Application of detonation diagnostics to the Flixborough Explosion

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HSE has recently brought together and digitised its archive of 900+ photographs taken by investigators at the site of the Flixborough explosion (Department of Employment, 1975). These images show damage to all of the important areas of the plant and also record the effect of the explosion on buildings and other objects in surrounding, open areas.

It has recently become possible to more fully interpret this evidence for several reasons:

1. Large scale detonation tests have been carried out that show how a range of standard objects are affected by detonations (SCI, 2104). Some of the most important objects in the context of Flixborough are lightweight steels such as angle iron fence posts and scaffold tubes.

2. The influence of gravity on the far field development of a vapour cloud in relatively light winds is better understood since Buncefield (Coldrick el at 2011, Gant and Atkinson 2011).

3. The development of blast waves from non-spherical sources is also better understood (SCI 2009, SCI 2014).

The Flixborough photographs show that the flame accelerated rapidly through the confined and congested plant, undergoing transition to detonation in the area around the release point where the cloud was at its deepest. This detonation propagated through almost all of the shallower cloud that covered the open areas surrounding the plant to a range of about 180m. Wherever the detonation wave impinged perpendicularly on ductile columnar objects such as angle iron fence posts, scaffold tubes and lamp posts, it caused a characteristic pattern of distributed plastic deformation: these objects were continuously curved in a way that matches the deformation of equivalent objects in detonation tests. Outside the area affected by the detonation the deformation was completely different: plastic deformation was concentrated in a single hinge.

These types of linear steel object are very common in industrial contexts and observation of curvature provides a very simple means of determining if a detonation occurred and what parts of the site were subsequently affected. The main limitation of the technique is that it cannot generally be used in areas affected by severe and prolonged fires - since such heating can also cause continuous curvature.

Wherever the detonation ran up against larger objects e.g. a reactor in an open area, the photographs show the effects of very high reflected pressures (of order 35-40 bar) on the upstream face. Pressures and damage levels on the downstream face were much less.

The main (three storey high) office building on the site was surrounded by the cloud. Direct exposure to the detonation reduced the building to rubble. Fortunately the incident happened on a Saturday and the office was unoccupied but this illustrates the additional risk when a detonation spreads to areas of a vapour cloud well away from congested areas. Occupants of buildings affected by any part of the cloud are in extreme danger whether there is congested plant nearby or not.

Application of the diagnostic tools developed here to other more recent vapour cloud explosions is discussed. There are very detailed records of the explosions at Buncefield (Buncefield Major Incident Investigation Board, 2007), Jaipur (MoPNG Committee, 2010) and San Juan (CSB, 2015). No examples of continuous curvature of lightweight steel elements have been observed in either case. Similarly there are no examples of asymmetric high pressure damage to objects in open areas. This and a variety of other evidence suggests that these events were high order deflagrations rather than detonations.

Background to the incident.

The plant operating company was a joint venture between Dutch State Mines (DSM), the UK National Coal Board and Fisons (UK). It produced Caprolactam – a main component of Nylon 6. The section where the release took place was devoted to the production of cyclohexanone and cyclohexanol by the oxidation of cyclohexane with air in the presence of a catalyst.

The reaction normally took place in a connected series of 6 adjacent reactors. At the time of the incident the fifth reactor had been removed for repair and replaced with a bypass pipe. This bypass was connected to the reactors on either end using a flexible bellows type fitting. It appears that the temporary connection was not subject to appropriate structural analysis or pressure test. On Saturday 1st June 1974 at 4.53 pm the 20” bypass pipe failed completely and there was a massive double ended release of cyclohexane at a pressure of at least 9 bar (130 psi) and a temperature of 155°C (311 F). Prior to the rupture the 5 remaining reactors would have contained approximately 120 tonnes (264,000 lb) of cyclohexane of which 80 tonnes (176,000 lb) was recovered after the incident. Of the 40 tonnes (88,000 lb) that was lost it has been estimated that 30 tonnes (66,000 lb) contributed to the cloud prior to ignition (Sadee et al 1976).

Workers in the site laboratory, which was 75 m (246 ft) from the leak point, saw and heard the release and were able to evacuate to a distance of about 150 m (492 ft) before ignition – these people survived. Eighteen workers in the adjacent control room did not evacuate and were all killed. The delay before ignition appears to have been about 45 seconds. Of the 72 people working on the site at the time, 28 were killed and 36 others suffered injuries. If the explosion had occurred on an ordinary working day, many more people would have been on the site, and the number of casualties would have been much greater.

Outside the Works injuries and damage were widespread but no-one was killed. Fifty-three people were recorded as casualties by the casualty bureau which was set up by the police; hundreds more suffered relatively minor injuries which were not recorded. Property damage extended over a wide area: 1000 houses were damaged within a range of 1500 m (4,921 ft) and a further 800 houses at a range between 1500 to 4500 meters (4,921 – 14,760 ft).

It is not known precisely where ignition occurred but rapid flame acceleration occurred and damage to objects within parts of the cloud is consistent with a transition to detonation.

HSE holds an archive of 900+ photographs from the incident investigation. A selection of the most important images have been assembled as part of a media package. This application locates the images on the incident site.

