

## **Explosives, Pyrotechnics, and Propellants**

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### **6.1 Chemical Composition of Some Explosives**

An explosive material is a material or a mixture of materials, which following activation liberates gases and heat due to a fast exothermal chemical reaction. A common feature of these materials, which makes them differ from explosive gases, sprays/mists, and dusts clouds, is that the oxygen of the atmosphere with which the material is mixed is not an essential participant in the heat generating chemical reaction. The different materials of this type used in common explosives may be grouped in the following categories:

- (a) dry mixtures of powders of materials that can burn (e.g. metals, carbon, sulphur, starch, wood), and materials that can supply oxygen (e.g. nitrates)
- (b) water-based suspensions (slurries) or gels of fuel powders (e.g. aluminum) in liquid solutions of solid materials that can supply oxygen (e.g. ammonium nitrate)
- (c) nitrated organic compounds (e.g. nitro glycol, nitro glycerol, di-nitro-toluene, tri-nitro-toluene, tri-nitro-phenyl-methyl-nitramine). Such materials contain the fuel (carbon, C and hydrogen, H) and the source of oxygen for combustion (nitro-groups,  $\text{NO}_2$ ) in the same molecule
- (d) primary explosives (e.g. lead azide), which, when exposed to mechanical impact above a certain strength, will decompose spontaneously by detonation. Such primary explosives are

used to initiate detonation in other less reactive explosives, which would just deflagrate when exposed to less vigorous ignition sources.

Commercial explosives used in practices are often mixtures/combinations of materials belonging to the categories (a) through (d). One example is given in Table 6-1.

**Table 6-1 Composition of a Typical Gelatine Dynamite**

Chemical component	% by mass
Ammonium nitrate	60 - 65
Nitro-glycole	20 - 21
Nitro-glycerole	5 - 6
Di-nitro-toluen	6 - 8
Nitro-cellulose (providing gelatine)	1
Additives to produce desired consistency (e.g. starch, "kiselguhr", wood powder)	Balance to 100 %

Another example is AN/FO, which is simply a mixture of solid crystalline ammonium nitrate moistened with diesel oil. In practice, categories (a) and (b) may interchange, depending on the amount of water added. For example, a saturated solution of ammonium nitrate in water may exist side by side with solid crystalline ammonium nitrate.

CENELEC (1997) defines explosive substances as solid, liquid, pasty or gelatinous substances and preparations that are liable to react exothermally and under rapid gas generation even without the participation of atmospheric oxygen, and which, under specified test conditions under partial confinement, will detonate or deflagrate rapidly during heating. It is important to note that this definition not only comprises the genuine explosives, but also pyrotechnics and propellants. Equivalent to explosive substances are:

- (a) substances or preparations capable of exploding under certain realistic conditions, and intended for use as blasting explosives, but not generally defined as explosives
- (b) initiation and igniting devices, and pyrotechnics
- (c) other products in which explosive substances or substances or preparations in accordance with a) are totally or partially confined and in which an explosion is initiated

## 6.2 Combustion Propagation in Explosives/Pyrotechnics/Propellants

### 6.2.1 Deflagration and Detonation

As in the case of premixed gases and sprays/mists and dust clouds, explosives, pyrotechnics, and propellants also possess two distinctly different modes of exothermal reaction, viz. deflagration and detonation. In fact, with these materials, the difference between the two modes are generally much more dramatic than with gases, sprays/mists, and dusts.

In the case of deflagration, the velocity of propagation of the reaction zone is much lower than the velocity of sound in the material. In a deflagration wave, the direction of flow of the reaction products is opposite to the direction of propagation of the reaction wave. The burning of a gun powder or of a rocket propellant charge is a deflagration process.

In the case of detonation the velocity of propagation of the reaction zone is supersonic and the flow of the reaction products is in the same direction as that of the reaction.

The mode of exothermic reaction of an explosive material once ignited, i.e. deflagration or detonation, depends on the mode of initiation of the reaction. Deflagration results if the ignition source is not generating a shock wave of the strength required for initiation of detonation. However, if the reactive material is confined, the liberated heat in a deflagration will generate a pressure rise in the still unreacted material, and substantial acceleration of the exothermal chemical reaction can result.

Table 6–2 illustrates the dramatic difference between the features of detonation and unconfined deflagration for one specific explosive material. The ratio of the two mass conversion rates is more than  $10^7$  and of the two energy production rates  $10^9$ .

### 6.2.2 Experimental Methods for Measuring Detonation Properties

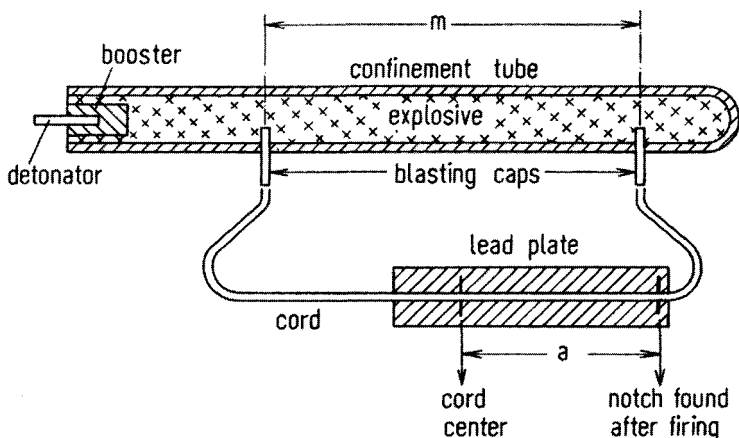
#### 6.2.2.1 Dautriche Method

The Dautriche method for determination of detonation velocities of explosives, as described by Meyer (1987), is illustrated in Figure 6–1.

**Table 6-2 Comparison of Deflagration and Detonation Properties of a Nitro-glycole Explosive of Density 1.5 g/cm<sup>3</sup> <sup>a</sup>**

Property	Deflagration	Detonation
Flame front propagation velocity	0.3 mm/s	7.3 km/s
Thickness of reaction zone	10 mm	1 mm
Liberated energy in reaction zone	1.9 kJ/g	6.7 kJ/g
Mass conversion rate	0.45 kg/m <sup>2</sup> ·s	~ 10 <sup>7</sup> kg/m <sup>2</sup> ·s
Energy production rate	85 MJ/m <sup>2</sup> ·s	7.4·10 <sup>10</sup> MJ/m <sup>2</sup> ·s

a. The data for deflagration were obtained at fully unconfined conditions.

**Figure 6-1 Dautriche Method for Measurement of detonation velocities in explosives. From Meyer (1987).**

The sample of the explosive to be tested is placed in a confinement tube, which may or may not be surrounded by a steel sleeve. The part of the sample along which the detonation velocity is to be measured, is defined by two blasting caps. The ends of a piece of detonating cord of known detonation velocity is connected to the blasting caps, and the cord is passed across a lead plate as indicated in the figure. The detonation wave in the test sample is initiated by the detonator/booster at the upstream end of the test tube, and a steady detonation wave front starts to travel along the confinement tube. As soon as this wave hits the first blasting cap, a second detonation wave is instantaneously initiated at the end of

the detonating cord connected to that cap. At the same time, the detonation wave in the test sample continues down the confinement tube, and eventually it reaches the second blasting cap. This then initiates a third detonation wave at the other end of the detonating cord. Eventually, the two detonation wave fronts in the cord, traveling at equal speeds but in opposite directions, collide and produce a notch in the lead plate at the point of collision. Clearly, the time required for the two opposite detonation waves to travel from the first blasting cap to the collision point at the lead plate is the same. Hence, for the wave going directly into the detonating cord of total length  $L$ , the time is  $(\frac{1}{2}L + a)/D_{\text{cord}}$ , whereas for the other wave it is  $m/D_{\text{sample}} \cdot (\frac{1}{2}L - a)/D_{\text{cord}}$ . By equating the two expressions, one gets

$$m/D_{\text{sample}} = 2a/D_{\text{cord}} \quad (6.1)$$

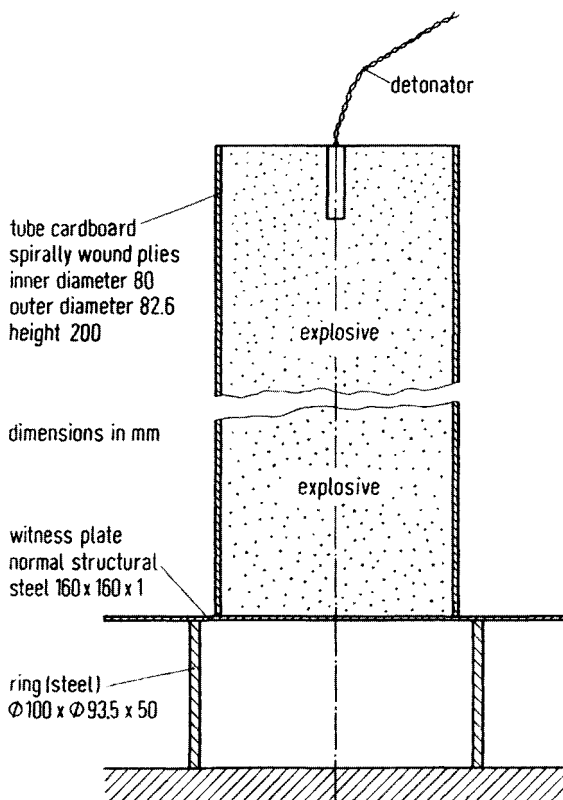
or

$$D_{\text{sample}} = D_{\text{cord}} \cdot m/2a \quad (6.2)$$

#### 6.2.2.2 Detonating Cap Sensitivity Test

In this case, the objective of the test is to determine the response of a sample of the explosive to a standardized detonating cap. The results are used to determine the classification of the explosive as a transport hazard. According to Meyer (1987), the test method illustrated in Figure 6-2 has been used in Germany.

