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Characteristics of the Vapour Cloud Explosion Incident at the IOC Terminal in Jaipur, 29th October 2009

Not Restricted

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Executive Summary

At approximately 6:10pm on 29th October 2009, a leak of Motor Spirit (petrol/gasoline) occurred on the Indian Oil Corporation's (IOC) Petroleum Oil Lubricants (POL) Terminal at Sanganer in Jaipur, India. This leak continued for some 75 minutes when the vapour cloud ignited, resulting in a severe vapour cloud explosion followed by major fires. The incident caused eleven fatalities, six on the IOC site and five offsite. The fires continued to burn for eleven days.

The incident has been investigated in detail by an independent inquiry committee (IIC) and their report provides a comprehensive description of the sequence of events and fundamental causes of the incident. However, it is apparent from the description provided in this report that the Jaipur incident shares a number of characteristics with an incident that occurred at the Buncefield terminal in the UK in December 2005, in particular, both incidents involved:

- The spillage large quantities of Motor Spirit (MS) over an extended period of time.
- Development of a vapour cloud that spread over a wide area.
- A severe explosion following ignition of the vapour cloud.

Understanding the Buncefield explosion mechanism was an important part of the investigation as the site had little pipework congestion, normally considered a pre-requisite for vapour cloud explosions. As a consequence, an initial review of the possible explanations for the severe explosion in the Buncefield incident was carried out for the Buncefield Major Incident Investigation Board (BMMIB) by the Explosion Mechanism Advisory Group. Subsequent to this, a more detailed examination of the evidence was carried out by a Joint Industry Project.

The conclusion of the Joint Industry Project was that the 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. This conclusion was based on interpretation and analysis of the sequence of events and a number of the effects of the explosion. The project also pointed to other incidents that suggested that the main elements of the Buncefield explosion had not been a unique event.

Given the similarities between the Buncefield and Jaipur incidents, an examination and assessment of the evidence pertaining specifically to the explosion at Jaipur has been carried out. This assessment complements the overall investigation carried out by the independent inquiry committee and has been based on evidence obtained during a three day visit to the site by the author on 8th – 10th February 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.

Summary of Findings and Conclusions

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 200kPa (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 show that the flammable vapour cloud covered almost the entire site. This represents an area approximately four times that in the Buncefield incident.
- As with the Buncefield incident, the overpressure and directional indicator evidence is consistent with a detonation propagating through most of the cloud.
- 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 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. In drawing this conclusion it would seem necessary for some of the directional evidence to be affected by lack of symmetry in the vapour cloud. This does not seem unreasonable.

The exact source of the transition to detonation cannot be determined due to the limited evidence from the Pipeline Division area. This is largely due to the need for restoration work prior to the visit to the site in February 2010. However, if the CCTV records that are in police custody at the time of writing were analysed, there is every chance that they would allow a firm conclusion to be reached.

Contents

1	Introduction	1
1.1	Acknowledgements.....	1
2	Overview of the Jaipur Incident.....	2
2.1	Overview of IOC Site	2
2.2	Events Prior to the Explosion	4
2.3	Events Following Ignition.....	4
3	Explosion Related Evidence from the Jaipur Incident	5
3.1	Data Collection Methodology	5
3.2	Overpressures	6
3.3	Directional Indicators.....	7
3.4	Pipeline Division Area.....	10
3.4.1	Possible mechanisms for transition to detonation.....	11
4	Conclusions	16
5	References	17
Appendix A	Summary of Observations.....	A-1
A.1	Gatehouse and South West Corner	A-1
A.2	Car Park and Stores Building.....	A-7
A.3	Warehouse and Lube Barrel Yard.....	A-9
A.4	Main Tank Area	A-13
A.5	Firewater and Pumping Area.....	A-17
A.6	Tanker Loading Area to South Side of the Site	A-20
A.7	South East Corner of the Site.....	A-26
A.8	Pipeline Division Area.....	A-29
Appendix B	Directional Indicators.....	B-1
Appendix C	Buncefield Incident	C-1
C.1	Overview of the Evidence Considered in Relation to Buncefield	C-1
C.2	Overpressure Damage	C-2
C.2.1	Damage within the cloud.....	C-2
C.2.2	Damage outside the cloud	C-3
C.3	Directional Indicators.....	C-4
C.4	Ignition Location	C-5
C.5	Similarities with Other Incidents.....	C-5

1 Introduction

At approximately 6:10pm on 29th October 2009, a leak of Motor Spirit (petrol/gasoline) occurred on the Indian Oil Corporation's (IOC) Petroleum Oil Lubricants (POL) Terminal at Sanganer in Jaipur, India. This leak continued for some 75 minutes when the vapour cloud ignited, resulting in a severe vapour cloud explosion followed by major fires. The incident caused eleven fatalities, six on the IOC site and five offsite. The fires continued to burn for eleven days.

The incident has been investigated in detail by an independent inquiry committee (IIC) and their report [1] provides a comprehensive description of the sequence of events and fundamental causes of the incident. However, it is apparent from the description provided in this report that the Jaipur incident shares a number of characteristics with an incident that occurred at the Buncefield terminal in the UK in December 2005 [2], in particular, both incidents involved:

- The spillage large quantities of Motor Spirit (MS) over an extended period of time.
- Development of a vapour cloud that spread over a wide area.
- A severe explosion following ignition of the vapour cloud.

Understanding the Buncefield explosion mechanism was important as the site had little pipework congestion, often considered a pre-requisite for vapour cloud explosions. As a consequence, an initial review of the possible explanations for the severe explosion in the Buncefield incident was carried out for the Buncefield Major Incident Investigation Board (BIIIB) by the Explosion Mechanism Advisory Group [3]. Subsequent to this, a more detailed examination of the evidence was carried out by 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]. This conclusion was based on interpretation and analysis of the sequence of events and a number of the effects of the explosion. 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 examination and assessment of the evidence pertaining specifically to the explosion mechanism at Jaipur has been carried out. This assessment complements the overall investigation carried out by the independent inquiry committee and has been based on evidence obtained during a three day visit to the site by the author on 8th – 10th February 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.

1.1 Acknowledgements

The author wishes to acknowledge the kind and helpful support of the IIC in allowing access to the IOC terminal and facilitating the visit, also the help provided by the IOC staff on site. In particular, the author thanks IIC member Sh. S.K. Hazra for his support and assistance.

The author also acknowledges the assistance provided by Professor Vincent Tam in relation to organising the visit and interpretation of the evidence, additional photographic material provided by Dr Bassam Burgan and helpful comments on the interpretation of directional evidence from Dr Graham Atkinson.

It should also be noted that the assessment reported here builds upon the analysis of the Buncefield incident carried out by the technical group of the explosion mechanism Joint Industry Project.

2 Overview of the Jaipur Incident

A brief description of the Jaipur incident is provided here to place the assessment of the explosion mechanism into the overall context of the sequence of events associated with the incident. The details provided in this section have been taken from the final report of the IIC [1].

2.1 Overview of IOC Site

An overall view of the site at a time before the incident, taken from Google Earth, is shown in Figure 1. Some of the key features of the site are shown on this view. A plot plan of the site is given in Figure 2.

The pipelines division of IOC occupied an area in the North West corner of the overall site, as indicated on Figure 1 and Figure 2 (north is approximately towards the top of the figures).



Figure 1: IOC Jaipur site showing site boundary (Red), the Pipeline Division area (Purple) and car park/stores building (Blue)

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.

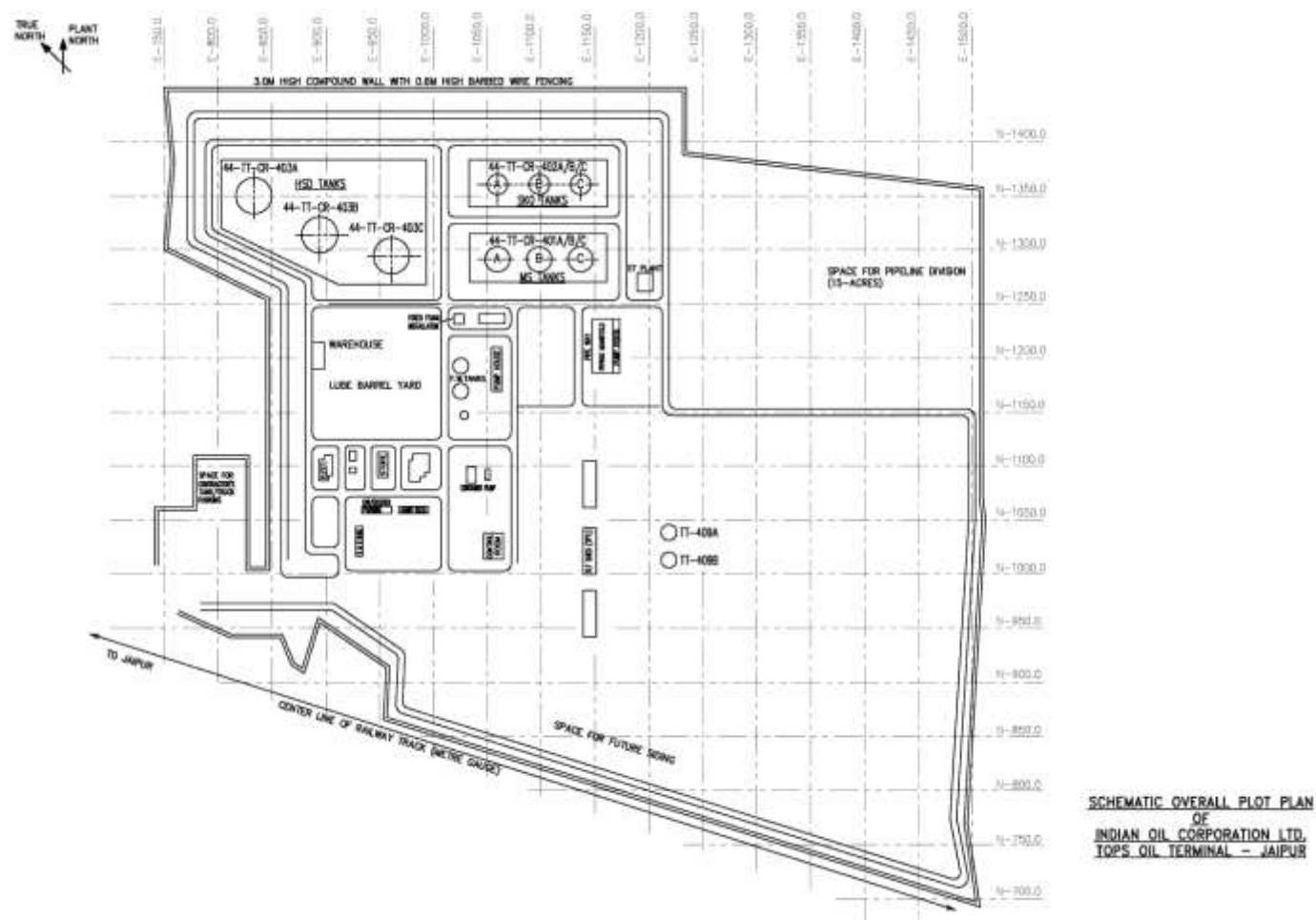


Figure 2: IOC terminal plot plan (provided by the IIC)

2.2 Events Prior to the Explosion

During the evening of the 29th October 2009, preparations were being made for the transfer of Kerosine and Motor Spirit to a neighbouring terminal operated by Bharat Petroleum Corporation Limited (BPCL). At approximately 6:10pm, during the process of preparing the MS tank (Tank 401-A shown on Figure 1 and Figure 2) for pumping, a large leak occurred from a 'Hammer Blind Valve' on the tank outlet. The leak resulted in a jet of MS directed upwards from the valve.

