applied sciences

MDPI

Article

Experimental Quantification of Fire Damage Inside Pyrotechnic Stores

David León [1,2,*], Blanca Castells [1,2], Isabel Amez [1,2], Juan Casín [2] and Javier García-Torrent [1,2]

[1] Department of Energy and Fuels, Universidad Politécnica de Madrid (UPM), Ríos Rosas 21, 28003 Madrid, Spain
[2] TECMINERGY–Laboratorio Oficial Madariaga, UPM Technical University of Madrid, C/Eric Kandel, 1 (Tecnogetafe), Parque Científico y Tecnológico de la UPM, 28906 Getafe, Spain
* Correspondence: david.leon.ruiz@upm.es

Abstract: A fire inside a pyrotechnic store can lead to simultaneous initiation of the stored articles, regardless of their risk category, producing a shockwave caused by the released gas pressure. In fact, several accidents have occurred throughout history in pyrotechnic stores. This indicates the high risk posed by pyrotechnics due to their flammability. Due to the lack of global or European legislation on guidelines for the design of pyrotechnic stores and associated risk assessment, the present research aims to analyze the consequences of a fire inside pyrotechnic stores and to establish globally possible effective prevention and protection measures in order to reduce explosion risk and avoid future accidents. The observed consequences and the reflected pressure (pressure measured when the wave is incident perpendicularly on the transducer) measured during fire tests inside a pyrotechnic store indicated the need to minimize the potential occurrence of fires. The limitation of the maximum permissible load, considering the volume of the store (kg/m^3), reduces consequence severity in the event of an accident. However, the maximum permissible levels should be so low as to make their use for retail sales of pyrotechnic products unviable. The solution is the use of automatic fire detection and extinguishing systems with a high cooling capacity in order to prevent the spread to nearby packaging by rapid detection.

Keywords: explosion; pyrotechnic stores; prevention

check for updates

Citation: León, D.; Castells, B.; Amez, I.; Casín, J.; García-Torrent, J. Experimental Quantification of Fire Damage Inside Pyrotechnic Stores. *Appl. Sci.* **2023**, *13*, 6181. https://doi.org/10.3390/app13106181

Academic Editor: Genevieve Langdon

Received: 24 March 2023
Revised: 27 April 2023
Accepted: 15 May 2023
Published: 18 May 2023

1. Introduction

Pyrotechnics are all those devices designed to produce combustion inside them, which generate exothermic oxidation–reduction reactions, able to produce smoke, spark, flame or sound effects [1]. It is common to use these fireworks to create a joyful atmosphere for celebrations [2]. The pyrotechnics industry is an important sector worldwide due to the large number of fans, jobs and trade generated. According to The Observatory of Economic Complexity (OEC) [3], pyrotechnic articles traded in 2018 were around USD 1.31 billion. China stands out as the main exporter, with USD 871 million, which means 66.6% of the market.

One of the major hazards associated with fireworks, and other articles with explosive nature, is their flammability [4]. This risk is not only limited to their use but also to their manufacture, transport and storage [5,6]. Regarding pyrotechnic article storage, [7] experimentally demonstrated that a fire inside a pyrotechnic store can cause the simultaneous initiation of the articles inside the store [7]. The overpressure inside the pyrotechnic store when a fire breaks out is produced due to the shockwave of the pyrotechnic articles and the pressure of the gases generated [8]. The shockwave resulting from the internal explosion is reflected by the structure, causing very high pressure peaks. The static pressure resulting from the gases released by the initiation of pyrotechnic articles inside the store is also high due to the lack of pressure relief valves in most cases. This pressure increases the rate of combustion of pyrotechnic mixtures, which promotes the simultaneous initiation or mass explosion of pyrotechnic articles. The total energy released in this process can even be three times the explosion energy of the pyrotechnic articles [9].

Numerous accidents have occurred throughout history due to fires inside warehouses and pyrotechnic stores [10,11]. One of the most catastrophic was in Lima (Peru) in 2001, when 277 people died, 247 were injured and 180 were missing due to an explosion in a local fireworks market. The fatal consequences of this event were aggravated by inappropriate storage and a high degree of confinement [12]. In Europe, one of the most catastrophic accidents occurred in Enschede (Netherlands) in 2000, when a warehouse explosion in the center of a residential area killed 23 people and injured approximately 800. According to the Dutch government, the company stored quantities of fireworks in excess, and they were stored inappropriately due to failures in the risk division [13]. The accidents that have taken place showed that the main effects of pyrotechnic explosions are fragmentation and projections of material from the store structure as well as subsequent projections of the stored pyrotechnic material. These effects are more dangerous when such warehouses or pyrotechnic stores are located within urban areas or are even part of residential buildings [14].

Previous tests carried out by international organizations have studied the risk of explosion in storage and transport of pyrotechnic products. The Clark County (WA) Fire Marshal's Office carried out a fire test on a temporary store constructed with wooden panels, with the front wall partially open, loaded with 400 kg of pyrotechnic articles of risk division 1.4G. All pyrotechnic materials were consumed 3 min after the start of the test and a maximum temperature of 1400 °C was measured. Fireworks were found projected 75 m away [15]. The UK's Health and Safety Executive (HSE) carried out three fire tests on the outside of steel ISO containers with different amounts of NEC (net explosive content), 228, 823 and 2600 kg, respectively. For the first test, the packages were completely burnt but in the same position. This indicates that there was no shockwave. In addition, the container was almost not deformed. Deformation was observed in the next two tests, and cracks were even visible in the third test. In both cases, shell debris was found at distances of 140 and 150 m, respectively [16]. NATO AC258 Group of Experts on the Safety Aspects of Transportation and Storage of Military Ammunition and Explosives carried out detonation tests on ten different pyrotechnic articles, all of division 1.4 G, inside steel ISO containers. Each pyrotechnic article was tested separately, with an NEC of 100 kg. For two of them, there was a more violent reaction than expected, with the container rupturing and detaching parts up to 74 m from the center [17].

In addition, researchers [18] have analyzed and compared the explosion phenomena between closed and ventilated storage containers. In this theoretical study, they showed that, for the analyzed conditions, ventilation systems are effective to reduce the pressure generated inside the storage plant, but only when the v/v° ratio (room volume over pyrotechnic volume) is lower than 1000. Basco and Salazano [8] proved that, when a large quantity of pyrotechnic material ignites, the equivalents with TNT can be adopted. It is also noted that, assuming a container failure pressure of 0.6 MPa, the maximum mass capable of being supported is very small compared to the typical amount stored.

Currently, European directives [19,20] directly address pyrotechnic stores separately from manufacturing facilities. However, these directives do not include recommendations about the design of structures or their risk assessment. These guidelines are provided by the Member States. A global regulation could be a breakthrough for the sector.

This research uses these previous studies as a reference and aims to further analyze the phenomenon that develops as a consequence of an interior fire in pyrotechnic stores. In addition, effective preventive and protective measures are evaluated in order to reduce the risk of explosion. With these results, it is expected to know the maximum permissible load, depending on the type of pyrotechnic product, supported by the store. Indeed, previously published literature already noted that regulations should define standards for firework storage depending on the NEC instead of gross weight [21]. This would allow national regulations to be unified into a global regulation and prevent future accidents and to unify criteria.

