INTERPRETATION OF OVERPRESSURE MARKERS AND DIRECTIONAL INDICATORS IN FULL-SCALE DEFLAGRATIONS AND DETONATIONS[†]

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INTRODUCTION
This paper provides guidance to those involved in the investigation of severe vapour cloud explosions (SVCEs) where overpressures exceed 100 kPa (1000 mbar) – these could include detonations and high-speed deflagrations. The information may also be relevant to the problem of assessment of the consequences of such events.

CONVENTIONAL OVERPRESSURE INDICATORS
The range of overpressure indicators most commonly used by those assessing or investigating vapour cloud explosions was given by Clancy [1] and has been widely used and reproduced e.g. in Lees [2] and in Scilly and High [3]. A typical selection of the indicators is shown in Table 1.

There are very few indicators in the literature for pressures between 69 kPa and 2000 kPa (crater lip for a condensed phase explosives).

The majority of these indicators have been derived from nuclear weapons data [4] and associated theoretical analyses with some additional information from condensed phase explosions. In most cases the nuclear test results provide very poor indicators of overpressure in vapour cloud explosions. This is because the duration of both positive and negative pressure phases in nuclear tests are extremely long and are associated with high and sustained blast winds. In most cases the extent of damage is dominated by the drag forces associated with these winds. Two examples serve to illustrate the point.

Cars: Glasstone [4] reports severe crushing of cars for overpressures of 34 kPa (340 mbar) and a positive phase duration of several seconds. It has not always been recognised by those quoting this result that the damage was primarily associated with the sustained 260 km/hr blast wind and the consequent rolling of vehicles rather than direct effects of overpressure. Glasstone reports total destruction of cars by a 200 kPa (2000 mbar) shock – only one axle from the test vehicle was recovered. The reasons for such extreme levels of damage become clear when one considers that the blast would have been associated with 1070 km/hr winds sustained for several seconds. The car would have been accelerated to speeds of many hundreds of kph and smashed to pieces. Our experience is that cars enveloped by vapour cloud explosions, and thereby exposed by overpressures in excess of 200 kPa (2000 mbar), are typically badly crushed but not totally destroyed.

They are not massively translated by the blast – sometimes remaining parked in neat lines.

Brick buildings: The figure of 50% destruction of brickwork by a blast with overpressure of 17 kPa (170 millibar) also grossly overestimates the likely effect of a vapour cloud explosion. A shock of this magnitude may produce significant cracking of masonry but again it is the sustained blast wind in nuclear tests that rip the weakened structures apart.

OVERPRESSURE INDICATORS SUITABLE FOR SEVERE VCEs
The general problem with the indicators listed by Clancy, Lees and others is that most are highly dependent on drag forces – rather than side-on overpressure. The relationship between overpressure and drag force and impulse is complex and potentially misleading as the above examples indicate.

Our experience is that the most useful types of object that directly show the effects of raised side-on overpressure are lightweight (ductile) metal enclosures. In the case of explosions in low lying vapour clouds these are not subject to large net impulses and the damage is dominated by direct overpressure effects. The following types of object can be found around chemical or fuel storage and process sites:

- Steel junction boxes
- Cars and vans
- Steel drums
- Parking barrier pillars

Table 1. Typical pressure indicators

Typical pressure for glass failure	1 kPa (10 millibar)
Minor damage to house structures	4.8 kPa (48 millibar)
50% destruction of brickwork of house	17 kPa (170 millibar)
Rupture of oil storage tanks	27 kPa (270 millibar)
Severe crushing of cars	34 kPa (340 millibar)
Loaded train box cars completely demolished	62 kPa (620 millibar)
Probably total destruction of buildings	69 kPa (690 millibar)

- Tanks
- Drain covers
- Buildings

Figures 1 and 2 show respectively a car and a crushed electrical connection box. In each case the deformation is symmetrical and the object has not been massively translated and dented in the process.

Other common objects that are primarily susceptible to drag forces include:

- Trees
- Lamp posts
- CCTV camera masts

Figure 1. Car crushed by a severe VCE without overturning

Figure 2. Junction box crushed by a severe VCE without demounting

It is possible for objects to be exposed to high over-pressures but low drag forces – for example a small area near the centre of a symmetric explosion. But in the case of damage caused by exposure to a progressive explosion front the degree of drag related damage is a useful indicator of the flame speed and hence overpressure. Lines of trees are particularly useful because they provide indicators of explosion severity that passes through the cloud. If lines of trees pass through the cloud boundary they may provide useful indicators of the rate of decay of overpressure outside the cloud.