The leak continued for some 75 minutes in calm, low wind speed, conditions. The nature of the release, with an upwards jet of MS, 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 MS were released from the tank.

It is notable that in the case of the Jaipur incident, the vapour cloud was not visible. Personnel on site were aware of the presence of the vapour by its odour. In the Buncefield incident, due to the much lower atmospheric temperatures (about 0C) the vapour cloud was visible as a mist spreading both across the site and offsite.

During this phase of the incident some personnel were able to make their escape from the site, whilst others were either incapacitated by the MS vapours or were caught within the vapour cloud when it ignited.

2.3 Events Following Ignition

As already described, a vapour cloud explosion occurred following ignition. An assessment of the explosion damage is provided in Appendix A. However, the most obvious effect of explosion was damage to many of the tanks on the site resulting in extensive and long duration fires, as illustrated by Figure 3.



Figure 3: Tank Fires following the explosion (picture supplied by Sh. S.K. Hazra)

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

3 Explosion Related Evidence from the Jaipur Incident

This section provides a summary of the evidence observed during the site visit in February 2010. A more detailed description of the observations is provided in Appendix A. Evidence related to directional effects of gas flow and overpressure is particularly important in relation to the interpretation of this incident. Again, this section provides a summary of the evidence; however the actual directional measurements are shown on an image of the site in Appendix B. Finally, in order to place the Jaipur evidence into context, a brief summary of the evidence obtained from Buncefield is provided in Appendix C.

Given the importance of directional indicators, it is worth providing some explanation at this point. They consist of the following types of evidence:

- 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

The analysis carried out for Buncefield showed that in explosions involving widespread low lying vapour clouds, directional indicators within the flammable vapour cloud point towards the source of the explosion event¹, that is, opposite to the direction of propagation of the explosion 'flame'. Outside the flammable cloud, the directional indicators point away from the cloud. Thus a lamppost inside the cloud would be bent inwards, towards the source of an explosion, whereas outside the cloud it would be bent away from the vapour 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 an 'inwards' 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 detonation.

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

3.1 Data Collection Methodology

The author walked around each area of the site making records primarily of overpressure damage and directional indicators.

Overpressure damage was recorded photographically and, where required, the location at which the photograph was taken was noted.

¹ This is not the same as the point of ignition

A 'Konus North 1' electronic compass was used for measurement of directional indicators. In each case, the measurement was taken from the 'upwind' position (i.e. where the flowing gasses appeared to be coming from) with the compass aligned towards the directional indicator. This method had some uncertainties given that judgement was required in determining what the most appropriate 'upwind' location.

Directional measurements were recorded on a plot plan of the site² and notes made of the type of indicator. In most cases a photographic record was also taken.

It should be noted that there were a large number of directional indicators and the approach taken was to take representative measurements in each area of the site. This approach was considered reasonable as there was general consistency between directional indicators in each area of the site.

The IOC site in Jaipur covers an area measuring approximately 700m east to west and 600m north to south. It is likely that the vapour cloud covered much of the site and it was therefore about four times the area of the Buncefield cloud. Given this large area and considerable amount of potentially relevant evidence, the observations are summarised for each area of the site in Appendix A. The quantity of material available does not allow all of the evidence to be presented in this report.

3.2 Overpressures

The incident on the IOC Jaipur terminal involved widespread severe pressure damage over almost the entire site. This evidence included overpressure damage to steel drums, steel boxes, vehicles, tanks and buildings. Examples of the damage observed are shown in Figure 4. This shows steel drums crushed down to their liquid level and a severely damaged road tanker.

Bent steel sheets were observed at a many locations around the site, however, though a photographic record has been taken of some of these, they have not been considered further in this report.

Much of this evidence has a close similarity to the evidence observed in the Buncefield incident. As described in Appendix C, the evidence indicates that the vapour cloud explosion generated overpressures that were in excess of 200kPa over most of the IOC site. The evidence is not consistent with overpressure generation in one particular area producing a pressure wave that decays as it propagates away from the source and across the site.

² No correction was made for the difference between true north and magnetic north as the difference was less than one degree and within the measurement uncertainty.



Figure 4: Examples of Overpressure Damage

It is notable that the site had little in the way of pipework congestion, though there were 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 deflagration³ 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.

3.3 Directional Indicators

The directional indicator evidence was again very consistent with that observed at Buncefield. Examples of directional indicators are shown in Figure 5.

³ In this respect, a deflagration is taken to be the widely recognised process of flame acceleration through a congested region as a result of flame distortion and turbulence generation. High speed flames are known to generate overpressure.



Figure 5: Example of directional indicators

The measurements have been collated and are plotted in detail in Appendix B⁴. A summary of the information within the flammable vapour cloud is shown in Figure 6, where the arrows indicate the approximate direction indicated for each area of the site. The direction of these 'average' arrows is based on the author's judgement⁵.

⁴ Indicators such as collapsed walls which only give a general direction are not included in the appendix.

⁵ Note that the estimated cloud boundary has been based on the combination of the overpressure and directional indicator observations combined with the knowledge that the site wall would tend to retain the cloud within the site. It is possible that the cloud extended offsite in some locations, but time did not permit any examination of this.

Many of the indicators were in open areas, providing evidence inconsistent with the vapour cloud explosion being as a result of a deflagration only. In the case of the Buncefield analysis, it was found that directional indicators could be explained by a detonation propagating through the low lying vapour cloud. Unlike a deflagration, a detonation is self-sustaining and will propagate across the open areas if the vapour cloud concentration is within the detonable limits (which are generally similar to the flammable limits for common hydrocarbons) and as a result directional indicators would be more widespread.

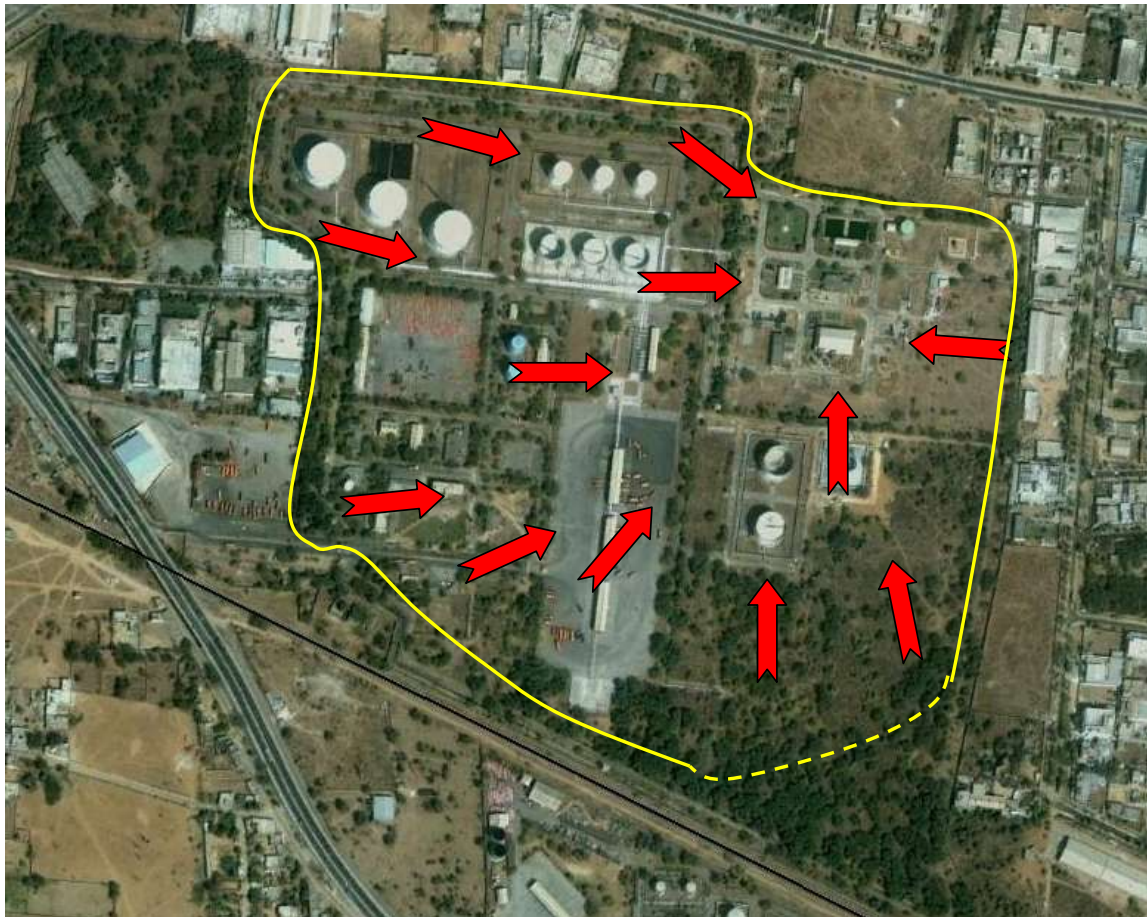


Figure 6: Overview of directional indicators and estimated cloud boundary (yellow line)

If it is assumed that a detonation was initiated in the incident, then the key issue is to try and identify where this initiation occurred. It is evident that all of the directional indicators point towards the Pipeline Division area, indicating that it was in this area that any detonation initiated. In fact, even if some as yet unknown explosion mechanism was proposed to explain the high pressure damage across the site, it would still require a source within this area⁶.

