The fireworks disaster in enschede
Part 1: Overview and reconstruction

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Saturday afternoon May 13, 2000 a major fireworks incident occurred at the company S.E. Fireworks in the city of Enschede, the Netherlands. Twenty-two people were killed and more than seven hundred were injured. Within a radius of hundreds of meters houses were destroyed by the blast and debris generated by the explosions and burnt because of the scattered fireworks.

The possible causes, safety regulations and safety control were investigated. By order of the Public Prosecutor the Netherlands Forensic Science Institute (NFI) and TNO Prins Maurits Laboratory (TNO-PML) performed the forensic and technical investigations into the reconstruction and the cause of this disaster.

Within an hour the incident developed from a moderate fire and some initiated fireworks in one of the buildings into a series of three explosions of increasing violence. Many people witnessed the accident (at distance) and numerous video recordings from different angles were made. After the disaster an extensive investigation was started. The observed explosion effects, the inventory of the damage in the area and all the forensic evidence were analysed. They form the basis for the reconstruction of the disaster. This will be presented in the first paper. Scenarios for possible causes of each of the events were developed and analysed. The second paper on the firework disaster in Enschede focuses on the chain of events and the lessons that have to be learned from this disaster, Weerheijm and De Bruyn[7].

Keywords : Explosion; fire; accident; damage analysis; forensics; fireworks; safety regulations; bulk storage; dangerous goods; transport classification.

1. Introduction

Saturday afternoon May 13, 2000 a major fireworks accident occurred at the company S.E. Fireworks in the city of Enschede, the Netherlands. Within an hour the incident escalated from a moderate fire and some initiated fireworks in one of the buildings into a series of three explosions of increasing violence. The first was a relatively small explosion in a container. Within a minute seven garage boxes (prefab concrete storage facilities) exploded. This was followed 66 seconds later by a further explosion of storage cells in the central storage building, whereby the most violent explosion occurred in storage cell C11. The resulting blast wave was comparable to an explosion with a mass between 4000 kg TNT and 5000 kg TNT. The possible causes, safety regulations and safety control were investigated.

The observed explosion effects, the inventory of the damage in the area and all the forensic evidence were analysed by NFI and TNO. They form the basis for the reconstruction of the disaster. This paper describes the observed facts and identification of the main, crucial elements in the chain of disastrous events.

2. Situation May 13, 2000

May 13, 2000 was a warm sunny day. Many people were outside enjoying the weather and

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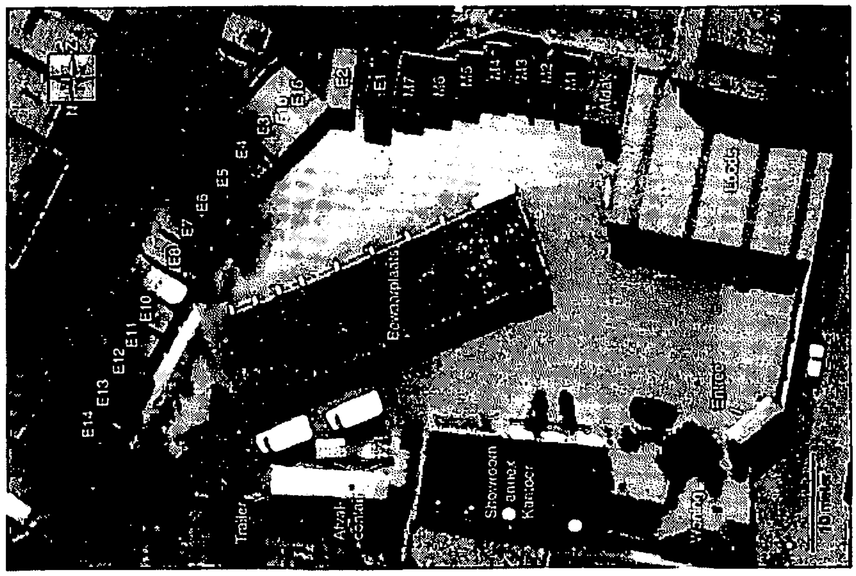


Fig. 1a The layout of S.E. Fireworks (Delta photo, adaptions NFI)

