DDT in Highly-congested Environments - the Buncefield Vapour Cloud Explosion

J.S. Puttock and A. Pekalski

Shell Global Solutions (UK)[1], Shell Technology Centre Thornton,
P.O. Box 1, Chester, CH1 3SH, UK

The Buncefield incident in 2005 involved a significant vapour cloud explosion on a site that had little pipe-work congestion and it therefore required investigation to determine how significant overpressures had been generated.

Numerous experiments, since about 1980, have shown that a flame burning through a thin cloud in open space does not accelerate significantly. However, the presence of obstacles (e.g. in petrochemical plant) in the path of the flame can generate turbulence and flame folding. Both enhance the burning rate and can lead to the positive feedback known as the Shchelkin mechanism. Thus, even without confinement, congestion can generate high flame speeds and therefore high pressure. This process has been quantified in hundreds of experiments performed since the 1980s.

At Buncefield, the density of pipework and other obstructions was very low. However, the two lanes adjacent to the depot were bordered by wide verges containing trees and very dense undergrowth. Indeed, the branches constituted a network of flow obstructions considerably denser than that presented by pipes etc. in highly congested process plant. However, this does not explain the damage in open areas; it has been concluded [[1]] that this was caused by a detonation following deflagration to detonation transition (DDT).

DDT in congested areas

The large-scale experimental study described by Harris & Wickens [[2]] provides insight into the processes that may have been involved in the incident. The experiments were carried out in a 3m-square test rig up to 45 m long, containing repeated obstacle arrays. Ignition was either by a low-energy spark or vented explosion. The long flame acceleration path provided in the experiments has similarities with the tree lines at Buncefield. But the congestion in the tree line appears more ‘severe’ than that in the experiments.

The experiments showed that flame acceleration to high speeds was possible with propane- and cyclohexane-air mixtures, leading to a sudden acceleration, the very rapid change starting typically at flame speeds in excess of 600 m/s. The subsequent propagation of this flame, even where no obstacles were present, was at detonation speed and produced characteristic diamond patterns on smoked plates and pressure profiles typical of a detonation. Thus we conclude that DDT had occurred in these experiments.

Lowesmith et al. [[3]] have recently performed experiments in a very similar rig, using methane and methane/hydrogen mixtures and studying the flame acceleration in more detail. They observed DDT in one experiment (2 km/s flame speed, shredded polythene cover). This was with a 50:50 (molar) mixture of methane and hydrogen.

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Correspondence to: jonathan.puttock@shell.com

The experiments conducted by Moen [[4]] were also aimed at assessment of potential for flame acceleration and transition to detonation in simulated industrial plant. A channel 1.8 m x 1.8 m x 15.5 meters was connected to a 0.9 m diameter tube 8 m long. The channel was filled with pipes of 0.22 m or 0.5 m diameter mounted in regular intervals. The sides of the channel were confined. Ignition (maximum 8.4 J) was either at the far end of the tube by one spark or four sparks at the channel end. Acetylene, propane, and hydrogen sulphide in air were tested. Only near-stoichiometric acetylene-air mixture underwent transition to detonation. The other fuels and lean acetylene, showed no significant flame acceleration. The observed flame speed ranged from 25 m/s to 200 m/s and peak overpressure typically less than 50 mbar. The continuous flame acceleration seen in more confined experiments was not observed here. It was concluded that, in order to have damaging overpressure, propane- or hydrogen sulphide-air mixtures must be more congested or be ignited by a stronger ignition mechanism e.g. transient flame jet ignition.

Table 1 summarises these and other relevant experiments.

Buncefield

Attempts at modelling the acceleration of the flame at Buncefield were reported in [[5]] and [[1]]. These used EXSIM [[6]] one of a number of congested-plant explosion CFD models that have been developed and used widely over the last 20 years. The model has been validated against a range of experimental data obtained for simulated petrochemical plant. Applying it to trees and hedgerows, is taking the model outside its validation range. Thus it could not be used as a fully predictive tool for this sort of scenario until we have adequate data obtained from explosion experiments involving dense vegetation. However, it was possible to simulate the vegetation by arrays of pipe elements. The simulation that appears to match the conditions at Buncefield most closely included representation of all scales of the congestion. This led to acceleration to a deflagration flame speed of about 600 m/s in Three Cherry Trees Lane near to the junction with Buncefield Lane. Thus the fact that there was major acceleration of the flame at Buncefield is consistent with current understanding.

Other work has shown that when flame speeds are of the order of sound speed and generate shock waves, then shock reflections appear to initiate a transition to detonation [[7], [8], [9]]. It is likely that this mechanism was involved in the transition observed in the 45m rig. However, it appears that the processes involved have received little attention. With a very complex layout of obstacles, the flame acceleration generates many pressure and shock waves ahead of the flame. In the presence of hundreds of obstacles, it is likely that two such will somewhere intersect and/or hit a solid surface at the same time. Such an event would cause considerable enhancement to pressure and temperature locally, and might create a hot-spot, or series of them, that may develop to detonation. In contrast to the extensive work on DDT inside pipes, such processes have been little studied.