Firstly, an assessment of the overpressure generated by the explosion of fireworks inside a warehouse under study is carried out. The aim is to assess the possible consequences in the event of an explosion inside the store and to have information about the degree of resistance of the structures and their design to withstand the effects of such an explosion. Secondly, an evaluation of the effect of a fire inside a pyrotechnic store is carried out. The possibility of simultaneous initiation of the pyrotechnic articles stored inside, the consequent explosion and its consequences are assessed.

In order to minimize the damage caused by fires inside pyrotechnic stores, an analysis of automatic fire detection and extinguishing systems for pyrotechnic stores is also carried out. Although nowadays image processing and artificial-intelligence-based fire detection systems use is increasing [22], most of the industry uses typical fire extinguishing systems. Analyses are carried out by full-scale tests to verify the efficiency and effectiveness of systems and agents to extinguish a pyrotechnic fire, avoiding the possible associated explosion.

2. Materials and Methods

This research study analyzes the risk of explosion in pyrotechnic stores and considers the development of effective measures for the prevention of and reduction in the effects of this. In order to achieve a full analysis, several tests have been carried out.

2.1. Overpressure Test

The purpose of this test is to determine the probability of propagation of a pyrotechnic article explosion to the rest of the packaging and to determine the consequences of a mass explosion inside the test chamber.

The test is carried out in a reinforced concrete explosion chamber, as shown in Figure 1, in which a piezoelectric pressure transducer (model 102A06 of PCB), with a measurement range between 0 and 3.47 MPa, has been inserted for continuous recording of the pressure during the tests. The transducer is placed on the ceiling, where the highest overpressure value is recorded, taking into account that the pyrotechnic articles are located in the center of the chamber's floor. Once the reflected dynamic pressure of the shockwave is recorded by the transducer, it is stabilized by a signal conditioner and recorded by a Yokogawa oscilloscope, capable of recording a frequency of 10×10^6 samples per second.

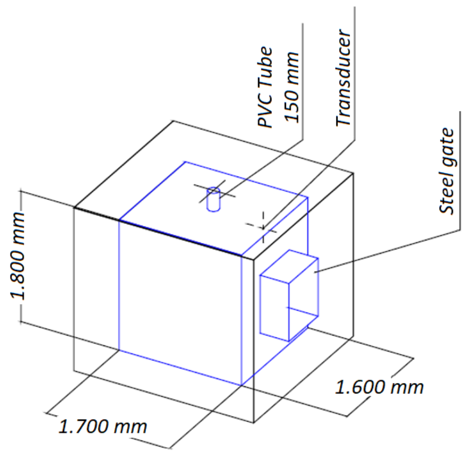


Figure 1. Explosion chamber's diagram.

The reflected pressure measurement is obtained by the difference in volts between the peak of the pressure curve, recorded by the transducer, and the reference or ground voltage. It is transformed into pressure units using the transducer calibration curve.

Pyrotechnic articles tested are division 1.4 G and category F3 flash banger with green fuse, with an NEC of 2.8 g per article and 10 articles per pack. In order to establish the relationship between the overpressure registered on the explosion chamber and the charge density, increasing pyrotechnic charges are tested (starting with a single article up to a maximum of two complete packages, providing a total NEC from 2.8 g to 56.0 g, respectively).

The initiation of the articles is carried out applying ignition by a 120 mJ electric igniter. The overpressure produced by the igniter is recorded previously in order to separate it in the final results.

2.2. Fire Tests

According to the different types of pyrotechnic stores structures, a warehouse with a brick structure plastered on both sides with a thickness of 7 cm and IPN 120 steel pillars and beams is built. It has a cubic shape with walls around 3 m long on the inner side, resulting in an internal volume of 27 m^3.

The walls are fire-resistant for 120 min (FR120) and the door is fire-resistant for 60 min (FR60). The pyrotechnic articles chosen for the fire test are selected as representative and the most unfavorable, i.e., mainly based on "flash" powder. These are fireworks up to category F3, with approximately 50 kg NEC. The risk division of all tested articles is 1.4 G. Table 1 shows more details about the pyrotechnic articles tested.

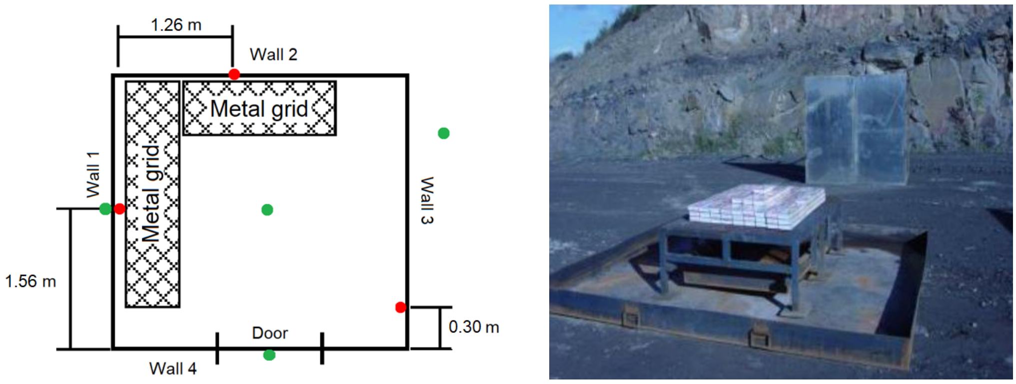
Table 1. Pyrotechnic articles tested.

Pyrotechnic Article Trade Name	Number of Boxes	Packages per Box	Units per Pack	NEC per Pack (g)		Total NEC (g)	
				Pyrotechnic Powder	Burst Powder	Pyrotechnic Powder	Explosive Powder
Rocket "N°4"	4	15	12	60	84	3600	5040
Rocket "N°3"	5	20	12	60	60	6000	3600
Battery flash bangers "Traca 10 m"	1	100	1	63	31	6300	3100
Flash banger "N°3"	1	100	10	0	17	0	1700
Flash banger "Especial"	1	83	10	0	23	0	1909
Battery mines "Color"	1	15	12	404	0	6060	0
Fountain "Super Volcán Diamante"	2	18	6	216	0	7776	0
Battery shot-tubes "Terminator"	1	6	1	554	56	3324	336
Total (g)						33,060	15,685

The articles inside the store are placed on two metal grids located close to two of the internal walls. The packages were removed from the original boxes (simulating possible storage in a pyrotechnic store). The boxes were placed empty inside the store to facilitate the propagation. Under each of the grids, a fountain box (category F2) was placed, which was initiated by 120 mJ electric igniters. Fountains are used as interior fire starters due to their spark effect, which facilitates the propagation of fire.

During the test, the temperature is measured by means of eight thermocouples. Four of them are INCONEL K type located on the inside walls of the store (two on wall 1, at 0.33 and 0.90 m height, one on wall 2 and one on wall 3, both at 0.90 m height) with a measuring range of −180 °C to 1350 °C (±1.0 °C). The rest are T type located on the outside of the door, outside of wall 1 and inside and outside the store, with a measuring range of −250 °C to 400 °C (± 1.0 °C). The pressure was measured by means of transducers located on the inner side of wall 1. A piezoelectric transducer is used for the overpressure and a resistive transducer for the static pressure (generated by the released gases). The test is recorded by a video camera located approximately 50 m from the store, oriented on the two walls on which the pyrotechnics are stacked. A diagram of the fire test can be seen in Figure 2a.