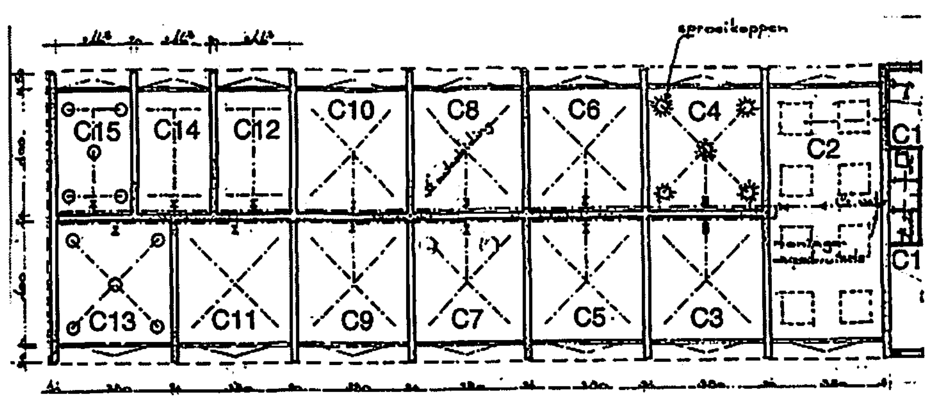


Fig. 1b The central storage building (Enschede, adaptions NFI)

attracted to the S.E. Fireworks (SEF) area due to the increasing firework effects. The SEF firework depots were situated in a residential area of the city of Enschede. The location and the layout of the SEF-depot is given in Fig. 1. The company S.E. Fireworks performed firework displays and shows, imported fireworks and did some trade in fireworks.

The depot consisted of a central storage building (cells C2-C15), seven prefab (garage) boxes and 14 ISO-containers. The central building had wooden doors and was constructed in cast, reinforced concrete with a wall and roof thickness of 20 cm. Cell 2 was the fireworks preparation and reparation room, the internal dimensions of the cells C12, C14 and C15 were 2.5 x 4.0 x 2.8 m^3 (width x depth x height). The other, larger cells had a width of 4 m.

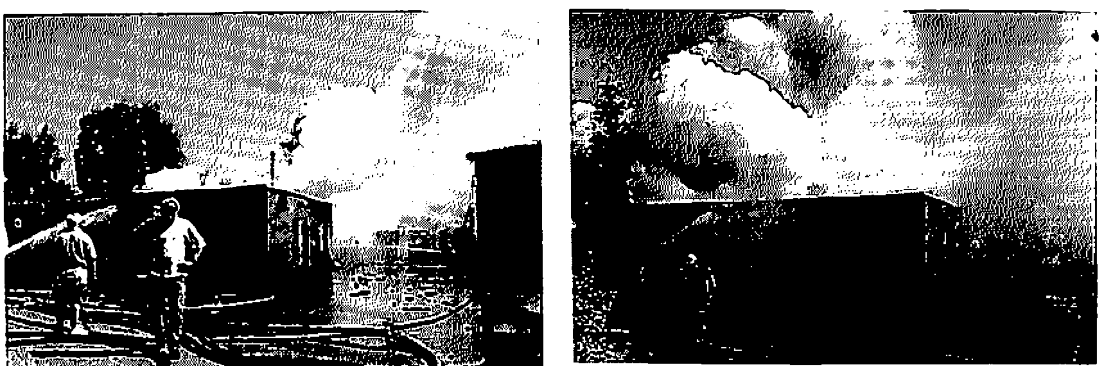
The walls and roof of the prefab concrete garage boxes had a thickness of 50 mm. The dimensions of the boxes M1-M6 were 2.6 x 5.2 x 2.3 m^3 (volume 30.4 m^3). M7 was slightly larger and had a wooden door, the others had the original thin, corrugated steel sheet doors. In order to prevent direct flame contact between cell doors in case of fire, the walls in the central building and the garage boxes were extended externally by 50 cm.

The ISO containers were standard 20 ft transport containers, with wooden floors and no additional fire protective measures were applied.

The total licensed quantities for storage were 158.500 kg (gross mass) of 1.4S or 1.4G fireworks. In some cells firework of the class 1.3G was allowed to be stored. The license permitted in total a maximum of 2000 kg 1.3G, while 136.500 kg of the class of 1.4 could be stored. The maximum and class (transport classification) of fireworks are given in Table 1.