The explosive sample is placed into a 200 mm-long cardboard sleeve of 80 mm internal diameter and wall thickness between 1.3 and 1.4 mm. The bottom end of the sleeve is sealed by a thin cardboard disk, which is glued into position. Because the cap sensitivity can be influenced by the density of the sample under test, the density is determined by weighing. The cardboard test sleeve with the test sample is placed upright onto a steel plate of 1 mm thickness, resting on a steel ring of 50 mm height, inside diameter 100 mm, and wall thickness 3.5 mm. A standardized test fuse is inserted at the top of the sample and initiated. If a proper detonation wave is initiated in the sample, a sharp circular hole is cut out of the steel plate. If no change in the condition of the steel plate, or only denting with or without fissure is observed, this is classed as a non-detonation.

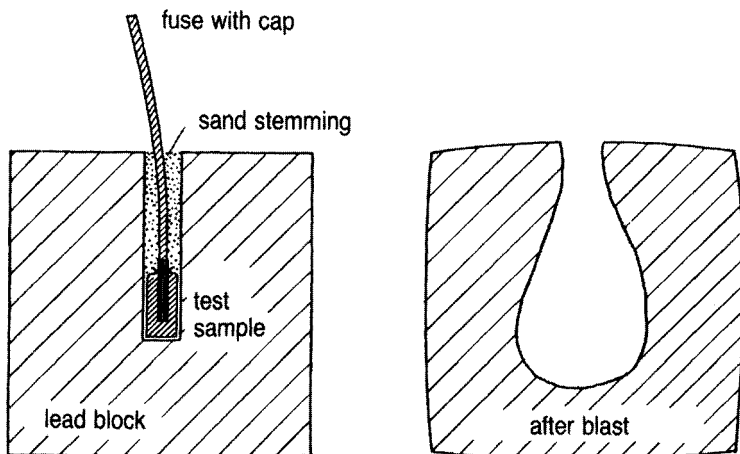


**Figure 6-2 The cap sensitivity test for classifying explosives with regard to the explosion hazard that they represent when being transported. From Meyer (1987).**

### 6.2.2.3 Trauzl Lead Block Test

The Trauzl lead block test is a comparative method for the determination of the strength of an explosive. The principle of the test is illustrated in Figure 6-3.

A sample of 10 g of the test material, wrapped in tinfoil, is introduced into a central bore hole (125 mm deep, 25 mm diameter) in a massive cylinder of soft lead, of height and diameter equal to 200 mm. A standardized blasting cap with an electric primer is introduced into the center of the explosive charge, and the remaining free space is filled with quartz sand of standard grain size. After the explosion, the volume of the resulting



**Figure 6-3 The Trauzl lead block test for comparing the strength of explosives.**  
**From Meyer (1987).**

bulge is determined by filling it with water. The volume of the original cavity is deducted from the result obtained. 10g of picric acid may be used as a standard explosive charge for comparison.

In a modified lead block test, recommended by BAM in Germany, the test sample is prepared as follows: A special instrument wraps the sample in a piece of tinfoil and molds it into a cylinder of 11 cm<sup>3</sup> capacity. The resulting bulk density should be only slightly higher than the bulk density by pouring. Liquids are filled into thin-walled cylindrical glass ampoules or, in special cases, directly into the cavity of the lead block. The initiation is effected by means of an electric blasting cap containing lead azide as the initiating charge and PETN as the secondary charge. The empty space above the test sample is filled with dried quartz sand as in the original method.

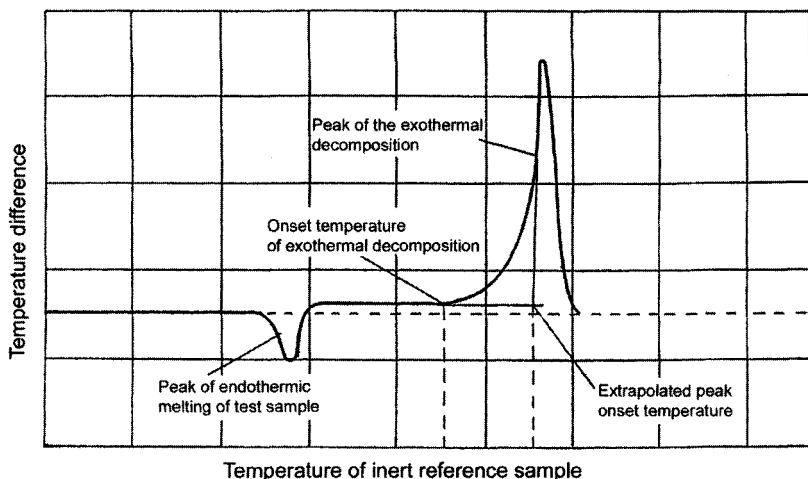
## 6.3 Ignition/Initiation of Explosives/Pyrotechnics/Propellants

### 6.3.1 Decomposition Temperature

The decomposition temperature of explosive materials, propellants, and pyrotechnics is the minimum temperature at which a small sample of the material, placed in an externally heated test tube, bursts into flame, decomposes rapidly or detonates violently.

Meyer (1987) describes the following method for determining the decomposition temperature: 0.5 g (0.01 g in the case of initiating explosives!) is placed in a test tube, which is then immersed in a liquid metal bath (preferably Wood's metal) at 100°C. The temperature of the bath is then raised at a rate of 20°C/min. until deflagration/decomposition takes place.

CENELEC (1997) defines the decomposition temperature as the lowest temperature at which a given quantity of the material tested ignites in a carefully standardized differential thermal analysis (DTA) test. The basic principle of DTA is that the sample under test and a sample of the same size of an inert material are heated in parallel and the temperature difference between the two samples recorded continuously. The sample size is in the range 0.1 and 0.5 g, whereas the heating rate shall not exceed 5°C/min. Figure 6-4 shows an example of the result of a DTA test. In this particular case, the first recorded difference between the temperature of the test sample and the inert reference sample is a modest negative peak due to endothermic melting of the test sample. However, as the temperature rises further, the major exothermal peak of the decomposition reaction appears. The decomposition temperature in this test is defined as the "extrapolated peak initial temperature," i.e., the reference sample temperature at which the steepest tangent to the rising part of the decomposition peak intersects with the base line, as indicated in Figure 6-4.



**Figure 6-4** Example of result of DTA test for the decomposition temperature of explosives, propellants and pyrotechnics. From CENELEC (1997).



Table 6-3 gives some results for a range of materials obtained by the DTA method.