A common practice in pyrotechnic stores is the storage of pyrotechnic products without their primary pack, fuse cover, etc. In addition to the previous test, in order to check the influence of these safety measures on the propagation of a possible fire, outdoor fire test UN Test 6 (c): External fire (bonfire) is used [23]. This outdoor test consists of placing several packages on a metal grid. The fuel is placed under this grid so that the fire envelops the packages. This test is used to determine if there is a risk of mass explosion and to assess the risk of dangerous projections by means of vertically positioned aluminum control screens. In this way, data are obtained to assess their risk division. Figure 2b shows the distribution of Test 6 (c). The fireworks tested are flash banger with green fuse (category F3), flash banger with safety fuse (category F3) and category F3 rocket. Flash bangers are tested with and without primary pack and rockets with and without fuse cover in order to compare the results when safety measures are present or not.



(**a**) (**b**)

Figure 2. (**a**) Diagram of the fire test. Type K thermocouples are shown in red color and type T thermocouples in green color. (**b**) Distribution of the pyrotechnic articles in Test 6 (c): External fire (bonfire) test.

2.3. Fire Detection and Extinguishing Tests

In order to analyze different automatic fire detection and extinguishing systems for use in pyrotechnic stores, tests have been carried out with various types of rapid detectors and with different types of extinguishing agents (gaseous, solid and liquid). An uninsulated metal H shed is used as a pyrotechnic store for the tests. The structure has rectangular galvanized steel profiles and a 0.8 mm thick galvanized steel Pegasus type sheet metal enclosure on the side walls and 1.2 mm thick galvanized sheet metal on the roof. The dimensions of the shed are 2.30 m $\times$ 2.44 m $\times$ 4 m (height $\times$ width $\times$ length). The exterior door consists of two 180 °C hinged leaves, made of galvanized sheet metal and with a security lock.

Previous tests have shown that fountains favor the propagation of fire to other nearby pyrotechnic articles, which is a high risk inside the store. Because of this, two types of fountains are used in the tests.

For each installed fire detection and extinguishing system, two different tests were carried out. During the tests, the temperature is recorded by means of three thermocouples located inside the store, with a measuring range of -250 °C to 400 °C (± 1.0 °C). The first (T1) is located in front of the box where the fire starts and at a height of 35 cm. The second (T2) is placed in front of the second box, 15 cm above the ground, in order to check the existence of fire propagation. The last one (T3) is located above both boxes at a distance of 140 cm and records data on the ambient temperature inside the store. After the fire has been extinguished, the test results are visually evaluated.

2.3.1. Internal Fire Test

In this test, the fire initiation occurs in a pyrotechnic article contained within a package, simulating the possible accidental initiation of an article in a store. Two boxes of pyrotechnic material are tested. The first of them (where the fire is generated as a result of the initiation of an article contained inside it) contains category F3 fountains with an NEC per unit of 61.08 g and a total of 6108 g in the package. The second box (placed behind the first one to check the propagation of fire) contains category F2 fountains with an NEC per unit of 5.5 g and a total of 1375 g in the package, of which 250 g is explosive powder. The total quantity of pyrotechnic material tested is 7233 g of pyrotechnic powder and 250 g of explosive powder. The flaps of the boxes are left open, simulating a common practice in pyrotechnic stores. Empty boxes are placed on the sides and on the top of the pyrotechnic packages to check the fire propagation. Test diagram can be seen in Figure 3.

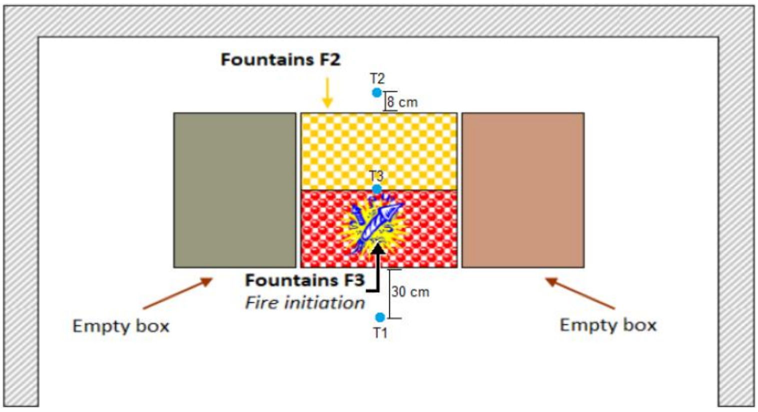


Figure 3. Diagram of articles in fire tests inside the package.

2.3.2. External Fire Test

In this test, the fire initiation occurs on the outer sides of the box, simulating a fire originated inside the store but not directly inside the package. A box with category F2 fountains with an NEC per unit of 5.5 g and a total of 1375 g, of which 250 g is explosive powder, is tested. The box is placed with the flaps closed. Again, empty boxes are placed on the sides and on the top of the pyrotechnic package to check the fire propagation. The fire is generated on two exposed sides of the box impregnated with petrol, which are ignited by 120 mJ electric igniters. Test diagram can be seen in Figure 4.

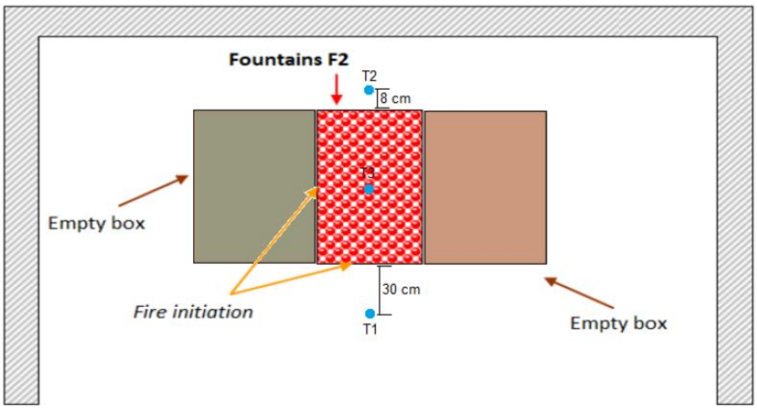


Figure 4. Diagram of articles in fire tests on the outer sides of the package.

The different systems installed and tested for fire detection and extinguishing were smoke detection with suction system and water mist Hi-Fog®, smoke detector with explosion extinguishers (foam-forming fluid FR CROS 134 P), ionization detector and CO_2 extinguishing system, ionization detector and HFC-227ea gas extinguishing system, optical smoke detector and water extinguishing system, optical smoke detector and foam extinguishing system and optical smoke detector and dust extinguishing system. More detailed information regarding these systems can be found in the Supplementary Materials.

2.4. Tests of Other Extinguishing Agents

These tests are carried out to analyze and evaluate the extinguishing systems typically used by pyrotechnic stores. The following extinguishing agents are tested: water mist, 0.25 and 0.55 MPa automatic water sprinklers, foam, FE-13 gas (HFC-23), HFC-200 gas and CO_2.

A thin sheet metal shed with the following dimensions is used as storage in the tests: 4 m × 2 m × 2.30 m (length × width × height). The automatic fire extinguishing systems are installed in this shed. More detailed information regarding these systems can be found in the Supplementary Materials.