Figures 1 to 6 show plans of the site and photographs before and after the incident.

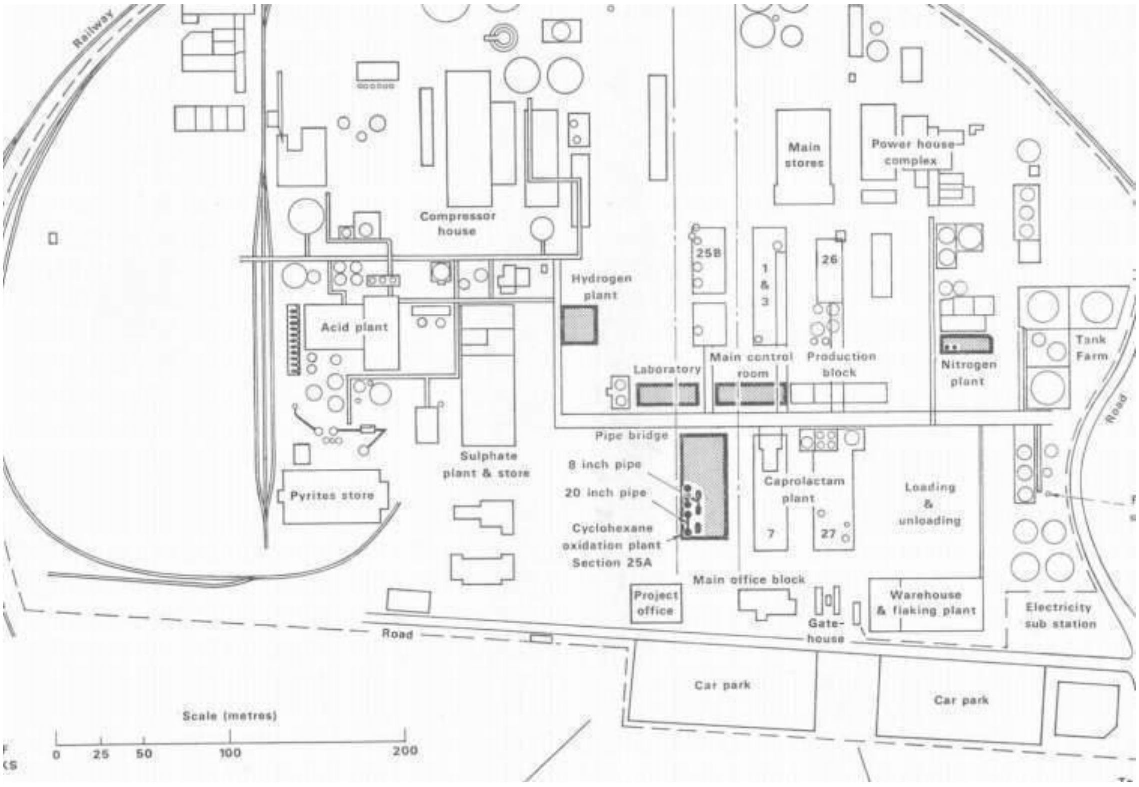

Figure 1: Overall view of Flixborough site

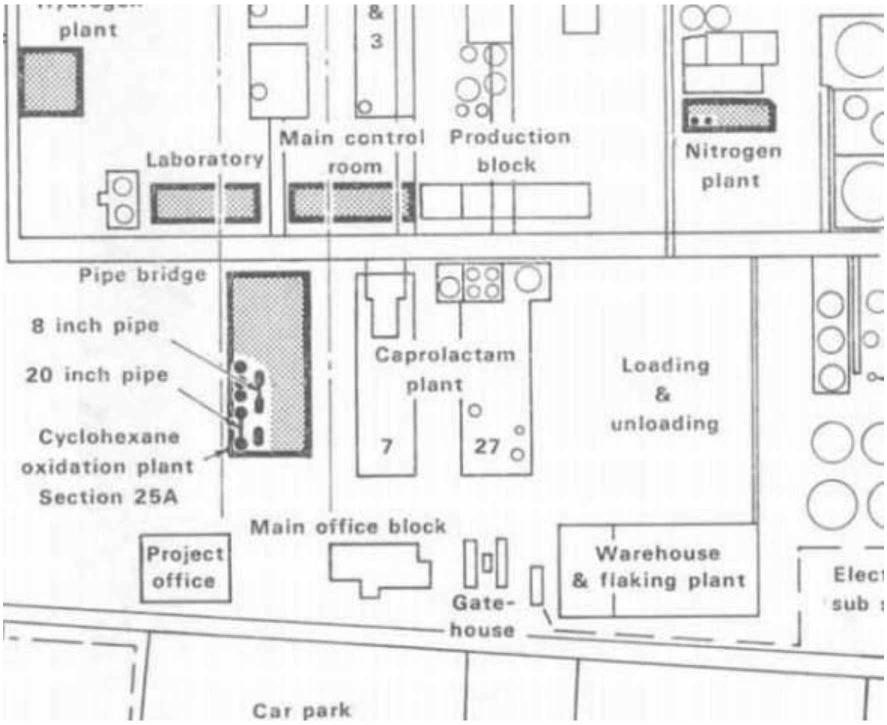

Figure 2: Close-up view of area where the vapour cloud accumulated

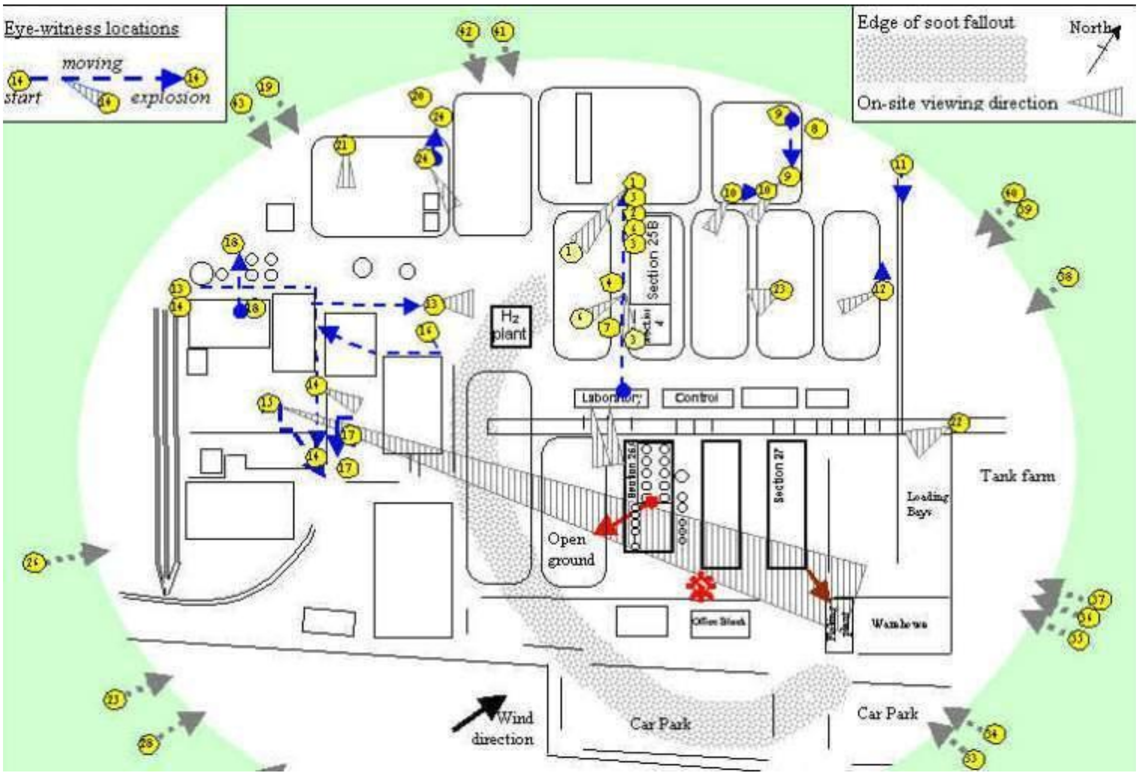

Figure 3: Graphic showing edge of soot fall out – which marks the edge of the rich part of the cloud

Figure 4: Flixborough site prior to the incident – release point marked X

Figure 5: Aerial view of the Flixborough site after the incident – release point marked X

Figure 6: Aerial view of the Flixborough site after the incident – release point marked X

Key:

1. Reactor 5 –scaffolded for repair in an open part of the site
2. Ruins of main office block (unoccupied as the incident occurred on Saturday)
3. Ruins of warehouse – drums and solids

Vapour cloud production at Flixborough

The series of reactors forming the pressure system that failed is illustrated schematically in Figure **7** and shown in a photograph in Figure 8.