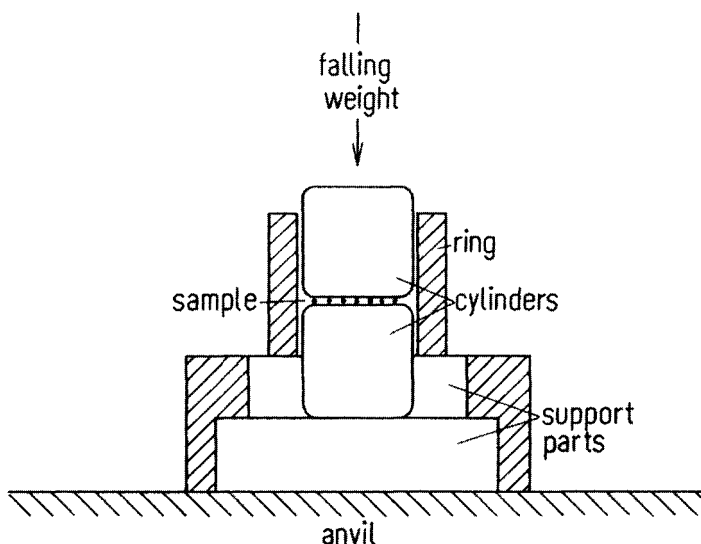
**Table 6-3 Decomposition Temperatures of Explosive Substances Used as Blasting Explosives, Propellants, Ignition Substances, or Pyrotechnics From CENELEC (1997)**

Chemically uniform substances				
No.	Chemical name	CAS-No.**	EINECS***- No.	Decomposition temperature °C
1	mannitol hexanitrate	15825-70-4	239-924-6	140 1)
2	mercury difulminate	628-86-4	211-057-8	151 1)
3	glycerol trinitrate	55-63-0	200-240-8	155 2)
4	oxydiethylene dinitrate	693-21-0	211-745-8	170 3)
5	pentaerithrityl tetranitrate	78-11-5	201-084-3	164 1)
6	N-methyl-N,2,4,6-tetranitroaniline	479-45-8	207-063-0	171
7	ethylene dinitrate	628-96-6	211-063-0	172 3)
8	cellulosenitrate (nitrocellulose)	9004-70-0		176 1)
9	perhydro-1,3,5-trinitro-1,3,5-triazine	121-82-4	204-500-1	208 1)
10	picric acid	88-89-1	201-865-9	214 1)
11	styphnic acid	5704-04-1	227-193-6	224 1)
12	dipicrylamine	131-73-7	205-037-8	244 3)
13	lead 2,4,6-trinitro-m-phenylene dioxide	15245-44-0	239-290-0	256 1)
14	lead diazide	13424-46-9	236-542-1	268 1)
15	2,4,6-trinitrotoluene	118-96-7	204-289-6	271 1)
16	dipicrylamine	131-73-7	205-037-8	301 3)
17	1,3,5-trichlorotrinitrobenzene	2631-68-7	220-115-1	305 3)
18	1,3,5-trinitrobenzene	99-35-4	202-752-7	327 3)
19	2-chloro-1,3,5-trinitrobenzene	88-88-0	201-864-3	330 3)
20	2,4,6-trinitrobenzoic acid	129-66-8	204-958-2	337 3*)
21	ammonium perchlorate	7790-98-9	232-235-1	341 3)
22	5-ISMN			183-193
23	ISDN			175-200
*) At 190 °C exothermal prereaction (decarboxylation)				
**) Chemical abstract service number				
***) European inventory of existing commercial chemical substances				
1)	DTA open;	0,1 g sample mass		
2)	DTA open;	0,5 g sample mass		
3)	DTA pressure-tight	0,5 g sample mass		

### 6.3.2 Drop Hammer Sensitivity Test

The sensitivity to impact of solid, liquid, or gelatinous explosives is tested by the drop hammer method. The principle of this method is illustrated in Figure 6-5.

The samples of the explosives are subjected to the action of falling weights of different masses. The parameter to be determined is the height



**Figure 6-5** Illustration of the drop hammer impact sensitivity test. From Meyer (1987).

of fall, for one specific weight mass, at which a sufficient amount of impact energy is transmitted to the sample for it to decompose or to explode. According to Meyer (1987), the U.S. standard procedures are:

#### 6.3.2.1 Solids

In the U.S. Bureau of Mines test, a sample of 0.020 g of the explosive is tested, using a fixed dropping mass, usually 2 kg. The result of the test is the minimum height at which at least one of 10 repeated trials results in explosion. In the U.S. BM apparatus, the explosives sample is held between two flat, parallel hardened steel surfaces, as illustrated in Figure 6-5.

#### 6.3.2.2 Liquids

In the case of the U.S. BM apparatus (illustrated in Figure 6-5), the same basic procedure as used with solids is applied with the following modifications:

- the mass of explosives tested is 0.007 g
- a disc of desiccated filter paper in which the liquid sample is absorbed is placed on the anvil, and the plunger is lowered onto the sample

According to Meyer (1987) The drop hammer method has been modified by the German Bundesanstalt for Materialprüfung (BAM), so as to obtain better reproducibility of data.

### 6.3.3 Electric Spark Sensitivity Test

#### 6.3.3.1 Original U.S. Bureau of Mines Test

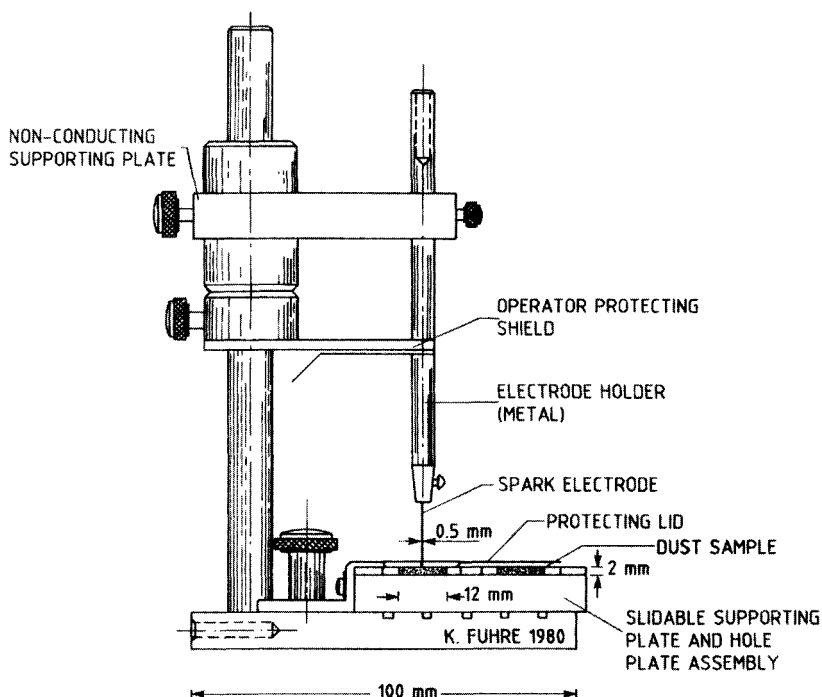
In this method described by Dorsett et al. (1960), the standard dust layer thickness tested was 1.6 mm. The layer was resting on a 25 mm-diameter steel plate that also served as the negative electrode. The positive needle-point electrode, connected to a capacitor bank charged to 400 V, was lowered by hand towards the surface of the dust layer until a spark discharge occurred. After an ignition occurred, the steel plate was cleaned, a new dust layer formed and the process repeated at progressively lower capacitance values until the lowest that gave at least one ignition in twenty trials was identified. The minimum ignition energy was defined as  $\frac{1}{2}CU^2$ , where C is the lowest capacitance giving ignition and U the charging potential of 400 volts.

#### 6.3.3.2 Nordtest Fire 016

This method, described by Nordtest (1982), is primarily intended to be used for pyrotechnics and explosives in pulverized form. It may, however, also be applied to normal combustible materials in pulverized form, which, when distributed as a thin layer resting on a flat metal surface, are able to propagate self-sustained combustion.

The test apparatus is illustrated in Figure 6–6.

The dust/powder is poured gently into the disc-shaped cavities formed by the slidable supporting plate/hole plate assembly and excess dust is removed by a scraper. Plane, circular dust/powder samples of thickness 2 mm and diameter 12 mm are thus obtained. The metal bottom of the



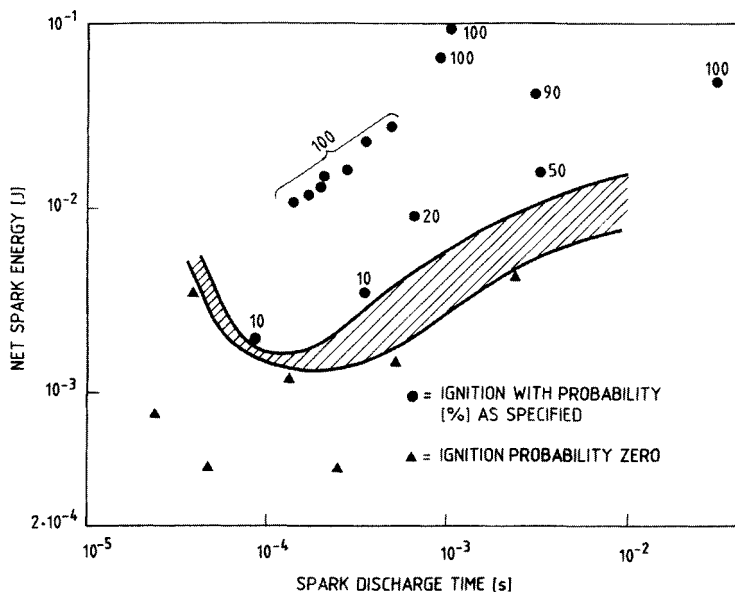
**Figure 6-6 Cross-section of Nordtest (1982) apparatus for determination of electric spark sensitivity of layers of explosives, pyrotechnics and propellants.**

cavities acts as the earthed one of the two electrodes forming the spark gap. A thin tungsten wire pointing downwards towards the dust/powder layer and with its tip just above the dust/powder surface, acts as the second high voltage electrode.

