The Effects of External Fire on Fireworks Stored in Steel ISO Transport Containers

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ABSTRACT

The increased use of steel ISO transport containers for storing fireworks led the UK's Health and Safety Executive (HSE) to commission research to gain a better understanding of the behaviour of fireworks in such storage when exposed to an external fire. Subsequent incidents involving storage of fireworks in ISO containers demonstrated that violent explosions could occur. This added impetus to the research programme. It was found that selection boxes of fireworks that were readily available to the general public were unlikely to present a significant hazard in bulk storage. More energetic fireworks, such as those used by professional display operators, were capable of generating sufficient pressure within the container to cause the doors to fail and for the walls and roof to become deformed. These more energetic trials used a range of firework types including star shells up to 200 mm in diameter, and resulted in unburnt stars being projected up to 140 m and unexploded fireworks being thrown to a distance of up to 32 m. Pyrotechnic effects (stars) were observed over an area in excess of 100 m diameter and thermal imaging indicated that a fireball with an effective surface temperature of 400 °C was produced over a diameter of 36 m. None of the trials produced violent mass explosion effects of the type reported in connection with recent incidents at Uffculme, UK and Enschede, The Netherlands.

Keywords: fireworks, storage, fire, explosion, ISO, container, classification, UN

Introduction

Large quantities of a whole range of materials, including fireworks, are shipped around the world in steel ISO containers. In recent years in the UK, manufacturers and retailers have used such containers to store a large proportion of their fireworks. Each container may be large enough to store tonnes of fireworks ranging from British Standard (BS) Category 1 (fireworks for indoor use) through to BS Category 4 (fireworks for professional display operators only), as defined in BS7114:1988.[1]

In 1980, tests in Seattle, WA USA,[2] demonstrated that the impingement of an external fire onto an ISO container of fireworks (2.5 tonnes) can result in a violent explosion. Two minutes after the fire was ignited, explosions projected the contents up to 61 m vertically and 213 m horizontally. Approximately 2 hectares of land sustained fire damage. Subsequently an accident at Stourbridge, Worcestershire, UK in 1996,[3] which involved 600 kg of fireworks, resulted in the doors of the storage container being blown open and the ejection of firework fragments, which caused minor damage to a fire engine. The gable end of a building some 20 m away sustained damage and a large wooden door caught fire. After the incident, the ISO container walls, roof and floor had been bowed out.

Based on this background, HSE's Explosives Inspectorate identified a need to gain a better understanding of the behaviour of fireworks stored in ISO containers when exposed to an external heat source. The Health and Safety Laboratory (HSL) was commissioned to perform tests to generate data that could form a scientific base from which future guidance on firework storage could be developed.

Figure 1. 6.1 m long ISO transport container.

The research commenced in 1996 and gained new impetus in 1998 when a serious fire and explosions occurred at a fireworks company in Uffculme, Devon, UK.[4] Eight ISO containers holding fireworks and located inside a large metal clad structure were involved in the fire. One of the ISO containers subsequently exploded causing considerable blast and fragmentation damage both on and off site. The recent accident at Enschede in The Netherlands,[5] where at least 20 people died, has highlighted the relevance of this research.

This paper describes the scientific work undertaken to date by HSL to investigate the behaviour of fireworks stored in steel containers when challenged by an external fire source and complements a previous HSE paper[4] that dealt with the wider health and safety issues raised by accidents in bulk fireworks storage.

Experimental

Mass, linear distance and peak noise measurements made during this work can be traced to national Standards.

ISO transport containers [6.1 m (20 ft) long] are commonly used for fireworks storage and were selected for these trials (Figure 1). Each container had two hinged full length doors at one end, with a rod and lever locking system to the top and bottom of the main body of the container. The floor was made of wood supported on I-section cross girders. The corrugated metal skin of the container was attached to the main structure by rivets. In the UK, a store for explosives must be maintained to a standard that prevents rust from contaminating the explosives being stored.[6] Often this requirement is met by lining the walls and ceiling of the container with wood or by maintaining a good painted

