

VAPOUR CLOUD EXPLOSION AT THE IOC TERMINAL IN JAIPUR

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At approximately 6:10pm on 29th October 2009, a leak of gasoline occurred on the Indian Oil Corporation's (IOC) Petroleum Oil Lubricants Terminal at Jaipur, India. This leak continued for some 75 minutes, when the vapour cloud ignited, resulting in a severe vapour cloud explosion (VCE), eleven fatalities and many tank fires. The sequence of events and cause of the spillage were investigated by an independent Indian committee. However, the VCE in the Jaipur incident shared a number of characteristics with the VCE at the Buncefield terminal in the UK in December 2005. Given these similarities, evidence related to the Jaipur VCE was collected by the author over a three day period at the site during February 2010, at which time much of the evidence on the site was relatively undisturbed. The combination of the evidence from the two incidents, supported by information from a small number of previous incidents, provides both an indication of the VCE potential for dense vapour clouds and the nature of key forensic evidence that is likely to be observed following such events. This evidence is summarised and comment provided on the implications for the assessment of explosion hazards on onshore sites.

1. INTRODUCTION

The vapour cloud explosion (VCE) and fires on the Indian Oil Corporation's (IOC) Petroleum Oil Lubricants Terminal caused eleven fatalities, six on the IOC site and five offsite. The fires continued to burn for eleven days.

The sequence of events and fundamental causes of the incident have been investigated in detail by an independent inquiry committee (IIC) [1]. However, the incident shares a number of characteristics with the Buncefield incident in the UK in December 2005 [2].

The unusual aspect of the Buncefield explosion was that the site had little pipework congestion, normally considered a pre-requisite for vapour cloud explosions. An initial review of the possible explanations for the severe explosion was carried out for the Buncefield Major Incident Investigation Board (BMIIB) by the Explosion Mechanism Advisory Group [3] followed by a more detailed examination as part of a Joint Industry Project.

The conclusion of the Joint Industry Project was that the Buncefield explosion most likely involved flame acceleration within a line of trees and bushes that led to a transition to a detonation, which then propagated through much of the vapour cloud generating high pressures [4]. The project also pointed to other incidents that suggested that the main elements of the Buncefield explosion were not unique to Buncefield.

Given the similarities, at a high level, between the Buncefield and Jaipur incidents, an investigation of the evidence specifically related to the explosion mechanism at Jaipur has been carried out. This assessment complements the overall investigation carried out by the IIC and has been based on evidence obtained during a three day visit to the site by the author on February 8th–10th 2010. At this time, much of the evidence on the site was relatively undisturbed, though as will be seen, restoration work had commenced in one area of the site.

2. OVERVIEW OF THE JAIPUR INCIDENT

2.1 OVERVIEW OF IOC SITE

An overall view of the site before the incident (taken from Google Earth) is shown in Figure 1 (north is approximately towards the top of the figures). Some of the key features of the site are shown on this view. The site measured approximately 750 m East–West and over 600 m North–South.

The pipelines division of IOC occupied an area in the North West corner of the overall site, as shown on Figure 1. The majority of the buildings associated with the main terminal were located in the South West corner of the site, as was the main site entrance. The pipelines division area contained a number of other buildings including a separate control room.

2.2 SEQUENCE OF EVENTS

During the evening of the 29th October 2009, preparations were being made for the transfer of kerosene and gasoline to a neighbouring terminal. At approximately 6:10 pm, during the process of preparing Tank 401-A for pumping, a large leak occurred from a 'Hammer Blind Valve' on the tank outlet. The leak resulted in a jet of gasoline directed upwards from the valve.

The leak continued for some 75 minutes in calm, low wind speed, conditions. The nature of the release is likely to have assisted in the production of vapour and post incident analysis indicates that a flammable vapour cloud appears to have covered much of the IOC site. The IIC estimated that of the order of 1000 Tonnes of gasoline were released from the tank prior to ignition.

The IIC estimated in their report that some 60 million litres of petroleum products were consumed in the subsequent fires on damaged tanks.

