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The Explosion Disaster of Enschede

New investigations five years after May 13th, 2000

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1. Introduction

On May 13th 2000, a large amount of fireworks exploded on the area of SE Fireworks and killed 22 people, injured 946, and caused damage to property of more than half a billion Euros.

Since several years a collection of facts and documents has been put together by victims and affected persons of this biggest European fireworks disaster after the end of World War II.

In autumn 2004, the authors were assigned to produce a new analysis of the disaster using all available recordings. A new evaluation from a chemical-/explosive-engineering point of view was carried out by Dr. A. Kappl (HTBLVA), supported by computational fluid dynamics calculations performed by arsenal research (section 5).

2. Investigations

At first a huge number of international statements concerning this event was gathered and compared. To complete our impressions, a total of four video recordings were handed over to us. These films show the event from different viewpoints. The studies of the MSNP [8] and the animation of the NFI [9] used at court became also a component of our investigations.

Precise material lists and of the chemical compositions of all relevant fireworks were placed at our disposal by the client. Contrary to the studies in 2000, we could rely on more precisely defined basic materials.

Thus, composition and net explosive masses (NEM) of most fire works involved could be used as design fundamentals. Hence this investigation is made up of two parts: an explosive-engineering / chemical part and a fluid-dynamical part.

3. Explosive-engineering part

3.1. Arial map of SE-Fireworks

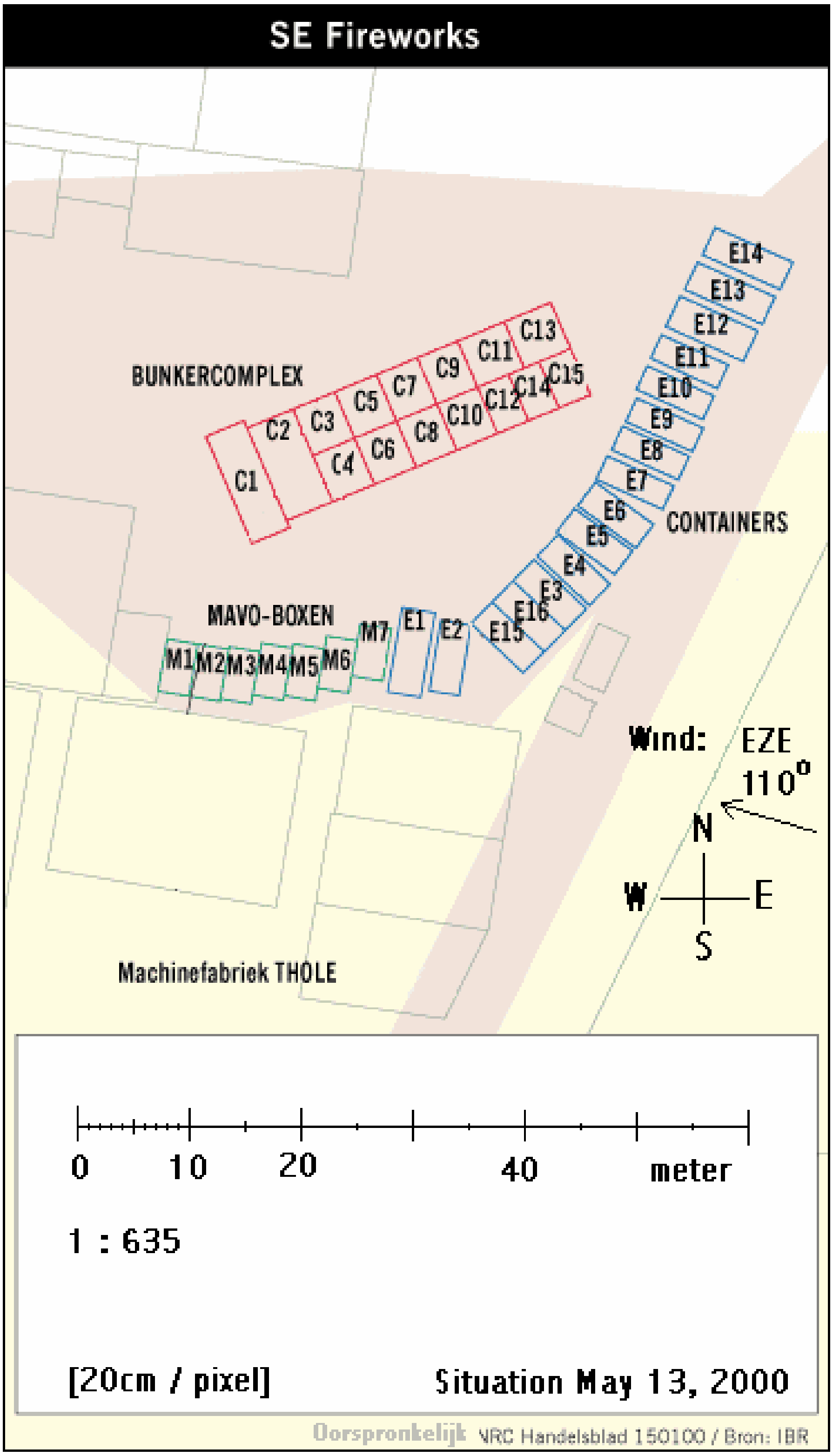

Figure 1: Arrangement of bunkers, containers and mavo-boxes of SE Fireworks

3.2 Stock list

The stock list provided to us by the client is given in table 1:

Bunker/mavo/ container nr.	Article.
C3	Fountains of different calibers (Danmark), flashkoord, Bickfort, tape match (Weco)
C4	Cakeboxes to 2½ inch (Lidu)
C5	Roman lights from 1 to 2½ inch (Lidu)
C6	Cakeboxes 2.5 inch (An Ping)
C7	Shells from 3 to 5 inch (Lidu. An Ping, Golden Horse)
C8	Cakeboxes to 2.5 inch and consumer fireworks (class 2) (An Ping)
C9	Shells of the calibers 3 and 4 inch Golden Horse and 4 inch titaniumshells (Lidu, An Ping, Golden Horse)
C10	Consumer Fireworks Happy Lion collectie (class 2) (Lidu, Jaimang)
C11	Assortment shells (Golden horse, 2.5, 3, 4 inch)
C12	Consumer Fireworks Happy Lion (first-class 2) and 6 inch Shells and star's mine (Lidu, Jaimang, An Ping)
C13	Shells of 8 inch. (Lidu, Golden Horse, in Ping)
C14	Consumer Fireworks (first-class 2) and 2.5 inch Shells (Golden Horse)
C15	Consumer Fireworks Happy Lion collection (first-class 2) and cake punch 2 inch, Wasa (yellow and red Anzündlitze), (Lidu, An Ping, Wasa chemistry)
M1	Fountains and/or vulkane (Jaimang)
M2	Cakeboxes 1.2 inch-25,49 Shots (Lidu)
M3	Cakeboxes 1.2 inch-25, 49 Shots (Lidu)
M4	Cakeboxes 1.2 inch-25, 49 Shots (Lidu)
M5	Cakeboxes 1.2 inch-100 Shots (Lidu)
M6	Cakeboxes to 2.5 inch, Consumer Fireworks(class 2) (Lidu, in Ping, Jaimang.)
M7	Shells of 6 inch to 10 inch (An Ping)
E1	Cakeboxes 1 to 2 inch and celebration crackers 150x10.000-T 809 (An Ping, Jaimang) a 10 kgs
E2	Shells of 6 inch (An Ping)
E3	Cakeboxes 1.2 inch (Lidu)
E4	Cakeboxes 1.2 inch and „Sun's". (Lidu. Jaimang)
E5	Cakeboxes to 1.5 inch, Cel Bration crackers (Lidu, Jaimang)
E6	Cakeboxes to 1.5 inch (Lidu)
E7	Cakeboxes 1.2 inch, 49 shots (Lidu)
E8	Shells 3 inch (Golden Horse)
E9	Shells to 12 inch (Golden Horse)
E10	Shells 6 inch and Consumer Fireworks(first-class 2) (Golden Horse, Lidu, Jaimang)
E11	Consumer Fireworks (first-class 2) and cake box to 4 inch (Lidu, Jaimang)
E12	Cakeboxes to 1.5 inch (An Ping)
E13	Cakeboxes bis1.5 inch (An Ping)
E14	Cakeboxes to 1.2 inch (An Ping)
E15	Not known, possibly order for a customer, normally empty
E16	Not known, possibly order for a customer, normally empty