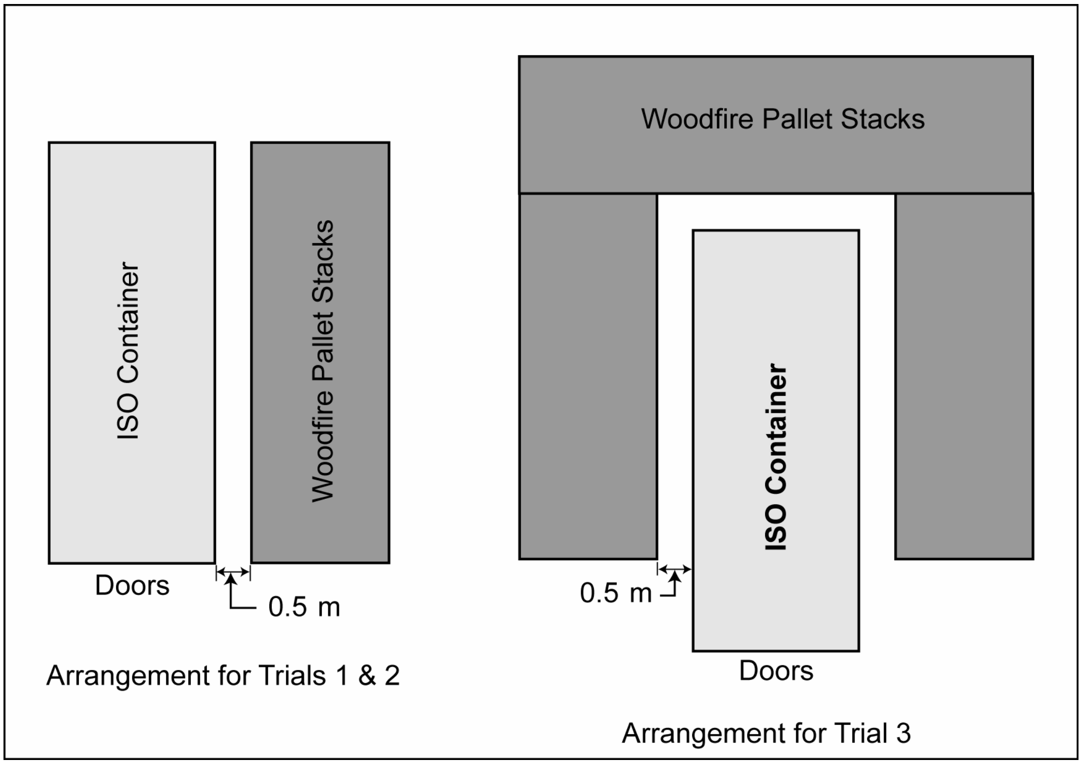

Figure 2. External fire arrangements for trials.

finish. For the purposes of these trials the containers were not wood lined.

To ensure that enough heat would be generated by the external fires, wooden pallets were stacked to the height of the containers, and 0.5 m from the container walls. Absorbent paper, doused with a small amount of kerosene (< 25 litres), was inserted into the spaces in the lower pallets and Plastic Igniter Cord (PIC) was interwoven with the doused paper along the full length of the pallets. Remote ignition of the PIC caused ignition of the doused paper along the full length of the pallets within 30 seconds; this ensured that the burning pallets provided an even flame front to act on the container.

The first two trials used relatively small volumes of fireworks stacked against the side of the container nearest to the external fire (Figure 2) whereas the third trial had fireworks stacked to both sides. Also the external fire arrangement was different in the third trial.

The three trials were intended to be representative of the bulk storage of fireworks with low, medium and high net explosive content (NEC). Details of the types of fireworks used for each trial are given in Table 1.

Labels on the selection (assortment) boxes for Trial 1 stated that they were “Display Fireworks” (i.e., BS Category 3). However, over 85% of the fireworks they contained were less energetic BS Category 2 fireworks; the remainder were BS Category 3 from which the selection boxes got their rating. Such boxes are readily available at retail outlets in Great Britain where the majority of the general public would purchase their fireworks (both these categories would generally be termed consumer fireworks in the US). They were packaged in outer cardboard transport packs, which were stacked two boxes deep along one side of the container and stacked on top of one another. The packs were pushed against the metal cladding of the container.

Trial 2 comprised a mixture of fireworks classified as UN1.3 or UN1.4, which represented a typical stock for a small professional display operator. The mixture of fireworks was agreed upon by representatives of the UK fireworks industry. The transport packs were stacked along

Table 1. Summary of Fireworks Loads Used in Trials.

