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Detonations and vapor cloud explosions: Why it matters

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A B S T R A C T

The methods used to evaluate the consequences of a vapor cloud explosion assume deflagrations within congested process pipework regions and consequently a significant effort has been invested in developing models to estimate the severity of these deflagrations. Models range from the simpler screening approaches to detailed Computational Fluid Dynamics. There is clear evidence from large scale experiments and incidents that transition from deflagration to detonation is credible and has occurred and it is the contention of this paper that deflagration is only the first stage in many major vapor cloud explosions and that detonation is readily foreseeable. Why does this matter? The methods currently used in the design and location of buildings on and around process sites are based on an incomplete picture of vapor cloud explosions. Whilst this might not have a significant effect in some cases, it is shown that there is the potential to significantly underestimate the explosion hazard. This will result in occupied buildings either being placed in the wrong location or under-designed for the explosion threat, increasing the risks to personnel on these sites.

1. Introduction

The assessment of vapor cloud explosion hazards by industry generally involves the identification of congested process pipework regions, estimation of the pressure generated in these regions and the decay of this pressure with distance from the region. Research dating from more than thirty years ago provided the basis of this approach, showing that a flame propagating through a flammable vapor cloud engulfing such congested regions could accelerate to high speeds and generate potentially damaging pressures. Industry has developed models that can be used to assess the hazards, ranging from the simpler screening approaches to detailed Computational Fluid Dynamics.

While it cannot be denied that such explosions are possible, it is the contention of this paper that many of the major vapor cloud explosion incidents, deflagration is only the first stage of an explosion process that then leads to detonation. Indeed, it is considered that given the conditions of fuel type, fuel concentration and confinement and/or congestion that could result in a severe deflagration, it is difficult to comprehend why detonation would not occur.

The evidence to support this contention comes from a combination of large scale experimental research, review of evidence from vapor cloud explosion incidents and consideration of how significant quantities of any vapor cloud can be involved in the generation of damaging overpressures.

Though the experimental evidence for deflagration to detonation transition can be traced back over thirty years and interpretation of incidents as detonations over forty years, it was only the assessment of the vapor cloud explosions at Buncefield, UK in 2005 and Jaipur, India in 2009 that has allowed confirmation that detonations (full C–J) are a realistic event.

Once this step has been taken however, a realization follows that it actually becomes difficult to justify the absence of detonation in any significant vapor cloud explosion. Additionally, whilst fluctuation in concentration can have significant effects in the pressures generated by a deflagration, such fluctuations have only a minor effect on a detonation if they are within the detonable range. Thus a detonation provides a much simpler means of wide ranging severe pressure damage.

As well as putting forward this contention, this paper considers why the inclusion of detonation in the assessment of vapor cloud explosion hazards matters. In summary, the methods currently used in the design and location of buildings on process sites are based on an incomplete picture of vapor cloud explosions. This might not have a significant effect in some cases; however in others there is the potential to significantly underestimate the explosion hazard. This will result in occupied buildings either being placed in

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the wrong location or under designed for the explosion threat they are exposed to. This will have a direct effect on the risks to personnel on these sites.

2. The evidence

2.1. Incident record

The Buncefield incident in 2005 (Buncefield Major Incident Investigation Board (BMIIB), 2006) provided a considerable amount of evidence related to the effects of a vapor cloud explosion in a large pancake vapor cloud. The evidence included damage to items such as cars, oil drums and instrument boxes within the vapor cloud. In addition, directional indicators in the form of bent posts, scoured paintwork and displaced items were present throughout the vapor cloud, even in large unobstructed areas. Analysis of the evidence combined with modeling studies led to the conclusion that the Buncefield vapor cloud explosion could not have been caused by a deflagration in congested areas alone and had involved a DDT, with the C–J detonation propagating through much of the vapor cloud (Steel Construction Institute, 2009). Simulations reported in this publication showed that the directional indicators were produced by the reverse flow of the combustion products behind the detonation front, which imparted a net negative impulse on objects and scoured paint off the sides of posts opposite to that struck by the detonation front. Whilst this net reverse impulse can also occur in high flame speed deflagrations, this would only be within the congested regions sustaining the deflagration. The directional indicators were however found in open areas, where a deflagration would not be sustained. Only a self-sustaining detonation propagating through these open areas provides an explanation for the indicators in these open areas.