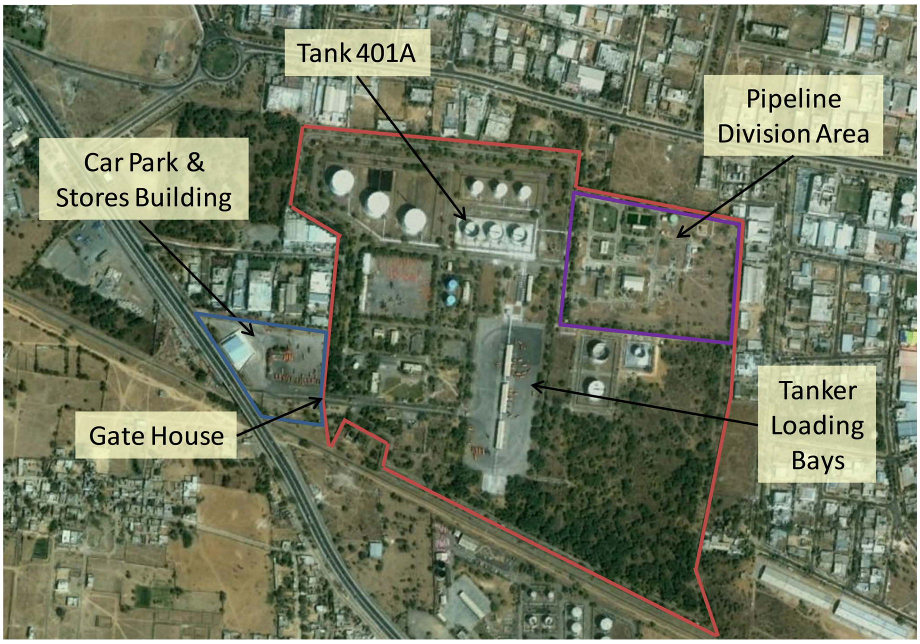

Figure 1. IOC Jaipur site

3. EVIDENCE RELATING TO THE EXPLOSION

The evidence that assisted in the understanding of the Buncefield explosion comprised:

Severe pressure damage to items within the vapour cloud. This included large items such as buildings and cars and smaller items such as oil drums, instrument boxes and engine oil filters.

- Directional indicators, both inside and outside the cloud, including:
  - Posts, stands and trees bent over, broken or collapsed
  - Scouring on one side of posts, steelwork and trees
  - Translation of objects such as pipes
  - Collapse of structures such as walls
- A rapid reduction in the level of pressure damage outside the vapour cloud.

Security video cameras also provided records of the development of the vapour cloud and partial views of the explosion.

The analysis carried out for Buncefield showed that in explosions involving widespread low lying vapour clouds, directional indicators within the flammable vapour cloud suggest flow or net load towards the source of the explosion event, that is, opposite to the direction of propagation of the explosion 'flame'. Outside the flammable cloud, the directional indicators point away from the cloud.

The explanation of this effect is found in the behaviour of the hot combustion products behind the combustion zone. Simulations carried out for the Buncefield Joint Industry Project showed that for both fast deflagrations and detonations passing through a low lying vapour cloud, the net dynamic load is opposite to the direction of propagation of the deflagration or detonation. This is primarily due to the drag forces from the high gas velocities generated by the expansion of the combustion products away from the deflagration or detonation front. These reverse drag forces exceed the initial load imparted by the explosion pressure wave, giving a reverse net load.

The high speed gas flow would also give the scouring observed on trees and paintwork and could translate some objects in the opposite direction to that of the explosion front.

Outside the cloud, the effects of the explosion blast wave dominate and the load on items is away from the explosion source.

One of the objectives of the investigation of the Jaipur explosion carried out by the author was to determine if any of the evidence observed in Buncefield was also present on the Jaipur site.

4. EVIDENCE AT JAIPUR

The IOC site in Jaipur covers an area measuring approximately 750 m east to west and 600 m north to south. It is likely that the vapour cloud covered much of the site was therefore about four times the area of the Buncefield cloud. As a consequence, the considerable amount of evidence observed during the Jaipur site visit in February 2010 is only summarised here, a more detailed description of the observations is provided in [5].