An electric spark of the desired net energy and discharge time is passed through the sample, and it is observed whether or not ignition occurs. An electric spark generator that permits independent variation of spark energy and spark duration is required. Twenty nominally identical tests are carried out at each combination of net spark energy and discharge time, yielding a frequency of ignition somewhere in the range of 0 to 100%. After each spark discharge, the dust/powder sample is shifted horizontally to allow each spark to pass through fresh dust/powder that has not been exposed to previous sparks. If ignition occurs, the sample tested is discarded and the test continued with a new sample.

The minimum electric spark ignition energy, defined as the net spark energy yielding an ignition frequency of 5%, is determined for various

spark discharge times or durations  $\Delta t$ . The ultimate result of the test is an electric spark sensitivity profile  $E_{\min}(\Delta t)$ , as illustrated by the hatched area in Figure 6-7.



**Figure 6-7** Electric spark ignition sensitivity profile of a given pyrotechnics product as determined by the Nordtest (1982) method.

## 6.4 Case Histories of Accidental Explosives/Pyrotechnics/Propellants Explosions

### 6.4.1 Ammonium Nitrate Explosion Catastrophe in Ludwigshafen, Germany (1921)

At 0730 on 21 September 1921 a major explosion occurred at Oppau near Ludwigshafen, in the works of the Badische Anilin und Soda Fabrik (BASF). The account given here is from Marshall (1987). The explosion killed 561 people, including 4 who stayed in Mannheim 7 km away from the explosion center; approximately 1,500 people were injured. In the town of Oppau, 75% of the houses—around 1,000—were destroyed. In the explosion, about 4,500 tons of a mixture of ammonium nitrate and

ammonium sulfate blew up. The material was most probably detonated by explosive charges that were customarily used to break up caked material. According to one source, the material was a co-crystallized mixture of ammonium nitrate with ammonium sulfate, in the molecular proportions 2:1, which would correspond to about 58% ammonium nitrate by weight. Another source claimed that the mixture that blew up was 50% by weight of nitrate and sulfate. The same source claimed that it was proved impossible to detonate any mixture containing less than 60% nitrate, but that the mixture was not homogeneous and may have contained up to 70% nitrate in some places. If, however, as pointed out by Marshall (1987), the mean content was 50% nitrate, some places must have been considerably leaner than this, and it is difficult therefore to see why the whole heap blew up. The decision to use explosives to break up caked material was based on exhaustive tests, and many thousands of actual cake break-up blastings had been conducted. According to BASF, the crater generated by the explosion was 10 m deep, 75 m wide and 115 m long. Within a radius of 250–300 m, all buildings were totally destroyed or so badly damaged that they had to be demolished.

#### 6.4.2 Ammonium Nitrate Explosion Catastrophe in Texas City, U.S.A. (1947)

This account is also based on Marshall (1987). The disaster occurred at 0912 on 16 and 17 April 1947 in the ships *Grandcamp* and *Highflyer*. *Grandcamp* was carrying about 2,300 tons of ammonium nitrate in paper sacks. According to one source, a fire had started among the sacks about an hour before the explosion. It was decided, to avoid damaging the nitrate, not to use water for extinguishing the fire. Instead one tried to put the fire out by battening down the hatches and admitting steam. As pointed out by Marshall, admitting hot steam probably just worsened the situation by heating up the nitrate.

The explosion killed over 200 people who had crowded to the dockside to watch the fire, the ship's crew of 32 people, and 4 people in two aircraft circling overhead. Severe damage occurred and new widespread fires were initiated in a nearby Monsanto complex, as well as in the tank parks of a number of oil companies in the neighborhood. Pieces of wreckage traveled up to one km.

The day after, at 1310 on 17 April, the second ship, *Highflyer*, which had caught fire the previous day as a consequence of the explosion on *Grandcamp*, also blew up. This ship was also carrying ammonium nitrate and, according to some reports, sulphur.

The total death toll due to the two explosions was estimated at 552. In addition, 200 people were missing and 3,000 sustained injuries. The material damage was estimated in excess of U.S. \$100 million (1947 prices).

This disaster shows that, in some circumstances, mild deflagrations or anaerobic fires in ammonium nitrate may escalate to a detonation even when barely confined. According to Marshall (1987) the quantity of ammonium nitrate that actually exploded cannot be stated with certainty. He suggested that about 2,000 tons of ammonium nitrate may have detonated in each of the two explosions, and that this would have been equivalent to about 1,000 tons of TNT in each case. The explosions led to pronounced “domino” effects by starting fires in nearby chemical plant oil storages and dry goods warehousing.

From the actions taken, it seems clear that the crew on *Grandcamp* had no training in how to deal with anaerobic fires. Furthermore, the harbor was inadequately equipped to deal with major fires in general. The death toll was undoubtedly considerably aggravated by the phenomenon of “negative evacuation,” i.e. people flocked to the scene to witness the fire. Had the authorities acted (or been able to act) to evacuate the area, the death toll could have been far less. According to Marshall (1987) the disaster in Texas City is not the only example of people being killed while being spectators at the scene of a disaster.

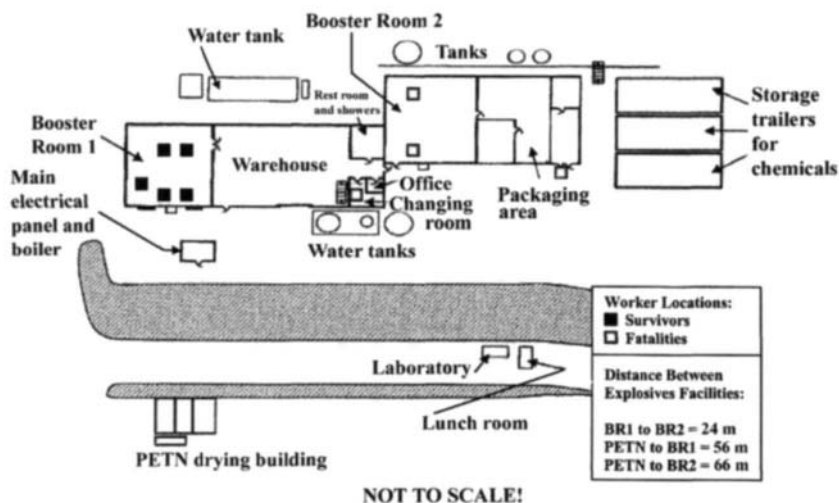
### 6.4.3 Explosives Mix Explosion in Mustang, Nevada, USA (1998)

#### 6.4.3.1 Introduction

On 7 January 1998, at 0754, two explosions in rapid succession destroyed the Sierra Chemical Company’s Kean Canyon plant east of Reno near Mustang, Nevada, U.S.A. killing four workers and injuring six others. Because of the loss of life and extensive damage, the United States Chemical Safety and Hazard Investigation Board (CSB) sent a team to investigate the explosion in an attempt to understand the causes of this incident. The present account is a brief summary of the comprehensive CBS (1998) report.

### 6.4.3.2 The Kean Canyon Plant and its Production

The Sierra Kean Canyon plant manufactured explosive boosters, mixed custom flux for gold smelting operations, and repackaged bulk soda ash for sale to the mining industry. When initiated by a blasting cap or detonation cord, boosters provide the added energy necessary to detonate less sensitive blasting agents or other high explosives. The boosters manufactured at the Kean Canyon plant consisted of a base mix and a second explosive mix, called Pentolite, both of which were poured into cardboard cylinders (see Section 6.2.2.2). The operators working in the plant were responsible for the preparation of the explosive mixtures, the operation of the mixing pots, and the pouring of the mixtures into the cardboard cylinders. Figure 6–8 gives an approximate outline of the part of the plant that was demolished by the accidental explosion.



**Figure 6–8** Approximate plan of the Sierra Chemical Company Kean Canyon plant east of Reno near Mustang, Nevada, USA. From CSB (1998).

The boosters were filled in the two Booster Rooms indicated in the figure. The primary explosives used in the base mix were TNT (2,4,6 trinitrotoluene), PETN (pentaerythritol tetranitrate), and a mixture of TNT and RDX (hexahydro 1,3,5 trinitro 1,3,5 triazine). Pentolite was a mix of TNT and PETN.