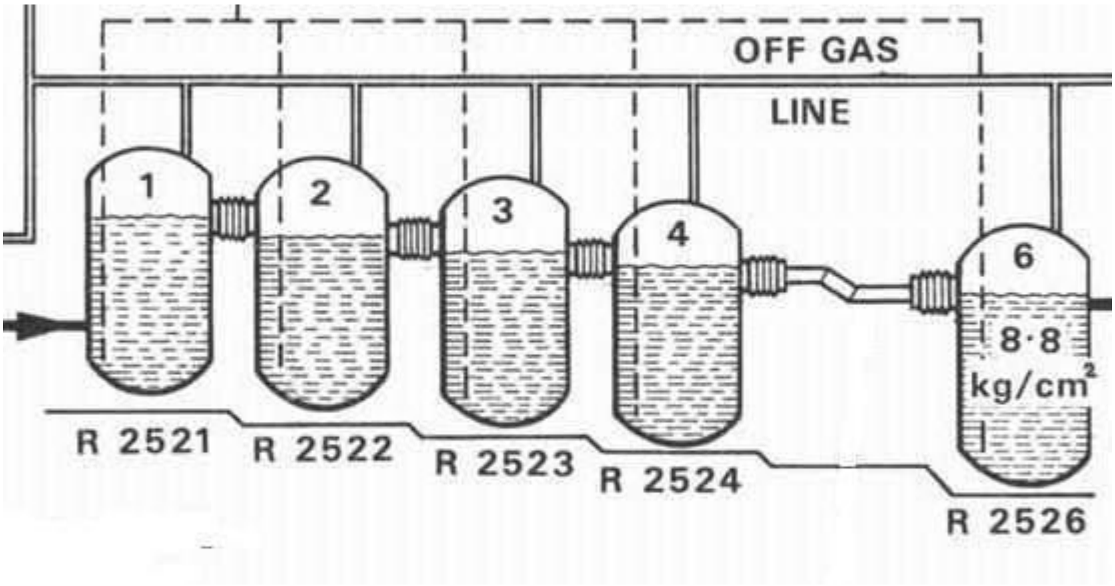

Figure 7: Schematic of reactor train including by-pass

Figure 8: Photograph of part of the reactor train after the incident the dog leg bypass was lost completely. Scaffolding has been erected after the incident.

Figure 9 shows a close-up of the 28” flanges left after the failure of the 20” by-pass. It can be appreciated that the source term would have been complex with expanding, two-phase jets issuing from both holes in opposite directions. These off-set jets would have collided, forming an angled fan of vapour and fine droplets. Later in the release the combination of tanks 1-4 would have depressurised less quickly than Tank 6: the release would have increasingly resembled a jet directed towards the car parking areas.

Entrainment of air would have progressively reduced the outward jet speed and the resulting diluted jet would have started to slump since it would still be significantly heavier than air. The typical downward velocities driven by buoyancy forces on the accumulating heavy cloud near the source would have been of order 5-10 m/s for pure vapour and 3-4 m/s for a vapour/air mixture close to the stoichiometric ratio. These estimates can be derived from equating the potential energy of the elevated heavy gas to the accumulated downward kinetic energy. There was also a light wind blowing from the South (see Figure 3).

The release time of about 45 seconds would have been sufficient for gravity to drive the establishment of a vapour current – with much of the accumulated vapour being concentrated in a relatively shallow layer at ground level.

Figure 9: Openings left after loss of bypass pipe.

The total mass of cyclohexane released was around 30 tonnes (66,000 lb) and overall plan area of the cloud was around 60,000 m^2 . Table 1 shows how the average depth of the cloud varies with its average concentration.

Table 1: Cloud depth derived from mass release rate and plan area

Average concentration (g/m^3)	**Average depth (m)**
85(stoichiometric)	5.8
170	2.9

There was noticeable fall out of soot from the explosion – even close to the upwind edge - which suggests much the cloud was quite rich. It seems likely that the average cloud depth over much of its plan area was around 3-4 m (9.8 – 13.1 ft). The depth close to the source would have been much greater i.e. >15m (>49 ft).

Explosion development at Flixborough

Figure 8 illustrates the high level of congestion and confinement in the plant areas at Flixborough.

The area where the release occurred would have been almost completely filled with flammable vapour – even at high levels. It is to be expected that a severe explosion would have been sustained in this area. The combination of large flame path lengths and highly confined and congested areas provided the potential for transition from a fast deflagration to a detonation (DDT). If this occurred the detonation could propagate away from plant areas into the open low lying areas of the cloud.

There is good evidence that this did in fact occur and spread to most of the areas of the cloud in the open. The sequence of images in Figure 10 to Figure 13,show the damage to the equivalent parts of the skirts of Reactors 2,3 6 and finally Reactor 5 with the wreckage of associated scaffolding. Reactor 5 had been relocated to an open area of the site for repair (necessitating the installation of the temporary by-pass pipework that failed).

The level of damage clearly increase as the reactors step down in elevation and (presumably) further away from the ignition point in the sequence 2,3, and 6. The damage to the vessel in an **open area** (Reactor 5) is noticeably more severe than those on the plant. This side of the reactor was facing the plant so if the cloud engulfing Reactor 5 detonated, then the reflected pressure on the upstream face would be around 35-40 bar (507 – 580 psi) – compared with the side-on overpressure in a detonation of around 15-18 bar (217 – 261 psi).

Figure 14 shows the back face of Reactor 5. Comparison with Figure 13 confirms that there is the clear asymmetry in damage level to be expected for an impinging detonation.

Figure 10- Reactor 2: Limited pressure damage to reactor skirt

Figure 11- Reactor 3: Limited pressure damage to reactor skirt

Figure 12: Reactor 6 (Number 5 missing). Significant pressure damage to the skirt

Figure 13: Reactor 5 - Located in open ground approximately 40 m (131 ft) from the leak. Substantial damage to the reactor skirt on the side facing the plant

Figure 14: Reverse face of Reactor 5 showing asymmetry in damage.

The curved scaffold tubes in the wreckage surrounding Reactor 5 are also significant (Figure 13 and Figure 14). Numerous pieces of scaffold boarding are visible in their midst and it is clear that there was no sustained fire around the vessel. It follows that the curvature of the tubes was caused by the explosion not by any subsequent fire.

The weight, second moment of area and degree of end constraint of these tubes is comparable with the angle iron used to fabricate the tents in Buncefield JIP detonation tests (SCI 2014). The general character of the deformation and extent of deformation are also comparable (Figure 15).