⁶ It is worthy of note that the Buncefield JIP left open the possibility that the high pressures throughout the vapour cloud could have been caused by a, as yet, poorly understood mechanism involving ignition of cellulosic matter by the thermal radiation from the flame. The author believes that, even if possible, it is difficult to see how such a mechanism could be sustained over such a large area as seen in the Jaipur incident with such varying ground conditions. However, even in this unlikely event, there would still be a need for the event to initiate at some point in the Pipeline Division area and much of the discussion provided in this report regarding the directional and overpressure evidence would apply equally to the alternative mechanism.

3.4 Pipeline Division Area

Figure 7 shows the directional indicators measured in the Pipeline Division area during the site visit in February (red arrows). The area where there is evidence of the flammable cloud but there appears to have been no significant pressure generation has been marked in yellow.

Approximate directional indicators interpreted from pictures and video taken in November 2009 are shown as yellow arrows. Similarly, approximate directional indicators corresponding to two boxes that appear to have been exposed to a directional pressure loading are shown as blue arrows (see Figure 65 and Figure 70 in Appendix A). Also shown are the positions of the tree to the north of the control room that does not appear to have suffered severe pressure/flow damage (see Figure 74 in Appendix A).



Figure 7: Directional indicators in the Pipeline Division area and area without apparent pressure generation

The main evidence for the lack of pressure generation in this yellow shaded area comprises:

- The lack of damage to the wall. It remained standing in this area but collapsed further to the west on the north wall and to the south on the east wall.
- The limited damage to the trees to the east of the main firewater pump house.

- The lack of scouring on the lamppost by the green firewater tank.
- The lack of significant pressure damage in the area of the green firewater tank.
- The blue arrow marked in the shaded area is consistent with a pressure wave travelling into the area from an explosion event to the south of the shaded area.

It seems likely that a flammable cloud was present in the 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. However, the possibility that the fire damage occurred as a result of fire propagating along the tree line after the explosion cannot be ruled out. In this scenario, it could be postulated that the vapour cloud in this area was below the lower flammable limit hence explaining the lack of pressure damage.

Another mechanism that would prevent pressure generation in this area is 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 300m 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.

Alternatively, it is possible that there was some thinning of the vapour cloud in this area to an extent that it could not sustain a detonation. However, this does not appear to be consistent with the ground level in this area and the persistence of the detonation throughout the rest of the site.

3.4.1 Possible mechanisms for transition to detonation

The following sections have been written assuming that the cause of the high pressures across the IOC site was the propagation of a detonation through the vapour cloud. The evidence is not consistent with a deflagration in 'congested' regions and detonation provides the only known explosion mechanism that can provide an explanation for the evidence. The sections therefore consider how a detonation might have been initiated in the Pipeline Division area.

Initiation of a detonation would require high flame speeds and overpressures. The evidence in the Pipeline Division area is therefore considered in more detail in the following section in an attempt to identify potential candidates for generating these high flame speeds and overpressures.

3.4.1.1 Deflagration to detonation transition in trees

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

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.

3.4.1.2 Initiation by confined explosion or combination of confinement and congestion

Another mechanism for generating the high flame speeds required to initiate a detonation is the venting of a confined explosion, particularly if this is combined with the presence of some congestion within or just outside the confinement. 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. These experiments involved the venting of an explosion from a 9m long 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.

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 the control room and the pipeline pump house.

The damage to the control room is shown in Figure 8 viewed from the north and south. It can be seen that on the north side, the damage at the west end does not seem that severe, whereas the level of damage appears to increase towards the east end of the building. On the south side of the building however, the level of damage is much greater, with complete collapse of the building having occurred. 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 that can be seen on Figure 8.
- The collapse of the roof downwards on the south side does not 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 8: Control room in Pipeline Division area (top picture from north taken by Dr B. Burgan, bottom picture taken from south by Sh. S.K. Hazra)

The damage to the pipeline pump house is shown in Figure 9. This picture was taken from the south of the building.



Figure 9: Pipeline pump house (picture taken by Sh. S.K. Hazra)

The degree of congestion in this building was greater; however the degree of confinement was less. Pressure damage has clearly been caused to the structure as evidence by the leaning exhaust tower. The evidence given in Appendix A shows that two oil filters were crushed in this building in a manner very consistent with damage observed within the Buncefield vapour cloud. However this would be consistent with a detonation passing through the building just as much as a detonation being initiated by the explosion in the building.

At first examination, the directional indicators and 'low' pressure region do not appear consistent with transition to detonation having occurred as a result of an explosion in one of the two buildings. However, the following points should be noted:

- Directional indicators are generated by flow from the expanding combustion products behind the 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 this symmetry the indicators naturally point back towards the starting point. This is a reasonable approximation in the far field, 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 metres 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 shown in Figure 7 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.
- The cloud may have been inhomogeneous such that the detonation front could not always follow a simple straight propagation path. This may also have resulted in the inability of the detonation to propagate into the trees along the north wall.

- Some of the directional indicators in this area 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.

The effects of these factors are difficult to assess as there are many possibilities. However one possible scenario is for the vapour cloud 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.

The 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 these and probably other scenarios.

It should be noted that it is believed that CCTV records of the incident exist. These are currently in the possession of the police. If the records are analysed, they stand a very good chance of solving the final parts of this puzzle.

4 Conclusions

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 200kPa (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 show that the flammable vapour cloud covered almost the entire site. This represents an area approximately four times that in the Buncefield incident.
- As with the Buncefield incident, the overpressure and directional indicator evidence is consistent with a detonation propagating through most of the cloud.
- 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 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. In drawing this conclusion it would seem necessary for some of the directional evidence to be affected by lack of symmetry in the vapour cloud. This does not seem unreasonable.

The exact source of the transition to detonation cannot be determined due to the limited evidence from the Pipeline Division area. This is largely due to the need for restoration work prior to the visit to the site in February 2010. However, if the CCTV records that are in police custody at the time of writing were analysed, there is every chance that they would allow a firm conclusion to be reached.

5 References

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- [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 Phase 1, <http://www.hse.gov.uk/research/rrpdf/rr718.pdf>, 2009
- [5] 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.
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A.1 Gatehouse and South West Corner

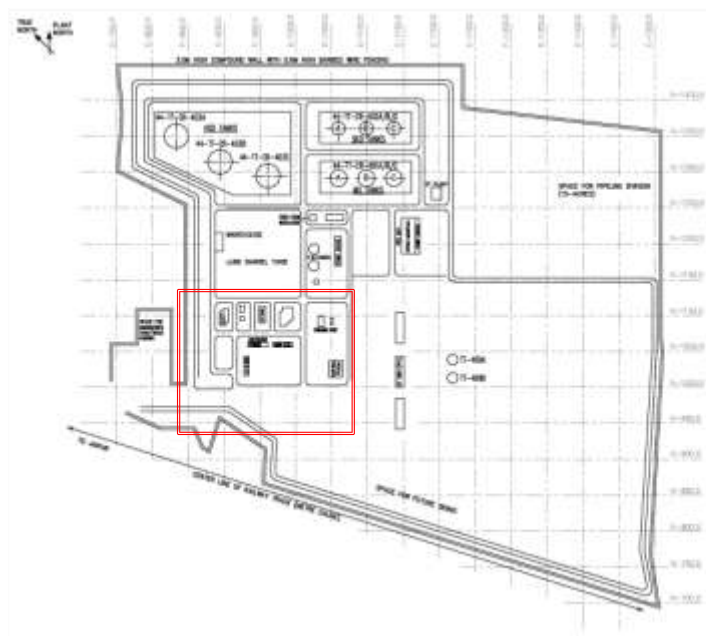


Figure 10: Area of the site being considered

There was considerable and relatively consistent damage to the site buildings in this area. This is illustrated in Figure 11, which shows two of the buildings in this area of the site. In general the concrete frames of these buildings had remained intact but the infill brickwork had often collapsed. However some buildings had suffered structural collapse.

Damage to the gatehouse appeared to be less than that to the site buildings. This will be referred to later when the external car park area is described.



Figure 11: Damage to buildings including the Administration Building (top left) and the Business Continuity Building (top right)

Damage to steel boxes was also evident, as illustrated in Figure 12. The larger box in this figure has been deformed rather than crushed. It is also notable that the whole box and supports are leaning over. This directional indicator was consistent with others in the area, pointing towards the east of the site.



Figure 12: Damage to boxes

The picture on the right of Figure 12 shows a smaller box fitted to a lamppost. Similar boxes were present on many lampposts around the site. The level of damage to the boxes was variable but the crushing damage was generally greatest on the front face. The sides and rear of the boxes tended to have less pronounced deformation inwards. It is notable that the front face on this particular box was a separate plate

fixed to box and may well have been weaker than the other sides. Other boxes had front faces similar to the rest of the box.

Damage to a number of motor vehicles was evident. As illustrated in Figure 13, damage was observed to a van (top left), a road tanker (top right), a car (bottom left) and a motor cycle (bottom right). It should be noted that the car had been in a car park where the concrete roof had collapsed, consistent with the flattening of the car. In all cases the level of damage was severe, with body panels being crushed or torn off. The tank⁷ on the road tanker had been crushed by the explosion, as had the tank on the motor cycle.



Figure 13: Examples of vehicle damage in south west area of the site

A second road tanker had been parked in this area at the time of the explosion and in this case the tank was not only crushed but also thrown off the frame of the tanker, as shown in Figure 14.

⁷ It is understood that the tank was empty at the time of the explosion.



Figure 14: Road tanker with tank displaced and crushed

A tank in this area showed crushing above what is presumed to be the liquid level, Figure 15, which also shows a damaged steel drum.



Figure 15: Crushing of tank and steel drum

Directional indicators were widespread in this area. They comprised uprooted or broken trees and scouring on trees and lampposts.

Figure 16 shows examples of directional indicators provided by trees. The lower left-hand picture shows distinct scouring on the right hand (westerly) side of the tree trunks. This type of scouring was evident on almost all of the trees in the area.

The lower right hand picture in Figure 16 shows a snapped branch pointing to the east of the site. The red roof of the gatehouse and the west wall of the site can be seen in the background of this picture, indicating that, close to the south west corner of the site, directional indicators were pointing to the east. (It should be noted that damage to the boundary wall around the full site had been repaired prior to the site visit in February.) Moving further east through the area, the directional indicators started to point more to the north east.



Figure 16: Directional indicators provided by trees

One additional item of evidence found within this area is worthy of mention, if not conclusive in itself. This relates to items of broken fibreglass sheet that were found in the debris at the south end of the Business Continuity building, which is the first building into the site from the gatehouse.

Personnel onsite confirmed that the fibreglass sheet had been mounted on a frame to provide a shade at the south end of the building, shown in Figure 17.