Trial No.	Contents of ISO Container	No. Cases	Gross Wt. (kg)	NEC (kg)	UN Classification
1	**BS Category 3 Selection Box Fireworks** (contain > 85% BS Category 2 fireworks)				
	Assorted selection boxes readily available to UK general public	72	1000	228	1.4G
2	**Mixture of UN 1.3G and UN 1.4G Fireworks** [Proportion UN 1.3 (by NEC) = 48%]				
	Chinese cakes/crackle mines	15	345.0	90.0	1.4G
	Titanium gerbs	1	8.0	4.0	1.4G
	2 oz Sticked rockets	1	30.0	10.0	1.4G
	2 oz Rockets	1	30.0	10.0	1.4G
	4 oz Rockets	1	60.0	20.0	1.4G
	4 oz Sticked rockets	2	60.0	20.0	1.4G
	30 mm Comet candles	1	50.0	23.0	1.4G
	30 mm Bombette candles	1	50.0	14.5	1.4G
	45 mm Comet candles	2	56.0	29.6	1.3G
	45 mm Bombette candles	2	56.0	20.0	1.3G
	60 mm Candles (assorted)	3	60.0	30.0	1.3G
	Shell 75 mm dia.	4	63.6	43.2	1.4G
	Shell 100 mm dia.	6	140.4	86.4	1.4G
	Shell 125 mm dia.	11	221.8	138.6	1.4G
	Shell 150 mm dia.	13	224.6	140.4	1.3G
	Shell 200 mm dia.	10	224.0	140.0	1.3G
	75 mm dia. colour mines	1	4.4	3.0	1.4G
	Totals	**75**	**1683.8**	**822.7**	
3	UN 1.4G shells				
	Boxes of 18 x 125 mm dia. star shells with flash composition burst charges	270	4050	2600	1.4G

one side of the container, up to three rows deep, and stacked on top of one another. To represent a typical store, some of the rockets had sticks attached and were placed head down in two plastic dustbins. Where appropriate, the packs of fireworks were pushed against the metal cladding of the container.

Fireworks for Trial 3 consisted entirely of 125 mm diameter star shells, which were classified UN1.4. These shells contained a blackpowder lift charge, stars, and a flash burst charge. The cardboard transport packs, which each contained 18 shells, were stacked 6 cases high by 5 wide, with 9 rows of cases from front to back in the container. These transport packs filled the rear 70% of the container. The remaining space between the front row of firework packs and the doors of the container was filled with boxes of vacuum packed wood shavings so that the air volume present was similar to that of a full container. Wood shavings were chosen because they had a packed density similar to that of the full firework transport packs. The fireworks and shavings were positioned centrally along the long axis of the container so that only the cartons at the back of the container were in contact with the metal cladding.

All the trials were recorded using normal speed video cameras and still photography was used to record the set-up and aftermath of each trial. In addition, Trial 3 was recorded using a thermal imaging camera to provide data on the expected fireball. After each trial the state of

Table 2. Chronology of Events for Trial 1.

Time (hrs:min:sec)	Event
00:00:00.0	External fire ignited
00:10:00.0	Audible roar from container
00:16:00.0	Effects in container continue sporadically for next 17 hrs
01:00:00.0	External fire burnt to embers
17:15:00.0	Last firework effect heard
18:10:00.0	Opened doors
18:10:01.0	Flames from doors
18:10:02.0	Effects heard and stars ejected
19:10:00.0	Frequency of effects reduced. Sporadic effects up to 23.5 hrs after external fire ignited

the container and the distance that debris had been projected was recorded.

Overpressure measurements were obtained using CEL414 soundmeters capable of recording noise levels of up to 160 dB(C). The sound pressure level obtained (in dB) was converted to the equivalent overpressure (P_{calc}), measured in kPa, by using the following expression.[7]

$$P_{calc} = P_0 \left(10^{\frac{\text{dB}}{20}} \right)$$

where $P_0 = 2 \times 10^{-8}$ kPa.

Results

Trial 1 (Selection Box Fireworks)

A summary of the events from the trial is given in Table 2. Considerable firework activity was heard 10 minutes after the fire was started, but the doors remained closed and no effect, apart from smoke, was visible outside the container. Sporadic ignitions of fireworks were still being produced 17 hours after the trial started.