Table 1: List of fireworks stocked in bunkers, containers and mavo boxes

The following contents of the bunkers served as a calculation basis:

- In C1 - Theatre effects. (Le Maitre, pyro pack, LMP) gross+/-50 kg
- In C2 - working bunker, 250 to 350 kg of auxiliary Material and Fire Works.
- In the bunkers C3, C4, C5, C6, C7, C8, C9, C10, C11, C13 an average of 5202 kg gross are stored.
- In the bunkers C12, C14, C15 on an average 1878 kg are stored gross.
- In the bunkers/mavo-boxes M1, M2, M3, M4, M5, M6, M7 are stored in an average of 3179 kg.
- In the ship containers E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11, E12, E13, E14 2890 kg gross are stored on average.
- No contents are known of E15 and E16. These containers were meant for the arrangement of Fire works and contained empty packaging or were completely empty.
- All fireworks were in the prescribed UN packaging.

After this list the gross total mass of Fire works amounts to approximately 120 metric tons.

3.3 Evaluation of the stock contents

In former studies the very high relation of net explosive masses (NEM) to gross total mass was taken into consideration only to a minor degree.

This relation actually lies, e.g., with 150-mm bombs (6 inch) within 80 percent (!), [6] this means:

A 150-mm or 6 inch bomb weighs 1500 grams; 650 grams of it are used for the effect charge, 450 grams for the distribution charge (that is usually a kind of flash light based on potassium-chlorate / aluminium / sulphur) and 100 grams for the propellant charge (made from high-qualitative black powder). In total: a 6 inch bomb consists of 1200 grams of explosives. In case of the misfortune-releasing container E2, where a gross total mass of 2890 kg is accepted, the NEM amounts to 2312 kg. So 190 kg of pure black powder are concentrated in propellant charges and 1084 kg are distribution charges! In case of a mass explosion this leads to a powerful explosion of all burning substances involved.

So in our calculations we considered also the burning of cardboard in the two violent main explosions. Because the calorific value of cardboard is about 4.7 KWh/kg, the effect of the explosion was **substantially strengthened** by the quick burning down of cardboard. Above all the combustion products steam and carbon dioxide cause a quick displacement of the surrounding air and therefore **a substantially strengthening of the blast effect**. This statement is supported by the yellow to orange fireball in typical carbon combustion colours.

3.4 Time schedule on SE Fireworks terrain; May 13th, 2000, [8]

Sequence of events (appended by the client):
(Time in seconds from video analysis)

2:58 PM: - First fire report; Explosions heard.

3:08 PM - First fire brigade arrived.
- Fire in C2.
- Of plumb line of small explosions heard.
- Fire works thrown out of both sides and trough sky-lights (six) in roof C2.
- Doors C2 dropped inwards.
- Fire works all over the site.
- Small fires around C2 and on roofs M1-M7, buildings "House" and "Shed".

3:18 PM: - Fire brigade opens C3 and extinguishes inwards C3 with tripod sprayer (750 l / min.)
- No visible fire or smoke in C3.

±3:21 PM:-Possible fire in C4; pilot of smoke;

3:27 PM: - Fire brigade says: "Fire still under control".

3:28 PM: - First ladder against bake side M6.
- Smoke between E2 and E 15.

3:30 PM: - From E1 high pressure sprayer on space between E2 and E15.
- Second ladder against bake side M1.

3:32 PM: - Low pressure fire sprayer from roof M7 into C 4 until 3:33:33 PM.

3:33:34 PM: - No more smoking between E2 and E15.

3:33:39 PM: - Twig on roof E2 and dust on front E2 are jumping up.
- Locking mechanism left door E2 tear loose.
- Smoke comes out of E2: straight upwards and along left door.
- Thus smoke from backside of E - group.

3:33:55 PM: - Carbon dust/carbon monoxide cloud emerging from E2 and is ignited by C-complex or burning fireworks. Big fire ball between C-complex and E2;

3:34:40 PM: - First heavy explosion; two explosion centres visible.

3:35:46 PM: - Second heavy(-est) explosion

The individual fire sources and explosions can be arranged in 5 phases:

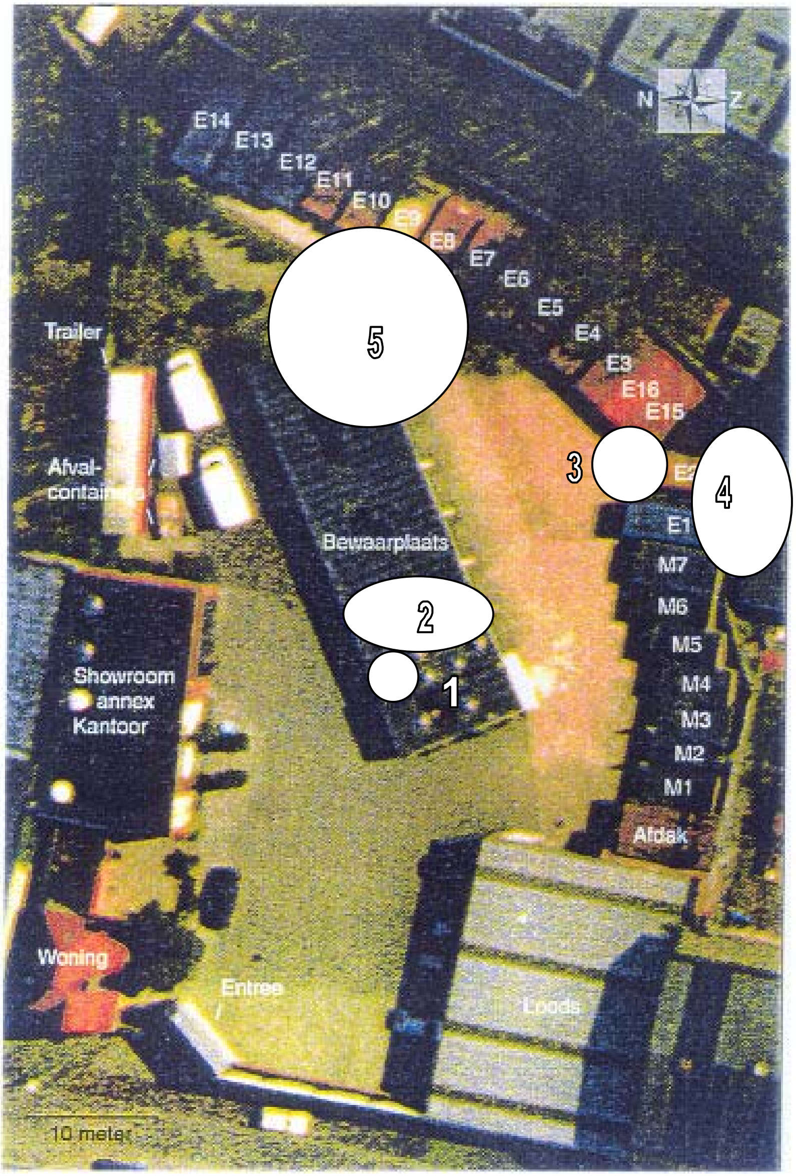

Figure 2: Locations of fire sources and explosion zones

1. Unknown Ignition in C2, source of fire
2. Transmission of the fire (e.g., by cable pipe-feed-trough) to C3. Vulcan’s on titanium/nitrocellulose-basis in C 3, highly sensitive to temperature, start to burn. Wall to C4 is broken by massive fire-fighting and big heat effect. 2.5 inch Cake boxes in C4 start to explode. Rests of several thousand 2.5 inch bombs are spread over the area of SE- Fireworks
3. Fire in E2, Carbon dust/Carbon monoxide gas coming out of E2 followed by partial explosion of E2,
4. Simultaneous explosion of E2, E1, also M7 and other Mavo-boxes explode simultaneously.
5. Simultaneous explosion of C9, C11, C13, E8, E9, E10 and thereby of all other fireworks that still remained in the area.

3.4 Remarks to the fire-fighting procedure of the fire department

After this schedule, the fire-fighting procedure of the Fire Department must be evaluated more exactly. The stock list revealed from the manufacturing firms and the chemical composition of the used products ("MSDS'es) showed the following scenario for C3:

The contents consisted mostly of "Fountains" (vulcan's named "Titaniumfountains" of Pyro-Tec Ltd. from Danmark). This vulcano's are used for indoor flame signs and for large outdoor fire bursts with heights up to 12 meters. In the majority they consist of pressed Nitrocellulose and Titanium powder.

The Titanium-content is 12% in maximum, according to the analysis protocol of Pyro-Tec, identification number MB II. Extinguishing titanium powder with water forms hydrogen, which produces detonating gas in reaction with air according to the following equation:

Equation:

$$Ti + 2\ H_20 \rightarrow TiO_2 + 2\ H_2$$

$$\text{"detonating gas"}\ \ 2\ H_2 + O_2 \rightarrow 2\ H_20$$

However, by using fire-fighting cannons with more than 750 litres of water per minute, a heat transfer from C3 to C4 due to burning metal is practically impossible. It seems to be more likely that burning vulcan's from C3 have penetrated by breaking the wall into the neighbouring space, or were carried over by the massive fire-fighting application in the neighbour stock C4.

In C4, there were different Cake Boxes of the calibre 2.5 inch. In the provided film-documents, the ignition of cake boxes in quick sequence can be clearly recognized. It is to be assumed, that the area of SE-Fireworks was littered with a large number of burning vulcan's and 2.5 shells.

3.5 First large explosion

How this ignition source could spread to the container E2, will never be completely explained. Unfortunately, the persons who could have given information about that were killed by the following explosions. However, two statements can be assumed with certainty:

A) Even in case of a full fire in C3 and C4 the heat release is not sufficient to trigger an explosion in container E2 by convection or radiation (see fluid-mechanical investigation in section 5.2 by *arsenal research*). This is contradictory to the computer animation by NFI. Even a back-draft or similar phenomenon could not heat up the container E2 adequately for its contents to reach a critical temperature.

B) An accumulation of highly flammable subjects close to container E2 is also a possibility. 134 volcanoes with a NEM of 3,5 kg were stored in C3. They produce a flame height of 10-12 meters with a burning-time of about 60 seconds! (Titanium-Fontains supervulcan Item. No. 30.016 and Titanium-Fontains mega supervulcan Item. No. 30.017).

How the ignition of E2 really was triggered in detail will still remain unproven. However, the possibilities are likewise limited.

Scenario 1:

There is a possibility that, e.g., a vulcan Fountain entered through a forklift opening to underneath the container. See following s figure 3.

Figure 3: Forklift openings in typical Euro container

Apart from the steel girders, the floor of Euro containers is only made of 20 mm plywood or planks. It is not entirely unlikely, that a vulcan Fountain burned through the wooden floor and set afire the Fireworks in E2.
If consequently several 6 inch bombs went up at the same moment, enough pressure would have built up inside E2 to break the locking mechanism and tear the container's door open. (see section 5.3.3 and calculations by *arsenal research*)

According to the calculations of *arsenal research* a collapse of the locked container door is possible only with a pressure of at least 2.7 bars. To achieve this pressure at least 10 to 20 bombs would have to explode at the same time. The sudden appearance of smoke visible in the video points to a explosion process inside E2 (see section 5.3.1 and calculations by *arsenal research*) and supports this theory.

Scenario 2:

Another theoretical option is that due to the smoke development nearby E2, a member of the fire brigade or the SE Fireworks personnel could have checked the container door of E2 and possibly opened briefly. In the meantime airborne remainders of 2,5-inch shells could have entered the container and set off further reactions. Theoretically this could have triggered a pyrolysis, which probably brought to explosion 1-2 boxes with six inch shells.

For this consideration also the following picture sequence can be used. Sheet metal, significantly dented outwards in the lower region, can be recognized here. This illustrates clearly the explosion effect of maybe some 6-inch bombs in the door area. (see figure 4).

Fact is that the tragic explosion process of the Enschede disaster was initiated from container E2.

The photographs make clear that such an explosion tore-off the right container door (seen from the front) upwards. A large amount of packing material was ruptured by the force of the explosion inside the container and began to burn. Additional six inch bombs exploded over a period of 20 seconds, and then the remaining contents of E2 converted in only one explosion. If only one third of the NEM is assumed, thus approximately 770 kg for this reaction, then this explosion in worst condition corresponds explosive-technically to the effect of approx. 231 kg TNT (average value factor 0.3 during full reaction in a bore hole). This explosive yield is surely sufficient to pierce the neighbouring container E1 and ignite its contents (distance about 2 m). Unfortunately E1 could not stop or brake the explosion, because there were large quantities of Flash Light Bangers (T 809, at Ping, Jaimang). - The stock list shows 150 times 10000 pieces to 10 kg per unit. Thus 1500 kg gross weight corresponding to 1000 kg net of these flash light bangers filled E1!