Figure 17: South end of the Business Continuity building

The fibreglass sheet had been broken up into many pieces and although some were irregular in shape, there was probably as many that were in near diamond or partial diamond shapes, as shown in Figure 18.



Figure 18: Broken pieces of the fibreglass sheet

Diamond shapes are a characteristic of a detonation as it involves complex interactions of shock waves that can show diamond type patterns. One means of carrying out measurements of detonations in gas mixtures is to place a smoked plate into the mixture. The shock waves in the detonation front will mark out diamond shaped detonation cells on the smoked plate. The author also has experience of polythene sheets used to cover large scale gas-air clouds being shredded into diamond shaped pieces by a detonation.

One particular example of the fibreglass is shown in Figure 19 and it is notable that the irregular edge (top right) has a fracture running through the fibreglass from the two corners. Using the line of this fracture forms a full diamond shape. The rule alongside, shows that the edges of the diamond are approximately 70-80mm in length, with the long axis of the shape being about 120mm in length. These dimensions are not inconsistent with the detonation cell size for a pentane air mixture. As the MS was primarily pentane and hexane [1], the vapour cloud probably contained a relatively high proportion of pentane.

This piece of fibreglass was retained to allow further examination if required.



Figure 19: Single piece of diamond shaped fibreglass sheet (note fracture line along irregular edge)

A.2 Car Park and Stores Building

The car park was located to the west of the gatehouse, outside the boundary wall of the site, with the stores building being to the west end of this. The general location is shown on Figure 20.

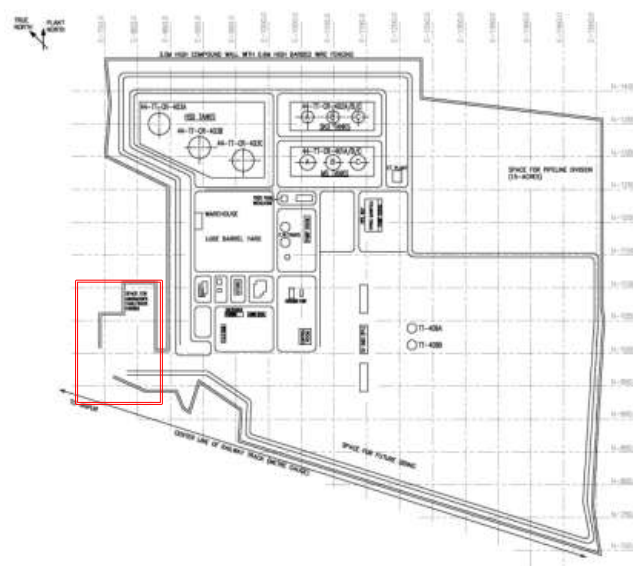


Figure 20: Location of car park and stores building

A CCTV camera tower in the north east corner of the car park and adjacent to the site wall had collapsed to the west as shown in Figure 16. This contrasted with directional indicators on the inside of the wall, which pointed to the east. Comparison with Buncefield suggests that the edge of the flammable (or detonable) cloud extended to a point close to the south end of the west boundary wall but not beyond it.



Figure 21: Collapsed CCTV tower and debris covering the car park

The figure also shows that the car park was covered with debris from trees, comprising mainly twigs. Site personnel confirmed that this was a result of the incident. Prior to the incident, the car park had been clear.

The stores building was located at the west end of the car park, as shown on Figure 1. The building was approximately 130 metres west from the nearest point on the site boundary wall.

The level of damage viewed from the outside appeared relatively minor with roller shutter doors and windows on the east facing side having been blown in. However, from the inside it could be seen that the east end of the roof had collapsed, having pulled away from the east wall. This is illustrated in the top right hand picture in Figure 22.

The lower pictures in Figure 22 also show that the roof beams and main support trusses had suffered deformation as a result of the explosion load on the roof.

It was also observed that the windows at the west end of the building had been blown out and that internal windows in an office area at the north east corner of the building had also failed.

Though this building had been damaged, the scale of damage was much less than that observed to buildings just inside the site boundary. This would be consistent with rapid reduction in the overpressures from the edge of the flammable cloud (which, as discussed, the evidence suggests was close to the boundary wall). This rapid decay would also explain the apparent lower level of damage to the site gatehouse, which appears to have been very close to the edge of the cloud.



Figure 22: Damage to the Stores building

A.3 Warehouse and Lube Barrel Yard

The warehouse and lube barrel yard were located approximately half way up the west side of the site, as shown in Figure 23. The warehouse was used for storing and filling steel drums and the lube barrel yard, to the east of the warehouse, was a general laydown area for steel drums and other equipment. At the north end of the warehouse, there had been a covered but open sided area used for storage.

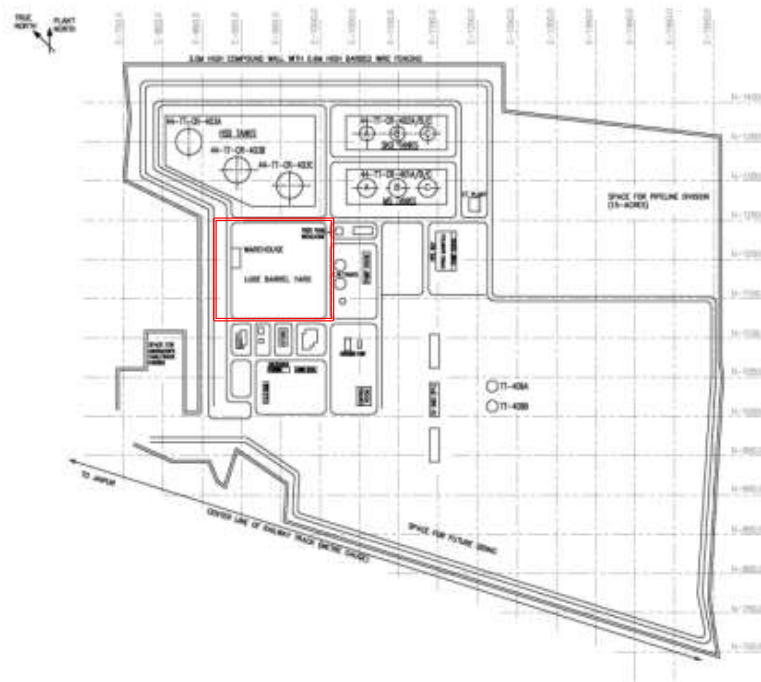


Figure 23: Location of the warehouse and the lube barrel yard

The warehouse had suffered both explosion and fire damage in the incident, as illustrated in Figure 24. Debris from the brick infill on the east side of the building had fallen outwards, possibly indicating an explosion within the building. A number of steel drums on the open loading bay showed clear evidence of crushing down to the liquid level, just as observed in the Buncefield explosion. These drums are shown in the right hand picture in Figure 24.

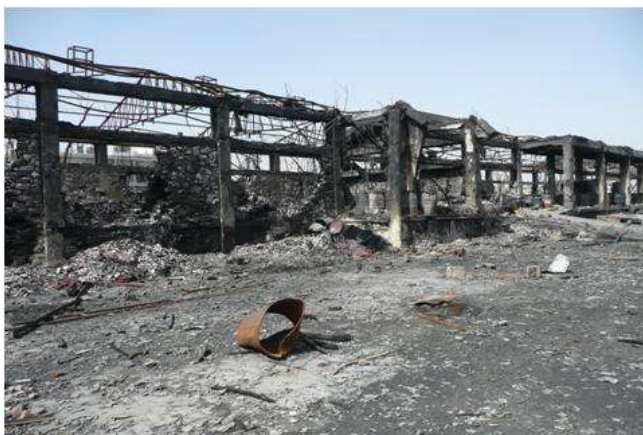


Figure 24: Fire and explosion damage to the warehouse and crushed drums on loading bay

The covered area to the north of the warehouse was used for storage of steel drums, cylinders and other equipment. It can be seen in Figure 25 that in this area the steel drums also showed evidence of crushing at the top, extending down to the liquid level.



Figure 25: Covered storage area to the north of the warehouse

Other equipment stored in this area included electric motors, pumps and cylinders, which can be seen in Figure 26. This equipment showed no evidence of pressure damage, though a steel box in this area (centre of left hand picture) showed clear evidence of pressure damage.



Figure 26: Equipment in covered area

It seems likely that absence of apparent pressure damage to the cylinders, motors and pumps was due to their greater strength compared to the drums and the steel box.

It is also worth noting that directional indicators are also shown in this figure. This is most clearly seen on steel column on the very left of the figure, which shows grey paintwork on the side but rusting on the rear (western) face where the paint has been scoured off. This is consistent with a flow in an easterly direction.

Figure 27 shows the rear (west side) of the warehouse viewed from the south end. It can be seen that a single storey building at the south end of the warehouse has collapsed and that some tree branches have broken in a westerly direction. A steel box directly behind the building showed pressure damage but was leaning slightly in an easterly direction (see inset picture taken from a different angle). This suggests that the edge of the flammable vapour cloud may not have extended to the site boundary behind (to the west of) the warehouse, but had only reached as far as the road that ran behind the warehouse.



Figure 27: View showing the rear side and south end of the warehouse

It was notable that most of the brick infill for the rear wall of the warehouse was still in place.

The lube barrel yard had contained steel drums containing lube oil, pipes and other general equipment, as shown in Figure 28.



Figure 28: Lube barrel yard (left hand picture taken by Dr B. Burgan)

The steel drums had mostly been on their sides and exhibited differing degrees of crushing damage. The pipes shown in the right hand picture of Figure 28 were located at the east end of the lube barrel yard and had been displaced to the east (left), with one pipe (out of picture) ending up on the other side of the road that ran along the east side of the lube barrel yard.

A.4 Main Tank Area

The main tank area was located on the north side of the site running from the west side of the site up to the west side of the Pipeline Division area as shown in Figure 29.