### 6.4.3.3 The Explosions

CSB investigation team identified four possible explosion scenarios that could account for the explosions that occurred, but based on the seismic data, interviews of workers, and the physical evidence observed during the investigation, they considered one of these as being more likely than the others. They concluded that most probably the first explosion occurred in the plant's Booster Room 2, indicated in Figure 6–8, whereas the second, larger explosion followed 3.5 s later in the PETN building, which is also indicated in Figure 6–8. The two explosions were recorded by the Seismology Laboratory at the University of Nevada, Reno, and they were also able to conclude that the site of the first explosion was somewhat further to the north than that of the second, larger explosion, which in accordance with Booster Room 2 being located further to the north than the PETN building. The interval of 3.5 s between the explosions was estimated by the laboratory to be accurate to  $\pm 0.2$  s.

Most probably the first explosion was initiated in a mixing pot in Booster Room 2 (see Figure 6–8), when an operator who had left about 25–50 kg of base mix in his mixing pot the day before, turned on the mixing stirrer motor of the pot the next morning. During the evening and night the mix had stratified and solidified, and the explosion initiation occurred when the bottom of the mixer blade, which was embedded in the solidified explosives mix in the pot, forced the explosive material by impact, shearing, or friction against the pot wall. Alternatively, explosive material was pinched between the mixer blade and the pot wall, causing the initial detonation in the pot. The shock wave from this initial detonation then instantaneously detonated the other several thousand kg of explosives in the Booster Room 2, leading to the first main explosion that completely demolished Booster Room 2, and also the rest of the building. Only three walls were left of Booster Room 1, as indicated in Figure 6–9, whereas Booster Room 2 was completely levelled with the earth, as can be seen in Figure 6–10.

When the first explosion occurred, a worker in Booster Room 1 saw a huge fireball engulf a truck that was parked immediately outside the building. This worker was thrown against one of the walls in Booster Room 1, as the ceiling and another wall of the room collapsed on top of him and the four other workers.

Seconds later the same worker heard a second, more powerful (louder) explosion in the PETN building. CSB concluded that this explosion was



**Figure 6–9** Remains of Booster Room 1 of the Sierra Chemical Company Kean Canyon plant east of Reno near Mustang, Nevada, USA, after explosives mix explosion in 1998. From CSB (1998).

most likely initiated by a heavy piece of equipment or burning debris from the first explosion falling through the reinforced concrete roof or the skylight of the building. The site of the PETN building and an adjacent magazine was now transformed to a 13 m  $\times$  20 m wide and 2 m deep crater. The explosions were felt as far as 35 km away.

A total of 11 employees were at the site at the time of the explosions. After the explosions, five workers in Booster Room 1 were trapped temporarily under the collapsed building, but were able to crawl out within a few minutes. Three of the five workers were seriously injured, whereas two only received minor injuries. Concerned about possible additional explosions, the workers from Booster Room 1, after calling for other possible survivors, went to the entrance to the facility. There they met two other workers who had been in the gravel pit below the site, approximately 100 m southwest of the PETN building. The other four workers who were believed to have been in or near Booster Room 2 had been killed by the explosions.

The blast effects of the explosions leveled the site and threw structural materials, manufacturing equipment, raw materials from the booster and flux operations, and other fragments up to 1 km away. The legs and cross



**Figure 6-10** Remains of Booster Room 2 of the Sierra Chemical Company Kean Canyon plant east of Reno near Mustang, Nevada, USA, after explosives mix explosion in 1998. From CSB (1998).

bracing from an empty tank, which previously stood at the corner of the changing room, were thrown 300 m away from the production building. The doors of one of the large magazines and a portable magazine located west of the production facility were sprung open by the negative pressure pulse; however, large quantities of explosive materials that were stored inside did not detonate. Many un-detonated boosters had been scattered throughout the site by the explosion. Other hazards remaining after the two major explosions as the after-fire progressed included fires, toxic chemicals, and potential detonation of the explosives in Booster Room 1.

#### 6.4.3.4 Events Leading to the Explosion

The CSB investigation concluded that the following sequence of events led to the explosion catastrophe. The day before the accidental explosion, one melt/pour operator working in Booster Room 2 (see Figure 6-8)

needed to leave work early, at 3 p.m. When he left, there were between 25 and 50 kg of base mix left in one of his mixing pots (no. 5). He mentioned that he had left some explosive mix in the pot to another operator in the room, who later confirmed this by visual inspection. This other worker, from having looked into the mixer, indicated that the depth of explosive mix left in pot no. 5 was about 100 mm, which matched his estimate of there being 25–50 of explosives in the mixer. The mixer blades extended about 50 mm down into the mix. Metallurgical analysis of mixer parts retrieved after the explosion provided further evidence supporting the conclusion that explosive material was left in pot no. 5, because the analysis showed that damage to the hub of the mixing blade was consistent with it having been in contact with detonating explosives.

An over-current protection device on the electrical mix motors in Booster Room 2 would stop the motor if the blade was unable to break up the explosives, but not before the maximum start-up torque had been applied to the explosives. Without continuous agitation, the different explosives and binders of the mix tended to stratify due to their different densities. This stratification would increase the initiation sensitivity of portions of the explosive material left in the pot. Turning on an agitator immersed 50 mm into a solidified mass of stratified explosives would present a high risk of explosion from the impact of the mixer blades.

Leaving material in the mixing pots overnight was not according to common practice in the plant, but this practice was not for safety reasons. Several months before the explosion, when material had been left overnight in the Comp B mixing pot in Booster Room 1, management made it clear that this was an unacceptable practice because it delayed the operation of the day shift workers.

The operator who left the material in his pot had been working in Booster Room 2 for eight weeks prior to the incident. His normal practice was to leave both of his mixing pots empty in agreement with common practice. Because he was the only person working his production line, he would normally know whether his pot was empty when he started work the next day. Since the pots in Booster Room 2 heated material much faster than the pots in Booster Room 1 could do, it is possible that he on the day before the explosion thought that leaving material in the pot would not delay production the next day. It was acceptable practice at the Kean Canyon facility to alter normal processes without discussion or management approval.

At the end of each day, operators were instructed to leave a steam line valve to each pot partially open to keep the boiler cycling, to prevent freezing of condensate in the lines. This amount of steam would be insufficient, however, to maintain any quantity of explosive mix in the pots above its melting point if outside temperatures were below the freezing point. During the night before the explosion, the outside temperature dropped to between  $-4$  and  $-7^{\circ}\text{C}$ . The operator who had left explosives in his pot offered the remaining material to the operator on the other production line in Booster Room 2. Because the operator who was leaving did not reach a firm agreement on whether the second operator would use the residual explosives, it is possible that no steam valves were left open that afternoon because leaving the valves open would make the remaining base mix too runny to pour. The operator who left early may have mistakenly thought that his remaining base mix would be used that afternoon and, thus, he failed to look in the pot the next morning before turning on the steam and mixer motor. The CSB investigation team concluded that this was the most likely scenario.

#### 6.4.3.5 Key Findings and Root/Contributing Causes

- U.S. standards require that companies using highly hazardous materials have in place an integrated safety management system. CSB's investigation of the Kean Canyon explosion catastrophe revealed that many essential elements of adequate process safety management were missing or deficient. The process hazard analysis (PHA) of the facility and operations was inadequate, and supervisors and workers from the plant had not been involved. The PHA for Booster Room 1 was conducted by company personnel from other locations and did neither consider safe location of buildings nor human factors issues. These deficiencies in the PHA program allowed unsafe conditions and practices to remain unrecognized and uncorrected. No PHA was conducted for Booster Room 2.
- There was no safety inspection or safety auditing program. Safety "walkthrough" inspections were unfocused and did not examine process safety management (PSM) program effectiveness. The result was that management was generally unaware of unsafe practices and conditions.
- The training programs for personnel working in the plant were inadequate. Worker training was conducted primarily in an

ineffective, informal manner that over-relied on the use of on-the-job training. Poor management and worker training led to a lack of knowledge of the hazards involved in manufacturing explosives.

