum shows significant variability in damage patterns to other drums, most of which are not consistent with the static test.

Figure 3: Damage to oil drums immediately adjacent to that shown in the HSE 2017a (circled)

Atkinson et al (2017a) also fail to show examples of damage to two other Jaipur oil drums, one near full and the other half full. Figure 4 shows these drums and a half full drum from a detonation test. The crushing of the half full oil drum from the test is very similar to the half full drum at Jaipur. It is clear that the response of oil drums varies significantly and that the conclusions drawn regarding exclusion of DDT cannot be sustained.

Figure 4: Recorded damage to oil drums at Jaipur (left and centre) and a drum from a detonation test (right)

Atkinson et al (2017a, 2017b) consider damage to other items including cars, buildings and instrument boxes. Similar comment can be made to those above for all of these items, they do not allow dismissal of DDT.

4. Conclusions

The most important message that needs to be communicated is that there is clear and indisputable evidence of high overpressures being generated throughout flammable vapour clouds in incidents, including in open and uncongested areas.

Review of the evidence from Buncefield and Jaipur has shown:

- The standard interpretation of VCEs being only deflagration in congested process regions is not consistent with the evidence from at least some VCE incidents.
- A scenario of a deflagration leading to DDT and the detonation continuing throughout the vapour cloud has been tested against a wide range of evidence and found to be consistent.
- Evidence interpreted to exclude DDT in some VCEs (Atkinson et al 2017a, 2017b) including Buncefield and Jaipur does not stand up to closer investigation.

There is no need to invoke a postulated new episodic explosion mechanism, particularly given the lack of supporting evidence from experimental studies already carried out to investigate the mechanism. It is also worth emphasising that a recent review of previous large VCEs has found no inconsistency in damage evidence when deflagrative and detonative combustion is considered (Chamberlain et al, 2018).

References

Abdel-Gayed, R. G. and Bradley, D., 1982, The influence of turbulence upon the rate of turbulent burning. Fuel-air explosions (ed. J. H. S. Lee & C. M. Guirao). Montreal: University of Waterloo Press

Atkinson, G., Hall, J., McGillivray, A., 2017a, Review of Vapour Cloud Explosion Incidents, Health and Safety Executive, Research Report RR1113.

Atkinson, G., Cowpe, E., Halliday, J., Painter, D., 2017b, A review of very large vapour cloud explosions: Cloud formation and severity, Journal of Loss Prevention in the Process Industries 48, 367-375.

Beyrau, F., Hadjipanayis, M. A., and Lindstedt, R. P., 2013, Ignition of fuel/air mixtures by radiatively heated particles, Proceedings of the Combustion Institute, Vol: 34, Pages: 2065-2072, ISSN: 1540-7489.

Beyrau, F., Hadjipanayis, M. A., and Lindstedt, R. P., 2015, Time-resolved temperature measurements for inert and reactive particles in explosive atmospheres, Proceedings of the Combustion Institute, Vol: 35, Pages: 2067-2074, ISSN: 1540-7489.

Buncefield Major Incident Investigation Board, 2006, Initial Report to the Health and Safety Commission and the Environment Agency of the investigation into the explosions and fires at the Buncefield oil storage and transfer depot, Hemel Hempstead, on 11 December 2005.

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

Burgan, B.A. 2014, Dispersion & Explosion Characteristics of Large Vapour Clouds, Steel Construction Institute, Document ED024, 2015, available at http://www.fabig.com/video-publications/OtherPublications.

Chamberlain G., Oran E., Pekalski A. 2018, Detonations in industrial vapour cloud explosions, 12th International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions, Kansas City, USA - August 12-17.

Davis S., Pagliaro J., Botwinick D., Engel D., van Wingerden K., Merilo E., Ziemba A., Groethe M., 2017, Large Scale Testing Confirms: A Deflagration to Detonation Transition Needs to be Considered When Facility Siting, 13th Global Congress on Process Safety, San Antonio.

Eyre, J.A. and Harrison, A.J 1987, The Effect of Obstacle Arrays on the Combustion of Large Pre-mixed Gas/Air Clouds, Combustion Science and Technology, 52.

Harris R.J. and Wickens M.J. 1989, Understanding vapour cloud explosions – an experimental study, Institute of Gas Engineers communication 1408.

Health and Safety Executive 2009, Buncefield Explosion Mechanism Phase 1, Research Report RR718.

Johnson, D.M., 2012, Characteristics of the Vapor Cloud Explosion Incident at the IOC Terminal in Jaipur, 29th October 2009, 8th Global Congress on Process Safety, Houston, TX.

Johnson D.M., Pekalski A., Tam, V.H.Y. and Burgan B.A., 2018, The importance of deflagration to detonation transition in explaining major vapour cloud explosion incidents, ISHPMIE XII, Kansas City.

Kuhl, A.L., 1981, First Specialist Meeting (International), The Combustion Institute, Bordeaux, 1981.

Li, T. and Lindstedt, R.P. 2017, Thermal Radiation Induced Ignition of Multipoint Turbulent Explosions, Process Safety and Environmental Protection. (4) 107, 108-122,

Moore, S.R. and Weinberg, F.J. 1983, A study of the role of radiative ignition in the propagation of large explosions, Proc. R. Soc. Lond. A 385, 373–387

Moore, S.R. and Weinberg, F.J. 1987, Further studies of the role of radiative ignition in the propagation of large explosions. Proc. R. Soc. Lond. A 409, 1–20.

Pekalski A., Puttock J., Chynoweth S. 2015, Deflagration to Detonation Transition in a Vapour Cloud Explosion in Open but Congested Space: Large Scale Test, Journal of Loss Prevention in the Process Industries, vol 36, p 365-370.

Thomas, G.O., 2018, Buncefield: A possible alternative multi-stage route to localised pressure generation, Process Safety and Environmental Protection 119, 253-260.