It is assumed that these Flash Bang-charges, which essentially consist of flash light powder, were ignited at once by the enormous force of the explosion by E2. Flash light powder mainly consists of 75% potassium-perchlorate and 25% aluminium. The detonation effect of these powders is rather harmless in small devices, but in a mass explosion the effect of a weak dynamite-like explosive can be reached (detonation speed approx. 2500m/sec)!

outwards dented section near door

*<u>Figure 4:</u> Container remnants after explosion, Number 2 is **not** container E2*

1000 kilograms of Flash Bang powder, estimated with an explosiveness of 0.3 to 0.5 in relation to TNT, have an equivalent effect of approximately 300-500 kg TNT. Consequently it can be said with certainty that the explosion transfer from E2 over E1 to M7 occurred practically without delay. A further unfortunate circumstance of the explosion disaster of Enschede was that container M7 had still more explosive contents than E2, i.e. shells from 150 mm to 250 mm (6 inch to 10 inch) with at least 3200 kg gross weight and a NEM of at least 2560 kg. This container must have exploded suddenly.

3.6 Second large explosion

The force of the first large explosion and the pressure wave following from it were sufficient to damage and/or partly open all shelters and containers at the SE Fireworks premises. It was a question of approximately 60 seconds, until the procedure of E2-E1-M7 repeated itself. Consequently, through the pressure wave from M7 the containers E8 to E10 were damaged and briefly afterwards allowed the explosive conversion. The ignition impact by the 300 mm shells stored in container E9 (12 inch) was so violent that it came to the second large explosion of practically all remaining fire works.

4. Chemical Part: Thermo chemical basics

A classical pyrotechnic mixture consists of one or more oxidizing agents as for instance a potassium-nitrate KNO_3 or potassium-perchlorate $KClO_4$ and oxidizable materials as solid mixture. A small selection of oxidizable materials is listed in table 1 [1,3,4]:

fuel	chemical symbol	heat of combustion (kJ/g)
Carbon	C	32.75
Aluminium	Al	31.0
Magnalium	Mg / Al (50/50)	27.9
Magnesium	Mg	24.7
PVC	$(-CH_2-CHCl-)_n$	18.4
Dextrin	$(C_6H_{10}O_5)_n \cdot H_2O$	17.6
Lactose	$C_{12}H_{22}O_{11} \cdot H_2O$	15.9
Sulphur	S_8	9.2

Table 2: Heats of combustion of oxidizable materials

Carbon (assigned usually as charcoal powders with approximately 80%C) ranges energetically higher than the metals, which seems surprising at first sight. Indeed, the formation heat of carbon dioxide is given in the literature "only" with about -393 kJ/Mol (according to -32,75 kJ/g of carbon). Aluminium delivers [4] with identical masses (1 g of fuel) a little less energy (formation heat of Al_2O_3 = - 1675 kJ/Mol = 31 kJ/g of Aluminium).

The previous conclusions of the Enschede explosion disaster stated that the presence of Flash Bang Shells is responsible for the large effect of the explosion. **From a chemical point of view this is not necessarily the case**. **There was already enough energy coming from unburned black powder and carbon from packaging board**. The important role of metalliferous effect charges, even if they are not explosive, will be outlined below.

In the past the most usual mixture for propellants of Fire Works has consisted of approximately 75% potassium-nitrate, 10% powdered sulphur and 15% charcoal powder, whereby the burn-up rate depends strongly on the extent of the homogenization, on the particle size and the grain size. The ignition temperature is 270°C. Without inclusion black powder burns down only in deflagration (sub sonic). The linear burning speed of black powder amounts to 8-10cm/s, the explosion speed lies between 80m/s and 600m/s, depending on inclusion [7].

An exact stoichiometric analysis of the decomposition products became only possible in the last decades. 56% of the reaction products are solids which develop in a complicated redox-procedure (table 3).

Gases	%	Solids	%
Carbon dioxide	26.3	Potassium-carbonate	34.1
Nitrogen	11.2	Potassium-sulphate	8.4
Carbon monoxide	4.2	Potassium-sulphide	8.1
Steam	1.1	sulphur	4.9
sulphur hydrogen	1.1	Potassium nitrate	0.2
Methane	0.1	Potassium-thiocyanat	0.1
Hydrogen	0.1	Ammoniumcarbonat	0.1
		Carbon	0.1
Sum of the gases	44.1	Sum of the solids	56.0

Table 3: Reaction products of black powder [2]

Therefore 1 kilogram of black powder delivers with its explosion about 440 g or 2300 dm^3 of gas and 560 g very hot solid particles. The combustion temperature is about 2400°C. Although its heat of combustion is bigger according to the degree of the conversion (2,4-3,4kJ/ g) the main part of its energy is used for heating up the solids (slags). Black powder works always propelling, which is desired to drive fireworks.

An additional fact is that thermit - a mixture of iron oxide and aluminum granules e.g. used for welding together railroad tracks - produces sparks of long duration in so-called "Kamuroshells". The combustion temperature is the same like black powder, around 2400°C.

Thermit delivers with its reaction: $3\ Fe_3O_4 + 8\ Al \rightarrow 4\ AL_2O_3 + 9\ Fe$ only solids (slag) and is not explosive. The heat effect remains local - except thermit is distributed with a strong mass explosion (like in Enschede). Then large amounts of ignitable energy sources like thermit, aluminum or carbon from burned fireworks-cardboard **lead to a dramatic increase of the explosion effect.**

This effect has been known for a long time and is applied, e.g., with highly effective Dropping Ammunition. Thus the torpedo and bomb explosive Torpex contains 21% of aluminium. New Russian and American war heads („thermobare ammunition“) contain more than 50% of pure Aluminium and exceed the air blast effect from customary TNT several fold [5].

Besides, the flash light charges (the existence of Flash Bang Shells is not essential) from thousands of heavy fireworks bombs with distribution charges and a fraction of more than 37% of the NEM [6] **certainly caused an essential reinforcement to the magnitude of the destructions in the two main explosions from May 13th.**

5. Fluid Dynamics Investigation

In order to gain insight, if certain scenarios were essentially possible or even likely, a numerical investigation was performed. A three-dimensional model of the SE Fireworks premises was generated (see figure 5), were especially containers C2 and E2 were modelled in higher resolution. Computational Fluid Dynamics (CFD) software was used to solve flow and heat transfer phenomena involved in the investigated scenarios.