The majority of the surface of the ISO container was cold to the touch after 18 hours when one of the doors was opened. The wooden floor of the ISO container was burnt through in a number of places and most of the transport packs of fireworks were blackened. Virtually all the packs were in their original positions with their contents charred but unburnt. Immediately after the door had been opened, the volume of smoke being generated increased, and within 1 minute the remaining contents of the container were engulfed in flame. Firework effects were heard 2 minutes after the door had been opened and soon became too numerous to log. Only sporadic effects were being produced 1 hour after the doors were opened. After all fire activity had ceased, the floor of the container had been completely burnt away. Generally, the ash from the fireworks and packaging was in the same location as the unburnt transport cartons. This indicated that no major explosions had taken place to dissipate the ash. The main structure of the container was blackened but intact. Both doors remained on their hinges, and there was no deformation of the corrugated steel skin.

Soundmeters, positioned at 100, 150 and 200 m from the container, were only used to monitor noise levels while the container was closed. None of the measurements exceeded 100 dB(C) (2 Pa).

Table 3. Chronology of Events for Trial 2.

Time (min:sec)	Event
00:00.0	External fire ignited
07:05.3	1st explosion. Smoke from side vent
07:08.0	2nd explosion. Smoke jets from vent and door area
07:11.7	3rd explosion. Increase in power of smoke jets
07:13.7	Explosion opens doors slightly. Allows stars to be ejected
07:14.7	Multiple explosions. Increase in smoke jet strength. Smoke changes from whitish grey to black
07:20.5	1st fireball ejected from bottom of doors. Doors still closed
07:26.8	Large explosion. Assumed to blow doors open but smoke obscures view.
07:32.5	Shell ejected confirming that doors are open. Multiple explosions continue
07:49.0	Explosion frequency substantially reduced
11:35.7	Intermittent small reports continue

Trial 2 (Mixture of UN1.3 and UN1.4 Fireworks)

A summary of the events from the trial is given in Table 3. The first explosion caused smoke to emanate from the container wall vents, and subsequent explosions over the next 9 seconds increased the pressure inside the container causing smoke to 'jet' out from the seals around the doors with increasing power and a few burning stars were seen to escape from the container through the door seals even though the doors still appeared to be closed. At the end of this phase the colour of the smoke being produced changed from whitish grey to black. A fireball was ejected from the base of the doors after 7 minutes 20.5 seconds and was followed shortly after by a large explosion. The doors were certainly open 27 seconds after the first explosion because shells could be seen as they were ejected from the container. The frequency of explosions was decreasing 44 seconds after the first event, and all major explosions had occurred within the first 4 to 5 minutes. Firework casing debris was found up to 34 m in front of the container and approximately 20 m in other directions. Unburnt star shells were found at distances of up to 140 m from the front of the container.

Both doors of the container were bent by the explosion but remained on their hinges. The wooden floor had been completely consumed by the fire. The walls and roof were slightly bowed out. Three small areas of the weld had failed between the floor and walls, the largest of these being 180 mm long and 15 mm wide.

Soundmeter readings at 250 and 400 m indicated that the peak noise levels obtained were 132.8 dB(C) (87 Pa) and 131.2 dB(C) (73 Pa), respectively.

Trial 3 (125 mm Diameter Star Shells)

Still photographs of the progress of the trial are shown in Figure 3. A summary of the events from the trial are given in Table 4 and noise measurements are given in Table 5.

Table 5. Noise Measurements from Trial 3.

Distance from ISO container (m)	Peak noise level dB(C)	Peak noise level Pa
100	147.5	474
150	141.8	246
200	140.6	214
250	137.1	143
350	138.2	159

The first large explosion occurred 12 minutes 36 seconds after the external fire was ignited and was followed by further explosions over the next 4 to 5 seconds. At this stage the colour of the smoke emanating from the door seals changed from light grey to black and was followed 1.5 seconds later by three explosions in

External Fire Engulfing Container	Main Explosion	Extent of Radiating Stars

Figure 3. Progress of Trial 3.

close succession and an increase in the flow of black smoke from the door seals. A fireball was visible at the container doors 12 minutes 45 seconds after the external fire was ignited, followed by major explosions that started 3 seconds later and continued for the next 18 seconds. During this time the visible extent of the pyrotechnic effects (stars) extended beyond the confines of the floor of the quarry in which the trial was conducted, indicating a diameter in excess of 100 m. After this period the frequency of the explosions started to subside. The last explosion occurred 2 minutes 36 seconds after the first large explosion.