Table 1 Licensed storage capacities

Location	Gross mass per cell	Transport classification
Central building cells C3-C11	7000	1.4S or 1.4G
Central building cell C13	500kg	1.3G
	or 7000 kg	1.4S or 1.4G
Central building, small cells	500kg	1.3G
C12, C14, C16	or 5000kg	1.4S or 1.4G
Mounting /preparation room C2	500kg, only during working hours	1.4S or 1.4G
garage boxes M1-M7	3500kg	1.4G or 1.4S
Containers E1-E14	3500kg	1.4G or 1.4S
Totals	158.500kg 1.4S/g or 136.500kg 1.4S/G and 2.000kg 1.3G	



(a) (b)

Fig. 2a Situation at 15.16 hours and Fig. 2b the escalation between 15.24 and 15.33 hours (pictures R. van Willegen)

3. Sequence of events

Due to the many people that were attracted to the accident, several video recordings from various angles are available. For learning and evaluation purposes, one member of the fire brigade was specially tasked to record fire fighting actions. Especially his recordings of the events have been very helpful in the reconstruction of the disaster.

The global time frame is:

14:45	Firework effects witnessed
15:00	Fire reported to fire brigade
15:08	Reconnaissance SE Fireworks terrain
15:16	Fire in C2 under control.
15.24	Smoke and fire effects from C4
15:33	Smoke from container E2 visible (video recording, time referenced to seismic recordings of the massive explosions)
15:34	Small explosion, massive deflagration of contents E2
15:34:40	Massive explosion garage storage boxes M7-M1
15:35:46	Explosion C11 (central building). Almost simultaneously the other cells and a number of containers exploded.

The figures 2^a and 2^b illustrate the situation and the escalation of the firework reactions in the period of 15.16-15.33 hours. The pictures of Fig. 3 show the final explosion (from a distance of about 600 m) and a top view of the explosion area with search sections taped out for the forensic investigation. The detailed time scheme and extensive event and damage descriptions are given in Weerheijm[6]. In this paper only the headlines are given.

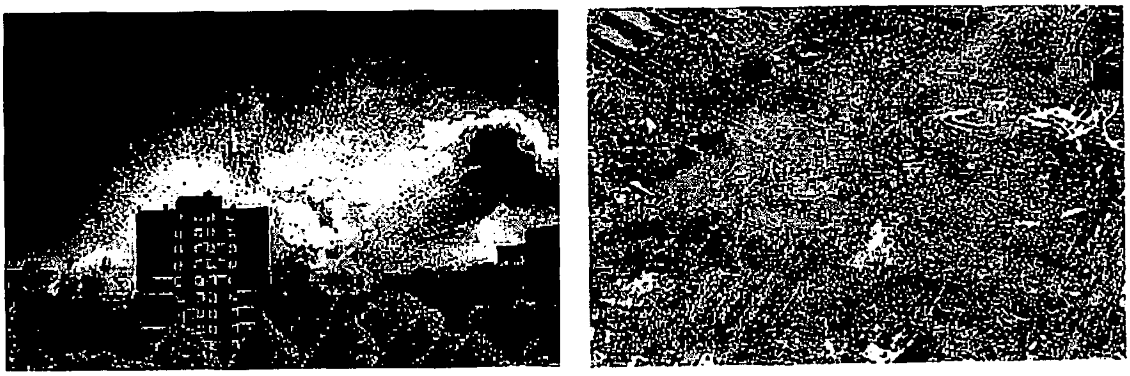


Fig. 3 Final explosion (from a distance of 600 m) and explosion area after the accident with forensic search sections. (Picture explosion area: SFOB)

3.1 Initial fire in cell C2

From the chronological accident facts, the paramount question emerges about the cause of the fire in the workshop, preparation cell C2 of the central storage building. Extensive forensic investigation was performed to examine the possibilities of:

- Sabotage, arson or improvised explosive devices;
- Malfunctioning, defects of the electrical and gas-installation or other equipment;
- Fire caused by human activities at the S.E. Fireworks terrain;
- (Self) ignition of firework articles, pyrotechnics or other fuels caused by instability or external effects.

In spite of the extensive forensic effort no definite proof was found for one of these scenarios. It should be noted that the strength of the final explosions had a devastating effect and most of the evidence of the initial fire was destroyed. Other forensic investigation concerned the possible traces of high explosives and ammunition. No traces of high explosives were found, therefore the explanations for the cause and the development of the disaster had to be found in the stored fireworks and storage conditions.