Figure 15: Angle iron deformed by a detonation (cloud depth 3m)

It is highly likely that damage to Reactor 5 and the scaffolding that surrounded it was caused by the progress of a detonation through the cloud in this area. At this point the detonation was apparently travelling outwards from a point close to the south end of the oxidation plant.

Similar examples of continuous curvature are seen in fence posts and barriers to the south of the cyclohexane oxidation plant (Figure 16, Figure 17 and Figure 18).

Figure 16: Curved fence posts in open areas to the south of the cyclohexane oxidation plant.

The original images are on the left. The images on the right are digitally stretched by 500% in the horizontal direction to allow the curvature to be seen.

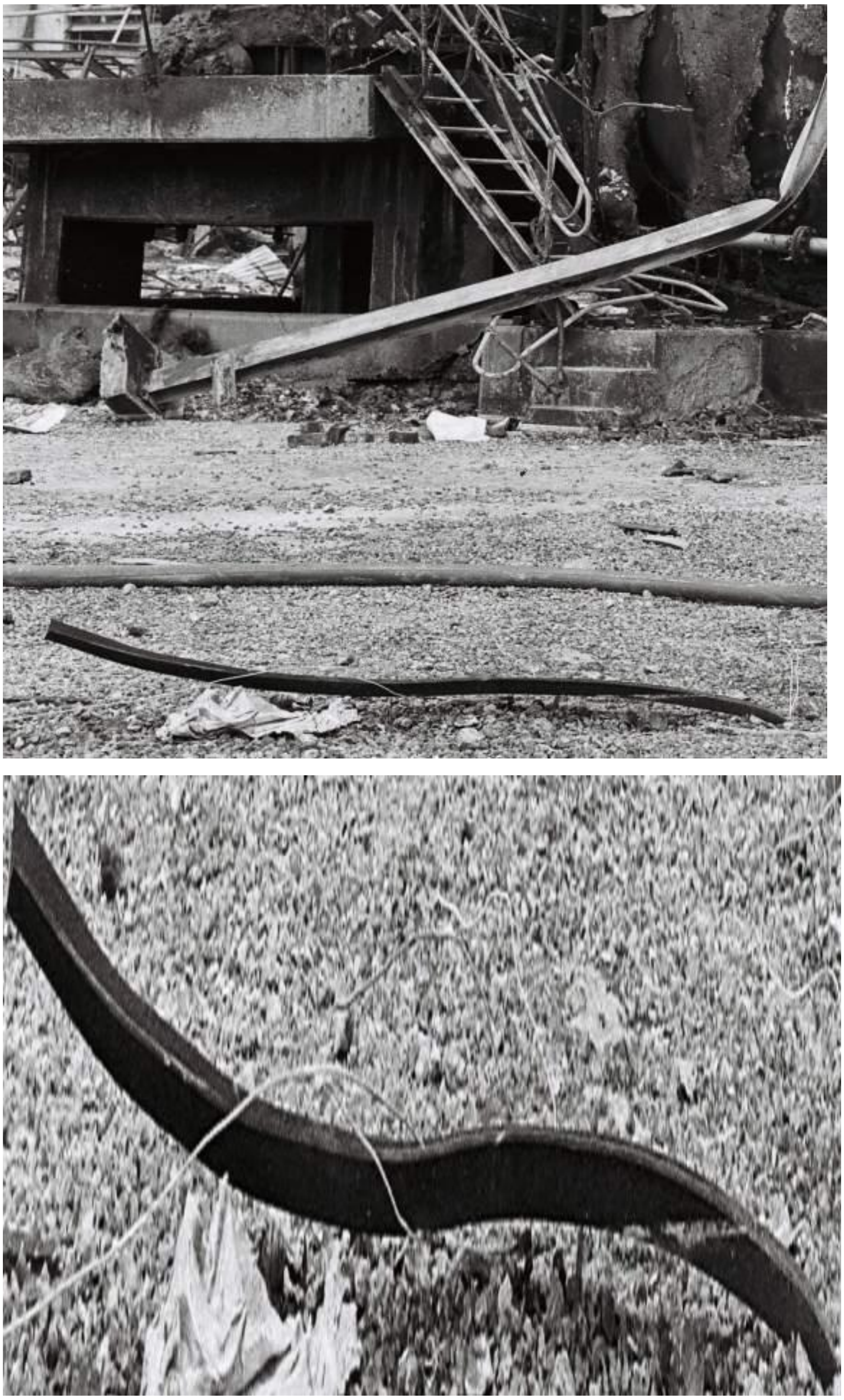

Figure 17: Curved fence posts in open areas to the south of the cyclohexane oxidation plant.

The original image is above. The image below is digitally stretched by 500% in the vertical direction to allow the curvature to be seen.