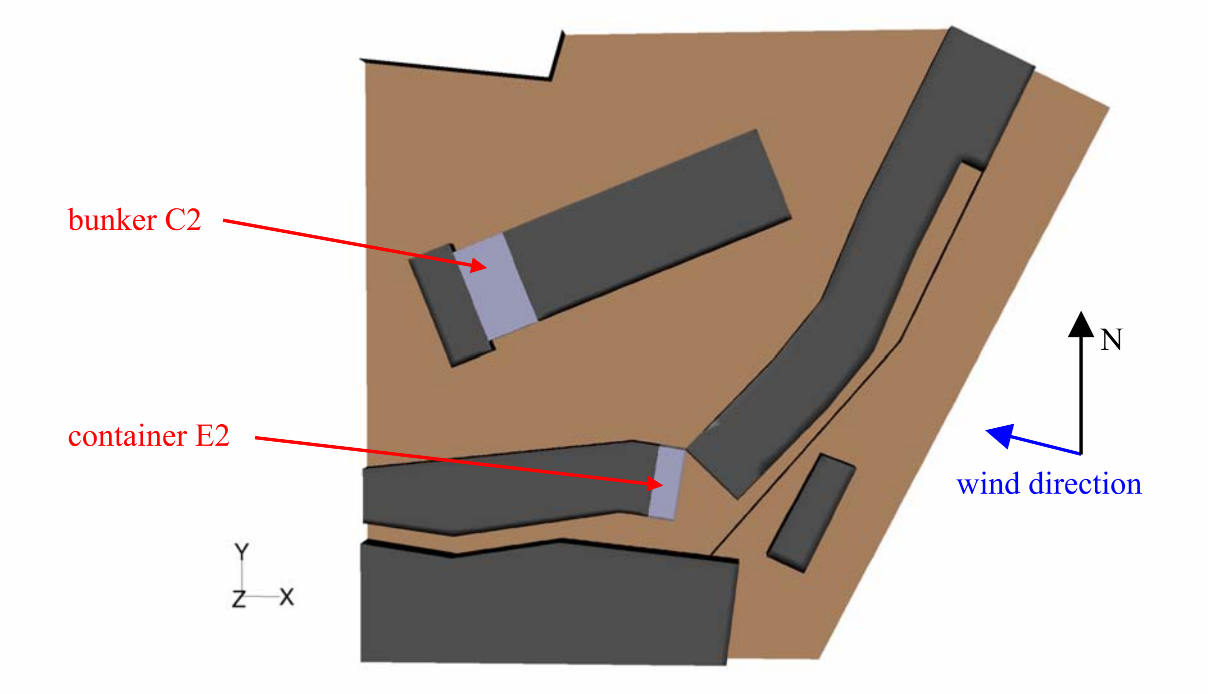

Figure 5: 3D simulation model of SE Fireworks premise

5.1 Combustible Material

From table 2 several materials were selected for the simulation set-up to act as primary carrier of combustion energy during the event.

material	chemical symbol	heat of combustion (kJ/kg)
carbon	C	32 817
aluminium	Al	31 054
„magnalium“	Mg/Al (50/50)	27 915
magnesium	Mg	24 776
sulphur	S_8	9 282
cardboard packaging	$C_6H_{10}O_5$ (cellulose)	16560 [13]

Table 4: Heat of combustion of regarded materials [4]

5.2 Heat Transfer from Bunker C2 to Container E2

One of the discussed possible scenarios assumed ignition of container E2 by direct heat transfer from the burning bunker C2. To investigate this possibility, a numerical analysis of this scenario including heat transfer and thermal radiation was performed.

The simulation was done under following conditions:

- Wind towards west-northwest at a velocity of 1m/s
- 2200K at source of fire in container E2

During the fire event actual wind speeds of about 4.5 m/s were registered. Initial simulations with that value showed a large influence, blowing away the smoke cloud rather quickly in west-northwesterly direction (~110°). This was in the opposite direction of E2 (see figure 1). Analysis of videos and cloud speed indicated somewhat lower wind speeds at the site.

Consequently for the simulation a wind speed of only 1m/s was chosen in order to be on the safe side. Higher wind velocities would make ignition by heat transfer even more unlikely, because of the wind direction pointing away from E2.

Figure 6 shows the path of hot combustion products rising due to buoyant forces and drifting slightly away from container E2 because of wind influence. The path lines are time averaged and therefore look much smoother then instantaneous pictures of smoke.

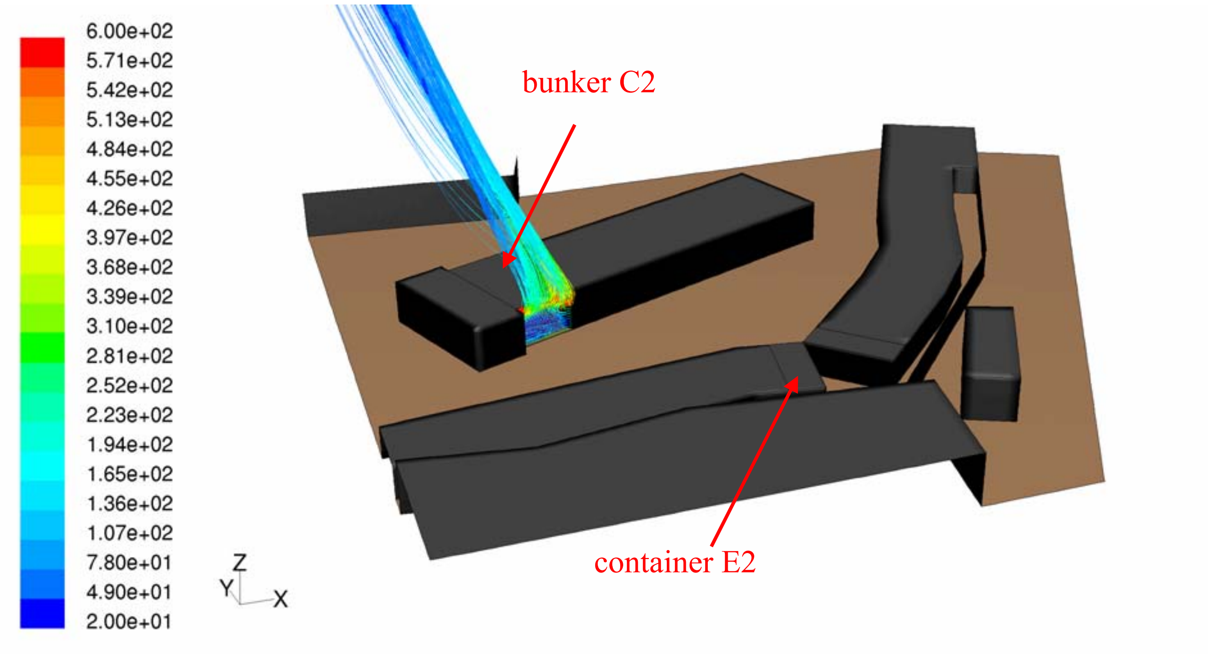

Figure 6: Time-averaged streamlines starting at source of fire in bunker C2 colored by temperature in [°C]

An impression of wall temperature in the surroundings of C2 is given in figures 7 and 8. Temperature level rises to a maximum of about 190°C at the outer wall of container E2. The depicted temperature field takes into account radiation and convective heat transfer. Due to the wind direction, the major influence comes from radiation by far. This is also seen from figure 8, where only the radiation temperature is depicted. The temperature field is almost identical.