4.1 DATA COLLECTION

The records collected during the site investigation were primarily of overpressure damage and directional indicators.

There were a large number of directional indicators and therefore measurements were taken from a representative selection of items in each area of the site. There was a good degree of consistency in each area of the site. The measurements were made using an electronic compass and recorded on a plot plan of the site, along with a note of the type of indicator. In most cases a photographic record was also taken. Overpressure damage was recorded photographically.

4.2 OVERPRESSURE DAMAGE

The incident on the IOC Jaipur terminal involved widespread severe pressure damage over almost the entire site. This evidence included overpressure damage to buildings, storage tanks, vehicles, steel drums and steel boxes. Examples of the damage observed are given in Figure 2. This shows damaged buildings, steel drums crushed down to their liquid level and a severely damaged road tanker.

Much of this evidence has a close similarity to the evidence observed in the Buncefield incident, and the investigation of that explosion indicated overpressures of at least 200kPa and probably significantly in excess of this level. The evidence from Jaipur indicates that the vapour cloud explosion generated these high overpressures over most of the IOC site.

The level of damage outside the site boundary was more difficult to determine as significant rebuilding work had been carried out. However, the site store building was located outside the main site boundary to the west of the main gate. No repair work had been carried out to the building and it was apparent that the level of damage was significantly less than to the on-site buildings.

The observations indicate that the level of damage on the main site was not consistent with:

- Overpressure generation in one particular area producing a pressure wave that then decays as it propagates away from the source and across the site. The level of damage was too even.
- Overpressures being generated by many confined explosions within buildings around the site. Damage remained severe to equipment well away from buildings.

The even distribution of severe pressure damage across the site is however consistent with pressure generation throughout a vapour cloud that was largely contained within the site boundary wall.

It is notable that the site had little in the way of pipework congestion, though there where areas of trees and bushes, which, as illustrated by the Buncefield incident, can result in flame acceleration and pressure generation. However, the area exhibiting high overpressures included many open regions, without trees, bushes or pipework. In these areas, a deflagration would not be sustained and overpressures would have decayed. The overpressure damage evidence is therefore not consistent with the vapour cloud explosion involving only deflagration.

4.3 DIRECTIONAL INDICATORS

The directional indicator evidence was again very consistent with that observed at Buncefield. Examples of directional indicators are shown in Figure 3.

Figure 2. Examples of Onsite Pressure Damage

Figure 3. Examples of Directional Indicators

The measurements were collated and a summary of the information within the flammable vapour cloud is shown in Figure 4, where the arrows indicate the approximate direction for each area of the site. Many of the indicators were in open areas, which is again inconsistent with the vapour cloud explosion being as a result of a deflagration only as a high pressure deflagration would not be sustained in an open area. They are consistent with a detonation however.

The directional indicators point towards the Pipeline Division area, indicating that it was in this area that any detonation initiated.

Figure 5 shows the detailed directional indicators measured in the Pipeline Division area during the site visit in February (red arrows). Directional indications from two instrument boxes that appear to have been exposed to a directional pressure loading only are shown as blue arrows. In addition, it can be seen that on the east side of the site, some directional indicators point 'outwards', suggesting they were outside the flammable cloud. Also shown are the positions of the tree that did not appear to have suffered severe pressure/flow damage.

There was also an area where a flammable cloud appeared to have been present but where there was no significant pressure generation. This has been marked in yellow on the figure.

Unfortunately, the Pipeline Division was the one area of the site that had been cleared of debris, so much of the evidence had been destroyed. As a consequence the information had to be supplemented by photographic and video material taken before the clearance work was started. Directional indicators taken from this earlier material are shown as yellow arrows.

It seems likely that a flammable cloud was present in the yellow shaded area at the time of the explosion as the trees along the section of the north wall to the east of the green firewater tank were all fire damaged. In addition, there was no particular change in the ground level to in the vicinity of the green firewater tank that would have prevented the vapour cloud from spreading into this area.