Pyrotechnic material tested are category F2 fountains with an NEC of 160 g per unit and 3840 g per package (Article 1) and category F2 fountains with an NEC of 25 g per unit and 2400 g per package, using two packages of this firework in the tests, distributed in four boxes (Article 2). Prior to the tests of extinguishing agents, preliminary tests are carried out in order to define the quantity of pyrotechnic articles and the location of the packages in order to ensure a rapid and complete propagation of the fire. Finally, the pyrotechnic articles are distributed as shown in Figure 5.

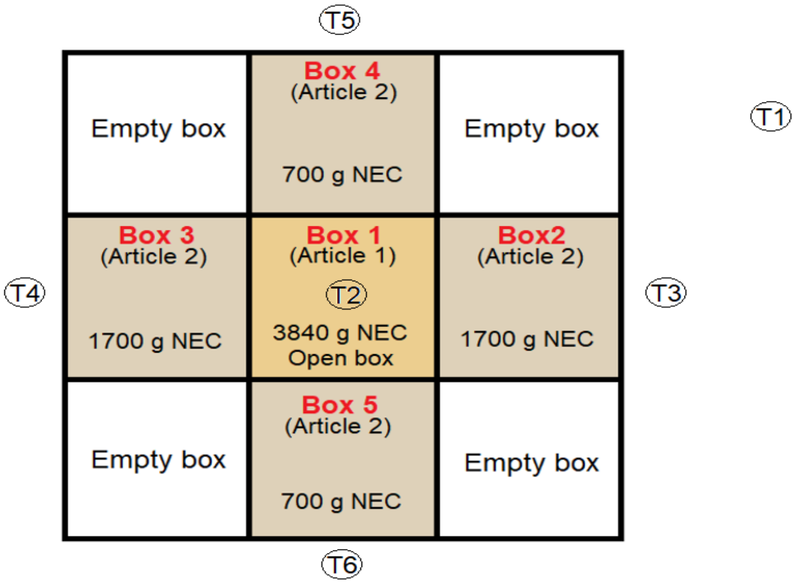


Figure 5. Diagram of the layout of the tests inside the shed.

The fire is started by the ignition with a 120 mJ electric igniter of one of the fireworks contained in box 1. During the tests, the temperature is recorded by means of six thermocouples located inside the shed, as shown in Figure 5. The temperature measurement range of the thermocouples used is −250 °C to 400 °C (±1.0 °C). Five of them record data nearby the pyrotechnic material and the last one records the ambient temperature inside the test shed (T1). After the fire has been extinguished, the test results are visually evaluated.

3. Results

3.1. Overpressure Test

From this test, reflected pressure (P_R) measured by the transducer is obtained. From these data, it is possible to calculate the incident pressure (P_i), which is the actual shockwave pressure of the pyrotechnic articles, by using the following equation [24]:

$$P_R = 2P_i \cdot \frac{7P_o + 4P_i}{7P_o + P_i}, \quad (1)$$

where P_o represents the atmospheric pressure. It has to be remarked that both the reflected pressure and the incident pressure do not take into account the shockwave generated by the electric igniter, which is known due to the previous tests carried out. The reflected-pressure-obtained data are consistent with the predictions obtained using the mathematical model of the manual TM 5-1300 [25] for black powder.

Incident pressure refers to the initial shockwave generated by the explosion. This wave is created by the rapid expansion of gases within the confined space, which creates a sudden and powerful burst of pressure that travels outward from the point of ignition.

Reflected pressure, on the other hand, is a secondary wave that is generated when the initial shockwave encounters a boundary, such as a wall or floor, within the confined space. This reflected wave travels back towards the point of origin and can interact with the initial incident wave, amplifying or altering its effects.

The probability that stored pyrotechnic products explode altogether will depend on many factors, including packaging type, fuse, arrangement of articles in the container or packaging, presence of products that ignite and can spread fire or the type of product. Previous tests carried out in the open air showed that the products known as flash bangers with green fuse and fountains propagated the explosion when an article is ignited; however, no mass explosion was observed. This behaviour is different when the tests are carried out in enclosed spaces, as in the case study, where it is observed that the behavior of the flash bangers with green fuse differs and generates a mass explosion in any studied case.

This behavior is predicted by the tests developed by the NATO working group AC/258 [17], which proved that some pyrotechnic products classified as 1.4 G might lead to a mass explosion when confined in enclosed areas.

The different mass explosions that occurred during the tests are represented in Figure 6, which collects the data for reflected pressure and incident pressure (kPa) vs. charge density (kg/m^3).

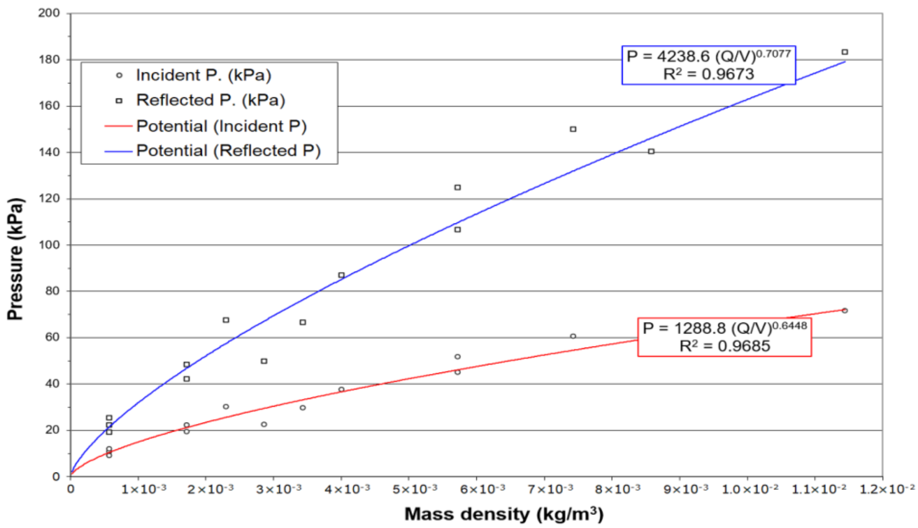


Figure 6. Effect of the charge density (kg/m^3) on the reflected and incident pressure of the shockwave generated by the mass explosion of pyrotechnic articles.

These data are fitted to potential pressure curves. Nevertheless, more detailed information can be found in the Supplementary Materials.

Due to the non-existence of pressure spillways in the stores for pyrotechnic products sale, the ignition of certain articles produces the explosion and rupture of the warehouse structure, mainly due to the effect of the pressure reflected on the internal walls of the structure and the pressure of the gases generated and contained within it. Pressure spillways are structures designed to relieve pressure within a confined space. Without these spillways, the pressure generated by an explosion or ignition can cause significant damage to the structure and even lead to its complete rupture.

From the data plotted in Figure 6, it can be noticed that incident pressure is significantly greater than reflected pressure, and, the greater the mass density, the greater the difference between both. The incident pressure wave can cause damage to nearby structures and objects and can also be harmful to human beings if they are within close proximity of the explosion. Nevertheless, reflected pressure can be particularly dangerous in confined spaces as it can cause additional damage to the surrounding environment and increase the risk of injury or death.

Using the model described in the manual [25], a structure capable of withstanding the mass explosion caused by the maximum charge tested, 20 flash bangers with green fuse, with a total NEC of 56 g is calculated.