Table 4. Chronology of Events for Trial 3.

Time (min:sec)	Event
00:00.0	External fire ignited
07:20.4	Fire engulfs container
08:46.9	1st bang/rumble heard. No change to container
08:48.0	2nd bang heard. No change to container
08:52.5	3rd bang heard. No change to container
10:05.6	White smoke stream from container vents
10:40.1	Copious smoke from top of doors
11:13.5	White smoke streams from vents and cracks around doors
12:36.4	1st explosion
12:39.7	2nd explosion
12:41.1	Double explosion
12:41.4	Black smoke jetting from door joints
12:42.9	Triple explosion
12:43.4	Black smoke jetting from doors. Start of multiple explosions
12:44.5	White ball of flame ejected from doors
12:47.6	Major explosions start
13:05.4	Majority of explosions complete
13:08.3	Penultimate explosion
15:12.3	Last explosion

Shell case debris was found in front of the container in an arc of 50° centred along the container main axis. The ground immediately in front of the container was blackened with ash and was almost devoid of firework debris, which had been blown out to a distance of 16 m where a pool of water arrested its travel. The majority of the shell casings collected at the water's edge although a few were found on the other side of the pool (32 m from the container doors). No complete shells were found beyond this distance. However, small fragments of shell casing were observed up to 150 m from the explosion point. Unburnt stars from the shells were found up to 100 m from the explosion point. Of the 4860 shells used, 51 were found to be intact and capable of re-use after the trial was complete.

Both doors of the container were slightly bent by the explosion but remained on their hinges. The wooden floor had been completely consumed by the fire exposing the supporting girders, some of which were also bent. The walls and roof were slightly bowed out in a manner similar to the container in Trial 2. One area of the weld had failed between the floor and walls over a distance of 100 mm.

Table 6. Fireball Dimensions for Trial 3.

Event	Start Time of Event (min:sec)	Effective Surface Temperature[EST] (°C)	Maximum Fireball Diameter (m)
External fire ignited	00:00.0	Ambient	n/a
1st fireball	12:44.5	>400	19
		>800	14
Major explosions (duration approx. 18 s)	12:47.6	>400	36
		>800	22

Analysis of the thermal images of the trial indicates that immediately prior to the first explosion the effective surface temperature (EST) of the external fire was in the range of 600 to 700 °C. This increased rapidly to over 900 °C once the explosions started. The dimensions of the fireballs produced are given in Table 6.

Discussion

Results from Trial 1 showed that 1 tonne gross weight of BS Category 2 and 3 selection box fireworks contained in cardboard transport packs are unlikely to explode with sufficient violence to breach the containment afforded by a steel ISO transport container. The fact that the ash from the fireworks and packaging was in approximately the same position as the original packaged fireworks indicates that relatively weak explosions had occurred and also supports this conclusion.

The external fire generated sufficient heat to ignite some of the contents of the container but it is thought that the insulation afforded by the cardboard boxes prevented rapid spread of the fire. This may have been further slowed by an oxygen depleted atmosphere within the container. The observation that the fireworks ignited over an extended period also supports this hypothesis. The slow ignition rate suggests that the damage sustained by the container is unlikely to increase if larger quantities of low energy fireworks of this type were stored in steel containers and exposed to external heat sources. Therefore, the UN classification[8] of 1.4G appears to be appropriate for this type of firework selection box when transported (or stored) in bulk in ISO containers.

An increased potential hazard arises once oxygen is admitted to the partially burned transport packs (i.e., when the container doors are opened). Re-ignition can occur within minutes, resulting in a fierce fire and the additional hazard of burning projectiles from the fireworks being ejected from the container. It would seem prudent to inform firefighters of these hazards and suggest that fires involving pyrotechnics such as those used in Trial 1, which are stored in ISO containers, should be allowed to burn out completely before the container is opened.

Progression of the three trials followed a similar pattern until the fireworks began to explode. The external pallet fires gained energy as more fuel was burnt until sufficient radiant heat was able to induce a fire within the container, causing the fireworks to start to ignite. This process took 7 to 10 minutes for all the trials described in this paper. After the first explosion, the less energetic fireworks used in Trial 1 were unable to produce sufficient pressure in the container to force the doors open. No deformation of the container occurred and the pyrotechnic effects were contained. Pressures generated by the more energetic fireworks used in Trials 2 and 3 were sufficient to open the container doors, but the time required to attain the necessary pressure varied. The times from first explosion to the doors opening were 22 and 11 seconds for Trials 2 and 3, respectively. This may reflect a slower increase in the rate of firework explosions for Trial 2 than for Trial 3 due to the nature of the fireworks and their packaging. However, the time for Trial 3 was probably shorter because of the larger external fire (Figure 2), which produced a larger heat input.