Pressure generation in this area would not have happened if it had been burned prior to the main vapour cloud explosion. Two site personnel present when the explosion occurred were interviewed and both stated that they saw flame or light prior to the main explosion. Though it is accepted that the blast wave will take longer to reach someone than the light (which is, to all intents, instantaneous), their description is not inconsistent with ignition occurring a short time prior to the main explosion event. It is worth noting however, that as these personnel had evacuated some 300 m to the west of the site, they had no clear view of the ground within the site due to the presence of the boundary wall.

5. POSSIBLE MECHANISMS FOR TRANSITION TO DETONATION

As already indicated, the overpressure and directional evidence is not consistent with only a deflagration in 'congested' regions. Transition to detonation is the only known explosion mechanism that can provide an explanation for the evidence.

Initiation of a detonation would require high flame speeds and overpressures and it is important to consider how these could have been generated. First however, some comments are provided on the directional indicators in the Pipeline Division area of the site.

5.1 PIPELINE DIVISION DIRECTIONAL INDICATORS

The following points should be noted in relation to the directional indicators and the 'low pressure' region shown in Figure 5:

- Directional indicators are generated by flow from the expanding combustion products behind a detonation front. The interpretation of the directional indicators in Buncefield is based on cylindrically symmetrical propagation of the detonation from one point. As a result of

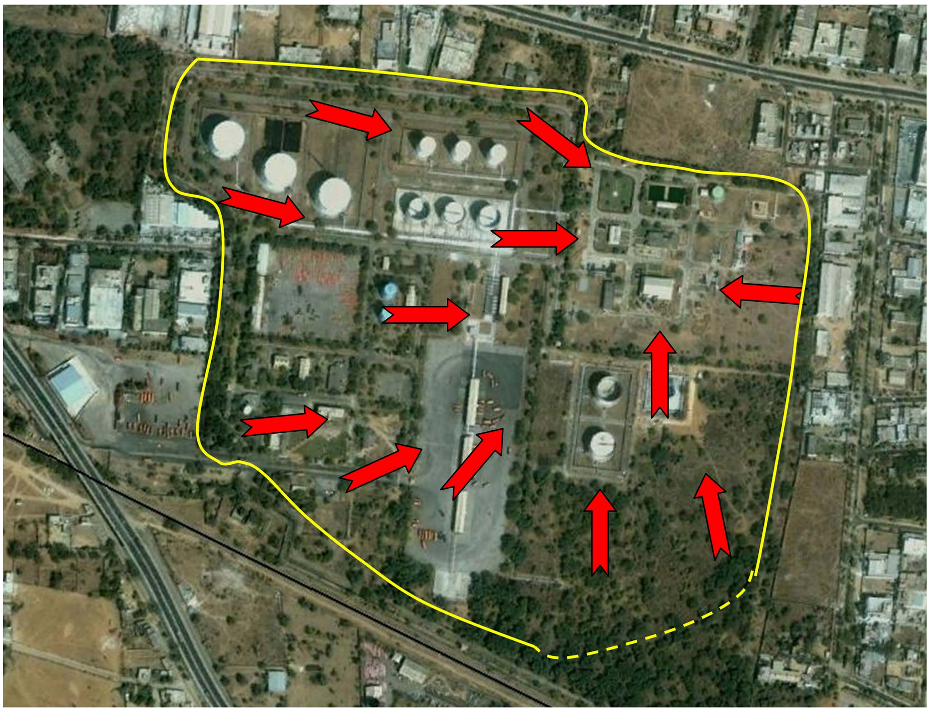

Figure 4. Overview of Directional Indicators and Estimated Cloud Boundary (yellow line)