- Written operating procedures were either non-existing or not available to the working personnel. Managers believed that, without using a blasting cap, it was almost impossible to detonate the explosive materials they used or produced. Personnel primarily relied on experience to perform their jobs. Procedures and other safety information were not available in the language spoken by most workers. Operators routinely made changes in the steps they took in manufacturing explosives. This resulted in the use of inconsistent and hazardous work practices. There were no written procedures for Booster Room 2.
- The whole facility was built with insufficient separation distances between different operations, and the construction of buildings was inadequate. Because unrelated chemical operations were located in the same building as Booster Room 2, one additional fatality and additional property damage resulted. Close proximity of structures allowed the explosion to spread to a second building.
- Safety inspections by regulatory organizations were conducted infrequently and inspectors generally did not have expertise in explosives manufacturing safety. This allowed unsafe conditions in the plant to remain uncorrected.
- Employees had not been involved in developing or conducting process safety activities. This resulted in a lack of understanding of process hazards and controls by workers. It also resulted in management not benefiting from the experience and insights of workers. Employees had not been involved in developing or conducting process safety activities. This resulted in a lack of understanding of process hazards and controls by workers. It also resulted in management not benefiting from the experience and insights of workers.
- Reclaimed, demilitarized explosive materials purchased by Sierra sometimes contained foreign objects. The risk of using contaminated explosive materials had not been adequately examined.

See Section 6.5.2 for CSB's recommendations for improvements.

## 6.4.4 Pyrotechnics Disaster in Enschede, Netherlands (2000)

### 6.4.4.1 Introduction

The following short summary is based on the accounts by Bruyn et al. (2002) and Weerheijm et al. (2002), which are in turn based on the results of the extensive forensic and technical investigations of this catastrophic accidental fire/explosion undertaken by Netherlands Forensic Science Institute (NFI) and TNO Prins Maurits Laboratory (TNO-PML).

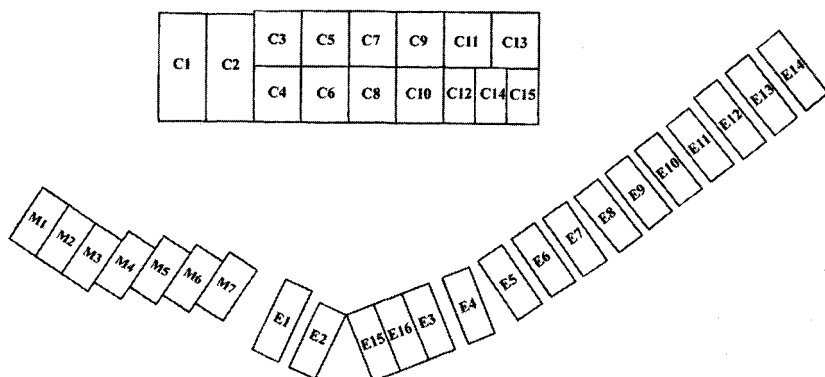
### 6.4.4.2 Overall Development and Consequences of the Disaster

The disastrous explosion occurred on Saturday afternoon, 13 May 2000, on the premises of the company S.E. Fireworks (SEF) in the city of Enschede in the Netherlands. SEF imported and traded with fireworks, and also performed firework displays and shows. Within one 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. The first was a relatively small explosion in a container. Within a minute, seven garage boxes (prefabricated concrete storage facilities) exploded. This was followed about one minute 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 that from explosion of 4,000–5,000 kg TNT. Most of the evidence for quantifying the final explosion strength was obtained from the window breakage and the observed damage of about 700 houses in the surroundings.

This disaster killed twenty-two people and injured 947. A complete residential area was destroyed, with about 500 houses being completely demolished and about 1,350 partly damaged. The main cause of house damage was massive conflagration of typical old houses with wooden floors, initiated by the throw out of fireworks.

### 6.4.4.3 The Situation Prior to the Fire/Explosion

The layout of the pyrotechnics storage facility prior to the fire/explosion is illustrated in Figure 6–11.



**Figure 6-11 Layout of the pyrotechnics storage premises of the company S.E. Fireworks (SEF) in the city of Enschede in the Netherlands in 2000.**  
Based on figure from Weerheijm et al. (2002).

The facility consisted of a central storage building containing 14 storage cells (C2-C15), 7 prefabricated garage boxes (M1-M7), and 14 ISO containers (E1-E14).

The central storage building had wooden doors and was constructed in cast, reinforced concrete with a wall and roof thickness of 20 cm. Cell 2 was used for fireworks preparation and workshops. The majority of the cells in the central building (C3-C11 and C13) were 4 m wide, 4 m deep and 2.8 m high, whereas three smaller cells (C12, C14 and C15) were only 2.5 m wide. The walls and roof of the prefabricated concrete boxes had a thickness of 5 cm. 6 of the prefabricated garage boxes (M1-M6) were 2.6 m wide, 5.2 m deep and 2.3 m high (volume 31 m<sup>3</sup>), and fitted with the original thin, corrugated steel sheet doors. M7 was slightly larger and had a wooden door. 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 0.5 m. The ISO containers were standard 6 m long (20 ft) transport containers, with wooden floors. They were not equipped with any additional fire protective measures.

The total licensed quantities for storage were 158,500 kg (gross mass) of 1.4S or 1.4G fireworks. In some cells, 3G fireworks could be stored, the maximum permissible stored quantity for the whole facility being 2000 kg.



#### 6.4.4.4 Global Sequence of Events

Due to the fact that many people were attracted to the accident, several private video recordings taken from various angles were made available to the investigators. These were helpful in the reconstruction of the disaster. The reconstructed sequence and times of the main events were:

- 1445: Effects of fire in C2 first observed (ejection of fireworks)
- 1500: Fire reported to fire brigade
- 1508: Preliminary inspection of the site by the fire brigade
- 1516: Fire in C2 under control
- 1524: Smoke and fire effects from C4 observed
- 1533: Smoke from between containers E1 and E2 visible
- 1534: Massive deflagration and minor explosion of contents in container E2
- 1540: Massive explosion of garage storage boxes M1–M7
- 1546: Explosion in C11 in the central building, followed almost simultaneously by explosions in the other cells in the main building, and in a number of the transport containers (E)

Figure 6–12 shows the fire ball from the final explosion from a distance of about 600 m, whereas Figure 6–13 is a top view of the completely demolished explosion area, with search sections taped out for the forensic investigation.

#### 6.4.4.5 Initial Fire in Cell C2

The fire in C2 was first noticed at about 1445 hours when activated firework was ejected and landed outside the SEF premises. A small fire in a garden was reported. When the fire brigade arrived, the doors of cell C2 were open at both sides and the plastic skylights were gone. Some fast pressure build-up must have occurred because the doors on both sides were blown out. No external blast damage was noticed. Possible mechanisms for initiation of the fire/explosion in C2 include:

- ejected fireworks
- sabotage, arson or improvised explosive devices



**Figure 6-12** Photograph, taken at a distance of 600 m, of fireball created by the final major explosion on the pyrotechnics storage premises of the company S.E. Fireworks (SEF) in the city of Enschede in the Netherlands, in May 2000. From Bruyn et al. (2002).



**Figure 6-13** Top view photograph of the explosion area after the final major explosion on the pyrotechnics storage premises of the company S.E. Fireworks (SEF) in the city of Enschede in the Netherlands, in May 2000. From Bruyn et al. (2002).

- malfunctioning or defects of the electrical and gas installation or other equipment
- fire caused by human activities on the SEF area
- (self) ignition of firework articles, pyrotechnics or other fuels caused by instability or external effects

The effects of the fire in C2 were:

- ejected fireworks, with the possibility of fire initiation outside the main building
- fire jets and heat radiation directed towards the garage boxes (M) and containers (E)
- fire heating of the walls to adjacent C-cells

The fire in C2 was fought from both sides of the central building. However, the firemen on the side facing the garage boxes (M) were killed in the subsequent explosion, and hence no direct witness reports of the fire development on that side of the building were available.

#### 6.4.4.6 Initiation and Possible Consequences Fire/Explosion in E2

The following possible initiation mechanisms for the fire/explosion in E2 were examined:

- external fire
- fireworks on and, or under the container
- burning magnesium (ejected from the workshop) on top of container
- fireworks before door slit

Considering the time frame, the very limited fire resistance of the container, the presence of an old small trailer with wooden floor between E1 and E2, a small fire would be sufficient to initiate a fire and activate the fireworks in E2. The effects following ignition in E2 were:

- smoke from door slit
- strong smoke development followed by intensive firework reactions

- flame jet (in two pulses)
- ejected fireworks and very severe external massive reaction of fireworks

For the possible consequences of the E2 reaction for the further escalation of the disaster the following effects were examined:

- ejection of debris
- failure of container (fragments and blast)
- flame jet (and possible external fireball)
- ejected fireworks

#### 6.4.4.7 Initiation and Possible Consequences of Fires/Explosions in the Garage Boxes (M)

The damage analysis strongly indicates that the most severe explosion of those in then garage boxes occurred in M7. The observed debris velocity of up to 200 m/s was most probably caused by the failure of the 5 cm thick walls of the prefabricated garage box M7. The resulting severe crushing of the fireworks in M6 and the thermal loading caused the exothermal chain reaction of the fireworks in M6, and subsequently in the other garage boxes. The reactions in all of the garage boxes occurred within less than 0.5 seconds. The resulting explosion blast was comparable to that of the explosion of 800 kg of TNT. A fireball of diameter 170 m was generated. The garage boxes were completely destroyed and fragmented into small debris. The combined blast, flame and debris loading was sufficient to initiate the final major explosions in the central building and the remaining E containers.