Regarding the store, a volume of 30 m^3 is considered in a cubic shape without venting surface and built of bricks. This warehouse represents a typical F1-, F2- and F3-category pyrotechnic store. The walls of the structure must resist the pressure of the shockwave for a certain time, defining the impulse [26]. Therefore, in order to properly define a warehouse structure capable of withstanding the mass explosion, it is necessary to determine parameters such as load density, wave pressure from explosion, incident time, etc. Once these parameters are known, it is possible to estimate the structure that the warehouse should have in order to resist the mass explosion.

Moreover, the structure capable of withstanding the mass explosion must be reinforced with longitudinal and transverse steel bars. These bars increase the flexural strength of the wall, preventing it from reaching the elastic limit. It is theoretically verified that the structure is capable of withstanding both bending and shear stresses, so a structure with these characteristics supports the mass explosion generated by 20 flash bangers with green fuse of 2.8 g NEC per unit. According to the study carried out, the maximum net amount of pyrotechnics that the previous structure would support would be 0.16 kg. The larger the volume of the store, the greater the maximum net amount of pyrotechnics it can hold. More detailed information regarding the structure considered in the present study can be found in the Supplementary Materials.

3.2. Fire Tests

The results of the fire test inside the pyrotechnic products warehouse were catastrophic. The test was carried out using 50 kg of NEC and therefore a load density of 1.85 kg/m^3. Approximately 15 s after the initiation of the two fountain units in each of the two packages arranged under both racks, a single strong explosion occurred, leading to the total destruction of the test store. This explosion was not preceded by any other pyrotechnic effect. After viewing the recording of the video camera in slow motion, it was possible to verify how the door was the first element to be destroyed. At this moment, a large fireball is observed inside the building, and, immediately after, the entire structure is destroyed. This sequence is shown in Figure 7.

Figure 7. Frames of the fire test evolution.

Previous studies noted the significant damage that a fireworks explosion can produce in a warehouse [16,27]. In the present study, the wall pillars where no pyrotechnic articles were placed did not suffer changes in their location or noticeable damage. On the other hand, the two pillars corresponding to the walls where the pyrotechnic charge was located were detached at distances between 80 m and 100 m. Two of the steel roof girders were found on the side of a nearby mountain, at distances between approximately 150 m and 200 m. The concrete floor was fragmented and sunken in the area where the rockets were located. The access door was detached at a frontal distance of approximately 80 m. Structural fragments were found up to distances of approximately 200 m.

As a consequence of the fast explosion, there are no measurements of temperature or static pressure of the gases due to the saturation and destruction of the corresponding sensors before registering any measurement. Only dynamic pressure data were recorded from the moment the artifices were started until the moment the building was destroyed (4 ms). These data are plotted in Figure 8.

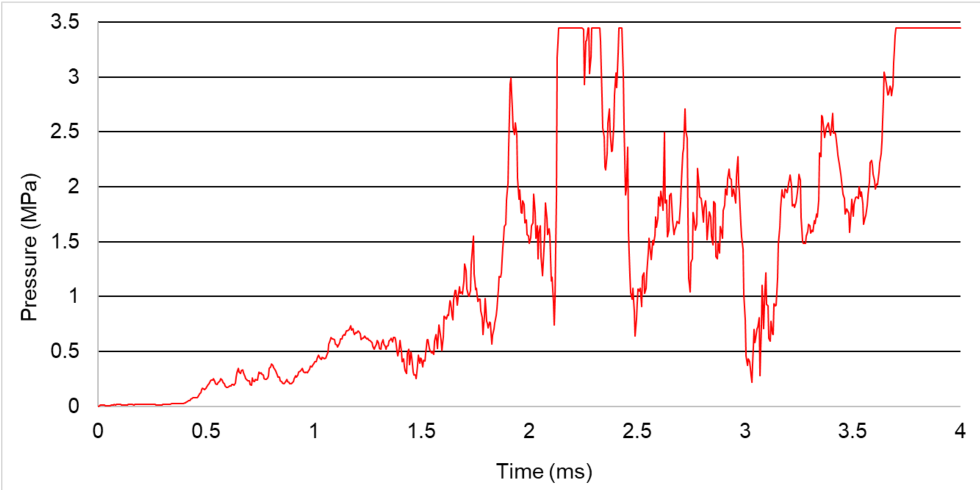


Figure 8. Recording of the dynamic reflected pressure over time in the fire test.

The pressure transducer upper limit was 3.47 MPa, which was reached during the explosion. From the plot, it seems that this limit is exceeded several times as a straight horizontal line is produced when reaching the upper limit. Therefore, it seems that pressures greater than 3.47 MPa cannot be recorded and are plotted as the maximum scale value. Aside from that, numerous overpressure peaks or pressure increases are observed in a very short time. The high-pressure values recorded and the different peaks observed indicate the existence of a very high and rapid simultaneity of the stored pyrotechnic articles explosion. In this sense, the fast and homogeneous fire generated by the fountains propagated on the existing pyrotechnic articles in the warehouse, together with the very high pressure values registered inside, have given rise to a considerable increase in the rate of combustion of the material and, therefore, have favored this rapid simultaneity of explosions and the catastrophic consequences.

Due to the impossibility of obtaining experimental values higher than the transducer limit, the mathematical model allows to theoretically calculate the shockwave generated by the mass explosion of the pyrotechnic materials tested in a warehouse with the same characteristics as the one tested. According to the results obtained, the simultaneous initiation of 50 kg of pyrotechnic material would produce a shockwave with a pressure of 18.58 MPa. It is shown that a regular pyrotechnic store is incapable of absorbing the pressures caused by the initiation of 50 kg of NEC, corresponding to category F3 pyrotechnic articles for sale to the public.

Knowing the maximum pressure that a certain warehouse structure can withstand, it is possible to calculate the maximum load density that could be stored inside to avoid its deterioration. The relationship is as follows [25]:

$$P = a \cdot \left(\frac{Q}{V}\right)^{b}, \tag{2}$$

where Q is the pyrotechnic load and V the volume of the store. However, parameters a and b depend both on the geometry of the store and on the location of the explosive charge in relation to the walls of the building. For this reason, even knowing the limit pressure, it is impossible to establish a single maximum load density for all warehouses as the geometry will play a decisive role. Nevertheless, the limitation of the maximum admissible load, in addition to considering the volume of the warehouse, would lead to a decrease in the severity of the consequences in the event of an accident. However, and considering most of the existing warehouses in these premises, the maximum authorized levels should be so low that they would make their use for the sale of pyrotechnic products to the public unfeasible. Therefore, and in order to reduce this risk of explosion, it is necessary to reduce or minimize the probability of a fire occurring inside the warehouse through the use of the corresponding security measures.

From Test 6 (c) or external fire (bonfire) tests carried out, it has been possible to verify that there is no influence on the type of fuse used to start the fireworks in the event of a fire, as well as on the use of fuse protectors. In the same way, the existence of the original primary packaging only leads to a delay in the initiation of all the articles existing inside it.

Although it is common practice, pyrotechnic articles or containers should not be stored outside their packaging since the ignition delay caused by their use may be sufficient to extinguish a possible fire inside the warehouse with the appropriate means.

In addition, as verified with previous tests, the effect of confinement negatively influences the risk of explosion in the warehouse. In this context, Series 6 tests are tests that are carried out outdoors, but the risk class obtained is used to classify the product for transport and storage, which are always carried out in enclosed buildings or containers. Because of this, these tests do not provide fully correct information about the mass explosion risk of fireworks in enclosed environments.