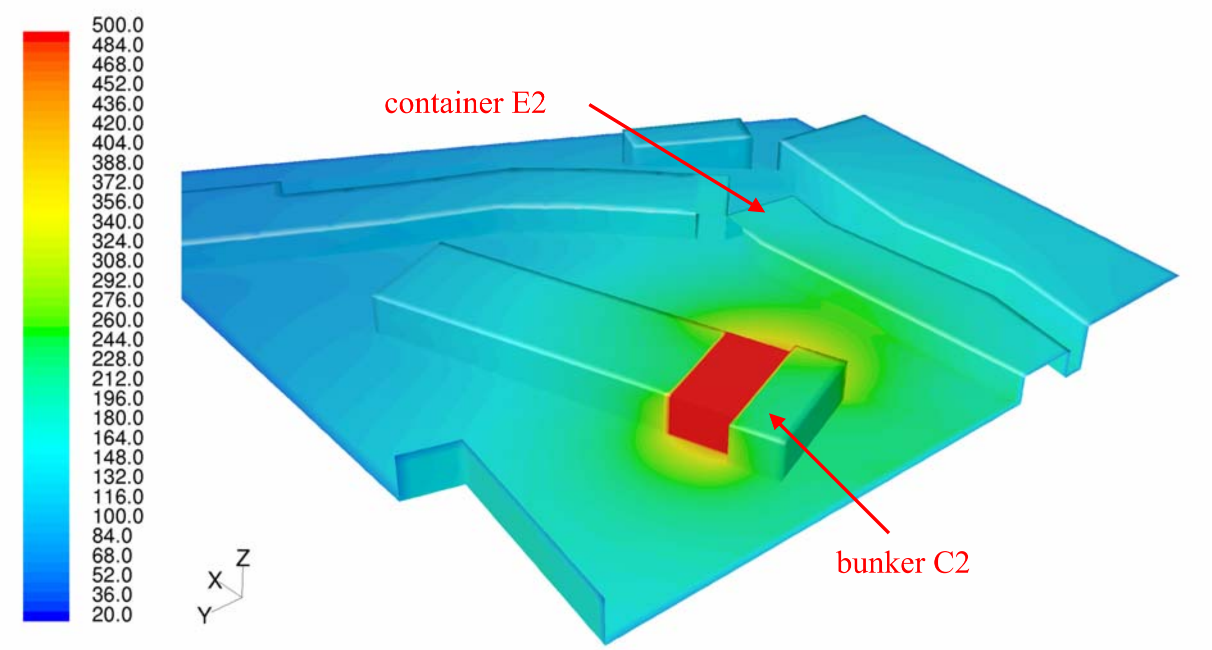

Figure 7: Total wall temperatures in [°C] (red color indicates 500°C and higher)

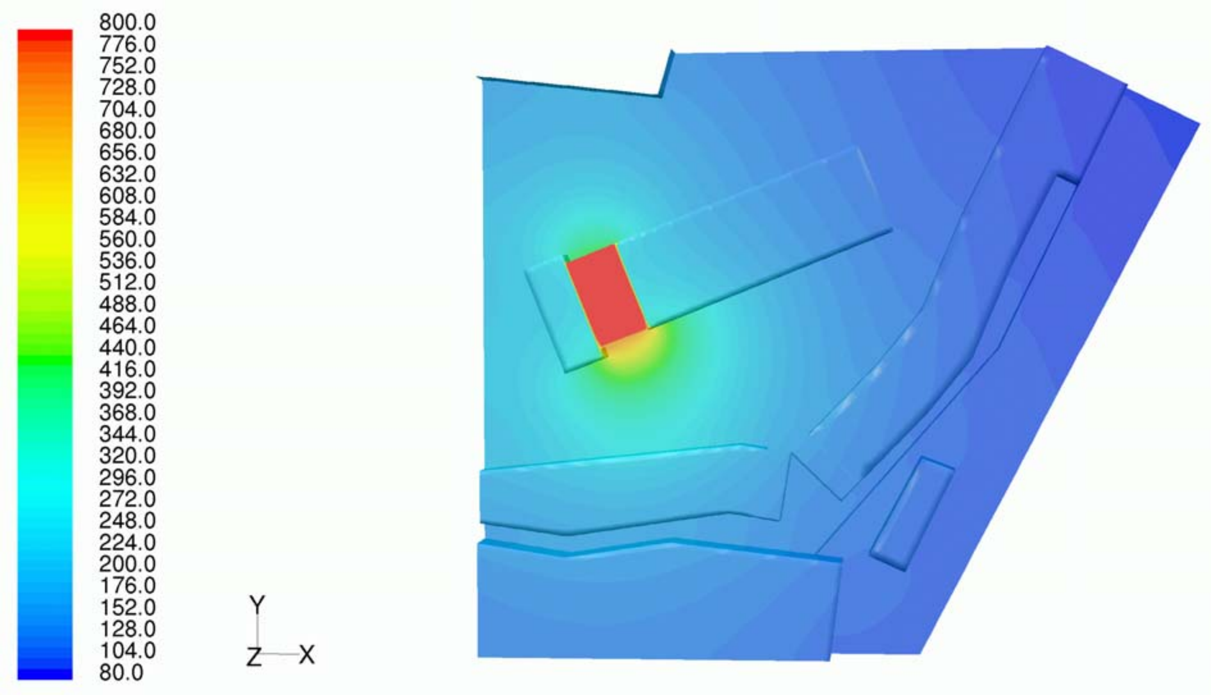

Figure 8: Wall temperatures [°C] due to radiation only

5.2.1 Conclusion

The wall temperature on the outer surface of container E2 was simulated to reach a maximum of 190 °C. This temperature has to be interpreted as steady state condition, which is reached after extended exposure over time with fire temperatures of 2200 K. These conditions were most likely not met during the actual fire, as firearms reached the site ten minutes after fire detection (see section 3.4) and started extinguishing. Also smoke and steam strongly reduces lateral transmission of radiation (in the simulation optically thin medium was used).

As a consequence the mentioned outer surface temperatures of 190 °C could – if ever – have been reached only for a rather short period. Under these circumstances an ignition of fireworks inside the container is not possible. The probability of ignition by direct convective or radiative heat transfer from C2 (or neighbours) to E2 can be neglected.

5.3 Ignition Scenario of Container E2

Based on available information (observations and video footage) of the disaster, the first major explosion at 3:34:40 PM (see section 3.4) most likely was initiated from the zone around container E2 or even from inside E2. Based on this information, a possible scenario was deduced and backed by CFD simulations.

5.3.1 Video Analysis

From available video footage a number of frames were extracted. The video was obviously taken from a roof north-northeast of the SE Fireworks premises. On the left side (behind the tree) the row of containers E14 - E3, E16 and E15 is visible. The next containers are E2 and E1, adjacent to E15 with an angle. Hence the top third of E2's front side can be recognized on the video recording.

The times given with the frames are relative to the start of the video. The video starts at approximately 3:33:35 PM as far as can be deduced from available information.

Frame 1 (time: .3.00 s): Smoke from region C2 is visible, little smoke around E2

front side of container E2

Frame 2 (time: 4.13 s): Smoke emanates from top of front door of E2. This is a hint, that E2's contains overpressure and the door is pushed open.

Frame 3 (time: 5.07 s): Puff of smoke from E2's door is clearly visible. The velocity of the cloud is slow, indicating that pressure in E2 is moderate. Most likely at this time, the front door of E2 is open.

Frame 4 (time: 9.00 s): Smoke from E2 starts to fill area between E2 and C2. Evolution of smoke is still moderate.

Frame 5 (time: 13.33 s): Smoke development quickly increases after 10 seconds. The smoke originates from E2 and spreads partly upwards, partly near the ground towards C2.

Frame 6 (time: 16.05 s): Smoke development rapidly increases even more. Large portions of the smoke are black, pointing at possible unburned carbon components from material in E2.

Frame 7 (time: 17.27 s): From the region of C2 on the right side, ignition becomes visible.