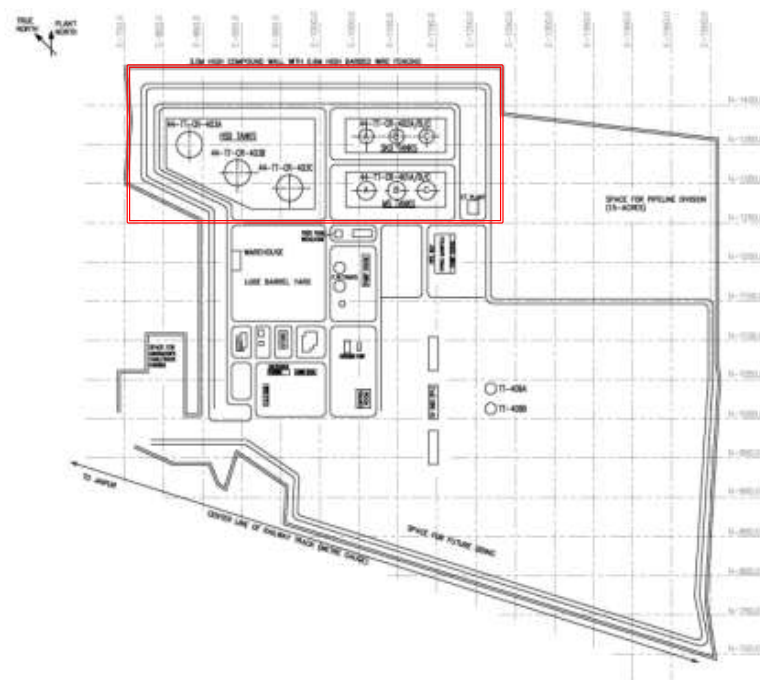


Figure 29: Location of main tank area

There were nine storage tanks in this area, 401 A/B/C, 402 A/B/C and 403 A/B/C. All of the tanks had been damaged by fire and as there was little other equipment in the bund areas, most of the evidence related to the explosion comes from the trees that round the north west corner and along the north side of the site. These trees generally provided very consistent directional evidence, with broken branches and uprooted trees pointing in an easterly direction, as shown in Figure 30. The amount of this evidence was considerable along the north side of the site. In addition these trees generally showed scouring consistent with gas flow in an easterly direction (note that some trees with particularly dark and corrugated bark did not appear as susceptible to the scouring or the scouring was not as evident).



Figure 30: Directional indication provided by trees in the main tank area

The only area where the directional evidence provided by the trees changed was close to the north end of the west boundary wall, particularly in the north west corner, as shown in Figure 31. It is also notable that the guard tower at this location was relatively undamaged.



Figure 31: Branches broken to the west in the north west corner of the site (viewed south west)

This suggests again that the flammable cloud did not quite reach the west boundary wall and particularly did not reach the north west corner.

Other evidence observed in this area included damaged boxes, crushed drums, damaged walls and displaced pipes. This evidence is shown in Figure 32.

Figure 32 (a) and (b) show damaged steel boxes to the north of Tank 403B and at the north east corner of the bund around Tanks 403 A/B/C. These show consistent damage to other similar boxes on site and the one in Figure 32 (a) has also been displaced towards the east.

Figure 32 (c) shows steel drums that have been both crushed and heat affected. These were also to the north of Tank 403B, adjacent to the steel box in Figure 32 (a).

Figure 32 (d) shows the west wall of the bund around Tanks 402 A/B/C. This wall had collapsed towards the east, as had parts of other bund walls that ran north south.

Figure 32 (e) shows damaged pipe retainers on the east side of a firewater pipe running north south. Figure 32 (f) shows damage to the north wall of the bund for Tanks 403 A/B/C due to the easterly displacement of the firewater pipe leading to Tank 403C.



Figure 32: Other evidence in the main tank area

Also notable in this area was a firewater pipe that had been displaced to the west, as shown in Figure 33. Although this appears to be inconsistent with other evidence in the area, it should be noted that the pipe is only restrained on the east side. It is possible that the pipe was loaded in an easterly direction and when this load was removed, it bounced back and ended up displaced in a westerly direction.

Finally for this area, the guard tower located about half way along the north wall (where the boundary kinks in slightly) suffered complete collapse, as shown in Figure 34. (Again it should be noted that the northern boundary wall had been rebuilt prior to the site visit in February.



Figure 33: Displacement of firewater pipe to the west



Figure 34: Collapsed guard tower on north wall

A.5 Firewater and Pumping Area

The main firewater tanks, the firewater pumps and the main product pumps were located in the centre of the site, as shown in Figure 35.

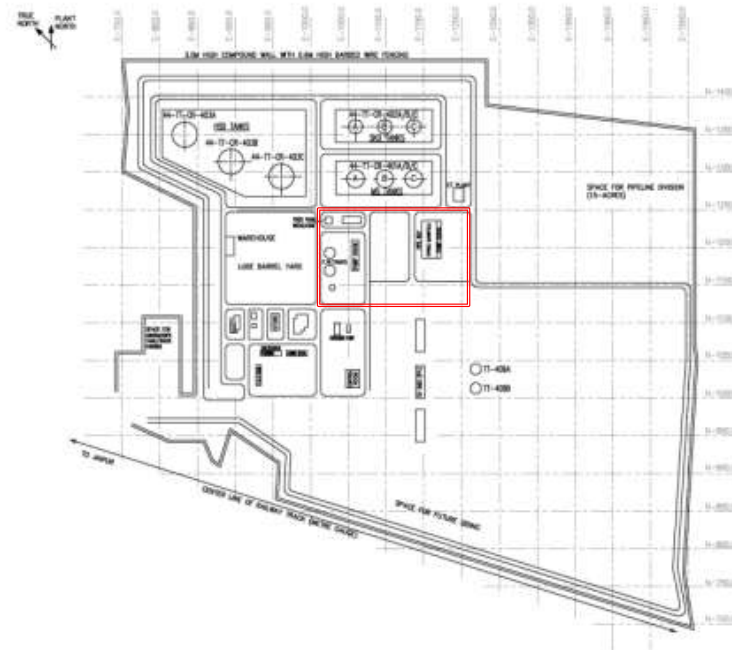


Figure 35: Area with firewater tanks, firewater pumps and main product pumps

The two blue firewater tanks were the most prominent feature of the site. At the time of the explosion, one of these tanks was near full and the other was empty and open to atmosphere to allow maintenance.



Figure 36: Firewater Tanks viewed from slightly west of south (left) and south east (right) (left picture taken by Dr B. Burgan)

Figure 36 shows two views of the tanks. The tank in the foreground in the left hand picture and on the left in the right hand picture was the empty tank. The roof had blown off the empty tank, landing to the east of the tank. This is most likely due to flammable mixture being present inside the tank as it was open to the atmosphere at the time of the incident.



Figure 37: Firewater tanks viewed from south west

It can be seen from Figure 37 that the empty tank, in the foreground, also suffered crushing damage that did not occur on the full tank. This figure also shows directional indicators in the form of bushes that have fallen over pointing in an easterly direction.

Other directional indicators were present in this area, as illustrated by the pictures in Figure 38. This shows a lamppost leaning to the east, scouring on a lamppost and box and a collapsed CCTV tower. In all cases (not just those shown in this figure) the indicators pointed in an easterly direction.

The firewater pump station was located to the east of the firewater tanks and the main product pump station to the east of the firewater pump station. These two buildings are shown in Figure 39 along with a collapsed CCTV tower located at the south of the main product pump building.

The brick infill on the east wall of both buildings had fallen outwards (in an easterly direction). The CCTV tower had also collapsed in an easterly direction. No significant damage was apparent to the equipment within the two buildings. The main product pump station had suffered some fire damage, probably as a result of spillage of product.



Figure 38: Directional indicators in vicinity of the firewater tanks



Figure 39: Damage to the firewater building (top left), the main product pump station (bottom left) and a collapsed CCTV tower at the south end of the main product pump station (right)

A.6 Tanker Loading Area to South Side of the Site

The tanker loading area was located to the south of the centre of the site, as shown in Figure 40. An area of trees was present from the south end of the tanker loading bay through to the road that ran along the southern boundary of site.

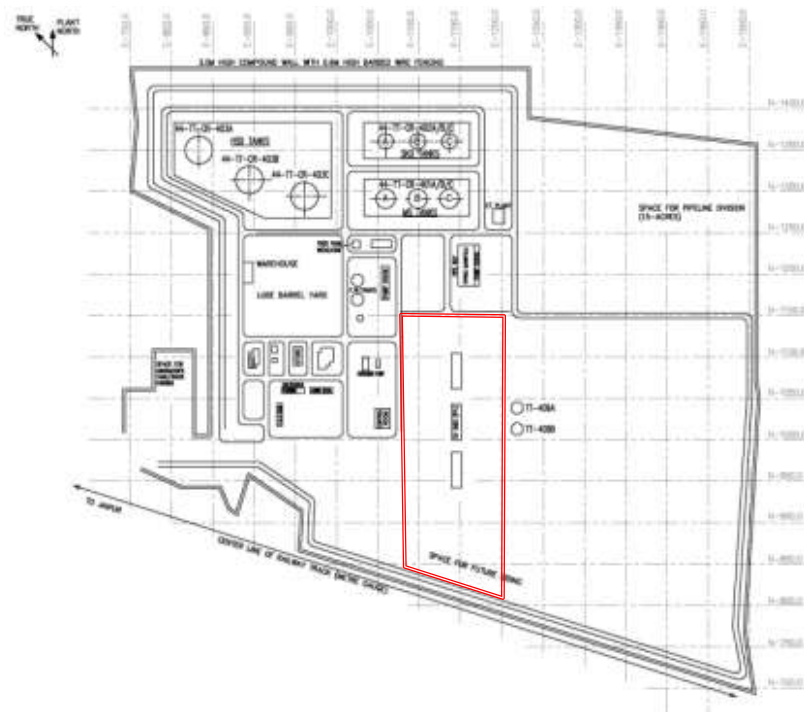


Figure 40: Location of tanker loading bay and area of trees leading to the southern boundary

The tanker loading area consisted of three linked gantries aligned approximately north south and within an open area some 250m long and 100m wide.

Figure 41 shows a satellite view of the tanker loading area (aligned to site north). Its relationship to the main firewater tanks and tanks 409 A/B/C can be seen on this figure. The tanker loading area was the largest area on the site completely devoid of trees and bushes. Site personnel stated that the open area around the gantries would have been kept clear of detritus.

At the time of the incident there were no tankers in the loading area.



Figure 41: Tanker loading area

The tanker loading gantries showed evidence of bulk overpressure loading. Figure 42 shows that the gantry had been displaced slightly to the north.



Figure 42: Displacement of the tanker loading gantry (viewed from the west)

Evidence of overpressure within the tanker loading gantry was also evident. For example, two steel drums were located under the gantry. Figure 43 shows that both of these drums had been crushed down to their liquid level.



Figure 43: Steel drums under the loading gantry

Directional indicators within the loading gantry were provided by paint scoured off the southern faces of the steel structure, which had then rusted, as shown in Figure 44 (left and bottom right pictures).



Figure 44: Directional indicators in loading gantry

The top right picture in Figure 44 shows steel sheet wrapped around one of the gantry supports. In all the instances, the directional indicators suggested flow that was towards east of north.

Pipework to and from the north and south ends of the gantries had fallen off its stands, as shown in Figure 45. The pipework at the north end had fallen to the east side of the supports, whilst the pipework at the south end had fallen either side of the supports.



