Explosions in Electrical Control Boxes as a Potential "Nested Bang-Box" Mechanism for Severe Vapour Cloud Explosions

Gill J.[1,2,*], **Phylaktou H.N.**[2,*], **Atkinson G.**[1], **Andrews G.E.**[2] **Cowpe E.**[3]

[1] *Health and Safety Executive's Health and Safety Laboratory, Buxton, Derbyshire, SK17 9JN, UK*
[2] *University of Leeds, Leeds, LS2 9JT, UK*
[3]*Health and Safety Executive, Bootle, Merseyside, L20 7HS, UK*
**Corresponding author emails:* *jason.gill@hse.gov.uk*, *h.n.phylaktou@leeds.ac.uk*

ABSTRACT

The ignition source for Buncefield, the United Kingdom's most severe recent vapour cloud explosion (VCE) was potentially electrical control boxes situated inside a pump house immersed in the vapour cloud. There are other reports of confined or bang box ignition sources for other VCEs, such as Port Hudson and Jaipur where it is proposed these ignition sources were responsible for transition to detonation (DDT). There has, however, been relatively little previous research into this type of ignition mechanism and its effect on the explosion severity. Commercially available electrical control boxes measuring 600 mm high, 400 mm wide and 250 mm deep were used to explore the pressure development, venting processes and flame characteristics of stoichiometric propane/air explosions using cling film, aluminium foil and the supplied doors as vent coverings. In this work the boxes were empty of their usual contents in order to establish a baseline for the effect of the internal congestion of the boxes. It was found that, in these empty-box tests the overpressure was dominated by the bursting pressure of the vent-covering and the external explosion, although clearly presenting significant ignition source to a potential surrounding flammable cloud, it produced no significant overpressure. The door produced a flat petal shaped flame that differed drastically from the rolling vortex bubble flame shape traditionally associated with vented explosions.

KEYWORDS: VCE, Vapour cloud explosion, vented explosion, bang-box ignition.

INTRODUCTION

The most recent severe Vapour Cloud Explosion (VCE) in the United Kingdom was the Buncefield incident in 2005 [1] which, due to the timing of the accident, did not result in any fatalities but caused damage exceeding £1 billion. The vapour cloud was a large unconfined, gravity driven pancake cloud and the resultant explosion was very severe. This incident was thoroughly investigated [2] and has triggered a large quantity of peer reviewed work [2-14], but remains the subject of research focus because of particular features of this event that are not fully explained or understood, as discussed below.

A review of large fuel storage site VCEs by Atkinson et al [15] showed that devastating whole-cloud explosions resulting from large unconfined vapour clouds are not only a possibility but a likely outcome of loss of containment in weather conditions that allow development of a very large, fairly homogeneous cloud of vapour. They reported no examples of large flash fire events, which would be the traditional risk expectation in low congestion storage depot sites, such as those reviewed in this work. The idea of very large homogenous cloud development [10, 16, 17] is also

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 356-365
Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.
Published by St. Petersburg Polytechnic University Press
ISBN: 978-5-7422-6496-5 DOI: 10.18720/spbpu/2/k19-130

relatively new and not widely understood. Atkinson et al [15] concluded that the the transition to a severe explosion regime seems to involve some degree of congestion or confinement. Based on the incidents studied the following may have acted as triggers: confined explosions in buildings (e.g. pump houses), dense vegetation, pipe racks and other moderately congested plant. The extent and density of congestion presented, however was considered as substantially less than that required for DDT [15].

Buncefield was unusual amongst historical VCEs in having overgrown vegetation in the area where transition to a severe explosion occurred; most of the other sites, for which there is very detailed forensic evidence, did not have any areas of dense vegetation or indeed any extended areas of densely packed pipework. Investigators of VCEs at Jaipur [15,18] and Port Hudson [19] have proposed that transition in these cases was the consequence of ignition with nested confined volumes e.g. at Port Hudson an industrial freezer within a concrete building submerged in the wider vapour cloud.