Frame 8 (time: 18.10 s): A second ignition zone appears near E2. Due to the dense cloud it is not clearly visible if there are still two separated ignition zones or if they already form one large zone.

Frame 9 (time: 18.60 s): Detonation of the entire zone between bunkers C, containers E and mavo-boxes M.

One possible conclusion from this video analysis is that combustible gases emanating from container E2 triggered a larger explosion which in turn generated enough energy to fuel the further course of the disaster. The question remains, how container E2 could be ignited.

5.3.2 Ignition Scenario of Container E2

As allready discribed in section 3.5, the container E2 and other containers were standardized Euro-containers. The floor of these containers consists of 20 mm plywood or wooden planks, which are reinforced on the bottom by steel girders (see figure 9). There are openings on the side or front to allow for pick up by a forklift. These openings are fairly large (see also figure 3). Consequently, there is a certain possibility that some kind of burning fireworks slipped under the container and burned through the floor. The content of E2 is given in section 3.2.

Figure 9: *Typical container floor and underside*

5.3.3 Required Pressure Forces for Failure of the Door Locking Mechanism at Container E2

Based on the assumption that the doors of container E2 were closed and locked, the internal overpressure was estimated, which would be necessary to blow open the doors. This overpressure could possibly be due to a combustion process inside the container, burning packaging material and some fireworks.

In order to estimate the required pressure level, following conditions are assumed:

- Eight latches (four each on upper edge and bottom edge) are locked. No reliable information is available on actual locking conditions and real construction of E2's locking mechanism. Therefore the worst case was assumed.
- The lockers are made of steel St52 with a tensile strength of about 520 N/mm² and an effective diameter of 15 mm.
- The pressure forces act on the inside door area of 4.95m².

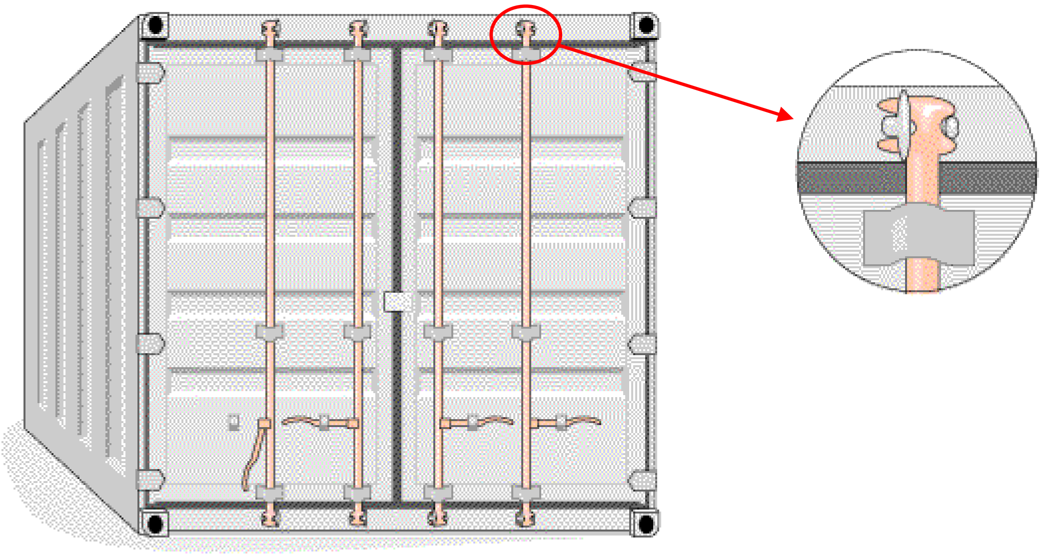

Figure 10: *Schematic view on a standard sea container with latch detail*

Under the assumption that all latches are broken simultaneously, simple setting up equilibrium of forces results in a critical pressure of about 2.6 bar. If a more realistic situation of uneven load to the latches is postulated, even lower forces could have triggered the failure of the doors.

The required amount of black powder was calculated from the following assumptions:

- The reaction took place under conditions at the thermodynamic equilibrium inside a closed system. A certain amount of fireworks must have burnt, setting free several cubic meters of burnt gases as well as combustion energy.
- Heat of reacting black powder 2400 kJ/kg
- Average reactants heat capacity 1.0 kJ/kgK
- Ideal gas law assumed
- First law of thermodynamics

From these basic assumptions the required mass of burned gunpowder amounts to about 5 kg. Rapid combustion or even detonation of this mass of gunpowder would result in an overpressure of approximately 2.7 bar inside E2.

Under these conditions, the door latches are failing, the doors swing open. While gases from inside E2 are escaping **(most likely containing un-burnt carbons from oxygen-starved combustion of packaging material**), pressure quickly decreases.

In return fresh air could probably be drawn into E2, further boosting combustion.

5.4 Carbon Particle Dispersion Initiating the First Big Explosion

A possible reason for the large gas explosion seen in frames 8 and 9 is the presence of combustible or volatile gases. The dark – almost black – smoke emanating from E2 seen in frames 6 and 7 leads to the conclusion, that unburned carbon from incomplete combustion was present. Because there were large amounts of packaging material (itself densely packed) in E2, significant amounts could have pyrolysed to some extent. **Carbon particles from a pyrolytic process inside the packing material of container E2 are assumed to play an important role initiating the first big explosion.**

To back this assumption, a multiphase fluid flow simulation was done in order to show that 590kg of pyrolysed packing material are able to disperse into a dilute mixture of particles and air above the area of S.E. Fireworks.

The simulation was done under following conditions:

- 2m/s wind speed from 110° direction east-south-east
- 2000K fire source temperature in container E2
- 590kg of carbon particles with density 700kg/m^3 and diameter 0.05mm are set free over 4 seconds in container E2.

The flammability concentration limit was given at 20g/m^3 and indicates the presented iso-surfaces in the image series of figure 11. The flammability temperature limit was given at 190°C which is reached and exceeded at the red color zones on the concentration iso-surface.

The simulation shows a correlation in time scale to the observations. This supports the consideration that additional chemical energy within the carbon particles can be distributed above the ground area. If pure carbon is assumed as particle material, about 19.3 GJ additional combustion heat must be taken into account.

In the simulation the movement of the particles is only driven by buoyancy forces. If additional forces due to dynamic combustion processes took place, larger particles than those with 0.05mm diameter could have been dispersed this way.

The particle temperature which was initiated at the fire source is sufficient to reach the flammability temperature limit during the whole dispersing process. This implies that the carbon particle explosion is not necessarily initiated by the fire in bunker C2.