Figure 45: Pipework at north (left) and south (right) ends of the tanker loading gantries

Directional indicators were present on this pipework and the supports in the form of scoured paintwork allowing the steel to rust.



Figure 46: Directional indicators on pipes and supports at the north (left) and south (right) of the tanker loading gantries

At the north end, the scouring suggested a more north easterly direction, whereas at the south end, the indicators scouring was suggesting a more northerly direction.

In addition to the tanker loading gantries, the area also contained six fire monitors, with three down each side. These fire monitors were positioned about half way between the gantry and the edge of the open tanker loading area. Figure 47 shows two examples of the fire hydrants. Scouring of the paintwork had occurred on all six of the fire hydrants (and can be seen as a red colour on the yellow pipe on the lower picture). Again the scouring indicated a flow direction to the east of north.



Figure 47: Fire hydrants adjacent to the tanker loading gantries.

Finally for this area of the site, there was a small area of trees to the south of the tanker loading area. Figure 48 shows the beginning of this area, where directional evidence, consisting of leaning bushes and scouring, indicated a northerly flow direction (top picture). However closer to the southern edge of this area,

there was evidence of branches having broken in a southerly direction (lower picture). This suggests that the vapour cloud reached down to the south end of the tanker loading area and extended to some degree into the area of trees. However it does not appear to have extended all the way through this area to the southern site boundary.



Figure 48: Area of trees to the south of the tanker loading area

A.7 South East Corner of the Site

The south east corner of the site contained three product tanks (409 A/B/C), not two as shown on the plot plan. Other than these tanks, the area was open land with areas of trees and bushes. The location is shown in Figure 49.

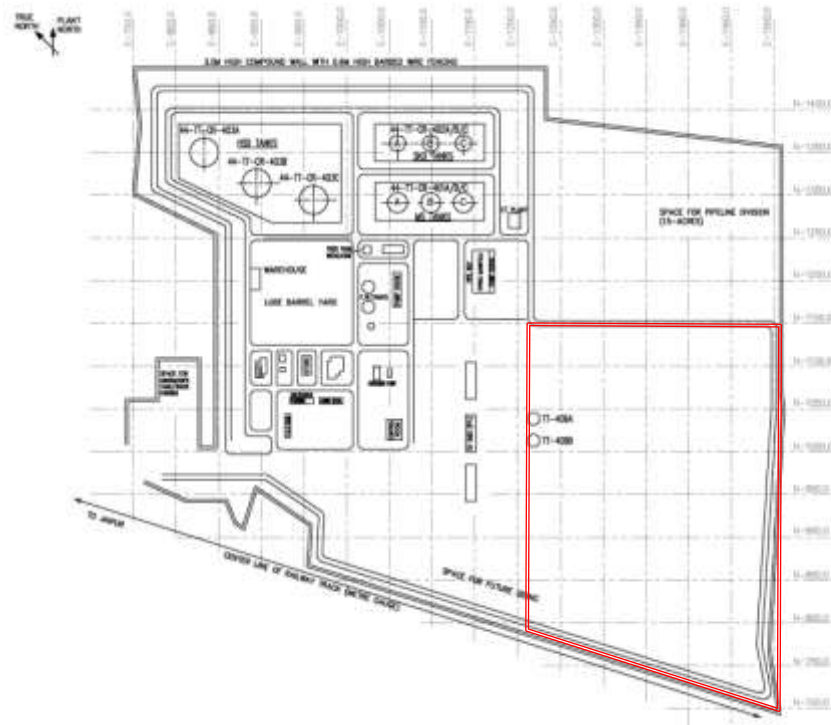


Figure 49: South east area of the site

There were a significant number of directional indicators around the area of the three tanks. Figure 50 shows some representative examples; scouring was present of paintwork on posts, boxes and fire hydrants (top pictures). The leaning tree in the top left picture also provides a directional indicator.

The figure also shows a stand bent over at the south end of the Tank 409 A/B bund and a tree bent over to the south of Tank 409C.

In all cases the indicators were consistent with a flow in a northerly direction.

The top right picture in Figure 50 also shows that Tank 409C had suffered crushing damage. This tank did not catch fire.



Figure 50: Directional indicators in the area around Tanks 409 A/B/C

Further to the east and south, the ground was relatively open with areas of trees and bushes. Figure 51 shows this area viewed from the east side looking west towards Tanks 409 A/B/C. It can be seen that most of the trees and small bushes are leaning to the right, which is slightly to the west of north.

Figure 52 is viewed from the other side of this area, near Tanks 409 A/B/C and looking in a south easterly direction. This suggests that the flammable cloud extended across much of the south east corner of the site. However there was insufficient time to explore this area fully and it is therefore not possible to determine how close the flammable cloud got to the south eastern corner of the site.



Figure 51: Open area in south east corner viewed from east side (Tanks 409B/C in the background)



Figure 52: Open area in south east corner viewed from a point close to Tanks 409 A/B/C

Finally, the northern most part of this area was marked by an east west road that passed along the southern boundary of the Pipeline Division. The trees along this road gave north to north-west directional indication, both in the form of leaning trees and scouring. Figure 53 provides an example, showing scouring on the right hand side of a tree at the east end of this road.



Figure 53: Tree at east end of the road along the southern boundary of the Pipeline Division area (site east wall in the background)

A.8 Pipeline Division Area

The Pipeline Division area was located in the north east corner of the site, as shown in Figure 54. This area had been fenced off from the rest of the site and had its own control room.

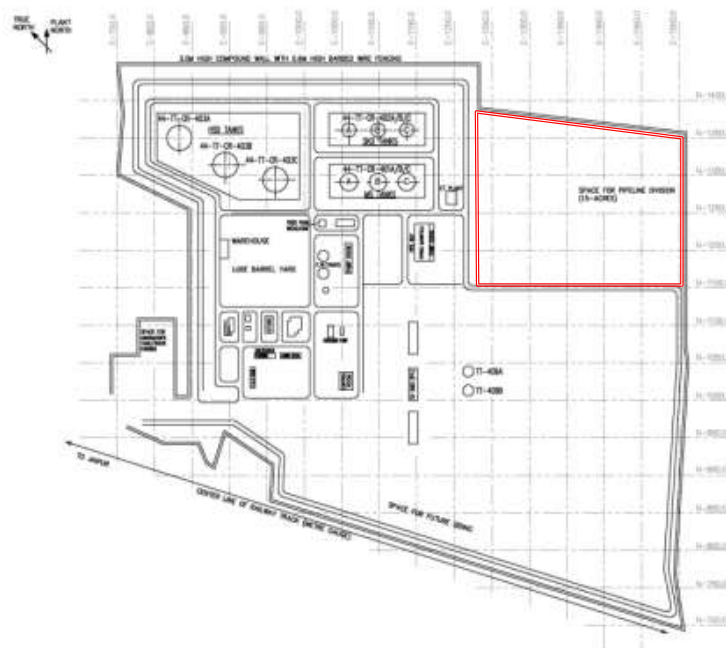


Figure 54: Location of Pipeline Division area

The Pipeline Division area is shown in more detail in Figure 55, with key locations marked.



Figure 55: Pipeline Division area

At the time of the site visit in February, there had been a significant degree of clearance work carried out in the Pipeline Division area of the site. Whilst a reasonable amount of directional information could still be gathered in this area, buildings and equipment that had suffered pressure damage had been removed to an area at the east of the Pipeline Division area. When discussing the overpressure damage in this area, therefore, reference is made to earlier photographic records.

At the western edge of the area, there were directional indicators pointing east, into the Pipeline Division area. Figure 56 shows examples of broken and felled trees. These trees were located just outside the western fence marking the boundary of the Pipeline Division area. The actual fence can be seen in the background of both of these pictures, having collapsed onto the ground in an easterly direction.



Figure 56: Broken and fallen trees to the west of the Pipeline Division area

During the site visit, the primary directional indicators in the centre of the Pipeline Division area were lampposts where the paint had been scoured off one side of the post. Figure 57 shows some examples of this scouring on the lampposts.



Figure 57: Scouring of paint on lampposts and crushing of boxes

The degree of scouring was variable, being very pronounced on some lampposts, relatively mild on others and in some cases not present at all. The absence of scouring was particularly noticeable along the road to the ponds and also at the pump house just by the green firewater tank. The lamppost by the green firewater tank, shown in Figure 58, seemed to have 'dirty' marks on the side facing south west, but these did not correspond with scouring. There was no pressure damage to the box fitted to this post. It is notable that the scouring shown in the top right picture in Figure 57 is on a lamppost just 40 meters to the south of the lamppost shown in Figure 58.



Figure 58: Lamppost and box by pump house

The tree line along the west end of the north wall, as shown in Figure 59, showed some signs of directionality in the form of scouring consistent with an easterly flow, but this seemed to disappear towards the east end of this section of trees.



Figure 59: Tree line on west half of north wall

The picture on the left of Figure 60 shows scouring on one of the trees that remained in this area at the time of the February visit. The scouring indicates an easterly direction.

The picture on the right of Figure 60 was taken in November 2009 and is looking south from the north west corner of the park area marked on Figure 55. The tree and steel posts shown in the figure also give a direction indication to the east.



Figure 60: Directional indicators in north west part of the Pipeline Division area (picture on right taken by Dr B. Burgan)

The severely damaged car shown in the left hand picture of Figure 61 was located in the car park marked on Figure 55 (effectively now looking north from the same position as the right hand picture in Figure 60). It is notable that this picture also shows that the north site wall had completely collapsed at this position.



Figure 61: Damaged car in Pipeline Division car park and collapsed smoking booth (pictures taken by Dr B. Burgan)

The collapsed smoking booth shown in the right hand picture of Figure 61 was located about 15m to the east of the car park.

Further information from this location is shown in Figure 62. These pictures were taken from a video sequence shot in November 2009. The video was taken from the same position as the right hand picture in Figure 60 and the camera is looking east towards the main firewater pump house and the green firewater tank. The sequence shows what appears to be a camera tower collapsed in a north south alignment alongside the pump house.



Figure 62: Sequence of frames taken from a video taken from near to the Pipeline Division car park by Dr B. Burgan

This sequence of frames also shows a tree with its branches broken in a southerly direction (top two frames). This tree had been removed by the time of the February visit but consideration of the positions of various items indicates it was on the opposite side of the road to the smoking booth and in the middle of the north side of the park area.