Their hypothesis is that failure of the innermost compartment or container would have triggered energetic jetting of unburned gas and then flames into the surrounding building. The resulting explosion would have been further enhanced by the effect of fragments of the innermost container and any other congestion within the building, resulting in a violent confined explosion in this second layer of the nested ignition source. Finally, the disintegration of the building within a very large cloud would have triggered a still more energetic and much larger explosion in the surrounding cloud. It is further proposed that, in the right circumstances, such a series of explosions could trigger DDT.

The Buncefield ignition also occurred within a closed steel electrical control box, inside a congested building [3]. The whole building was immersed in the larger unconfined vapour cloud. If the nested ignition source mechanism has to be invoked to explain transitions at Jaipur, Amuay and Port Hudson then it is possible that this was also the cause at Buncefield. In fact, there is evidence that the density of vegetation at Buncefield was well below that which would be necessary to drive run-up to DDT [15] .

There has, however, been relatively little research into this type of strong external cloud ignition mechanism (nested bang-box) and its effect on the explosion severity, despite calls [8] for further research into this aspect after Buncefield. There have been no previous studies of nested ignition scenarios where an external cloud was ignited by a vented explosion from the building which in turn, was ignited by a vented explosion from the control box. It certainly cannot be ruled out that this type of nested ignition event was the primary reason for the transition to a severe explosion in most if not all of the historical incidents. This is especially the case if a large homogenous cloud covers an area for several tens of minutes; gas ingress into buildings and small volumes containing ignition sources is is highly likely over long timescales.

The research into explosion venting has been carried out exclusively by venting into the atmosphere. There is a great deal of useful research into this type of vented explosions [20-24] and a number of authors [22-24] have identified various pressures peaks that are associated with the with the dynamics of exlosion venting and attempted to define the conditions that would lead to one or other of these pressure peaks to the highest during the explosion.

However, the importance of an initiation of a VCE explosion through the powerful ignition from a vented explosion (bang box ignition) has been appreciated since the pioneering work of Harrison and Eyre [25], but until recently there has been no systematic investigation of this mechanism of VCE initiation. A recent study by Daubech et al. [14] provided some further insights into the mechanism of this type of explosion, with both experimental and computational tests. Their experimental set up consisted of a 4 m^3 chamber connected to an unconfined 54 m^3 volume with ignition in the 4 m^3 chamber. With smaller vents from the chamber the VCE overpressure was measured to be as high as 10 times larger as compared to the fully unconfined case (no bang box).

The aim of this programme of work is to investigate the effects that an ignition in a congested standard industrial closed steel electrical control box will have on the ignition characteristics and severity of an explosion in an external volume in a congested space. This paper is the first part of that programme, providing base data on the explosion development in empty electrical boxes and different vent covers, other than the standard hinged door. The aim was to find a vent cover material that would allow multiple tests to determine the worst case scenario for congestion levels inside the box, without destroying a large number of boxes in the process. The initial data presented here provided some useful insights into the dynamics of flame shape and pressure development initiated in electrical control boxes.

METHODOLOGY

Commercially available electrical control boxes 600 mm high, 400 mm wide and 250 mm , volume 0.06 m^3, with a 3 point locking mechanism were fitted to the back wall of a 8 m^3 frame rig as shown in Figs. 1 and 2. The door when fully open had a vent area, A_v, of the large side of the box and a vent coefficient $K_v = V^{2/3}/A_v$ of 0.64 and a ratio of the surface area of the box, A_s, to A_v of 4.08. NFPA68 [26] venting guidance predicts a P_{red} of 1.75 mbar for propane and the European Guidance [27] predicts a P_{red} of 30 mbar by extrapolation, but this is for a 100 mbar vent static burst pressure, so the European venting guidance is not valid for the large vent area of this work. It will be should that the measured P_{red} are greater than these design predictions, due to the action of the vent cover static burst pressure, P_{stat}, which is not known in the present work.

Fig. 1. Test rig in-situ with electrical box with door on in place ready for testing.