3.3. Fire Detection and Extinction Tests

3.3.1. Internal Fire Test

The results of the internal fire tests are shown in Figure 9. Figure 9a shows that smoke detection by aspiration is carried out very quickly as it can be seen that the existing thermal gap was slightly lower than 20 K for thermocouple T2, which presents the greatest increase. With the Hi-Fog® water mist system, the fire can be stopped approximately in the third minute, but part of the material remains at a high enough temperature to produce a latter ignition, as can be seen after 25 min, once the 50 L water bottle has run out. This causes the propagation of the fire and the ignition of the material contained in the packaging closest to the T2 thermocouple, measuring a maximum temperature of approximately 160 °C. Possibly, a larger amount of water (100 L water bottles) would have been able to prevent subsequent reignition; however, the price of this system is high if compared to other fire detection and extinction systems.

The results of the smoke detection test with explosion extinguishers are shown in Figure 9b. Noted were the existence of a flame in the pyrotechnic material packaging and the spread of the fire before the explosion of the extinguishers. The existing fire extinguisher on the ground and adjacent to the rear packaging extinguished the fire developed in the same packaging approximately 1 min after the start of the fire (see thermocouple T2). The other extinguisher, placed on the packaging of the pyrotechnic material that caused the fire, was unable to extinguish it, which led to the immediate propagation and reignition of the products inside (see thermocouple T1). In addition, the explosion of the extinguishers causes the dispersion of the packages, which affects the temperatures measured in thermocouple T3, as the distance from the thermocouple to the fire increases. After reignition, another explosion extinguisher with a fuse was manually thrown onto the fire, which completely extinguished the fire. This fact suggests the possibility of having extinguished the fire in the event of the existence of a third explosion extinguisher. The price of this system is very low compared to other fire detection and extinction systems. Furthermore, it is very quick and easy to install and maintain.

Figure 9c indicates that CO_2 does not act fast enough to extinguish the fire generated by pyrotechnic articles. The pyrotechnic material contained in the first package cools down around minute 3, when the temperature in the thermocouples closest to the fire (thermocouples T1 and T3) was slightly above 20 °C. However, it is not possible to completely extinguish the fire, which produces a reactivation and subsequently spread to the second packaging at approximately minute 8. It can be seen that the maximum temperature reached in the T2 thermocouple (the closest to the second packaging) exceeds 150 °C. The price of this system is high compared to other fire detection and extinction systems and requires a complex installation. In addition, it has the disadvantage of the high toxicity of the gas, which is the main reason why it is not indicated in those places where there is a permanent presence of people.

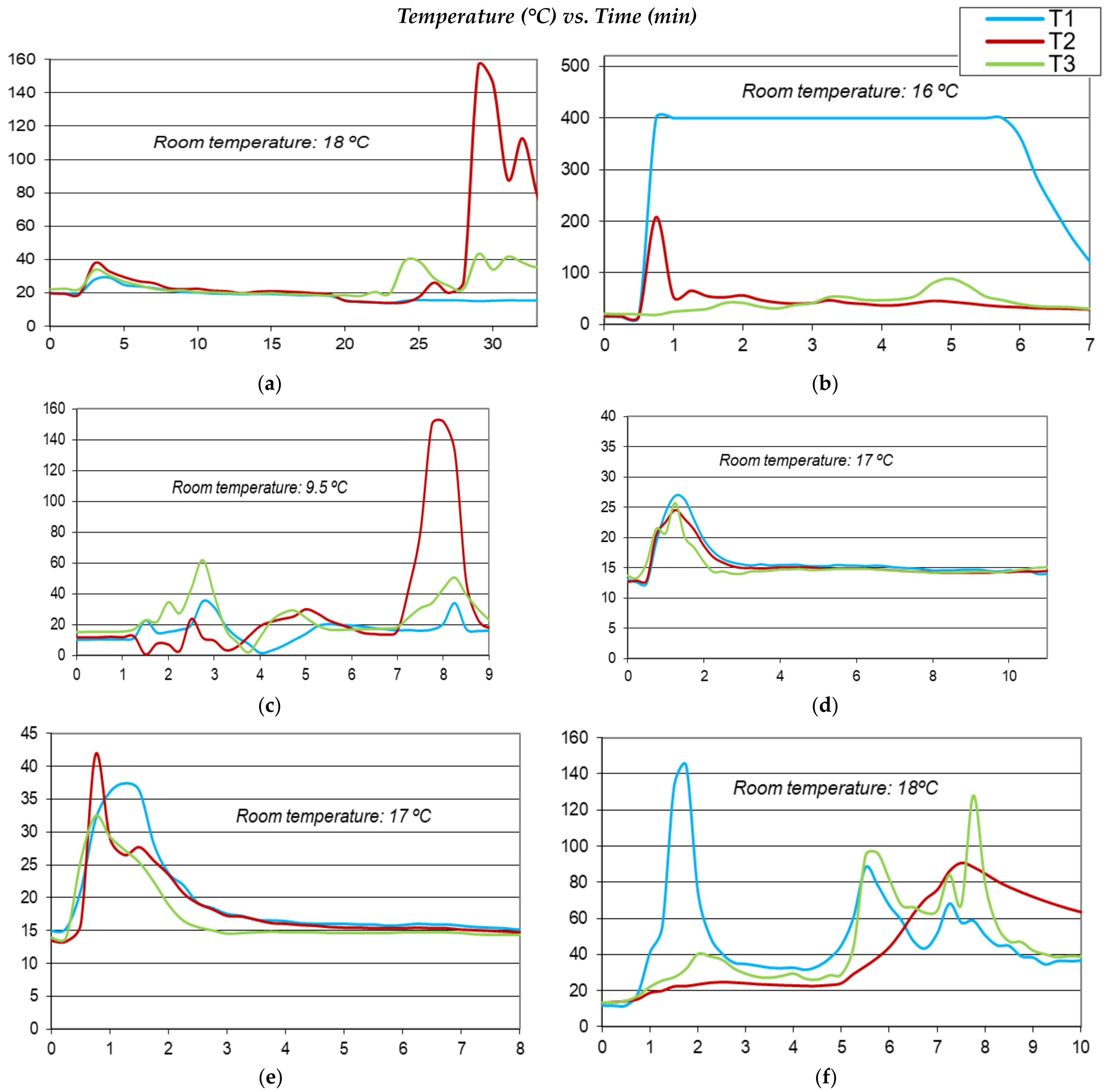


Figure 9. Results of internal fire tests: (**a**) smoke detection with suction system and water mist Hi-Fog®. (**b**) Smoke detector with explosion extinguishers. (**c**) Ionization detector and CO_2 extinguishing system. (**d**) Optical smoke detector and water extinguishing system. (**e**) Optical smoke detector and foam extinguishing system. (**f**) Optical smoke detector and dust extinguishing system.

For the optical detection system for smoke and water as an extinguishing agent, Figure 9d shows that, after starting the fire, the temperature in the vicinity of the pyrotechnic load rises to approximately 27 °C at T1 thermocouple (the closest to the source of fire), moment at which the extinction of the fire begins. Approximately 3 min later, the fire had been completely extinguished, cooling the environment and the material, as observed in the measurements of the three thermocouples with a temperature of approximately 15 °C. Subsequently, it is visually verified that the fire is completely extinguished and that only three pyrotechnic articles had started. Aside from the efficiency of the system, it has to be highlighted that the cost and maintenance of the installation are lower than for other systems.