INERTIAL EFFECTS – WHAT COUNTS AS A LIGHTWEIGHT METAL ENCLOSURE?

Most of the objects listed above are fabricated from steel sheet with a thickness of order 1 mm. If unrestrained a 1 mm sheet will respond to a pressure differential of 100 kPa (1000 mbar) by accelerating at a rate of

$$a = 100,000/7.5 = 13,300 \, \text{m/s}^2 \text{ (The density of steel}$$
$$\text{is taken as } 7500 \, \text{kg/m3)}$$

The typical duration of the overpressure pulse in a vapour cloud of depth 3 m is approximately 20-30 ms. The resulting maximum velocity U and displacement (during pressurisation) S of an unrestrained piece of sheet steel can be estimated as:

$$U = at = 0.025 \times 13,300 = 333 \, \text{m/s}$$
$$S = 1/2 \, at^2 = 1/2 \times 13,300 \times (0.025)^2 \sim 4 \, \text{m}$$
$$\text{(note deflection will continue)}$$

These figures are approximate (as the movement will eventually affect the pressure applied) but it is clear that the inertia of such sheet material will not prevent very large deflections (if the sheet is not restrained). In fact in our experience extremely large displacements of various unrestrained cladding sheets are observed around the sites of very violent vapour cloud explosions.

Of course, the observed deflections visible in Figures 1 and 2 are all much smaller than 4 metres. This is because the constituent sheets were restrained. In general this restraint arises in three ways:

1. The compressive strength of the enclosure. A certain level of applied external over pressure can be resisted elastically. When the load is removed the enclosure is undamaged.
2. The compressive strength of objects within the enclosure. The boundary sheets move until they come up against strong or heavy objects within. These restraining objects could be: a terminal strip in a junction box; the support framework in a car door; liquid in a drum etc.
3. The pressure rise associated with adiabatic compression of the enclosed gas – the internal pressure rise partially off sets the external overpressure. Comparing the ratio

of volumes before and after compression allows an estimate to be made of the internal pressurisation. For example, a box reduced in volume to 40% of its original volume indicates an internal overpressure of approximately 200 kPa (2000 mbar).

SHAPE RECOVERY

Some caution has to be exercised in deriving estimates of the maximum overpressure from the final (deformed) shape of enclosures because of the possibility of continuing deformation and shape recovery after the external pressure declined.

The drum in Figure 3 shows almost complete volume recovery when the (high) external pressure falls – although the creasing associated with severe plastic deformation remains. Fortunately most electrical or hydraulic junction boxes have large hinged fronts that provide a good seal during rapid compression but fly off or leak rapidly and relieve the internal pressure during the (typically slower) phase of external depressurisation. Steel enclosures may be found where close forming of the shell around objects within indicated that venting had been rapid enough to prevent significant volume recovery as in Figure 4.

Similarly, broken windows rapidly and effectively vent most vehicles, as the pressure falls. Door panels may remain closely formed around the underlying framework or car roofs remain pressed into seats; in these cases the maximum extent of plastic deformation will be preserved (Figure 1).

SELECTED OVERPRESSURE INDICATORS
STEEL DRUMS

Steel drums are commonly located in chemical and fuel storage sites. Crushing of the ullage wall and plastic bowing of the end wall as shown in Figures 5 and 6 are indicators of pressures in excess of about 200 kPa (2000 mbar). If there has been a subsequent fire the drums may show evidence of internal pressurisation but creasing of the sort shown in Figure 5 is never removed.

Figure 3. Drum crushed in a SVCE but showing near complete volume recovery

Figure 4. Steel enclosure crushed by a SVCE – minimal shape recovery

JUNCTION BOXES

Our experience in a range of explosion tests is that boxes with a height and width of around 600 mm or less are rather strong. Pressures of at least 2000 mbar are required to produce the high levels of compression visible in Figure 4. Smaller boxes are stronger still and pressures of well in excess of 200 kPa (2000 mbar) are indicated by levels of compression shown in Figure 2.