The final frame in the sequence in Figure 62 also shows the relatively undamaged line of trees along the north wall from the firewater tank eastwards. There is also what appears to be an undamaged tree in front of the firewater tank in this frame. This tree was located on the north side of the firewater ponds and appears to be undamaged in its upper branches. It is possible that this is only due to the upper branches being above the cloud and in the absence of any other evidence (the tree had been removed before the February site visit) this is not considered to be a reliable interpretation.

The final point to note regarding the final frame in Figure 62 is that there appears to be scouring on the north side of the lamppost in the centre foreground.



Figure 63: View looking south at north west corner of pond area, Tank 409A in the distance (picture taken by Dr B. Burgan)

Figure 63 shows a view taken in November 2009. This figure also shows directional indicators in the form of trees, a tilted frame and the collapsed tower captured on the video frames shown in Figure 62. Though it is difficult to interpret evidence provided by the trees, overall, they appear to be indicating a flow approximately towards the east, though possibly with a slight northerly component.

The frame is tilted in a south easterly direction, however it should be noted the frame would naturally tilt forwards or backwards as its resistance to sideways deflection is likely to be greater. In addition, on the assumption a sign had been fitted to the frame, the force in the forwards/backwards direction would have been considerably greater than that in the sideways direction. The tilting of the frame therefore only suggests that the force on the face towards the camera was greater than the force on the other side. This would be consistent with flow from (at least) the 90 degree angle from a westerly direction through to the north.

Taken together, the evidence provided by the frame and the trees gives a directional indicator pointing approximately to the east.

The camera tower appears to have collapsed in a north south direction. Further evidence related to the collapse of the camera tower is shown in Figure 64, taken in November 2009. The full picture, shown on the left of the figure, shows a view looking west from the east side of the main firewater building in the Pipeline Division area. The collapsed camera tower can be seen on the far (west) side of the building. The pictures on the right of Figure 64 provide expanded views and show that the top of the camera tower appears to be on the right hand side of the picture, indicating that the tower has collapsed in a northerly direction.



Figure 64: View from the east of the main firewater pump house looking west, showing collapsed trees and camera tower (picture taken by Dr B. Burgan)

Figure 64 also shows a collapsed tree on the east side of the main firewater pump station in the Pipeline Division area. This has collapsed in a northerly direction.

Figure 65 shows the main firewater pump house in the Pipeline Division area. This pump house was located to the west of the green firewater tank and just south of the firewater ponds. It is understood that there had been a roof on the structure, but it had been relatively open on the sides. There was little in the way of congestion in this building and the only pressure damage observed to equipment was to an instrument unit where the front panel had been distorted inwards and it was tilted backwards. The sides of the box did not show signs of crushing. This evidence would be consistent with it being struck by a blast wave on its front face.



Figure 65: Main firewater pump house in Pipeline Division

Further to the east again, just to the north and west of the firewater pump by the green firewater tank, two trees were photographed in November 2009 as having fallen or broken to the north and east, as shown in Figure 66. It is also notable that in these pictures, the north wall was damaged but had not collapsed fully.



Figure 66: Trees broken/collapsed in a northerly direction (pictures taken by Dr B. Burgan)

Further information regarding the condition of the trees and wall in this area can be gained from a sequence of frames taken from a video shot in November 2009 from a position by the green firewater tank. This sequence of frames is shown in Figure 67.



Figure 67: Sequence of frames taken from video shot near firewater tank in Pipeline Division area by Dr B. Burgan

These frames show that the north wall had not collapsed to a position west of the main firewater pump house, which can be seen in the bottom frame. The second frame down on the left also appears to show a tree collapsed or broken to the north close to the point where the wall changes from being undamaged to collapsed. This may well be one of the trees shown in Figure 66. The middle two frames also indicate that the damage to branches on the trees along the north wall and to the west of the firewater ponds was not as severe as damage to other trees on the site.

Finally, the second frame down on the right and the bottom frame show a tree where the branches have broken in a northerly direction.

Moving along this north wall further east and past the green firewater tank, Figure 68 shows that the trees did not appear to show any sign of pressure damage. They did however show signs of having been burned. It is understood from site personnel that this section of wall did not require re-building.



Figure 68: Trees along the north wall at the most eastern end

The lack of significant overpressure in this area is also supported by the lack of damage to a firewater hose cabinet located close to the north wall in this area, as shown in Figure 69. Though clearly fire damaged, this cabinet does not show any obvious pressure damage.



Figure 69: Firewater hose cabinet located to by the north wall to the east of the green firewater tank

The red box that can be seen on the right of Figure 68 is shown in closer view in Figure 70. This shows that the south side of this box had been deformed and that the box stand was leaning to the north. This suggests that the box had undergone pressure loading from a southerly direction.



Figure 70: Red box showing uneven damage

At the far east end of the Pipeline Division area, the directional indicators were mixed. To illustrate this, Figure 71 shows views taken along the tree line on the east wall.



Figure 71: Damage and directional indicators along the east wall

The top left picture shows a tree at the north end of the wall broken in an easterly direction. The pipes shown next to the tree had also rolled down from the left, which is consistent with the directional indicator provided by the tree.

However, the top right picture, taken looking south from the same location, shows evidence of branches broken in a westerly direction.

The box shown in the bottom left picture has clearly suffered some pressure damage, however there was no clear scouring to provide a directional indicator. The CCTV tower, located in the south east corner of the Pipeline Division area had collapsed in an easterly direction.

Much of the ground at the east end of the Pipeline Division area had been covered with debris removed cleared from the damaged buildings. However, two trees were still present, being some 40m west of the east wall and 80-90m south of the north wall. These trees are shown in Figure 72. Both provide a direction indication consistent with flow in to the west. The tree in the left hand picture (taken looking south) also showed clear scouring on the east side of the trunk. Note that the tree shown in the right hand picture can be seen in the background of the left hand picture.



Figure 72: Trees at the east end of the Pipeline Division area

There was severe damage to buildings within the central region of the Pipeline Division area. An example is shown in Figure 73, which illustrates the damage to the store building.



Figure 73 Damage to store building on Pipeline Division area picture (picture taken by Sh. S.K. Hazra)

Figure 74 shows damage to the control room building, with the upper picture taken from the north side of the building and the lower picture taken from the south side of the building. This figure shows that the damage to the south side of the building is more severe than to the north side. In particular, it is noted that the roof of the control building on the south side appears to have been pushed downwards.

It is also notable that there appears to be a largely undamaged tree just to the north of the control room, seen on the right hand side of Figure 74.



Figure 74: Damage to the Pipeline Division control building (top picture from north taken by Dr B. Burgan, bottom picture taken from south by Sh. S.K. Hazra)

At the time of the site visit in February, most of the buildings in the Pipeline Division area had been completely demolished and the rubble cleared.

Figure 75 shows the pipeline pump house and the diesel engines as they were in February 2010. There was evidence of pressure damage to the oil filters on both engines. This damage was consistent with the damage observed at Buncefield, however, it should be noted that the oil filters on the IOC site were larger. It is notable from the two right hand pictures in this figure that there appeared to be only limited damage to the exhaust system from the tops of the engines. This does not appear to be consistent with the oil filter damage.



Figure 75: Pipeline pump building in February 2010

As has been noted, the pipeline pump house had been tidied up by February 2010. Figure 76 shows the pipeline pump house, viewed from the south, before the clear up operation. The picture shows that a tower to the south of the building had collapsed, possibly in an easterly or north easterly direction. In addition, one of the exhaust stacks from the diesel engines appears vertical whilst the second one, on the left, has tilted to the east.



Figure 76: View of pipeline pump house from the south (picture taken by Sh. S.K. Hazra on 11th December 2009)

Report Number: 11510
Issue: 1.0

Closer in views of the two exhaust stacks are shown in Figure 77. It should be noted that the building had had a roof and partial walls.



Figure 77: Closer in views of the two exhaust stacks on the pipeline pump house (pictures taken by Sh. S.K. Hazra on 11th December 2009)

Appendix B Directional Indicators

The directional information gathered during the site visit comprised marked up site plot plans showing the position at which a measurement was taken and the compass bearing of the directional indicator. This information has been summarised in the figure on the following page.

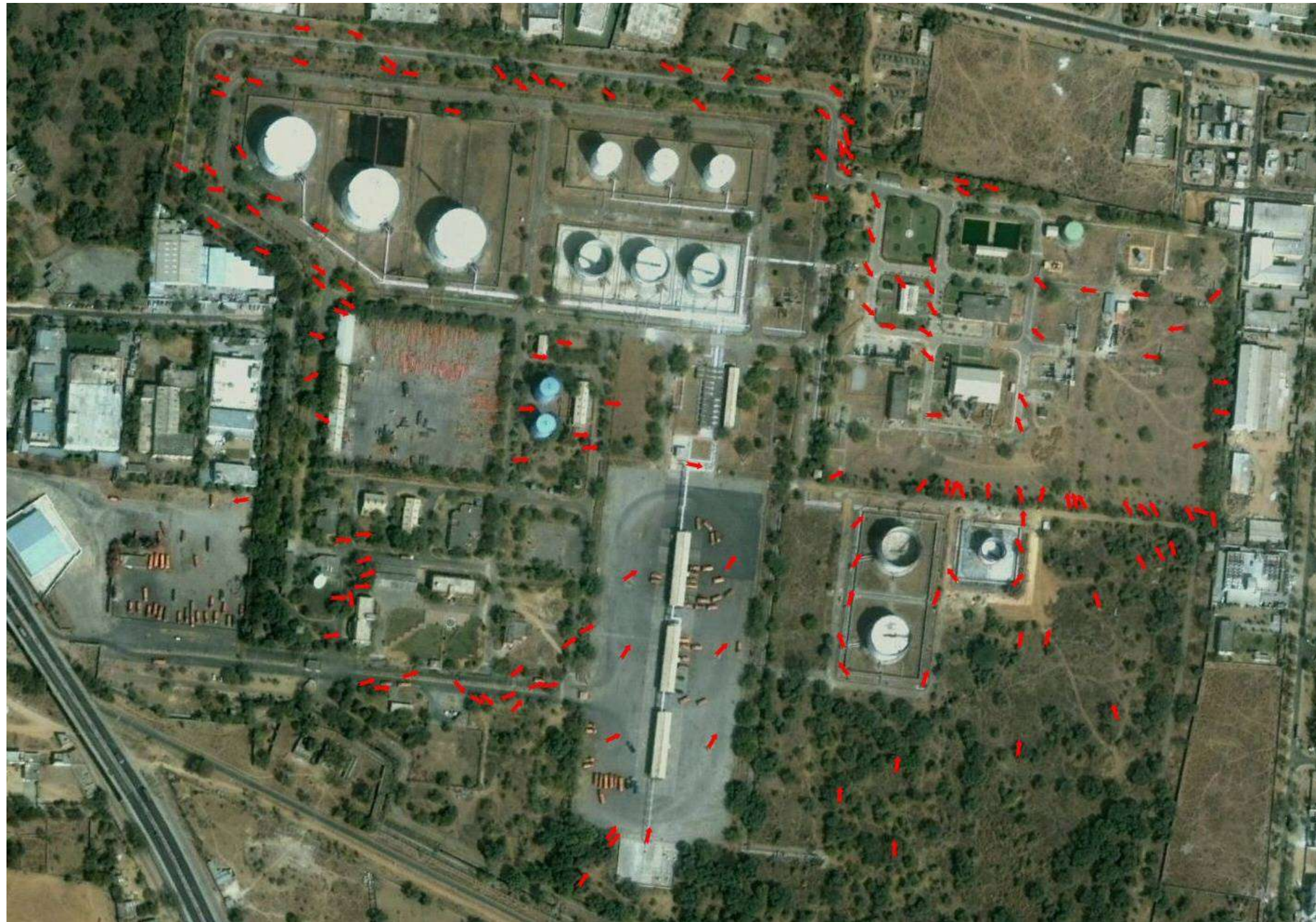


Figure 78: Directional Indicator Measurements (arrow shows location at the base of the arrow and direction measured)