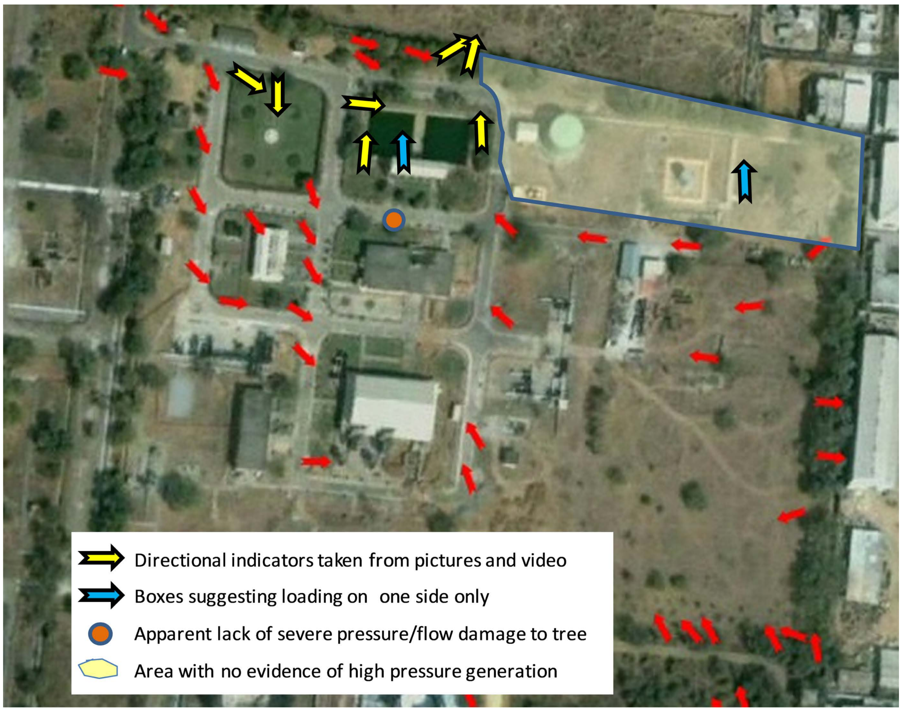

Figure 5. Directional Indicators in the Pipeline Division Area

this symmetry the indicators naturally point back towards the starting point. This is a reasonable approximation at some distance from the point of initiation, however if part of the cloud has been burned prior to detonation, this symmetry does not exist in the near field. (It is worth noting that compared to near laminar flame speeds of a few meters per second; a detonation propagating at close to 2 kilometres per second effectively converts the unburned cloud in the near field to high pressure combustion products almost instantaneously. The burned cloud, which is at atmospheric pressure, is very quickly surrounded by high pressure combustion products.)

- The expansion process would therefore extend into any burned region of the vapour cloud that existed prior to the transition to detonation. Thus some of the directional indicators may have been in burned parts of the cloud but still within reach of the flow generated by the expanding combustion products from a detonation.
- Some of the directional indicators may be due to the effects of a blast wave propagating away from the detonating cloud. In this case, they would point in the direction of the detonation propagation rather than in the opposite direction.

Given these comments, the following considers the possible causes of a transition to detonation.

5.2 DEFLAGRATION TO DETONATION TRANSITION IN TREES

The transition to detonation in the Buncefield incident was considered to have occurred as a result of flame acceleration in a line of dense trees and bushes that was of the order of 100 m long. This generated high flame speeds (probably well in excess of the ambient speed of sound) resulting in a transition to detonation.

It is notable that the line of trees along the north wall of the Pipeline Division area was of a comparable length. However, it was not as deep and there were no dense bushes at a lower level, as were present at Buncefield. In addition, there appears to have been some gaps in the tree line. If a deflagration had accelerated in the tree line from the north east corner of the site, it would have decelerated at each of the gaps.

Though flame acceleration in this tree line as a means of producing the deflagration to detonation transition has some attraction, as it naturally produces the area of burned cloud where there is no evidence of significant pressure generation, a detonation initiating near to the north wall would be inconsistent with many of the directional indicators in the centre of the Pipeline Division area.

Also, unless there was some dense area of trees and bushes in this tree line that has not been evidenced on any of the records of the incident, the author considers it unlikely that the flame speeds required for transition to detonation could be achieved.