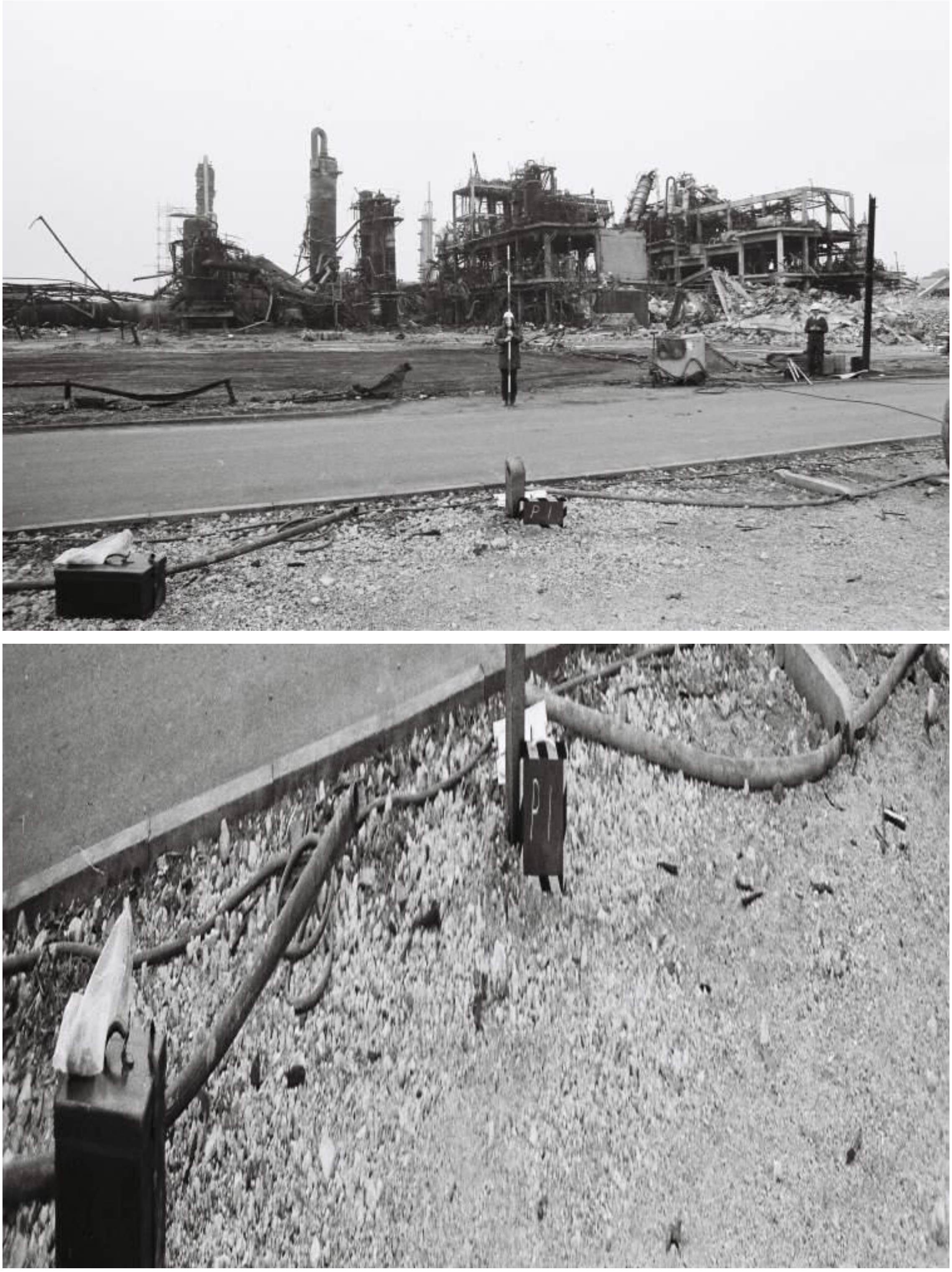

Figure 18: Curved barriers

The original image is above. The image below is digitally stretched by 500% in the vertical direction to allow the curvature to be seen.

Continuous curvature was also observed in lamp posts within the cloud (Figure 19 and Figure 20). The most pronounced curvature along the length of the posts was observed around the fringes of the cloud where the mixture would have been detonable through the whole depth.

Figure 19: Lamp post within the cloud – approx. 130 m (426 ft) south of vapour source.

Figure 20: Lamp post within the cloud – approx. 180 m (590 ft) NE of vapour source

Outside the cloud the posts did not exhibit plastic deformation along the whole length (Figure 21 and Figure 22). Plastic deformation was concentrated near the base of the main stem – where the moment of blast forces would have been greatest.

Figure 21: Lamp post outside the cloud to the East

Figure 22: Lamp post outside the cloud to the North

It is useful to examine why the occurrence of continuous curvature disappears so rapidly beyond the edge of the cloud. Figure 23 shows dynamic pressure just inside and just outside a 3m deep propane/air detonation (Fluid Gravity 2009, SCI 2009). The maximum pressure falls off very quickly.