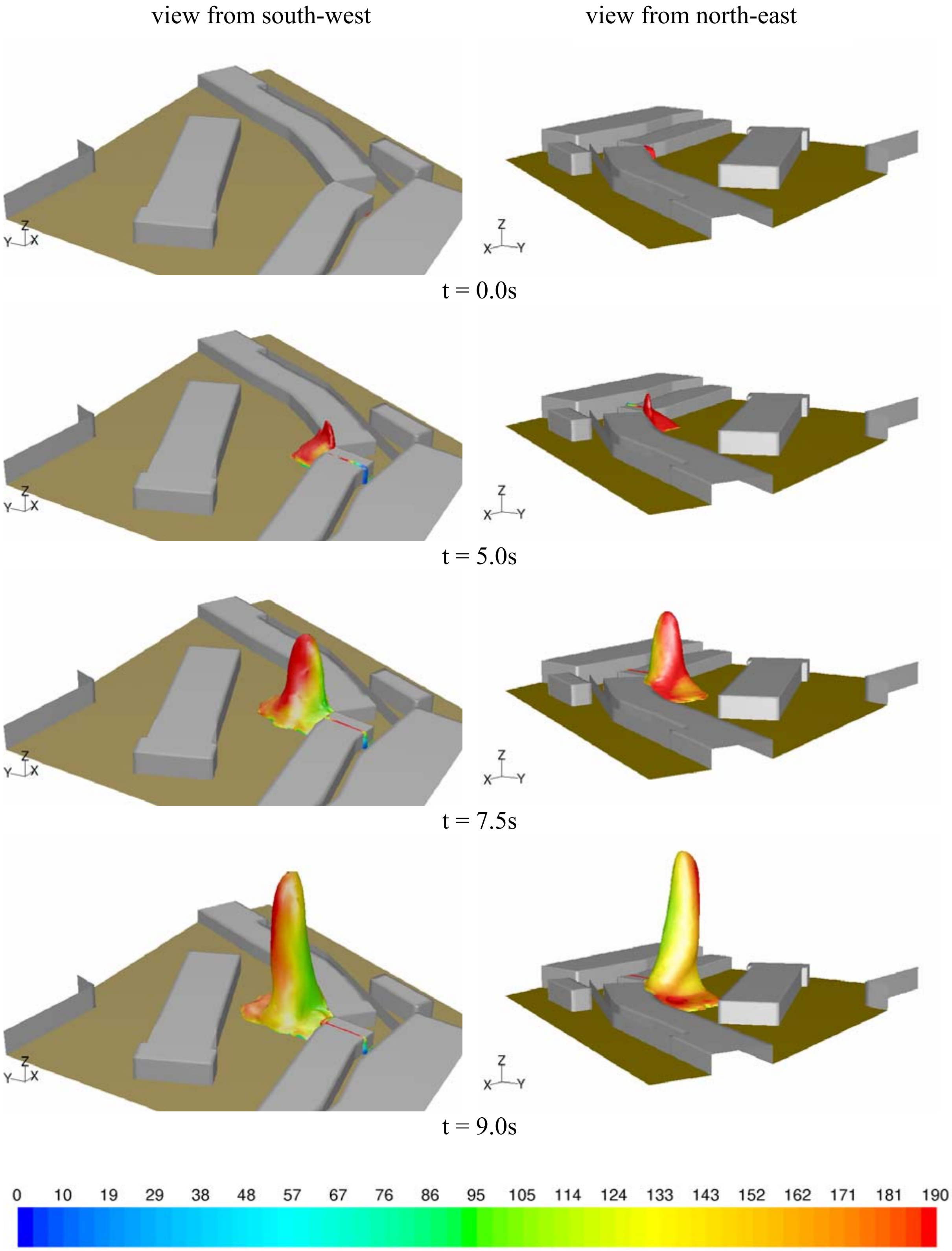

Figure 11: Series of the dispersing pyrolysed carbon particles emanating from container E2 colored by temperature [°C] (red color indicates 190°C and higher);The iso-surface depicts the concentration limit of flammability

5.4.1 Conclusion of Smoke Propagation Solution

The CFD simulation clearly shows a reasonably coincidence with the video observations. Remarkable is a lip of combustible gases, which advances at ground level towards the row of C-bunkers. Additionally a larger cloud is driven straight upwards by buoyant forces. The region indicated by the iso-surface in figure 11 is the region where ignition could have taken place because of adequate concentration of reactants. The actual smoke cloud is even larger and looks more like in the video.

From this scenario an ignition of a gas and/or dust explosion by another source of fire (bunker C2 or fireworks) seems most likely. The energy set free from this explosion taking place mostly in the open space between C-bunkers and E-containers respectively M-boxes could consequently have initiated the further course of the disaster.

Remark:

These findings outline a possible scenario, which could be backed to some extent by simulation. The physical conclusions were based on all available information and video observations. Yet there is no proof that the outlined scenario is the correct option. Rather it is acknowledged, that it is a very possible option.

6. Summary

6.1 Burning metals or not?

On account of the precise chemical composition of the Vulcan Fountains in bunker C3 and the huge amount of water used by the fire-fighters a classical metal fire can be excluded practically. The metallic content (titanium) of the extinguished Vulcan’s is between 0.5% to a maximum of 12%. However, **large amounts of hot steam have been generated and promoted the breakthrough of the wall to bunker C4**. **Fact is that bunker C4 caught fire despite of massive fire-fighting applications.**

6.2 Transmission of fire from C4 to E2

The simulation of *arsenal research* shows that:

- An ignition of E2 was **not possible** due to heat transfer by means of radiation or convection (back-draft effects) originating from C4.
- A rupture of the container E2’s doors was possible by the explosion of a **limited number of shells inside E2.**
- Consequently a cloud of incompletely burned gases and particles flowed out of E2 resulting in a cloud of smoke as seen in the video observation.
- This cloud and particle stream from E2 was directed upwards by buoyant forces and has thus contributed to the picture of a coal dust/carbone monoxide cloud in the air (most likely made up of incompletely burned material from inside E2). This cloud was ignited by readily available sources (airborne fireworks and bunker C).

A scenario on how E2 could possibly have been ignited was developed and backed by fluid dynamics simulation.

6.3 Explanations for the big air blast effect:

With mass explosions the effect charges have to be counted just like black powder. Assuming all calibres larger than 6 inch with a net explosive mass (NEM) of at least 80% there were

in	C7, C13	8.032 kg
in	M7	2.543 kg
in	E2, E9, E10	6.936 kg

Altogether this amounts to 17.511 kg of objects with the ability for mass explosions. From the 1.000 kg of flash light powder in E1 and the remaining containers with approximately 30% NEM on an average, we have to add 30.432 kg NEM. So the total NEM on the area of SE-firework was 48 metric tons with a gross explosive mass of 120 tons. According to conventional calculations with 30% NEM on the average one would have to suppose 160 t gross weight on the SE-Fireworks area. However the high fraction of large-calibre shells reduces this quantity by 25 per cent.

From explosion-technical and fluid dynamics views the large air blast effect can not only be explained by the large quantity of explosive material. Rather the circumstance is to be considered that **unburned reaction products of black powder e.g. sulphur or carbon monoxide and unburned packing as for instance cardboard very probably increased fire ball and pressure wave**. These reaction products could not strengthen the shattering effect, **but acted strongly pushing onto the environment**. The small crater development in contrast to the large blast wave effects supports this observation.

Explosion-technical investigation   Fluid dynamics analysis

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Vienna, Austria
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Alfred Kappl teaches in a college for engineering in Vienna. There he is responsible for the chemical and explosive-engineering education of civil engineers. He also conducts country-wide courses for education of pyrotechnicans. At the end of the 90’s he developed non-toxic fuel air explosives (FAE) of the 4th generation by order of the Dynamite Nobel Group. As an expert for large scale explosions he was assigned as the leading control-engineer for the biggest European block flat blasting in 2003 in Linz, Upper Austria.

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