CARS

We have carried out a range of tests using solid explosives and gas explosions in closed containers – providing a range of pressures and impulses. Our experience is that

Figure 5. Crushing of drum wall in the ullage – not seen below 200 kPa

Figure 6. Plastic deformation of drum end cap – not seen below 200 kPa

crushing of cars to the level shown in Figure 1 indicates an overpressure of in excess of 200 kPa (2000 mbar).

TYRES
Tyres on vehicles exposed to the cloud may be deflated by severe vapour cloud explosions. Figure 8 shows a typical example.

The tyre side wall and bead has been pushed inwards over the inner safety rim of the wheel. Pressure applied slowly in a hydraulic test does not have this effect – even for maximum pressures in excess of 10 bar. In this case all faces of the tyre (and especially the load bearing face with tread) collapse inwards balancing the internal and external pressure. There is never sufficient net force to stretch the tyre bead over the inner rim. When the pressure is removed in a static test the tyre re-inflates to the original pressure.

In an explosion inward deflection of all faces of the tyre occurs with the lightweight sidewall moving particularly rapidly. As the sidewall and bead contact the inner rim there is still sufficient pressure difference to stretch the bead over the rim. This difference is illustrated in Figure 9.

The failure of tyres in this fashion indicates overpressures well in excess of the inflation pressure of the tyres involved – which is typically 200–300 kPa (2000–3000 mbar).

EXAMPLE: USE OF INDICATORS TO DETERMINE DECLINE IN OVERPRESSURES OUTSIDE THE CLOUD
Our experience is that overpressures outside a pancake shaped vapour cloud decline very rapidly outside the cloud – on a length scale comparable with the cloud depth. An example is shown in Figure 10. The cars furthest from the camera were clearly exposed to the vapour explosion as they have been crushed and set alight. The black hatchback has been significantly crushed – as has the rear portion of the light coloured vehicle in the foreground. Pressure damage to the front and sides of this vehicle is slight.

DIRECTIONAL INDICATORS
In two important vapour cloud explosions at Ufa [5] and Port Hudson [6] it has been observed that objects (trees, posts, masts etc) are broken or displaced towards the source of ignition, that is to say in the opposite direction to direction of propagation of the explosion. This is a counter-intuitive finding which has prompted various explanations. Makhviladze, has suggested that the tree fall at Ufa was caused by the inflow driven by strong upward convection [5].

In fact results of recent modelling work on deflagrations and detonations in **shallow** (pancake shaped) clouds show that over most of the cloud:

> **Both deflagrations and detonations always produce a backwards[1] impulse[2]**

> **But**

> **Shockwaves (without associated local combustion) from a remote explosion always produce an impulse away from the explosion.**

Figure 7. Two views of damage to box (300 × 300 × 150 mm) caused by 100 kPa (1000 mbar) overpressure (static test): slight bowing of back but no plastic deformation of front

Figure 8. Tyre pushed off inner rim during explosion

Notes

1. *Relative to the direction of explosion propagation.*
2. *These are pressures associated with rapid local combustion. It is possible to have a net forwards impulses from a deflagration if the flame velocity and associated pressure are very low but there is a relatively powerful* *(remote) explosion in the direction the flame came from. This certainly happens and gives a pattern of weak short-range impulses radiating out from centres of congestion.*

The exception to the first rule is a narrow zone around the perimeter of the pancake cloud where the net impulse
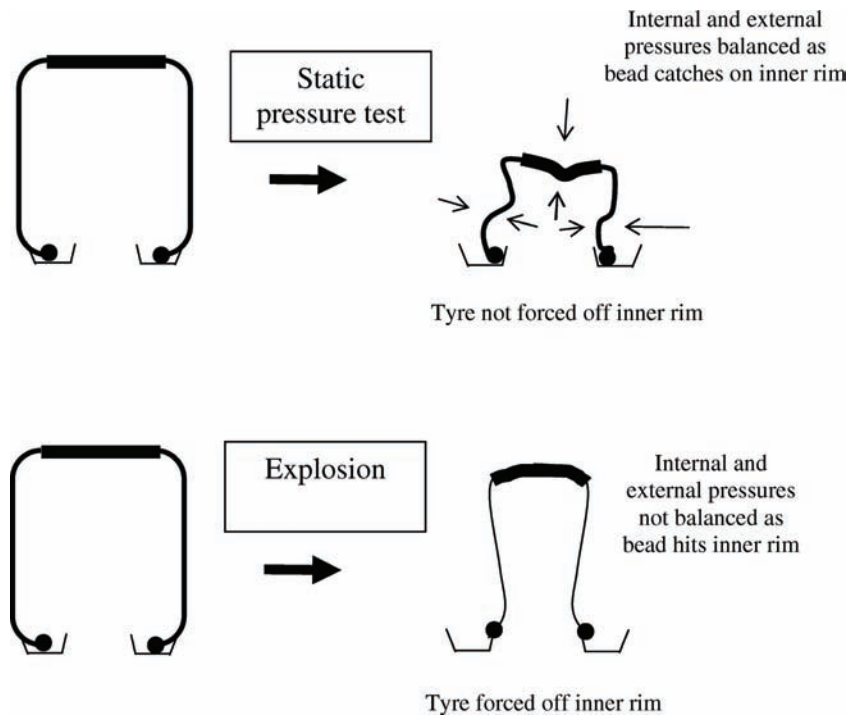