The explosion sequences in Trials 2 and 3 also followed a similar pattern. The first few explosions caused white smoke and steam to be ejected with increasing force from the wall vents and gaps around the doors. As the explosion frequency increased, the colour of the smoke and steam changed to black, and within a few (4–6) seconds a fireball was ejected. This was followed 3 to 6 seconds later by a larger explosion. Multiple explosions continued until the reserves of fireworks in the container had been consumed. In Trial 2, where a number of different types of fireworks were used, the period from the large explosion to completion of the trial was indistinct because some of the better protected pyrotechnics (i.e., those in thick Roman candle tubes), continued to eject effects for a further 4 hours. In contrast, Trial 3—where only shells were used—was completed within 5 minutes where all but one of the shells that exploded had functioned within 20 seconds of the first explosion. The similarities between the two trials indicate that a broadly similar mechanism may have applied during the explosion of the fireworks even though the NEC differed significantly.

In Trials 2 and 3 fireballs were generated. Data from Trial 3 indicate that, during the major explosions phase (12 minute 48 seconds to 13 minutes 5 seconds), the fireball attained an effective surface temperature (EST) of at least 400 °C over a diameter of 36 m and had a hotter core (EST of at least 800 °C) over a diameter of 22 m. Fireballs of this size and temperature could cause problems for firefighters, particularly if many ISO containers of fireworks are stored close together and result in the production of numerous fireballs.

The trials described in this paper were performed primarily to assess hazards associated with bulk storage of fireworks in ISO containers. However, the same types of container are used in many countries to transport large quantities of fireworks. Therefore, the results of these trials may have implications for the UN classification for the transport of fireworks. The UN approved test for determining the hazard division within Class 1, the UN Series 6(c) Test,[8] requires a volume of packaged articles (i.e., fireworks) of at least 0.15 m^3 to be exposed to an external fire. The test criteria indicate that if a fireball extends beyond the witness screens (4 m from the test piece), or if fiery projections are thrown more than 15 m, the product should be classified as UN1.3 for transport. Results from Trial 3 suggest that stars from 125 mm diameter shells could be projected beyond 15 m if transport packages were subjected to a UN Series 6(c) Test even though the volume of fireworks used in such a test would be much less than that used for the trial. This would necessitate a change of classification of this particular type of shell to UN1.3 from its current UN1.4 classification for transport. There is also evidence from tests with unpackaged shells to suggest that smaller shells may also need to be reclassified since Shimizu[9] estimates that shells of only 75 mm diameter can project stars over a 20 to 25 m radius, well in excess of the 15 m limit set for UN1.4 classification. However, distances that stars are projected may be affected by the packaging and further work would be necessary to evaluate this.

It has already been stated that the time from first explosion to the container doors opening in Trial 3 was approximately half that observed for Trial 2. On this basis it would be expected that Trial 3 would have generated a greater pressure more quickly than Trial 2 and hence caused more damage to the container, particularly as the NEC of that trial was 2600 kg compared to 826 kg for Trial 2. It would therefore be expected that the scatter of debris would have been greater for Trial 3. This was true for the scatter of firework casing debris, which was found 34 and 140 m from the containers in Trials 2 and 3, respectively. Noise levels were also lower for Trial 2 than for Trial 3. However, both containers suffered approximately equal damage. Their doors had been blown open and the walls and roofs were bowed out to approximately the same extent. There is evidence to suggest that the greatest overpressure was in Trial 2, not in Trial 3. Three ruptures were observed between the walls and floor of the container used in Trial 2 compared to only one in Trial 3, and unburnt stars were found 140 m from the container in Trial 2 compared to 100 m in Trial 3. The increased distance that unburnt stars were projected in Trial 2 may be due to the directional nature of some of the firework types used (i.e., Roman candles) or, more likely, the fact that Trial 2 contained some shells of up to 200 mm diame-