As can be seen in Figure 9e, for the foam extinguishing system, once the fire has started, the temperature rapidly rises to approximately 42 °C in the T2 thermocouple, indicating that the fire has spread to the second packaging. At this point, the fire extinguishing begins. Due to a lack of pressure in the water network, the mixing system (foam/water) stopped working, so the only extinguishing agent was water. Despite this, as in the previous system, it is possible to extinguish the fire before reaching high temperatures inside the warehouse, as observed in the T3 thermocouple, where the temperature does not exceed 35 °C. However, these tests did not verify the efficiency of the foam extinguishing agent; even so, this system has the advantage of having additional water in case of system failure. The cost and maintenance of the installation are higher than those of the water system due to the addition of foam. Moreover, for the extinguishing agent to work correctly, a minimum pressure in the water network must be guaranteed.

Finally, the powder extinguishing system in Figure 9f showed that, after 50 s, the fire is spread to the subsequent packaging, as can be seen by the increase in temperature in the T2 thermocouple. The temperature in the vicinity of the first package (T1 thermocouple) is approximately 150 °C. until the powder extinguishing bottle ABC is discharged. Although part of the generated fire is extinguished, it does not completely disappear. This gives rise to the appearance of reignitions in the existing pyrotechnic articles in both packages, which causes all the existing load in the warehouse to burn, reaching an ambient temperature inside it (see T3 thermocouple) of more than 120 °C. The price of this system is higher than the water system with a network connection.

According to the results, it is shown that the best extinguishing system analysed is the optical smoke detector and water extinguishing system due to its high efficiency because of a high cooling capacity and low installation and maintenance cost. The next best performing system has been the optical smoke detector and foam extinguishing system. The efficiency of this system could have been higher if the mixing system (foam/water) had worked properly, but it is a more expensive system.

3.3.2. External Fire Test

The results of the external fire test are plotted in Figure 10. Figure 10a indicates that the aspirating smoke detector registers the fire approximately 20 s from the start and when the temperature slightly exceeded 20 °C. The nebulized water is capable of extinguishing the fire before it penetrates the interior and causes the initiation of the existing pyrotechnic articles inside.

In the case of the smoke detection system and explosion extinguishers, Figure 10b shows that, once the fire is generated, the temperature in the surrounding area of the pyrotechnic load rises slightly to approximately 42 °C. At this moment, the detection and explosion of the extinguisher initiates, completely extinguishing the fire.

For the system with an ionic detector and HFC-227ea gas as extinguishing agent, Figure 10c shows that, after approximately one minute has elapsed since the start of the fire and having reached temperatures between 30 and 45 °C in all three thermocouples, the system extinguishes the fire and prevents its spread to adjacent packages. The system has the advantage of the non-existent toxicity of the gas, unlike in the case of CO_2, but the cost of the system is still high compared to other systems.

Figure 10d shows the results for the water extinguishing system. Once the fire is generated, the agent is detected and discharged after approximately 10 s, but the flame cannot be extinguished. However, thanks to the fact that the extinguishing system does not stop acting at any time, the fire is completely extinguished after approximately five minutes.

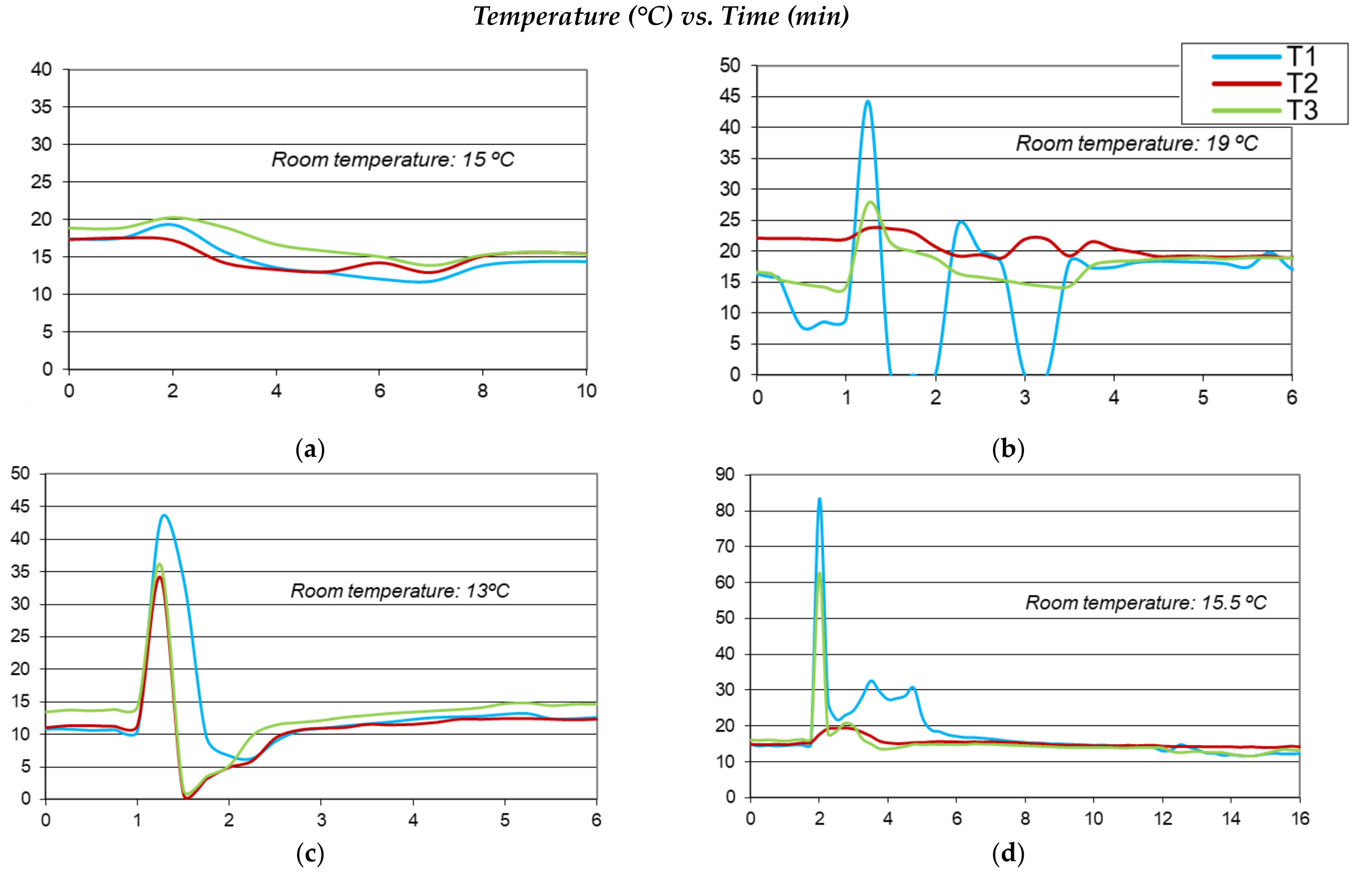


Figure 10. Results of external fire tests: (**a**) smoke detection with suction system and water mist Hi-Fog®. (**b**) Smoke detector with explosion extinguishers. (**c**) Ionization detector and HFC-227ea gas extinguishing system. (**d**) Optical smoke detector and water extinguishing system.