#### 6.4.4.8 Initiation and Explosion Effects of Explosion in Central Storage Building

Considering the central building, the strength of the explosion was by far sufficient to blow the wooden doors into the cells whereby the fireball engulfed the whole building. The contents of all cells could have been ignited. The local damage, however show clearly that the explosion in storage cell C11 was most severe and dominant. A single explosion in C11 and the sequential sympathetic reactions in the other cells can explain the total damage. Crucial in the explanation is the reaction velocity of the

fireworks in C11. Hypotheses to explain the devastating mass explosion in C11 are:

- storage of firework of the transport class 1.1
- combined storage of 1.3G and 1.1 fireworks. Fireworks of the class 1.3G were stored, but due to door impact the packages were severely damaged and the firework obtained the 1.1 characteristics
- after initiation of the stored 1.3G class fireworks, temperature and confinement conditions accelerated the deflagration process towards a detonation-like reaction flame jet and possible external fireball

#### 6.4.4.9 Observed Explosion Effects

The major explosion effects were craters, fireballs, blasts, and debris. The video recordings and the damage at the explosion area showed that the sequence of three main explosions, i.e. in container E2, in the garage boxes (M1–M7) and the central building (C-cells), had successively increasing strengths. For this reason the final disastrous explosion destroyed evidence and traces of the preceding explosions, which hampered detailed analysis. Nevertheless, the following conclusions could be drawn from remaining evidence.

No crater or evidence for blast damage due to the E2 explosion was found. A very severe fireworks fire and the ejection of firework articles from the container into the surroundings characterized the “explosion” in E2. The observed effects correspond to fireworks of transport classification 1.3G.

As regards the second main explosion in the garage boxes (M1–M7 in Section 6–11), video recordings showed that the fireball of the explosion increased to a diameter of about 85 m in 0.3 seconds. The explosion appeared to be due to an exothermal reaction of the contents of the garage boxes, starting in M7 and terminating in M1. The boxes were completely destroyed, and no remaining debris could be recollected. However, the video recordings showed debris being ejected at velocities of the order of 200 m/s. The exothermal reactions were violent, but a detonation did definitely not occur. The concrete floors in the garage boxes were severely cracked, 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. However, 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 chemical reactions in the cells (from M7 towards M1). In general the blast strength of an explosion can be quantified from the building damage in the surroundings and especially from the window breakage. However, in this case the final explosion destroyed most of this evidence as regards the explosions in the garage containers. At one video recording of the second of these explosions, however, window and roof tile damage is visible. The radius of the observed fireball corresponded to exothermal reaction of about 17,000 kg of propellant. Further valuable information about the strength of the explosion in the garage boxes was obtained from the seismic signals that were recorded of both of the two last major explosions. The ratio of the signals, the local damage and the blast damage to the surrounding area suggested that the explosion in the garage containers produced a blast wave of the same strength as that produced by about 800 kg TNT.

The strength of the explosion in the garage boxes was by far sufficient to blow the wooden doors into the C-cells of the central building. Furthermore, the fireball engulfed the whole central building, and the contents of all the C-cells were probably ignited. The central building was completely destroyed. Violent exothermal reactions occurred in many of the cells in the central building, but the final, major explosion was clearly dominated by the reaction in C11. This emerges from the facts that a large crater of depth 1.3 m was formed just under cell C11. Although the crater extended to the areas below some other C-cells, it was clearly the result of a single major explosion event. The floors of the other cells showed no damage of the type to be expected from independent, severe explosion reactions. Only the edges of the cell floors adjacent to C11 were severely damaged and contributed to the crater.

Debris from the central building caused many casualties and severe damage to surrounding buildings. Debris was found up to a distance of 580 m from the explosion centre. From the angle of impact and the traveling distance of the largest debris, ejection velocities could be estimated. Because the angle of ejection was unknown, only an approximate range of ejection velocities could be determined. For most of the collected debris the estimated velocities were in the range 30–100 m/s. The highest estimated velocity was 150 m/s.

The diameter of the final major fireball was 135 m, corresponding to exothermal reaction of about 86,500 kg of pyrotechnics/propellants. It is evident that this fireball was not caused by the contents of cell C11 only.

Exothermal reactions of the pyrotechnic material stored in other cells and also the storage containers must have contributed. On the video recordings the shape of the fireball shows quite clearly some additional “sub sources” which may be caused by container reactions.

#### 6.4.4.10 Conclusions

- In spite of extensive investigation, no definite evidence for the initial cause of the chain of events had been found by the time of the publication of the papers by Bruyn et al. (2002) and Weerheijm et al. (2002). There was no indication of sabotage, and no traces of high explosives had been detected, only of fireworks-related substances.
- In addition to the initial fire in the central building, three other crucial events promoted the escalation of the accident. These were the severe firework reactions in container E2, followed by the explosions in the garage boxes (M) and finally by the massive explosion in the storage cell C11 of the central building, accompanied by the reactions in the other storage cells and containers.
- Window breakage, structural damage, crater dimensions, debris and the seismic signals enabled quantification of two major explosions. The first occurred in the garage boxes and had a blast strength equivalent to about 800 kg TNT. The blast produced by the final, much more powerful explosion had a strength equivalent to about 4000–5000 kg TNT.
- In spite of the violent character of the explosions, they were all subsonic deflagrations. This is in accordance with the nature of the exothermal reactions being the cause of the explosions. No evidence of detonations was traced.
- The types of stored firework articles, the excessive quantities stored, and partly inadequate storage conditions, probably made it possible for the event to escalate from the initial moderate fire to the final disastrous explosion.
- Much larger quantities of some types of firework were stored than licensed, which contributed to making the storage unsafe. If the stored quantities had been in agreement with the premises of the licenses granted for storage, the fire in the workshop of the central storage building could never have escalated to the disaster that actually occurred.

- The minimal fire resistance of the storage containers, and inadequate safety distances between the various storage units, also contributed to the escalation.
- Weerheijm et al. (2002) concluded that further research would be needed to enable definite conclusions to be drawn on the origin and stepwise escalation of the catastrophic explosions in Enschede, and also for enabling specification of improved requirements for safe storage and transportation of the types of pyrotechnics that gave rise to the catastrophe.

## 6.5 Measures for Preventing and Mitigating Accidental Explosions of Explosives, Propellants, and Pyrotechnics

### 6.5.1 General Safety Considerations for Facilities Producing Explosives According To Sejlitz (1987)

#### 6.5.1.1 Basic Rule

The planning of a process and/or a workplace should always be based on the following basic rule:

- a minimum number of persons for handling
- the smallest possible quantity of explosive material in
- the shortest possible time

#### 6.5.1.2 Characteristics of the Explosive Material

Before conducting any work with explosive materials, all their basic safety properties must be known. These data makes it possible to evaluate both the various risks of ignition/initiation associated with handling and processing the material, and expected consequences of such ignition/initiation. The most important basic safety properties are (see Section 6.2 and Section 6.3):



- ignition/initiation sensitivity (e.g. impact, friction, heat, electric/electrostatic sparks)
- chemical stability (e.g. possibility of exothermal decomposition during storage)
- effect of ignition/initiation (e.g. when the material is unconfined, enclosed, or in the processing vessels/containers)
- health risks (e.g. acute and long-term exposure)

#### 6.5.1.3 Explosion Protection

On the basis of the basic safety data of the material(s), one can decide whether the planned work

- can be performed in an open work room, or whether it
- must be performed under shielded conditions

The degree of rigidity of shielding depends on the severity of the effects of ignition/initiation of the material in question, and may take the form of

- simple protection screens inside the work room
- smaller, laboratory-scale bunkers inside the work room
- special full-scale bunkers (often with pressure resistant observation windows)

#### 6.5.1.4 Automation and Remote Process Operation

In the case of dangerous operations it is often preferable to automate the process and run and control it remotely. However, this may also sometimes introduce additional risk elements, such as:

- Reduced operator attention may result in too late detection of operational errors.
- Automated, remotely operated processes may prevent the operator from acquiring the knowledge of the basic processes that he may need in the case of irregularities and errors.

- The possibilities of efficient interaction with the process in case of irregularities and errors are reduced.
- The work may appear less interesting and challenging to the workers.