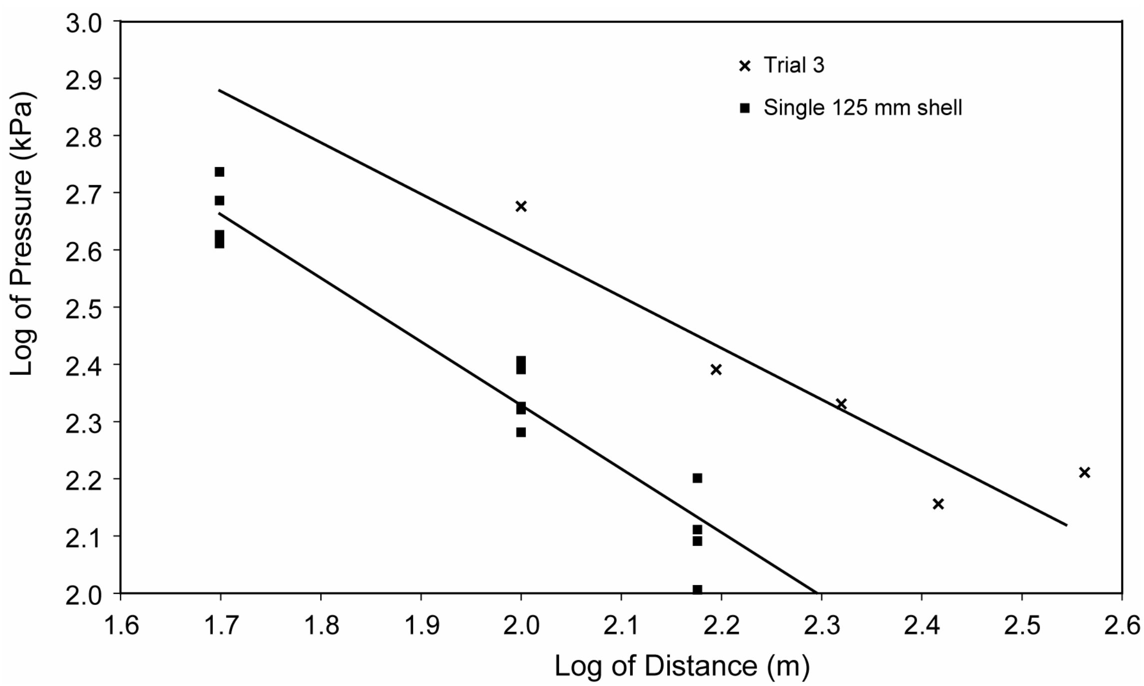

Figure 4. Overpressures measured during Trial 3 and preliminary tests using single 125 mm shells.

ter which would radiate stars to greater distances than the 125 mm diameter shells used in Trial 3. Shimizu[9] estimates the average diameter of the star burst from a 120 mm diameter shell to be 70 to 100 m compared to 130 to 150 m for a 190 mm diameter shell and 210 to 230 m for a 220 mm diameter shell. These figures compare well with the distances that unburnt stars were projected in the present trials. The presence of larger shells may also explain the additional ruptures in the container walls during Trial 2 because the burst charge would be larger and would place a higher instantaneous strain rate on the metal of the container than would a smaller shell.

The differences in the results from Trials 2 and 3, outlined above, are too small to reflect the difference in the NEC between them. These demonstrations show that the damage that a transport or storage container might sustain cannot be predicted with confidence from the net explosive content alone when an external fire occurs and firework explosions are induced inside the container. Assuming that all the pyrotechnic content of Trial 3 (2600 kg NEC) was blackpowder and that the stars in the shells would not contribute to a mass explosion because of their slow burn rate, it can be calculated that approximately 1147 kg of composition in the lift and burst charges was available for instantaneous ignition. Recent work undertaken at HSL[10] has indicated that as little as 500 g of blackpowder are sufficient to destroy a simple rectangular brick or block structure. The strength of the ISO container is likely to be greater than that of the brick or block building and a larger NEC would be required to disrupt it. However, since the much larger NEC used in the ISO container did not completely destroy the container, this indicates that the events observed did not include mass explosions of significant proportions of the contents.