3.2 Observed explosion effects

The major explosion effects are the crater, fireball, blast and debris. The video recordings and the damage at the explosion area showed that the major three explosions, respectively container E2, garage boxes and the central building, had an increasing strength. Consequently the final explosion destroyed evidence and traces of the preceding explosions and hampers the detailed analysis. Nevertheless the following conclusions could be drawn from remaining evidence. In this paper we focus on the main conclusions and don't discuss the explosion effects, more information is given in the second paper[7] and details are given in reference [6].

3.2.1 Firework reactions in container E2

No crater or evidence for blast damage due to the E2 explosion was found. A very severe firework fire and the projection of firework articles characterise the "explosion" in E2. The observed effects correspond to fireworks of transport classification 1.3G, see also Merrifield and Myatt [5].

3.2.2 Explosion in garage boxes M7-M1

The second major event occurred in the garage boxes. From the video recordings it is seen that the fireball of the explosion swells to a diameter of about 85 m in 0.3 s. The explosion appeared to be a sympathetic reaction of the contents of the boxes from M7 towards M1. The boxes were completely destroyed, no remaining debris could be recollected. The video recordings show debris launch velocities of the order of 200 m/s. The reactions were severe but a detonation definitely did not occur. The concrete floors show severe cracking, and the floor slab of M7 was moved more than 1 m horizontally and a large depression of the soil at the original location was found. No crater was formed. The walls of the boxes were clearly sheared off and the direction of the deformed reinforcement bars formed clear evidence for the propagation direction of the sympathetic reactions in the cells (M7 towards M1). In most cases the blast strength of an explosion can be quantified from the building damage in the surroundings and especially from the window breakage. The final explosion destroyed most of this evidence. At one video recording of the second explosion, however, window and roof tile damage is visible. More information about the strength of the explosion is obtained from the seismic signals that were recorded of both major explosions. The ratio of the signals, the local damage and the blast damage to the surrounding area concluded that the explosion had a strength of about 800 kg TNT equivalence. The radius of the fireball corresponds to 17.000 kg propellant.

3.2.3 Final explosion:

The relation between the events in E2, the garage boxes and the central building is described in Weerheijm and de Bruyn[4]. The strength of the explosion in the garage boxes was by far sufficient to blow the wooden doors into the cells of the central building and the fireball engulfed the whole building. The contents of all cells were probably ignited. The central building was completely destroyed, see Fig. 3 and 4. Sympathetic reactions occurred but the explosion in the central building was clearly dominated by the C11 reaction. This emerges from the facts that:

- In C11 a crater was formed with a depth of 1.3 m. The crater extended to the other cells and was clearly the result of one explosion event;
- the floors of the other cells show no damage of independent, severe explosion reactions, only the edges of the cell floors adjacent to C11 are severely damaged and contribute to the crater (see Fig. 4)
- the remaining reinforcement stubs of the floor-wall connections of all cells show deflection directed away from cell C11;

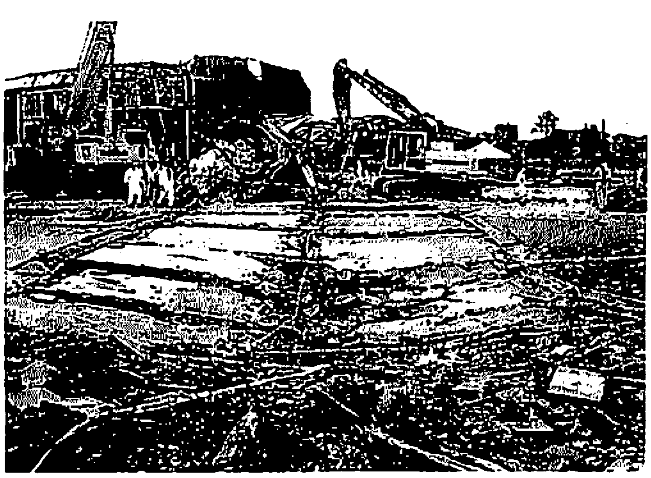


Fig. 4 Damage central building

Fig. 5 Debris at 165 m

Debris from the central building caused many casualties and severe damage to buildings. Debris was found up to a distance of 580 meter. (see Fig. 5). The angle of impact, the throw distance of the major debris was related to the "required" launch velocity. Because the launch angle is unknown, only an approximate range of launch velocities could be determined. Most of the collected debris had a launch velocity in the range 30 – 100 m/s. Maximum reconstructed velocity was 150 m/s. Please note that most of the debris that could be collected was most probably not from C11 or the adjacent cells, because these were broken in small pieces due to the high explosion pressures in the cells.