Fig. 2. Three point locking mechanism of the control box doors.

The left side wall of the box was cut away and replaced with 5 mm polycarbonate for viewing purposes. For some of the tests the door was removed using the hinge pin and the opening was covered with cling film or aluminium foil. Due to the shape of the box aperture, taping with duct tape was the most efficient method of attaching the foil or film membrane.

Tests were conducted using stoichiometric propane/air mixtures ignited by a Talon^{TM} tungsten hot wire firework central ignitor on the back wall of the box. The gas concentration was controlled with mass flow controllers. The box was filled by purging the box with pre-mixed gas at the desired concentration and monitoring the exhaust with a gas analyser to ensure purging was complete. Overpressure measurements were made using fast response pressure transducers, located internally and externally to the box, as shown in Fig. 3. Time of flame arrival was recorded using fast response thermocouples set at distances from the ignition point of 25 mm, 250 mm (vent), 500 mm and 750 mm. In some of the tests high-speed (up to 3200 fps) and mid-speed (240 fps) videography was taken and from these flame position and flame speed determinations were made.

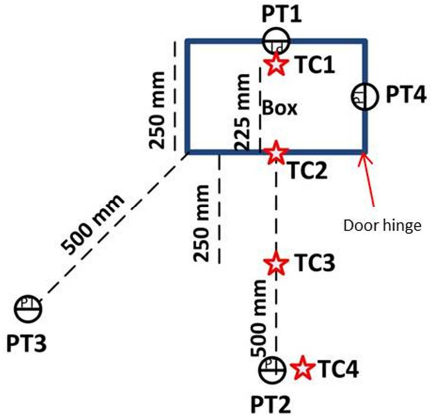
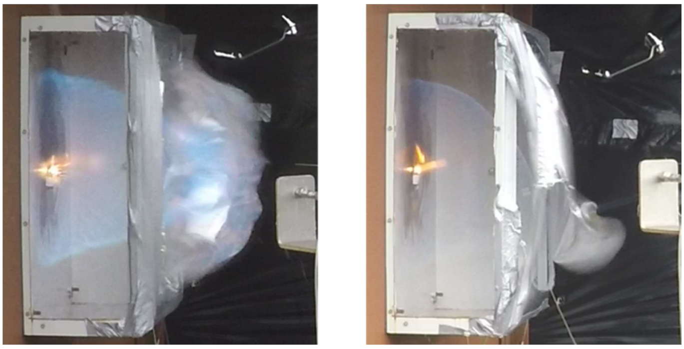


Fig. 3. Plan view of location of pressure transducers.

RESULTS

Dynamics of pressure development and box venting process

The door had a defined failure mechanism through plastic and elastic deformation of the three point locking mechanism, as shown in Fig. 2. The locking pins were held by weak plastic fixings at two points, designed to be removable by the user to install sundry items such as locking handles. However, in both tests the failure was slightly different; in test 1 both pins were detached from the centre and the lower pin completely removed. In test 2 only the top pin was detached from the centre and there was an increase of 16-17 % in the internal overpressure. In both tests the door started to open before the flame reached it.