Appendix C Buncefield Incident

This appendix provides a description of the types of evidence observed following the Buncefield incident. Most of the information provided in this section has been obtained from the report of the Joint Industry Project [4] and is reproduced here to allow the evidence from Jaipur to be placed in context. In the Buncefield incident, a low lying vapour cloud was produced following the spillage of about 300 Tonnes of MS. The vapour cloud spread across the site and offsite with the scorched area indicated in Figure 79 taken to define the extent of the flammable cloud.

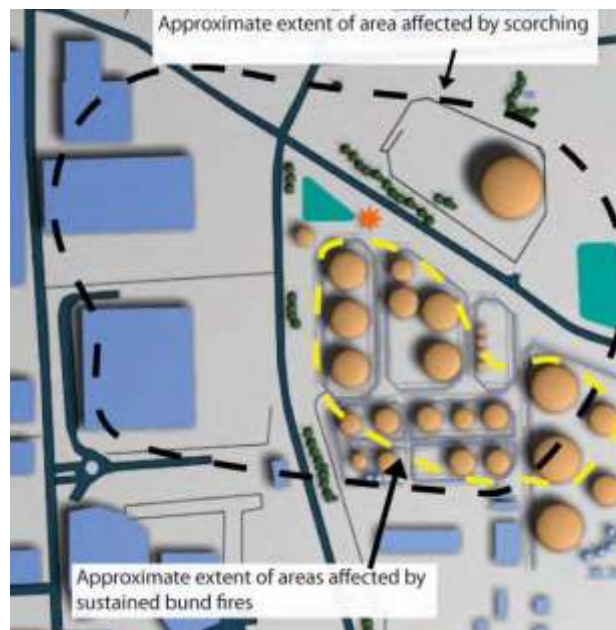


Figure 79: Extent of the vapour cloud was taken to correspond to the scorched area

C.1 Overview of the Evidence Considered in Relation to Buncefield

The evidence considered in relation to the explanation of the Buncefield explosion mechanism included:

- The timings of the various phases of the explosion, obtained mainly from CCTV records.
- The magnitude of the overpressure required to cause the observed damage and the variation of this overpressure, both within and outside the cloud.
- Directional indicators providing information on the direction of the net dynamic load or sustained gas flow and the variation of this within and outside the cloud.
- The ignition location.
- The similarities to previous incidents.

Though it is understood that CCTV records exist for the Jaipur site, at the time of writing, these were in the custody of the police and not available for examination. The timing of the various phases of the explosion is therefore not considered further. Explosion simulations and experimental results were used to assist in the interpretation of the evidence observed at Buncefield.

Each of the remaining factors is considered in summary below. Further details related to the Buncefield incident can be obtained from the project report [4].

C.2 Overpressure Damage

The most significant aspects of the overpressure damage in the Buncefield incident were:

- Pressure damage was observed within almost all the areas of the vapour cloud that indicated overpressures in excess of 200kPa (2barg) within the cloud.
- There was a rapid decline in the overpressure level from the edge of the cloud.

The items within the cloud that exhibited pressure damage included; steel junction boxes, cars and vans, steel drums, tanks, engine oil filters and drain covers. A description of the type of damage observed to a number of these items is provided in the following section. The decay in overpressure from the edge of the cloud is then discussed.

C.2.1 Damage within the cloud

Examples of the types of damage observed within the Buncefield vapour cloud are shown in Figure 80.



Figure 80: Examples of the types of pressure damage observed within the Buncefield cloud; (a) Damage to near full steel drum in static test; (b) Damage to car; (c) Crushing of oil filter; (d) Crushing of steel box

C.2.1.1.1 Steel junction boxes

A number of steel junction boxes were found within the area engulfed by the cloud. Typically these boxes had been crushed in on the sides

The Buncefield Joint Industry Project conducted a number of experiments including static loading tests and dynamic tests involving exposure to pressure waves generated by high explosive. The results of these experiments indicated that overpressures in excess of 200kPa were required to cause the observed pressure damage.

C.2.1.1.2 Cars and vans

Damage to cars and vans within the cloud was extensive. On the basis of experimental studies and comparison with data from earlier studies, the project concluded that the cars had seen in excess of 200kPa overpressure.

C.2.1.1.3 Oil Filter

A crushed oil filter was observed within the area of the cloud. The project concluded on the basis of experimental work that the filter had been exposed to overpressures well in excess of 180kPa.

C.2.1.1.4 Steel drums

Damaged steel drums were located in various parts of the site. They included full, partially empty and empty drums and the translational displacements during the explosion were generally small (<5 m).

The drums had often been exposed to a combination of compression from the explosion followed by heating by the subsequent fires. However, static experiments indicated that the deformation of near full drums was typically of the form shown in Figure 80. The drum is compressed and deformed above the liquid level in a manner consistent with observations on site.

The experiments indicated that overpressures in excess of 180kPa would be required to cause the observed damage.

Where drums had been exposed to fires, the drums had ballooned out due to internal expansion. However they retained signs of the deformation caused by the explosion pressure.

C.2.1.1.5 Drain covers

Many drain covers located within the cloud had been blown downwards, into the drain, and deformed significantly.

C.2.2 Damage outside the cloud

As already described, severe overpressure damage was observed within the vapour cloud. It was also observed that the degree of damage fell rapidly from the edge of the cloud. This is illustrated in Figure 81, which shows a sudden change in the level of overpressure damage to a row of cars that appears to have traversed the cloud boundary. The cars at the far end of the row show severe pressure damage, however the car in the foreground shows significant damage at the rear of the car.



Figure 81: Change in Damage Level to Cars at the Cloud Boundary

Simulations carried out by the project of the detonation of a low lying vapour cloud showed that rapid pressure decay would be expected. For example, one simulation showed that at a distance of 30m from the cloud boundary, the overpressure reduced from the detonation pressure of 2MPa inside the cloud to 70kPa.

C.3 Directional Indicators

Many directional indicators were observed following the Buncefield incident. These consisted of bent posts, scoured paintwork and trees and translation of some objects. Examples of directional indicators are shown in Figure 82



Figure 82: Directional indicators inside the Buncefield cloud

Simulations carried out for the Joint Industry Project showed that both fast deflagrations and detonations passing through a low lying vapour cloud give a net dynamic load that is in the opposite direction to the propagation of the deflagration or detonation. This is primarily due to the high velocities generated in the combustion products venting behind the flame or detonation. The high velocity gas would also give the scouring of trees and paintwork and translate some objects.

Taking the directional evidence inside the cloud as indicating the direction of flow of the combustion products, the evidence was plotted on a map of the site, as illustrated in Figure 83 (red arrows).

As can be seen, the directional indicators were present throughout most of the vapour cloud. This evidence was probably the most important in distinguishing between the 'deflagration only' and the 'deflagration to detonation transition' scenarios considered by the project. The deflagration would have only given these directional indicators within the congested regions (the tree lines). Outside the congested regions, items would have been bent away from the explosion source (as they are only affected by the blast wave and not the high velocity combustion products). This was not what was observed, with items only being bent away from the explosion source outside the cloud, as illustrated by the yellow arrows on Figure 83.

Given that the arrows within the cloud point in the opposite direction to the direction of propagation of the detonation, their tendency to point towards a single location was taken to indicate the area where the transition from deflagration to detonation occurred.

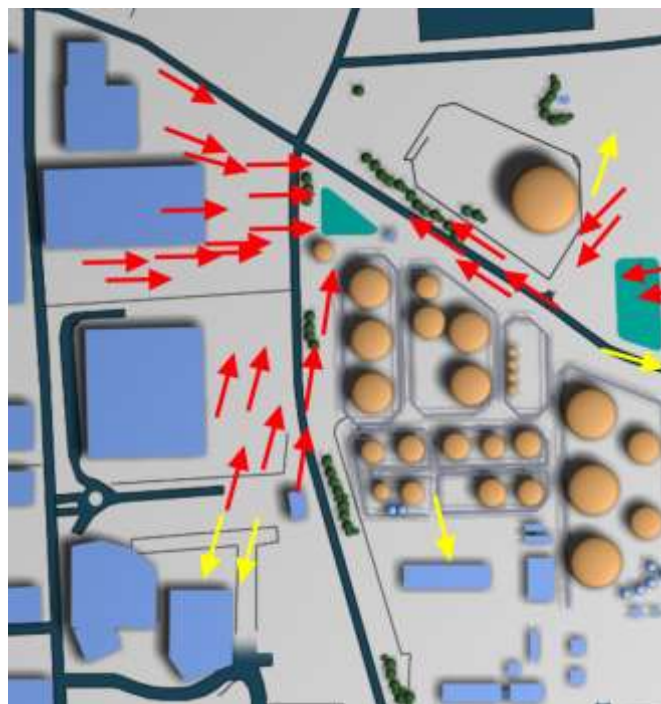


Figure 83: Buncefield directional indicators

C.4 Ignition Location

The project concluded that there was a weight of evidence that ignition occurred within the emergency firewater pump house on the north side of the Buncefield site.

C.5 Similarities with Other Incidents

The Buncefield was compared with other vapour cloud incidents and concluded that two had produced similar evidence in terms of the pressure damage and directional indicators. These incidents occurred in Port Hudson, USA [5] and Ufa (Russia, 1989) and were reported to have involved detonations. In both cases comparable overpressure damage occurred in the vapour cloud and the same directional evidence was observed within the vapour clouds.