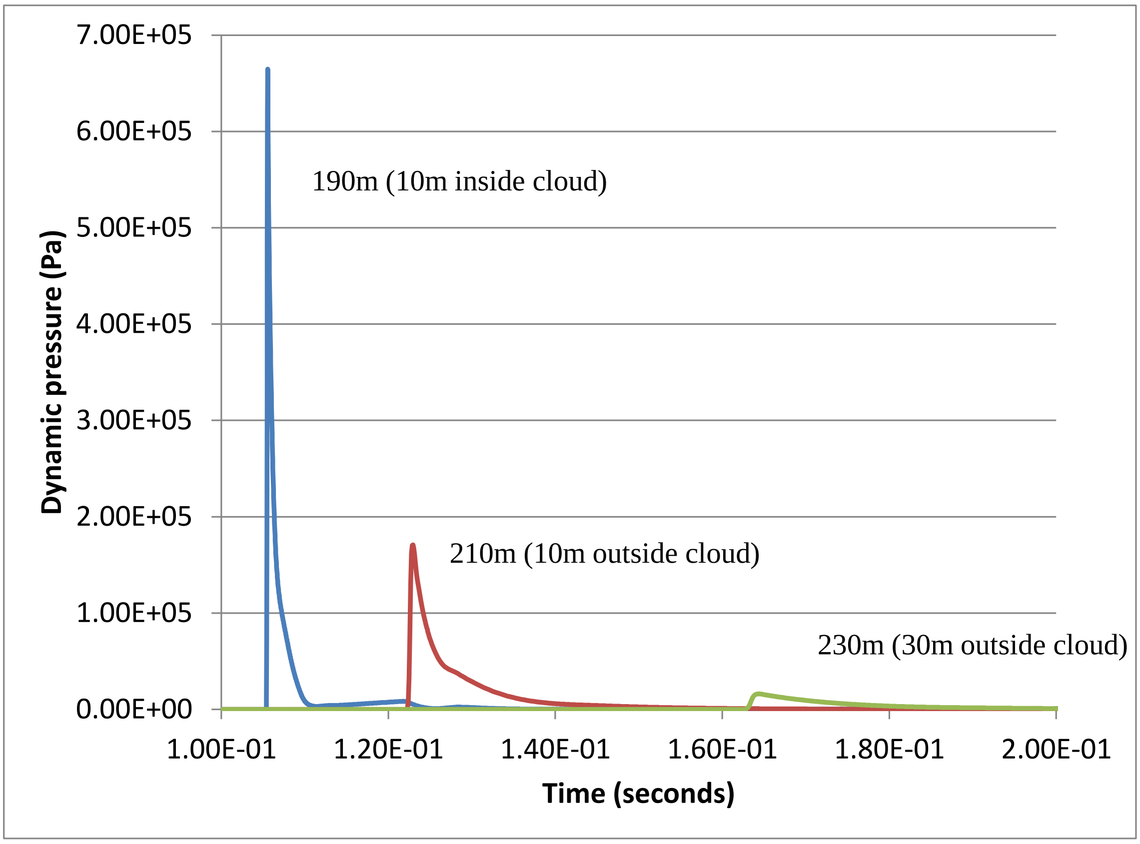

Figure 23: Dynamic pressure in and close to the edge of a 3m deep detonation (cloud radius 200m, measurement height 1.5m, measurement radius 190, 210 and 230 m)

The kinetic energy (per unit length) absorbed from the drag impulses in the first 5ms is shown in Table 2; expressed as the proportion of the energy required to cause local plastic deformation (Atkinson and Hall 2016).

Table 2 : Energy absorbed from a detonation shock

Distance from cloud edge	Energy absorbed (as a proportion of that required to cause local plastic deformation)
-10 m (within the cloud)	270%
+10 m (outside the cloud)	109%
+30 m (outside the cloud)	27%

This suggests that local plastic deformation is confined to areas very close to the edge of the cloud and this type of damage effectively marks the edge of the detonation.

Comparison with other incidents

This type of continuous curvature, with plastic deformation distributed along the length rather than being concentrated in hinges, is only observed for extremely high impulsive load profiles. No continuously curved spars or posts were observed at the Buncefield, Jaipur, Amuay or San Juan sites. Some examples of columnar objects affected by a severe explosion but not a detonation are shown in Figure 24 to Figure 26.

Figure 24: Typical deformation of a lamp post at Buncefield

Buncefield Major Incident Investigation Board (2007)

Figure 25: Lightweight open steel structures in the centre of the Jaipur explosion

(MoPNG Committee, 2010)

Figure 26: Section of boundary fence in the San Juan incident (CSB, 2015)

Extent of the detonation at Flixborough

Deformation of lamp posts is a useful means of determining which open areas were affected by cloud detonation. Figure 27 shows results of this analysis.

Red arrows indicate continuous curvature of the main lamp post stems or mid-span hinging and probably indicate direct exposure to detonation of the surrounding cloud. The direction of arrows indicates the final direction of the stem in the photographs. Numbers correspond to the ID numbers chalked on boards and included in the original photographs.

Blue arrows correspond to lamp posts where plastic deformation was confined to an area near the base of the main stem.