#### 6.5.1.5 Quantities of Explosive Material

As already mentioned, the quantities of explosive material being handled at any time at each workplace should be as small as practically feasible. The following principles should be taken into account:

- For a given production volume per day, the mass of material handled at any workstation at any time gets smaller if the transfer rate of explosive material through the process (mass per unit time) increases.
- A well-designed material flow system permits frequent transports of explosive material to and from the work rooms, which reduces the amount of explosive material stored in the work rooms at any time. This makes it possible to keep the buffer stores of explosive material in the work rooms at a minimum.

#### 6.5.1.6 Avoidance of Accidental Ignition/Initiation

The equipment in which explosive materials are processed/treated/handled shall be designed to ensure that the materials are not exposed to:

- *Mechanical impact*

Only approved equipment and tools shall be available at the work place. Experience has shown that if non-approved equipment such as hammers, rubber mallets, crowbars etc. has been available, operators have used this to solve problems that have arisen, and by doing so initiated explosion accidents.

- *Friction*

Equipment and tools shall be designed/constructed in such a way that dust cannot enter threaded couplings, bearings etc. Furthermore, foreign bodies and impurities (hand tools, bolts and nuts, gravel from transportation boxes etc.) must be prevented from entering

apparatuses/equipment containing explosive material, thereby giving rise to explosion initiation by friction.

- *Exothermal chemical decomposition*

Accidental explosions have occurred in cases where explosive materials that have first been made chemically unstable by impurities or heating, have been enclosed in e.g. a ball valve or between the walls of a double-wall pipe. Whenever, such possibilities exist, the equipment/apparatus must be controlled and cleaned regularly.

- *Adiabatic compression*

This can occur during pressing and other treatment of gun powder, if the air in the pressing tool has not been evacuated before pressing, or if the air trapped in the gun powder is being subjected to a pressure rise by other means.

- *Heating/fire*

All equipment/apparatus where explosive materials are heated electrically shall be equipped with several independent protection systems against over-heating. Hot work (welding etc.) always present a significant fire/explosion risk factor if carried out on premises where the rooms and the equipment/apparatuses have not been adequately cleaned before the hot work is initiated.

- *Electrostatic discharges*

Static electricity is always a significant risk factor when producing/treating/handling very sensitive explosive materials. The possibility of ignition/initiation by electrostatic sparks (discharges between two electrically conducting electrodes) can be effectively eliminated by connecting all conducting components/apparatuses/equipment/tools, as well as the operator, to earth. For the operator, using electrically conducting shoes is only effective if the floor is also conducting and connected to earth. If this is not the case, the operator must be equipped with a separate cable to earth. If the material can be ignited/initiated by brush discharges, special precautions must be taken to avoid such discharges.

#### 6.5.1.7 Good Practices for Apparatus Design

Quite often accidental initiation/ignition of explosive materials occur because they become exposed to excessive mechanical forces in contact

with parts of apparatuses or tools, or to heat. Such accidents can occur even under normal operating conditions, but they are more common under circumstances deviating from normal operation, e.g. start-up, shut-down, cleaning, maintenance/overhaul, repair, and irregularities in the performance of equipment/apparatus (see Section 6.4.3.4).

It is important to consider the possibilities of irregular performance of equipment/apparatus, and the ease by which it can be cleaned, maintained, overhauled and repaired, at the earliest stage of selecting/designing new equipment/apparatus. Careful consideration should be given to the following:

- *Selection of construction materials*

The construction materials used in equipment/apparatus must not be able to react chemically with the explosive materials produced/treated/handled in the equipment apparatus. They should be able to withstand mechanical stress and wear due to rubbing etc. On the other hand, the use of mechanically strong materials may increase the risk of ignition/initiation by impact, rubbing etc., and in such cases softer and less mechanically strong construction materials will have to be used. However, all types of construction materials can represent an ignition/initiation risk if dimensioned/used in a wrong way. There are no materials that are either fully adequate or fully inadequate in any kind of practical situation.

- *Free space around moving parts of equipment/apparatus*

Hazardous frictional stresses may be generated if an explosive material gets squeezed between moving parts of equipment/apparatus and another object, e.g. a tool. In order to prevent other objects from creating such situations, the free space around moving parts should either be so large that the introduction of another object will not be able to create hazardous stresses, or so small that the another object will not be able to enter the space.

- *Design and construction of equipment/apparatus*

It is essential that the design and construction of equipment/apparatus facilitates easy cleaning. It is a good working principle that equipment/apparatus should be designed and constructed in such a way that complete cleaning or inspection can be performed daily in a safe and efficient way. This requires that:

- all surfaces are smooth, preferably honed or polished
- there are no narrow gaps, grooves, holes or cracks in which explosive material can escape the cleaning operation
- there are easy-to-handle and well-dimensioned couplings and other fixing elements, and that bolts and nuts are secured in an adequate way
- pipelines are easy to dismantle and inspect
- there are effective arrangements and procedures to prevent spill of explosive material, and accumulation of dust from such materials

#### 6.5.1.8 Written Work Instructions

In addition to a good process design it is important that the operator has the knowledge, skills and motivation to run the process in a safe way. Hence, well-written, easy-to-understand work instructions shall always be readily available. These may include information on the following aspects:

- properties of the explosive material(s)
- the work operations to be undertaken
- risks associated with the work
- guidelines/regulations to ensure safe work procedures
- measures to be taken in case of deviation from normal material and process conditions
- routines for cleaning/housekeeping
- control and maintenance of production equipment
- special work instructions for more comprehensive and difficult installation and maintenance work

#### 6.5.1.9 Ten Mnemonic Rules

- (1) Work with the smallest practically possible quantity of explosive material at any time.
- (2) Be well informed about methods of work and safety instructions.
- (3) Make sure that there are adequate escape routes.
- (4) Use only approved tools and other apparatus/equipment.
- (5) Keep the work place in order. Materials, tools and apparatus/equipment, which are not used for the time being shall not be stored in the work rooms.
- (6) Give notice of and/or correct any errors or undesired deviations from normality.
- (7) Make sure that all explosive materials that are not being processed are well packed and clearly marked.
- (8) Make sure that all trash/refuse explosive materials are well packed and clearly marked.
- (9) Never conduct production work with explosive material in a store room for explosive materials.
- (10) Keep the work place clean and tidy at any time. Spill of explosive material should be removed immediately (by gentle sweeping).

#### 6.5.2 General Safety Considerations for Facilities Producing Explosives According to CSB (1998)

Partly based on the experience gained from investigating the Sierra's Kean Canyon plant explosion catastrophe in 1998 (see Section 6.4.3), CSB (1998) recommended that the following aspects be considered:

- Adequate process safety management (PSM) in explosives manufacturing facilities requires both careful planning and careful implementation.
- Prevention of primary explosions, as well as further propagation of explosions, requires clear understanding of explosives safety principles and safe practices.

- Process Hazard Analyses (PHA) shall include examination of safety-distance requirements, building design, human factors, past incident reports, and lessons learned from explosives manufacturers.
- Written operating procedures shall be specific to the actual process of concern and address all phases of the operation.
- Procedures, chemical hazards, and process safety information shall be communicated in the language(s) understood by personnel involved in manufacturing or handling of explosives.
- Explosives training and certification programs for workers and line managers shall provide and require demonstration of a basic understanding of explosives safety principles and job-specific knowledge.
- Pre start-up safety reviews shall be performed to verify operational readiness whenever changes/modifications have been made.
- Adequate implementation of all elements of mandatory official process safety management standards shall be verified by performing periodic assessments and audits of safety programs.
- The employee-participation program shall effectively include workers and resolve their safety issues.
- Explosives safety programs shall provide an understanding of the hazards and control of detonation initiation sources. These include:
  - foreign objects in raw materials
  - impact by tools or equipment
  - impingement
  - friction
  - sparking
  - other electrostatic discharges

Specific handling requirements for raw materials shall be followed strictly. Substitute raw materials may introduce additional ignition risks requiring special concern.

CSB (1998) further suggested that the following issues be addressed in plant design or modification:

- Unrelated chemical or industrial operations or facilities shall be separated from explosives facilities using quantity distance guidelines.
- Operations in explosives manufacturing plants shall be separated by adequate intra-plant distances to reduce the risk of propagation.
- Process changes, such as the construction or modification of buildings, or changes in explosive ingredients, equipment, or procedures shall be analyzed and PSM elements shall be updated to address these changes.
- Facilities shall be designed to reduce secondary fragmentation that could result in the propagation of explosions.
- Process and safety training guidelines for personnel involved in the manufacture of explosives shall be developed and disseminated. Such guidelines shall include methods for the demonstration and maintenance of proficiency.
- Safety guidelines for screening of reclaimed explosive materials shall be developed and disseminated.
- Adequate frequencies of safety inspections of explosives manufacturing facilities shall be maintained due to their potential for catastrophic accidental explosions.