5.3 INITIATION BY CONFINED EXPLOSION OR COMBINATION OF CONFINEMENT AND CONGESTION

Another mechanism for generating the high flame speeds is the venting of a confined explosion, particularly if this is combined with the presence of some congestion within or just outside the confinement.

On the basis of the evidence of the directional indicators, the only two confined or confined/congested regions that appear to be in any way consistent with the directional indicators are those in the centre of Figure 5, the building to the North being the Pipeline Division control room and that to the south being the pipeline pump house.

The damage to the control room is shown in Figure 6. Damage to the north side of the building was less severe than that on the south side of the building, where there was complete collapse of the building. The building gives the appearance of having been 'squashed' down on the south side.

There are two comments that can be made regarding the control room:

- It appears to provide a dividing line between high pressure damage to the south and a lower level of damage on the north side. This is also supported by the apparent lack of damage to the tree on the north side of the control room, as indicated on Figure 6.
- The collapse of the roof downwards on the south side does not initially appear consistent with an internal explosion that vented out from the south side building. It might be expected that an internal explosion would have blown the roof upwards and away from the building. However, it is possible that the concrete roof would have had sufficient inertia such that it did not have a chance to move significantly during an internal explosion. If the flame venting from the building then resulted in a transition to detonation, the high external pressure could have pushed the partially failed roof downwards. In the absence of any further evidence, however, though this explanation could be considered to be physically plausible, it must be viewed as speculation.

Figure 6. Control Room in Pipeline Division Area (top picture from north, bottom picture taken from south)

The pipeline pump house had some pipework and structural steel congestion both within the building and outside to the south. However the degree of confinement was less. There was clear evidence of pressure damage within and outside this building, including two oil filters that were crushed in a manner very consistent with damage observed within the Buncefield vapour cloud. However this evidence would be consistent with a detonation passing through the building rather than a detonation being initiated by the explosion in the building.

One possible scenario is for the vapour cloud to have been ignited to the north of the control room and propagated at near laminar speeds towards the control room. If there was a confined explosion in the control room, this could have initiated a detonation in the vapour cloud on the south side, or it could have aided flame propagation towards the pipeline pump house further to the south, with a detonation being initiated by an explosion in this building. The directional indicators would then be produced by a combination of asymmetric propagation of the detonation combined with direct overpressure effects.

Alternatively, the detonation could have been initiated by an explosion in the pipeline pump house. Initiation by an explosion in the control room is probably easier to match with the directional indicators, however there is insufficient evidence available to be able to confirm or rule out either of these scenarios.

6. SUPPORTING EVIDENCE

6.1 EXPERIMENTAL STUDIES

The exact composition of the vapour cloud at Jaipur is not know, but some indication of the potential for detonation can be judged by consideration of large scale experimental studies involving fuels that would have comparable properties in terms of detonability.

The Buncefield Joint Industry Project report describes a series of experiments in which the author was involved where transitions to detonation were observed in propane air and cyclohexane air mixtures [6]. These experiments involved the venting of an explosion from a 9 m long, 3 m square chamber into an external congested region. Transition to detonation occurred within a few metres of flame propagation, showing that this mechanism is at least credible.

Other unpublished experiments carried out using a 9 m long, 4.5 m square chamber examined the effect of external gas clouds and pipework congestion on the pressures generated by vented confined explosions. The experimental arrangement is shown in Figure 7.

These experiments involved variations of parameters such as fuel type, ignition location, vent area, internal and external congestion arrangement. In some of the experiments,