A second similar vapor cloud explosion occurred in Jaipur, India in 2009 (Johnson, 2012). The evidence of severe pressure damage and directional indicators was spread throughout the vapor cloud. Examples of the damage and directional indicators are shown in Fig. 1 and Fig. 2 respectively. The level of damage observed at Jaipur requires pressures of several bar and is consistent with the damage caused by the passage of a detonation. Again, most of these areas had little or no congestion that could sustain a deflagration leading to the conclusion that there had been a DDT, with most of the cloud undergoing detonation.

Looking further back into the incident record, there are two incidents of particular note:

- Port Hudson, Missouri, 1970, in which a propane cloud was ignited in a rural area, generating severe explosion damage (US National Transportation Safety Board, 1971). No pipework congestion was present; however, the cloud engulfed buildings and wooded areas.
- Ufa, Russia, June 4, 1989, in which a propane cloud produced by a pipeline failure was ignited by passing trains (Makhviladze and Yakush, 2002). There were widespread directional indicators throughout the vapor cloud in the form of fallen trees. These were viewed at the time as being due to the wind generated by a rising fireball, but are entirely consistent with the event being caused by a detonation of the cloud.

The Port Hudson incident was reported to involve a detonation of the propane vapor cloud and shared many characteristics with the Buncefield explosion, including the same pattern of directional indicators within the cloud. In an analysis of the Port Hudson incident (Burgess and Zabetakis, 1973) it was stated in relation to the damage inside the Port Hudson cloud, “We think that it is significant that the wind direction was everywhere opposite to the postulated direction of the detonation”. (‘Wind direction’ in this case is taken to be the implied direction of the gas flow associated with the propagating detonation.) These are exactly the same types of directional indicators observed at Buncefield and Jaipur.

It is notable that all of these incidents involved low lying dense vapor clouds spread over a large area with significant parts of the cloud containing no obstacles. This type of cloud will show evidence of detonation much more clearly as:

- High levels of pressure damage throughout the cloud, including the open areas, cannot be explained by deflagrations in the more limited congested areas.
- The mechanism that results in the directional indicators, expansion of combustion products in the opposite direction to the detonation, will be more evident. In fact, if a hemispherical vapor cloud were ignited centrally, the reverse directional indicators would not occur because no reverse flow would be possible.

As a consequence, the fact that clear evidence of detonation is limited to a relatively small number of vapor cloud explosion incidents does not mean that DDT is limited to these incidents. Explosions involving more hemispherical vapor clouds that are largely contained within congested process areas will not have such unequivocal evidence. Secondly, it is likely that investigators would not have appreciated the types of evidence that might occur within the vapor cloud because it is only following the Buncefield incident that there has been a systematic assessment of the effect of detonations.

There is also evidence that the current methods for estimating the overpressures in vapor cloud explosions do not match the damage caused in some major incidents (Bauwens and Dorofeev, 2013). Predictions based on the Primary Explosion Site (PES) tend to under-predict, whilst an averaged whole cloud case matches the incident record better. It is suggested that this failure to match incident data is actually a symptom of detonation occurring of at least some of the vapor cloud.

A final observation is that eyewitnesses to the Buncefield and Port Hudson explosions described a ‘flash’ followed by a large

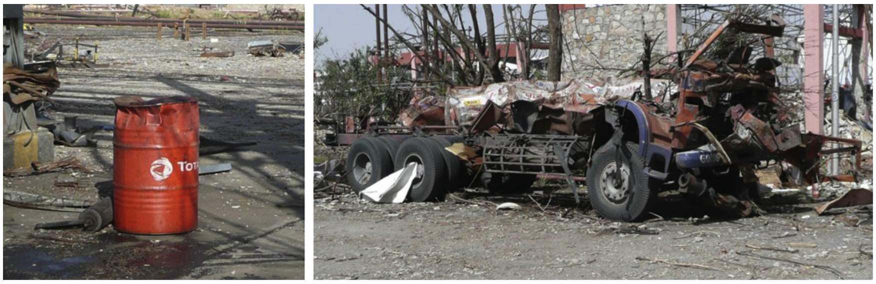

Fig. 1. Pressure Damage at Jaipur.