Most evidence for the final explosion strength was obtained from the window breakage and the observed damage in the surroundings. Window breakage was inventoried in three different directions up to a distance of 850 m. The distance, position, dimensions and breakage percentage of about 700 houses served as input for the calculation of the source strength. The methodology to determine the failure probability coupled to the dynamic load is given in Weerheijm et al., 2001. The damage to the houses, within the radius of 500 m, were categorized to levels A, B, Cb, Ca, or D. These categories were developed during the

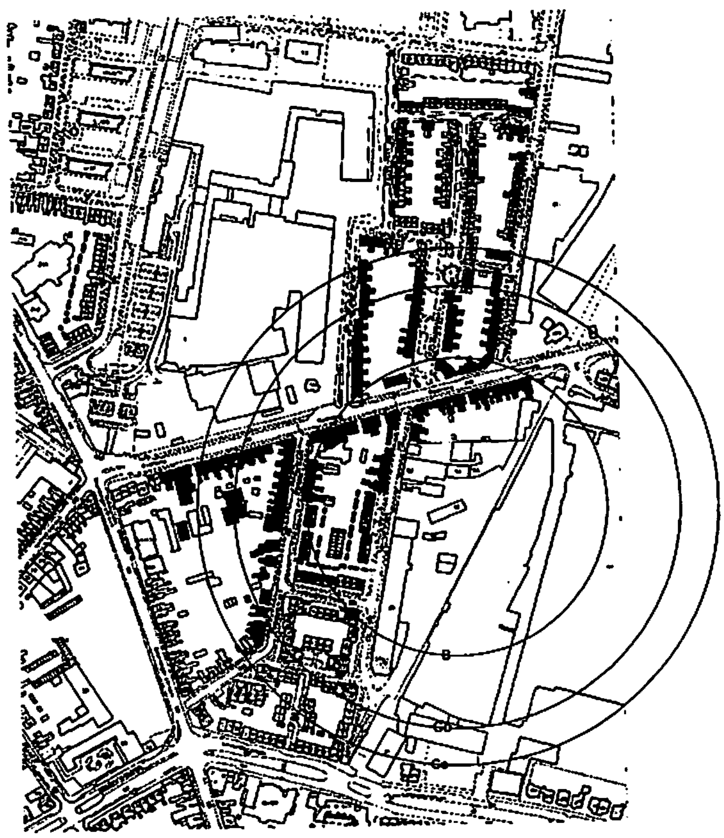


Fig. 6 Damage radii

second World war II and are commonly accepted. The zones are given in Fig. 6 with the radius for damage level Ca is about 230 m.

The final, devastating explosion proved to be in the range of 4000-5000 kg TNT equivalence. The size of the fireball was 135 m, corresponding to 86.500 kg propellant. It is evident that that these effects are not caused by the contents of cell C11 alone. Sympathetic reactions of the other cells and also the containers contributed to the observed effects. On the video recordings the shape of the fireball shows clearly some additional "sub-sources" which may be caused by container reactions.

4. The explosion effects and the stored fireworks

For the lawsuit the question about the relation between the explosion effects that occurred and the quantities and type of involved fireworks is paramount. Hitherto, no definite information is available of the quantities and type of fireworks that were stored in the different cells. Information is available from the sales list of SE Fireworks and the hearings. This information is insufficient to answer the question. Please note that the local damage to the floors, and the visual effects on the videos give us information about the firework reactions in the specific cells, while fireball, debris and damage are caused by the sum of all firework reactions (a combination of mild and very severe reactions).