Comparison of the overpressure output from Trial 3 and that from preliminary tests using single 125 mm shells (Figure 4) shows that the overpressure output from the container trial was 1.6 to 2.3 times greater than the pressure produced by individual shells over distances of 50 to 250 m, respectively. The increase in the difference in pressure between the two tests at greater distance is probably due to pressure peaks from individual shell explosions coalescing as they travel away from the explosion point. The data suggest that close to the explosion the overpressure in Trial 3 was not more than twice that obtained for a single shell. Overpressure generally increases as the cube root of the charge mass, which indicates that the observed maximum overpressure from the trial was generated from the instantaneous explosion of a maximum of 8 shells. This further confirms that, in general, shells used in Trial 3 exploded sequentially over a period of seconds or minutes. It appears that sufficient explosive needed to be consumed to generate the pressure necessary to burst open the ISO container doors. Once this had happened the energy of any remaining explosions was effectively vented to atmosphere without causing appreciable additional damage.

The debris from Trial 3 included 51 shells that were intact and capable of explosion if correctly fused. This supports the conclusion that mass explosion of the container contents did not occur. It also highlights one of the potential hazards that firefighters may be exposed to during a clean-up operation. During HSL's trials, shells were only found outside the container, but this may not necessarily be the case in all situations. Unexploded shells could be covered in ash, which could cause ignition if not damped down sufficiently. Since explosion of a shell close to a person could cause severe injury, emergency services should be informed of this hazard.

The preceding discussion attempts to explain the effects observed during the trials described in this paper. However, it does not explain the ferocity of the explosions reported from the incidents at Uffculme[4] and Enschede.[5] In both cases the contents of the storage containers started to function as described in Trials 2 and 3 of this paper, but rapidly escalated to produce effects normally identified with mass explosion events (UN classification 1.1). In these incidents blast damage was observed at a considerable distance from the source of the explosions. Assuming that only fireworks were stored in the containers, it seems likely that a large proportion of the pyrotechnics in the store must have exploded instantaneously. To simultaneously expose such large amounts of pyrotechnic composition, well-made and well-packaged fireworks would require a considerable disrupting force. This might be achieved if large shells, or more likely, fireworks containing significant quantities of flash powder, such as report shells, were present. No fireworks of this type were used in HSL's trials, which may explain why the events observed at the incidents were not reproduced.

Conclusions

1) Selection boxes designated 'BS Category 3 display fireworks', which contain a mixture of low energy Category 2 and 3 fireworks, similar to those used in Trial 1, are unlikely to cause explosions that will have sufficient force to damage an ISO container. Therefore, the pyrotechnic effects are likely to be contained.

2) Opening the doors of an ISO container of BS Category 3 display fireworks selection boxes—after the contents have been ignited by an external fire—can result in a rapid escalation of the fire leading to a heightened hazard from pyrotechnic effects outside the container.

3) Some fireworks types, such as the 125 mm star shells used in Trial 3, currently classified as UN1.4, are likely to throw fiery projections beyond the 15 m distance specified in the test criteria for the UN Series 6(c) Test and may require a UN1.3 classification. As a result of these findings a review of certain aspects of firework classification may be necessary.

4) If sequential explosions of fireworks in an ISO container occur, as has been demonstrated in the trials described in this paper, the weakest point of the container (the door bolts) will fail and allow subsequent explosions to vent. Although star shells of up to 200 mm diameter have been tested as part of a mixed load (Trial 2) during the current trials, larger or more energetic shells would need to be assessed before this conclusion could be widely applied.

5) These trials have not reproduced the mass explosion effects reported at the incidents in Uffculme and Enschede. This suggests that fireworks other than those tested may have been present in those incidents, or that the fireworks were confined differently. In Tri-

als 2 and 3 the initial explosions blew open the ISO container doors, which would have reduced the confinement around the fireworks.

Further Work

The current work has shown that the UN classification of fireworks may need to be reappraised in some instances. At the time of writing, papers have been submitted by The Netherlands for consideration at the UN and a European collaborative research proposal has been submitted for funding under the Framework V programme. The latter will test large quantities of a range of firework types when stored in ISO containers challenged by an external fire source. To date, however, it has not been possible to provide an adequate explanation of the mass explosion effects reported from the Uffculme and Enschede incidents. As a result, HSE has instigated research to investigate current fireworks classifications, using UN Series 6(c) Tests, to explore the possibility of high energy shells causing disruption of fireworks packaging leading to mass explosion behaviour, and is considering the merits of developing small scale methods of screening fireworks that are able to predict their likely behaviour when stored in large quantities. Findings from this research will be published in due course.

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