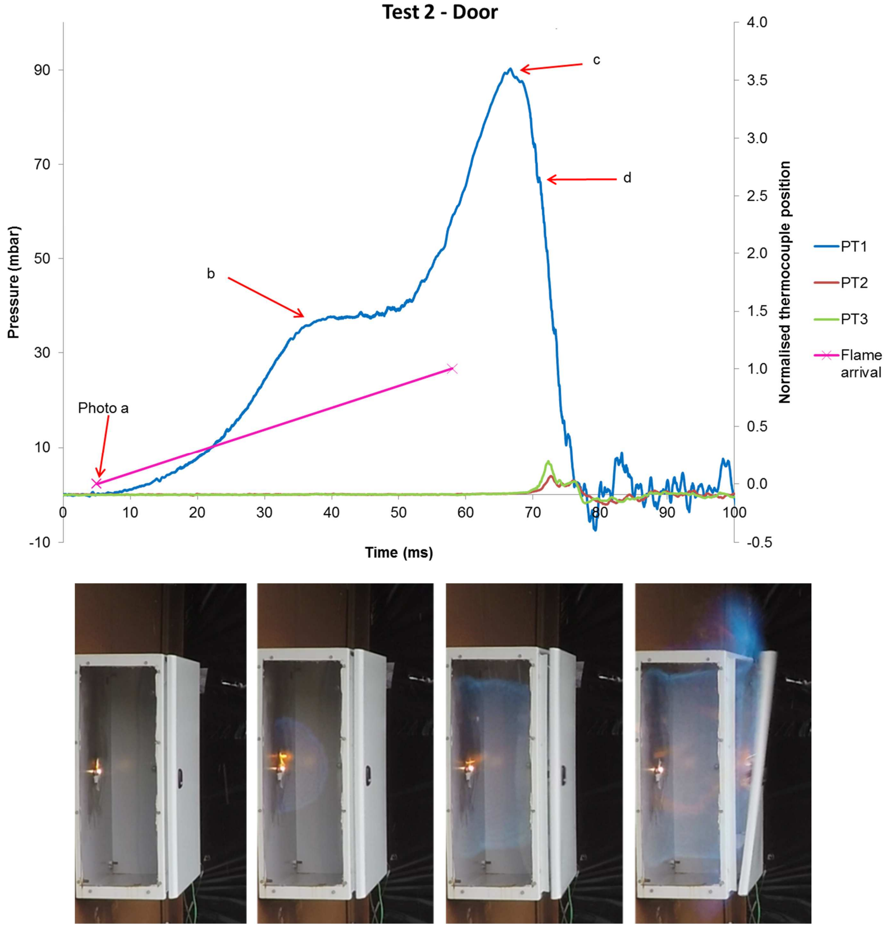


(a) (b)

Fig. 4. An example of two of the foil failure mechanisms. (a) The foil burst and was almost completely detached (test 4). (b) The failure started as the tape detached from the side in the early stage of the event, the foil then tore from this point along the centre (test 3).

In the foil tests, the way they burst was variable and the random size of the hole left by the venting process influenced the internal overpressure. In test 3 approximately 50 % of the vent was removed and in test 4 nearly all the vent was removed. On analysis of the explosion video it is apparent that the hole size depends on the strength of the foil fixing. In test 4 the foil burst rather than tore, as shown in Fig. 4a; in test e the tape detached from the side of the aperture in the early stages of the event, before the flame exit and the foil started to tear in this area, as shown in Fig. 4b. Fig. 4 shows for both explosions that when the flame leaves the vessel and bursts the vent, it is still well away from the side walls. The flame propagates in the direction of the vent, even for this vessel with a very sort distance from the spark to the vent cover.

In Test 4 the venting process with foil was rather similar to that for a door with a vertical crack appearing down the edge of the box closest to PT3. Following the rapid development of the crack the central parts of the foil near the opening was effectively unrestrained. The foil is light and rapidly accelerates to match the velocity of the gases emerging from the fissure.