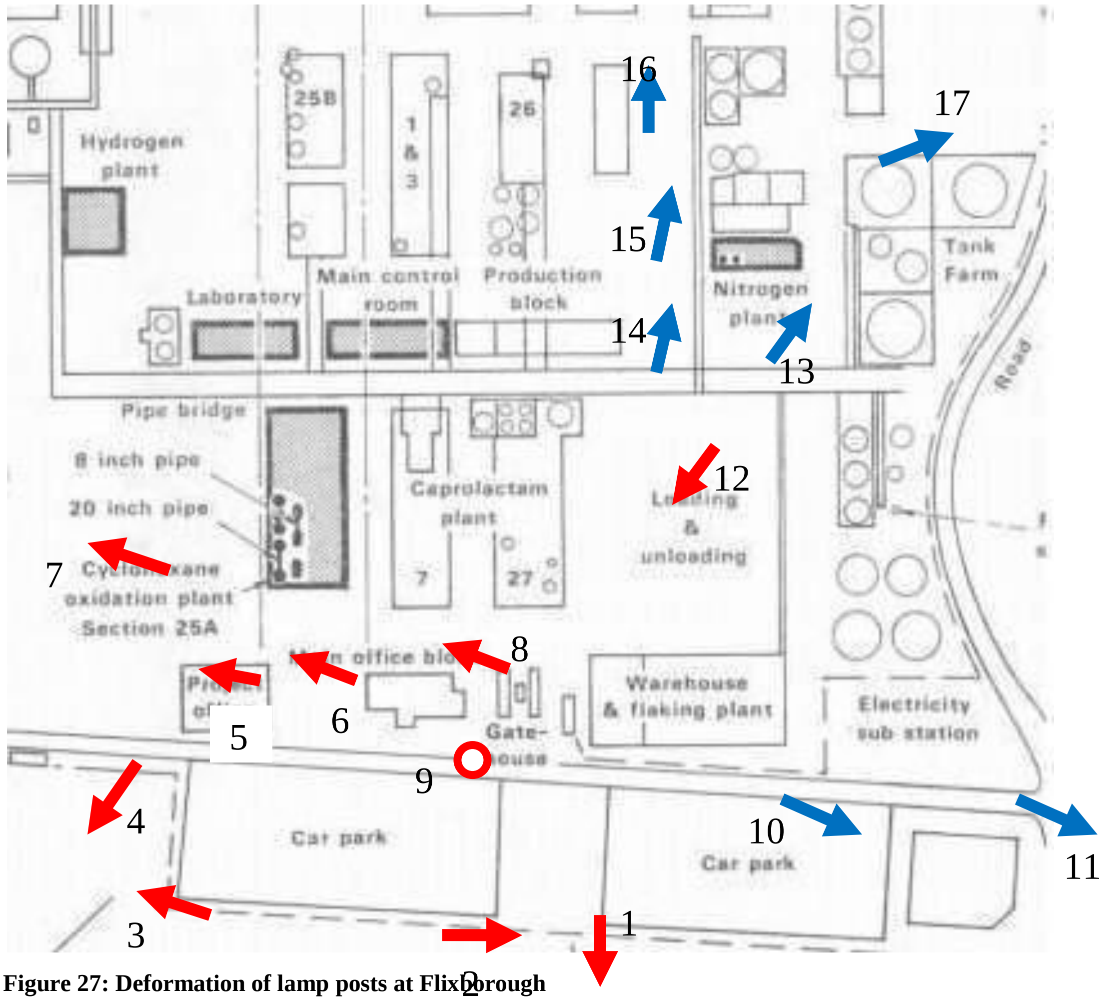

Figure 27: Deformation of lamp posts at Flixborough

It appears that detonation affected a high proportion of the cloud away from the main plant areas. However no clear pattern emerges from the direction of the red arrows that might allow the tracking of detonation's progress.

Because of the directional nature of the source term and the relatively short release period, gravity would certainly not have had time to even out horizontal concentration gradients around the site – especially in areas where there were substantial buildings. For this reason it is likely that the cloud would have been very patchy. Once initiated a detonation would thread its way through such a cloud via a circuitous route. The extremely high drag forces exerted on an exposed lamp post reflect the local direction of explosion propagation and it is perhaps not surprising that such widely spaced markers cannot resolve the way the detonation propagated.

Blue arrows correspond to smaller and slower impulses and the direction is generally radially away from the cloud, as is to be expected.

Summary

The cyclohexane oxidation plant at Flixborough contained some heavily congested and confined areas. The release would have filled the part of the plant where it occurred to full depth giving a 3D character to the developing explosion – which would also have increased overpressures.

There is clear evidence that the cloud detonated when the flame reached the area around the leak. The detonation then progressed into the lower lying areas of the cloud in open areas around the plant. Characteristically high impulsive loads were exerted on posts and spars that were perpendicular to the direction of detonation propagation.

The imposed loads were much higher than the minimum level required to cause failure and were imposed in a time very much shorter than the natural period of flexural vibration of the elements. The result was the propagation of a zone of plastic deformation along the length of elements, leaving them with continuous curvature.

This type of curvature is easy to identify in incident records and provides a good indication that a detonation has occurred. Conversely for incident sites where there are a variety of light-weight steel columnar objects (fence posts, lamp posts, scaffold tubes etc.) that suffer significant pressure damage without the appearance of continuous curvature, it is reasonable to assume that there has been some form of fast deflagration (Atkinson 2011, Atkinson and Hall 2016).

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