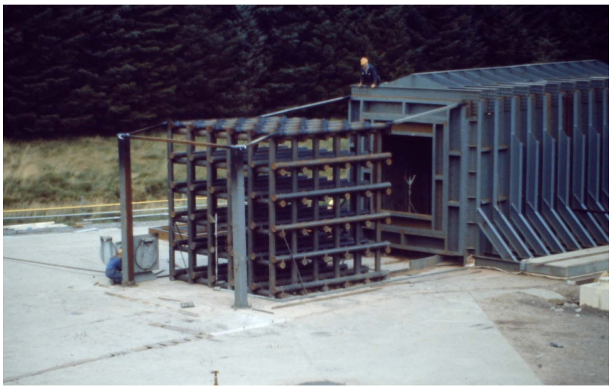

Figure 7. Configuration for Explosion Experiments

there was evidence of transition to detonation. Figure 8 shows images taken from high speed cine of a propane-air experiment where the explosion chamber was fitted with a vent panel with one quarter open area and there was no pipework within the chamber and the external regular pipework region being formed by 168 mm diameter pipes giving an overall volume blockage of 10%. The external region was covered with polythene sheet to allow the propane-air cloud to extend from the chamber into the external congested region.

The images show the flame venting from the chamber into the external gas cloud (left to right then down). As the flame exits from the far side of the congested region, a bright area develops at ground level (fourth picture). An arc shaped front then propagates in the opposite direction from this point in the last two frames.

The interpretation of these images is that the deflagration undergoes a transition to detonation as it propagates out of the congested region and this detonation then travels though unburned mixture that surrounds the congested region. The speed of the circular shaped front in the last two frames is consistent with the expected detonation speeds (1800 m/s).

The two programmes of experimental studies suggest that flame speed between 600 and 700 m/s are sufficient to result in transition to detonation in stoichiometric propane-air clouds and that such flame speeds can be generated relative quickly when confinement and moderate amounts of congestion are combined.

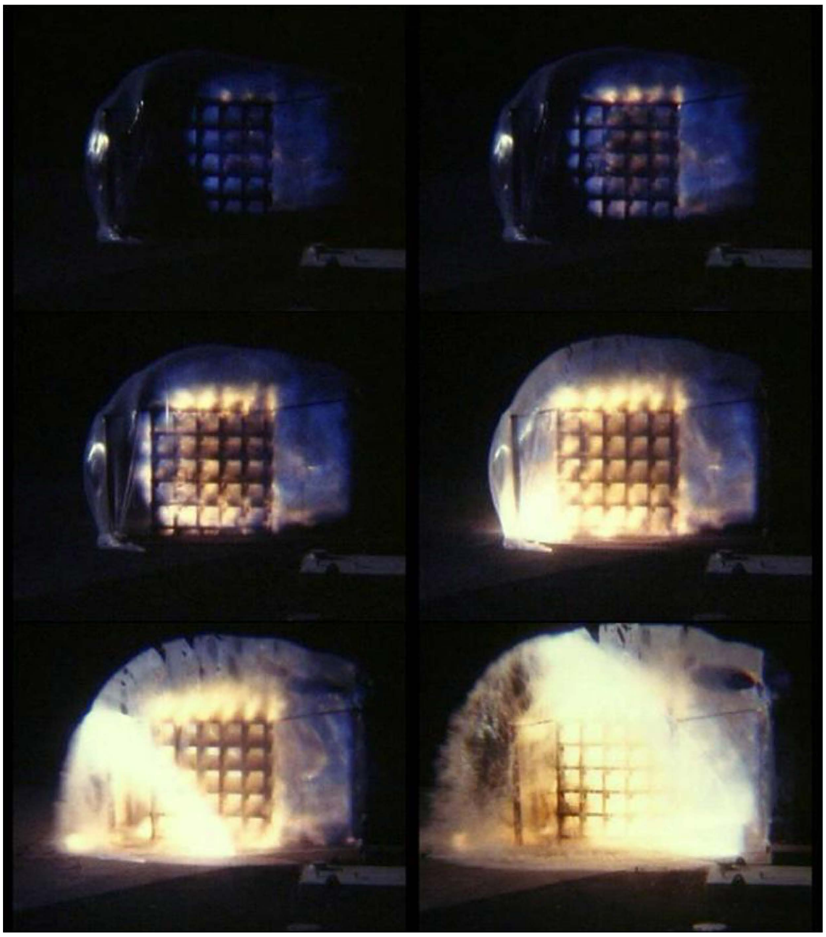

Figure 8. Sequence of Images from High Speed Cine

6.2 PREVIOUS INCIDENTS

In addition to the Jaipur incident, there is at least one other incident that is considered to have involved a detonation following ignition of a cloud within a building. This involved a release from a propane pipeline in a rural area at Port Hudson, Franklin County, Missouri on December 9th 1970 [7].