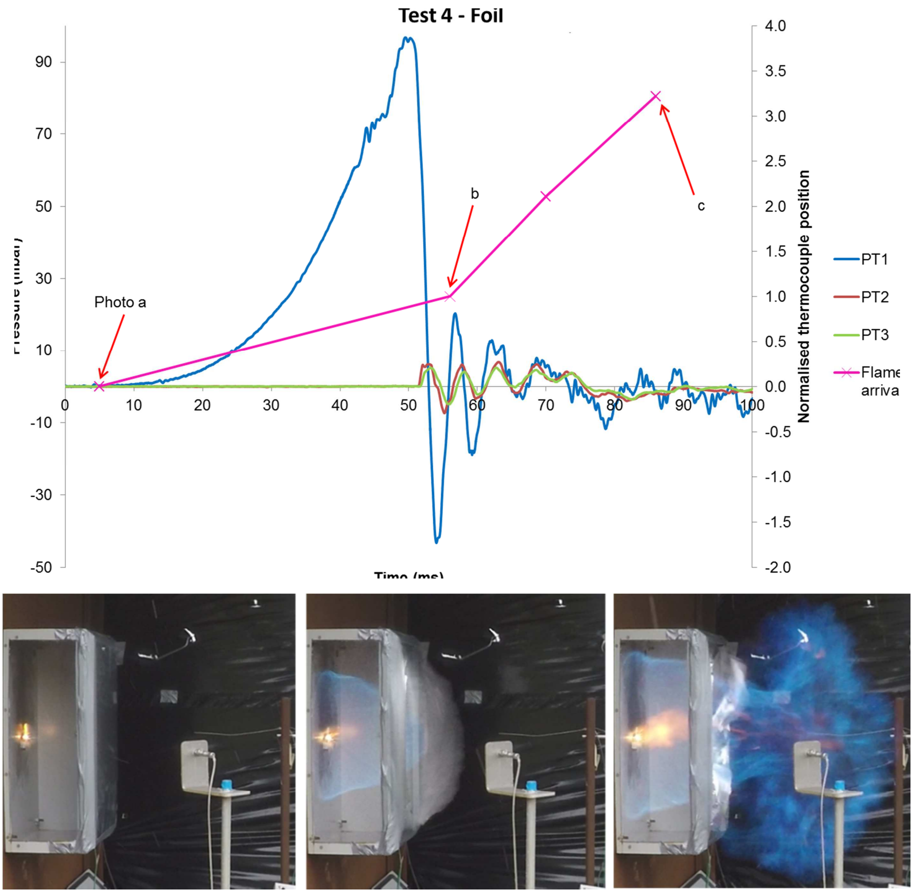


(a) (b) (c) (d)

Fig 5. Test 2. Pressure and flame transit trace. Photo (a) showing flame start. Photo (b) showing partial venting as door distorts. Photo (c) showing beginning of full venting. Photo (d) showing flame exit.

The pressure records of Tests 2 and 4 are shown in Fig. 5 and Fig. 6, which demonstrate that for both the door and the foil vent the vent burst pressure dominated the overpressure and other pressure peaks were not significant. The P_{red} in Fig. 5 were much higher at 90 mbar than those predicted from venting standards at < 2, mbar for NFPA 68 [26]. The initial pressure rise of test 2,

(Fig. 5) and test 4 (Fig. 6) is at a similar rate, but in test 2 as the door opens it deflects at the top and venting begins with a much lower open area than when the vent is full open. The pressure rise stalls as the vent is opening further. This causes a slight delay (~15ms) in reaching the bursting point of the door, compared to the bursting point of the foil in test 4. There is also a reduction in flame speed within the box in test 2 compared to test 4, which is due to the early partial venting of the door compared to the foil vent cover. In test 2 the flame exits before the peak pressure is achieved, in test 4 the flame exits after the vent has burst and the pressure within the box is relieved. In test 2, as the door is still in front of the vent as the flame exits, the flame is distorted and diverted away from the external thermocouples. In test 4 acceleration of the flame externally can be seen.



(a) (b) (c)