The license shows that only a limited amount of 1.3G class articles were allowed (2000 kg) to be stored in some specific storage cells of the central building. The bulk of the storage capacity (136.500 kg) concerned class1.4 G articles. The safety regulations are based on the principle that the effects observed in the UN transport classification tests are also representative for the potential effects in (bulk) storage and transport conditions. Or in other words, the test conditions should cover the scale effect and confinement in storage conditions. It is obvious that the effects in the Enschede disaster do not match with the 1.4G and 1.3G transport classification criteria. This means that large amounts of 1.3G, or even 1.1 articles were

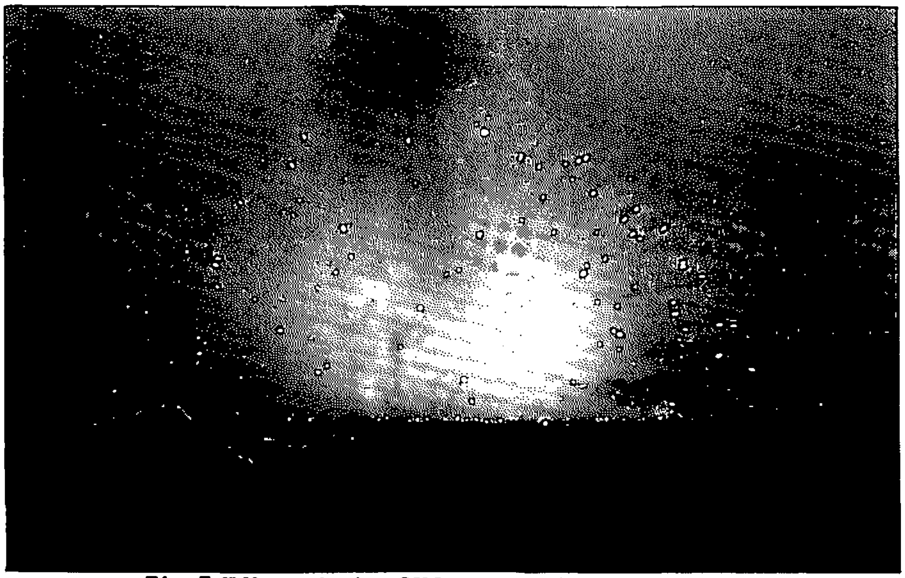


Fig. 7 Effects during UN 6c test with report shells

stored or the transport classification methodology is not well suited to cover bulk storage conditions and define storage safety regulations. The latter aspect is covered in the second paper [7], here we want to mention the classification tests that were performed on various kind of firework articles. Based on the sales list of SE Fireworks a selection was made of articles that could be of a class 1.3G or higher. Comparable, similar articles (display and sound effects) were purchased and tested for transport classification. The selection covered cakeboxes, roman candles, colour- and report shells as well as fountains and rockets. Especially the titanium report shells and the larger shells showed severe reactions. Some of the articles tested were classified as 1.1. Figure 7 illustrates one of the 6c tests with report shells. The test series are given in Jong and Dirkse[3,4]. The tests learned that the selected items were of class 1.3g or 1.1. Because no definite information is available of the amounts and types of stored fireworks, it can not be concluded that the disaster was caused due to the kind of stored fireworks only. Scale effect and confinement conditions may have been of major importance. This aspect is discussed in more detail in the second paper with the chain of events and the potential effects.

5. Concluding remarks

- The explosions at S.E. Fireworks in Enschede on May 13, 2000 caused 22 lethalities, 947 injuries, a complete residential area was destroyed. 500 houses were completely demolished and 1350 houses were damaged. The main cause of the damage in the neighbourhood was the massive conflagration of the old houses with wooden floors caused by the throw out of fireworks.
- In this first paper we focused on the observations and facts. Besides the initial fire in the central building, three crucial events are identified that dominate the escalation of the accident. These are the severe firework reactions in container E2, followed by the explosions in the garage boxes and finally the massive explosion in the storage cell C11 of the central building and the sympathetic reactions of the other storage cells and containers.
- In spite of the extensive forensic investigation no definite evidence for the initial cause of the chain of events was found. There was no indication of sabotage. No traces of high explosives were detected; all traces indicated fireworks related substances.
- Window breakage, structural damage, crater dimensions, debris and the seismic signals enabled the quantification of the two major explosions. The explosion in the garage boxes had a strength of the order of 800 kg TNT equivalence while the strength of the final explosion is within the range of 4000–5000 kg TNT.

- Probably the classes of stored firework articles, quantities and storage conditions caused the initial fire to escalate into the disastrous explosions. The second paper addresses more in detail the safety analysis of some of the critical aspects and events during the escalation of the fires and explosions and the lessons to be learned for the bulk storage and transport of pyrotechnics.

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