The investigators of the Port Hudson incident stated that the vapour cloud explosion involved a detonation of the propane cloud and that this had occurred following ignition within a building. The building was described as a 'two storey concrete warehouse', so may have been relatively strong.

In this case there are two possibilities; the explosion in this building directly initiated a detonation or the venting flame interacted with some external obstacles (possibly trees) resulting in flame acceleration and transition to detonation. Though no certainty can be given to any conclusion, eye witnesses reported seeing an initial explosion followed by a much larger one. This does not support a direct initiation of a detonation as the explosion vented from the warehouse as in this case it would not be possible to see two separate events.

One important item of evidence in relation to this event that supports the comparison with Jaipur relates to the directional indicators. The incident report included the following statement within their report on the incident:

> *"We think that it is significant that the wind direction was everywhere opposite to the postulated direction of the detonation"*

7. CONCLUSION

The information collected from a three day site visit in February with assistance from material recorded by others prior to this visit allows the following conclusions to be drawn:

- The evidence obtained from the IOC Jaipur site has a high degree of consistency with the observations made following the Buncefield incident, both in terms of overpressure damage and directional indicators.
- Overpressures in excess of 200 kPa (2barg) were generated across almost the entire site, which is not consistent with the event being caused by an explosion in one area of the site producing a decaying blast wave that then propagated across the site.
- The vapour cloud explosion could not have been caused by a deflagration alone given the widespread presence of high overpressures and directional indicators in open areas.
- The overpressure damage and the directional indicators are consistent with a detonation propagating through a dense vapour cloud that covered almost the entire site.
- The directional indicators point to the source of the detonation being in the Pipeline Division area in the north east corner of the site.
- Unlike Buncefield, the possibility of the detonation occurring as a result of flame acceleration in trees does not appear consistent with the evidence.
- The exact source of the transition to detonation cannot be determined due to the limited evidence from the Pipeline Division area, largely due to the need for restoration work prior to the visit to the site in February 2010. However, the most likely cause of the detonation is flame entering either the Pipeline Area control room or the pipeline pump house, causing a confined or partially confined explosion that then initiated a detonation as it vented from the building.

More generally, it is important to note that the directional and overpressure evidence observed in the Jaipur explosion appears to be a characteristic of vapour cloud explosions in dense low lying clouds where a detonation has been initiated and has been seen in previous incidents.

The significance of this forensic evidence should not be lost to future explosion investigations.

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REFERENCES

1. "Independent Inquiry Committee Report on Indian Oil Terminal Fire at Jaipur on 29th October 2009"; Committee constituted by MoPNG Govt. of India, completed 29th January 2010.
2. BUNCEFIELD MAJOR INCIDENT INVESTIGATION, '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 11th December 2005 Buncefield Major Incident Investigation Board', 13th July 2006
3. Explosion Mechanism Advisory Group report, Buncefield Major Incident Investigation Board, August 2007
4. "Buncefield Explosion Mechanism", http://www.hse.gov.uk/research/rrpdf/rr718.pdf, Phase 1 Report, 2009
5. "Characteristics of the Vapour Cloud Explosion Incident at the IOC Terminal in Jaipur, 29th October 2009", DM Johnson, GL Noble Denton Report 11510, August 2011, available at http://www.fabig.com/go/GL-InvestigationofExplosionEvidence-Jaipur.pdf.
6. "Understanding Vapour Cloud Explosions - An Experimental Study", R.J. Harris and M.J Wickens, Institution of Gas Engineers 55th Autumn Meeting, Communication 1408, 1989, U.K.
7. "Detonation of a flammable cloud following a propane pipeline break", DS Burgess and MG Zabetakis, US Bureau of Mines, Report of investigation 7752, US Department of the Interior, 1973.