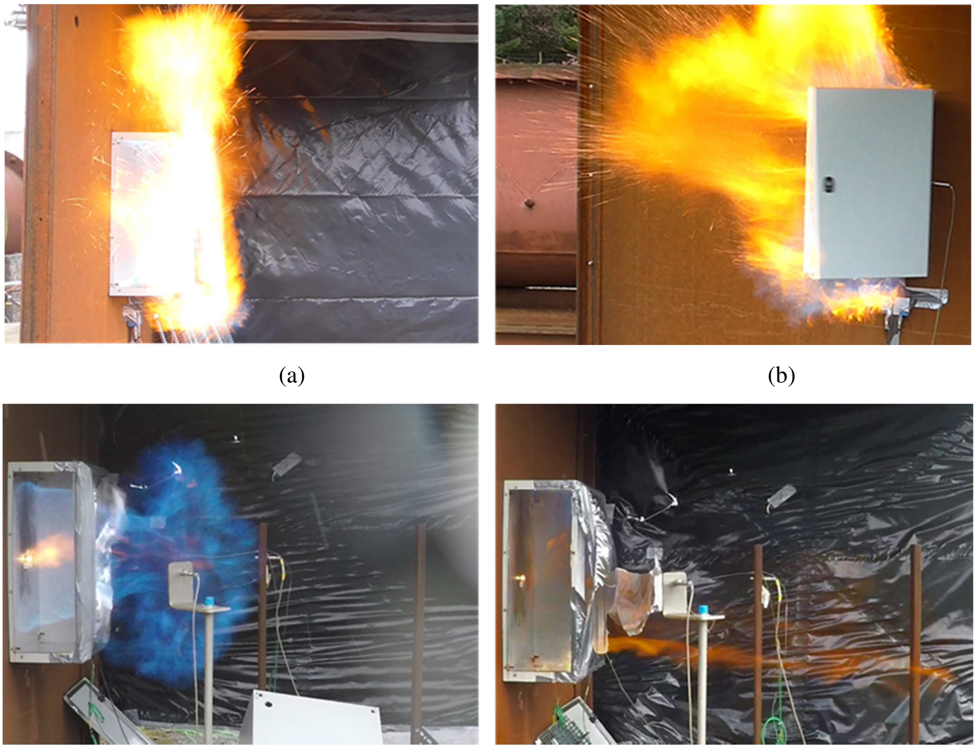
Fig 6. Test 4. Pressure and flame transit trace. Photo (a) showing flame start. Photo (b) showimg flame transiting vent. Photo (c) showing flame 500 mm from vent, 750 mm from ignition source.

Measurements from high speed video of the vent failure in Test 4 indicated an initial foil displacement speed of 20 m/s. The internal pressure in the vented explosion when the vent burst was 97 mbar which, assuming a dynamic head, pressure loss at the vent would correspond to a mean vent area flow speed of 122 m/s. This initial pressure is only developed across a small open area and diminishes to about 5 mbar as the vent opens further. The rapid vent pressure relief is followed by small pressure oscillations and these are also registered further out, but these are not significant.

In the cling film test the membrane stretched ahead of the flame until it burst on the TC3. As the film is stretched and thins, surface defects, such striations caused in manufacture, are likely to have an increasing influence on bursting or tearing. This failure mechanism and the associated pressures were so different from the behaviour with a door or foil vent cover, that this method of vent cover was abandoned.

Flame characteristics

What is of interest in the results of these tests is the vented flame structure. In the door tests the vented flame shape was consistently a flat petal shaped (Fig. 7a and b). In test 4 the flame shape was a rolling vortex bubble (Fig. 7c), which induced little turbulence to the external volume, as detailed by Daubech et al. [14]. In test 3 the vented flame shape was broken down into a jet (Fig. 7d), but the flame took 44 ms to travel 500 mm from the vent, compared to 30 ms for test 4 and the jet was only established in the latter part of the event.


(a) (b)

(c) (d)

Fig. 7. Vented flame shapes witnessed in testing - test 1 (a) and (b), test 4 (c) and test 3 (d).

Maximum pressures and flame speeds

Table 1 shows for overpressure measurements; PT2 and PT3. The results for PT4 were identical to PT1. Figure 5 and Fig. 6 show pressure time traces for tests 2 and 4. The cling film vent cover results are clearly lower than the vent covers as they do not have a defined bursting pressure due to their stretching. The foil P_{red} were similar to those of the door, in spite of the differences in the pressure time characteristics in Fig. 5. On this basis it is recommended that the foil cover is a reasonable basis to investigate the influence of obstacles in the electrical box in future work.

Replacing the complete box so that new doors can be tested is expensive, as 100+ explosion configurations are planned for this future work.