Figure 9. Response of tyre to static and explosive pressures

Figure 10. Rapid decline in overpressure outside the flammable cloud

and consequent deflection may be outward. The relationship between the width of this zone and the cloud depth is still under investigation for detonations and fast deflagrations.

The use of blast direction indicators in tracing the development of an explosion therefore requires care. If blast indicators radiate outwards from a number of foci that coincide with congested areas of plant, then the direction of explosion propagation probably cannot be uniquely determined from this data alone. The Texas City incident provides a very clear example of this kind of damage pattern [7].

If (as at Ufa and Port Hudson) all blast indicators in a shallow cloud radiate inwards towards a single focus this is very likely to be the origin of the explosion – see Figure 11. This kind of highly symmetric general damage is likely to be caused by a detonation or very high intensity deflagration event.

Blast indicators in three-dimensional clouds (depth comparable to width) are still more difficult to interpret. Figure 12 shows the pattern of directional indicators at Flixborough. It is not clear whether the intense blast was localized in the epicentre or extended further out at ground level. In such a deep cloud the direction of the net
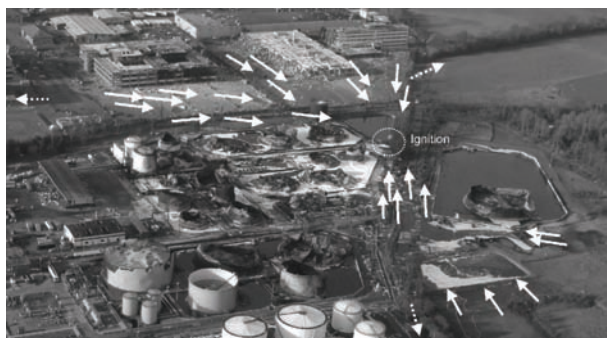

Figure 11. Example of indicators of net drag impulse towards likely ignition point

Figure 12. Directional indicators (net drag) at the Flixborough incident

impulse associated with a detonation or fast deflagration can be outward.

TYPES OF DIRECTIONAL EVIDENCE TO LOOK FOR
Deformation
Moderately sized trees and branches, lamp posts, CCTV masts, fencing etc may be bent or snapped at points of weakness or close to the ground. In many cases the impulse of drag forces may not be sufficient to completely displace the broken part and the final shape indicates the direction of the net drag impulse (Figure 13).

Abrasion
Many standing objects can be abraded by debris driven by the explosion. The effect is noticeable in surfaces covered by paint (Figure 14) but can also be seen in tree bark and other types of surface. The pattern of abrasion may

Figure 13. Posts and trees deformed by drag forces in the explosion

Figure 14. Directional abrasion of post

provide directional information – if only one side or part of one side is affected.

Objects can be both abraded and deformed. In these cases our experience is that the directions of the net drag impulse and movement of the debris causing abrasion are typically coincident. This is not entirely self-evident and the net drag impulse and level of abrasion damage

respond in different ways to flow speed, density and particle loading etc.

Displacement
Some substantial objects such as vehicles and skips can moved a little way by drag forces during the explosion. In these cases the displacement of the object can be determined and gives an approximate indication of the direction of the net drag impulse.

CONCLUSIONS
Some information has been provided to aid the interpretation of overpressure and directional evidence in severe vapour cloud explosions.

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