It is for the above reasons that the Buncefield Explosion Mechanism Task Group concluded that DDT was the likely source for the overpressure generation [[1]] (although with a minority

Fuel, mole % in air	Configuration	V_t, [m/s]	P_t, [bar]	Reference
Hydrogen, 24.8 %	30.5 m x 2.4 m x 1.8 m 13% top venting	230	0.65	[[10]]
Hydrogen, 36 & 38 %	10mx3mx3m Open-top lane with obstacles	220, 240	1.0	[[11]]
Acetylene, near stoichiometric	15.5m x 1.8m x 1.8m. Obstacles ID 0.22m	250	2.0	[[12]]
Acetylene, near stoichiometric	15.5m x 1.8m x 1.8m. Obstacles ID 0.5m	400	-	[[12]]
Acetylene 7.8%	15m x 1.8m x 1.8m. Open-top lane with obstacles	375, 435	> 0.15	[[13],[14]]
Cyclohexane, 2.3%	45mx3mx3m. Open-sided lane with obstacles	600	-	[[2]]
Cyclohexane, 2.3%	45mx3mx3m. Open-sided lane with obstacles	600	-	[[2]]
Propane, 4.0 %	45mx3mx3m. Open-sided lane with obstacles	600	-	[[2]]
Propane, 4.0 %	10m radial vessel with obstacles	500	-	[[15]]
50:50 methane/ hydrogen e.r.=1.07	18mx3mx3m. Open-sided lane with obstacles	750	3	[[3]]

Table 1. DDT in fuel-air mixtures by flame acceleration in partly confined and congested configurations. V_t – flame velocity at the transition, P_t- pressure just prior to the transition

opinion suggesting another mechanism). A joint industry project ("Buncefield Phase 2" JIP) is now under way to conduct large-scale field experiments to study some of the processes that may have been involved in the Buncefield explosion.

Other possible mechanisms

A second mechanism that may be able to trigger transition to detonation, transient flame jet ignition, has also been investigated at large scale. Experiments were conducted at Rauffoss in Norway [[16], [17]] and at DRES [[18]]. In the former, the set-up was an 11m long, 0.66m diameter tube, connected to a plastic bag 2m in diameter. Ignition of the fuel/air mixture was by a weak ignition source at the closed end. The end of the tube connected to the plastic bag was open, or partly blocked by circular disc with an orifice plate to resemble worst case situations. The rig at DRES was similar, but larger and filled with flame acceleration obstacles located at regular intervals. In both cases, transition to detonation only occurred with acetylene-air mixtures. No detonation was observed with ethylene, propane, and vinyl chloride monomer. One of the most important parameters identified for successful transition to detonation was flame jet velocity at the exit. A minimum of about 600 m/s is required for initiation of the most sensitive mixtures.

The overall conclusion was that phenomena of transient jet flame transition to detonation in fuel-air mixtures are identical to those in fuel-oxygen mixtures, but much larger scales are needed. The extrapolation of their results to other fuel/air mixtures was reported to require a minimum pipe exit diameter of approximately 2.0m, 3.0m, 9.0m, and 40m, for hydrogen-, ethylene-, propane-, and methane-air, respectively for a successful transition.

The aforementioned experimental results are in conflict with other experimental work where stoichiometric methane- and propane-oxygen mixtures diluted with nitrogen in unconfined conditions resulted in positive initialization of detonation by the interaction of the starting ring vortex and the emerging flame jet via orifices of 50, 101, and 140mm [[19]]. The required minimum orifice diameter was much smaller, seven times the detonation cell width. The importance of the vortex combustion process in the jet initialization to detonation has also been demonstrated in ethylene-oxygen mixtures [[20]].

The chemical time scale, i.e. induction zone that characterize detonation propagation differs significantly between fuel-air and fuel-oxygen mixtures. The flame temperature and expansion ratio also differs; values for hydrocarbon-air mixtures are always less severe.

At Buncefield, it is believed that there was jet-flame ignition of the cloud from the fire-pump building [[1]]. However, (a) the flame velocity from that building would have been lower than that needed to initiate detonation, and (b) the damage evidence shows that extreme flame speeds did not occur in the vicinity. Other possible sources of jet-flame initiation are much smaller than the necessary scales discussed above.

Another suggested mechanism is an episodic combustion process involving the ignition of small leaf particles or debris by forward radiation from the flame [[1]: App. E]. This would involve localised bursts of intense combustion interspersed with periods of slower flame progress, resulting in localised high overpressures but a subsonic average flame speed. The basic mechanism was suggested theoretically in the 1980s by Moore and Weinberg [[21]], but subsequent attempts by several groups experimentally to confirm its viability were unsuccessful. However, the Buncefield Phase 2 JIP will include large-scale experiments to test this hypothesis.

Similar incidents

Ten incidents with similarities to the Buncefield event can be identified. Two examples:

- Port Hudson [[22]]. Possible mechanisms for transition to detonation: congestion due to vegetation or transient flame jet. (The most likely ignition source is a refrigerator motor located in a concrete block warehouse. The concrete warehouse does not rupture easily; so high flame velocities could have been generated).
- The explosion at Brenham, Texas in 1992 [[23]] involved a leak from underground salt-dome storage of LPG. It occurred in early morning, stable, low-wind so that a flat cloud a few metres deep and about a kilometre across developed. It was ignited by a car driving into it. Very high overpressures were developed, levelling the few houses in the vicinity and the blast was heard over 200 km away. The area was partly covered by deciduous forest; density of undergrowth is unknown.

Other similar incidents are discussed by the Buncefield explosion task group [[1]: App. G].

There is clear experimental evidence that detonation can be initiated in highly-congested but unconfined environments and a high probability that this was the cause of the high overpressures in a number of major incidents. The detailed mechanisms involved in this deserve more study.

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