Table 1. Results of ovepressure measurements

Test	Vent covering	PT1 (mbar)	PT2 (mbar)	PT3 (mbar)
1	door	78	2	4
2	door	90	4	7
3	foil	72	3	3
4	foil	97	5	5
5	cling film	9	>1	>1
6	cling film	15	2	2

Table 2 details the flame transit time measured from TC1. The results from the external thermocouples for test 6 may be anomalous as the cling film expanded to a point that it burst on TC3, moving it and potentially thermally isolating it from the flame temporarily. The average flame speed inside the box is close to the spherical laminar flame speed of about 3 m/s for propane. The flame speed downstream of the vent is much higher due to the turbulence induced by the vent bursting. However, these flame speeds are much lower than those measured by Fakandu et al. [23] for a 10L vented vessel with end ignition and an open vent. All these flame speeds are too low to give significant dynamic over-pressures. However, the flame size shown in Figs. 6 will give a strong ignition source when there is an external cloud around the vessel.

Table 2. Flame transit times from TC1

Test	Vent covering	TC2 (ms)	Average flame speed (m/s)	TC3 (ms)	Average flame Speed (m/s)	TC4 (ms)	Average flame Speed (m/s)
2	door	53	4.25	-	-	-	-
3	Foil	44	5.11	69	10	88	13.15
4	foil	51	4.41	65	17.86	81	15.65
6	cling film	44	5.11	92	5.21	97	50

CONCLUSIONS

The dominating factor for the internal overpressure was the vent burst pressure for these very large vent area explosions. This effect has been documented before by Fakandu et al. [23], who reported a proportional correlation for different gases between static bursting pressure of the membrane and the dynamic bursting pressure during an explosion in a small volume vessel (10 litre). Their vessel was elongated with a L/D of 2.8. The boxes in these tests are a larger volume (60 litre), with a different geometry and an L/D of 0.34 and the size of the vent would make determining static bursting pressure difficult, especially with the door.

The door has different failure mechanism to the foil, when applied strongly; the foil bursts and rips open and is removed from the full area of the vent, whereas the door hinges open and obstructs the vent during flame exit. The foil rupture opens quickly and moves easily out of the way of the flame exit. But in both tests the vent area is increasing during the venting, the full vent area is not exposed immediately. The external overpressures were either very low or non-existent. There is also the potential that the failure mechanisms of the vent covers may have an effect at a larger scale. Earlier work in this programme [28] has demonstrated that steel cladded panels on a building can act as turbulence-inducing congestion as they hinge open during an explosion and severely increase the overpressures produced in the event.

The explosions in the boxes with the door do not produce the rolling vortex flame shape seen by Daubech et al [14], and seen in test 4, a flat petal shape is produced. What is a not known is how the flat flame shape and overpressures produced by these explosions affect the ignition mechanisms in an external volume, but this is the focus of a later stage in the programme. As the door opens in the early stages of the explosion unburned gas is forced through the gap in the door creating turbulence. If this is vented into a flammable external volume there will be a larger external explosion, which is the subject of future work.

In tests 1 and 2 the door remained attached to the hinges. The door on the box, proposed as the ignition source for Buncefield, was detached and travelled some distance and the box was distorted from the internal overpressure [3]. It should be noted that these test were, conducted with new high quality, strong boxes that are constructed with pressed mild steel but have a relatively weak locking mechanism and had no congestion. The box at Buncefield was highly congested. Further work will be carried out in this programme to look at the effects of differing congestion levels.

Cling film does not seem to be a valid method for further testing due to its behaviour when heat and pressure are applied. If the foil, strongly attached and bursts, the burst pressure appears to be slightly higher than the door. It does suggest that a foil membrane is a valid method for further tests to investigate the effect of added congestion in the boxes on flame speeds and overpressures. But when addressing a bang box effect, standard vented explosions with cover other than the doors probably can't be used to substitute for the door fronted boxes, because of the significantly different external flame shapes which will form the ignition source of the external cloud.

DISCLAIMER

This paper and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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