In the tests carried out, it is verified how, in the first moments, a certain amount of smoke is produced prior to the generation of flame or fire. It is observed that a rapid response of the detectors is important to achieve timely action, with ionic and aspiration detectors being the most sensitive and fastest, although they also have a higher cost.

It is observed that all the fire detection and extinction systems evaluated are effective for extinguishing the fire produced outside the packaging of pyrotechnic products as they all produce the fire extinction before the fire has penetrated the existing pyrotechnic articles inside the packaging.

In the case of a fire caused by the pyrotechnic material itself, the recommended extinguishing system must have a very high cooling capacity, such as water or foam. Fountains generate a large amount of flame and/or fire, increasing the probability of spreading to the rest of the surrounding pyrotechnic articles and packaging inside the warehouse. For this reason, the extinguishing agent must act on the entire material as otherwise the reignition of the device does not find any difficulty. Therefore, the location of the extinguishing systems and the stacking during storage of the packages should be carefully considered. These systems are usually located in the ceiling of the warehouses; however, if the ceiling is significantly high or the packages are stacked to a high height, it is possible that, in case of fire, the extinguishing agents do not reach the pyrotechnic articles located at the bottom of the packages.

If systems are compared, the only system that has managed to extinguish the fire caused by the pyrotechnic products has been the water network due to its continuity and high cooling capacity. The low economic cost of installation and maintenance is important, although it is necessary to have a network socket and ensure a supply 24 h a day. For water mist systems and explosion extinguishers, a greater number of tests should be carried out considering the different possibilities that these two fire detection and extinction systems admit. The same occurs for the foam/water mixer because, although extinguishing is achieved, the system does not work correctly due to insufficient water network pressure. Finally, it was noticed that systems based on gases and dust are less effective for this type of fire.

3.4. Tests of Other Extinguishing Agents

Each one of the extinguishing agents mentioned in Section 2.4 has been tested. This section presents the obtained results, comparing the different agents. In most of the cases, the data obtained by the thermocouple that measures the ambient temperature inside the warehouse (T1 thermocouple) are not taken into account as they do not present any significant variation.

3.4.1. Automatic Water Sprinklers

Water sprinklers were found to be one of the most commonly used and effective extinguishing systems [28]. Figure 11 shows the temperature record of the different thermocouples during the fire test using water sprinklers as an extinguishing agent. The maximum temperature (40.9 °C) is obtained in the T5 thermocouple for the test using 0.25 MPa sprinklers and in the T6 thermocouple for the test with 0.55 MPa sprinklers, where 15.5 °C is reached. In both tests, it is observed that, after less than a minute, the extinguishing agent begins to act. Once the test is finished, it is visually observed that, when using low-pressure sprinklers, the fire spreads to various articles contained in box 1 but does not spread to the adjacent boxes. For high-pressure sprinklers, there is no spread to adjacent boxes and no spread to any article contained in box 1 other than the source of the fire.

The extinguishing agent tested is considered to be suitable for use in automatic fire extinguishing systems in establishments selling pyrotechnic articles. This conclusion is reached because the propagation of the fire and the future reignition of the articles are avoided. High-pressure 0.55 MPa sprinklers are even more effective as they manage to extinguish the fire before it spreads inside the box itself and because the thermocouples reach a lower temperature than in the case of high-pressure 0.25 MPa sprinklers, not exceeding 16 °C in any of the thermocouples, with the ambient temperature being 9.8 °C.

3.4.2. Foam

The results obtained during the fire test using foam as an extinguishing agent are shown in Figure 12. The ambient temperature during the test is 12.2 °C. During the test, the maximum temperature is reached at T3 thermocouple at the start of the fire, which records 14.0 °C. As can be seen, the thermal jump is minimal due to the rapid and effective action of the extinguishing agent. After less than one minute, the temperature begins to decrease, and the fire is completely extinguished. Once the test is finished, it is visually observed that, with this extinguishing agent, there is no propagation to the adjoining boxes or to any artifice in box 1, so it is also an extinguishing agent suitable for use in systems for automatic fire extinguishing in establishments selling pyrotechnic products. This agent extinguishes the fire quickly and with almost no temperature rise as measured by thermocouples. The reason is that the addition of foam to the water network increases its cooling capacity.

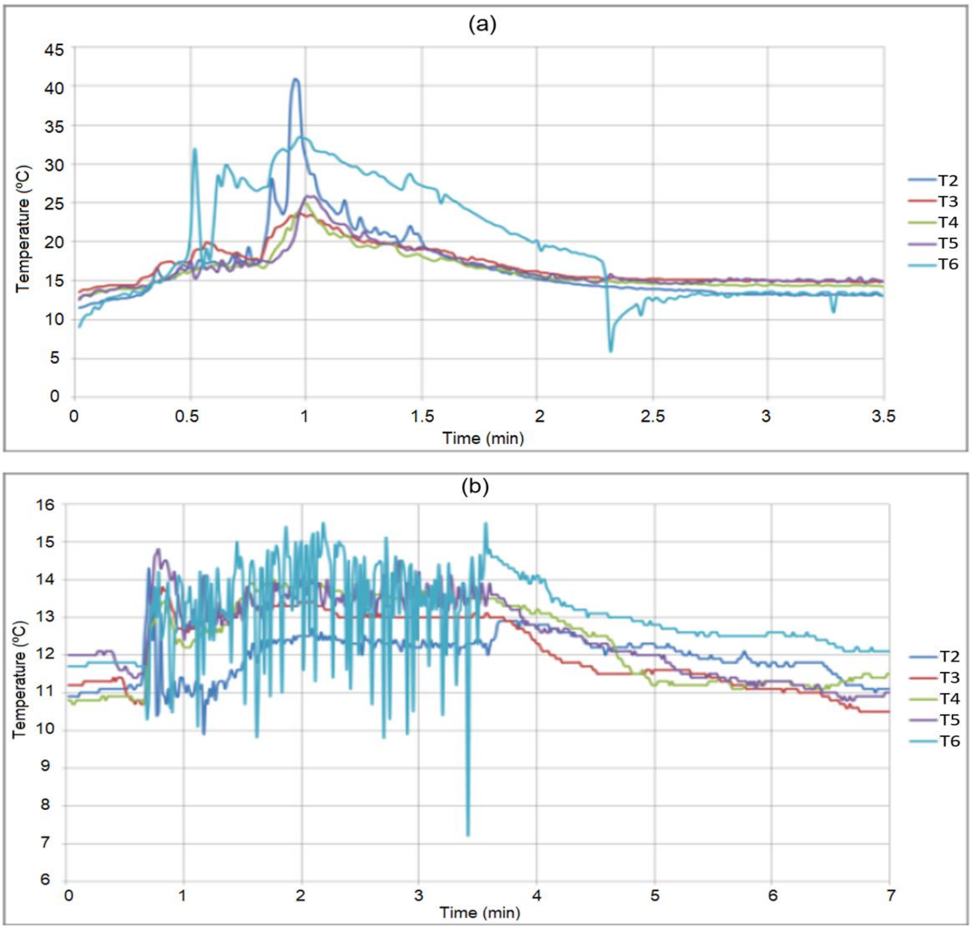


Figure 11. Temperature recording in the automatic water sprinklers test. (**a**) 0.25 MPa sprinklers. (**b**) 0.55 MPa sprinklers.

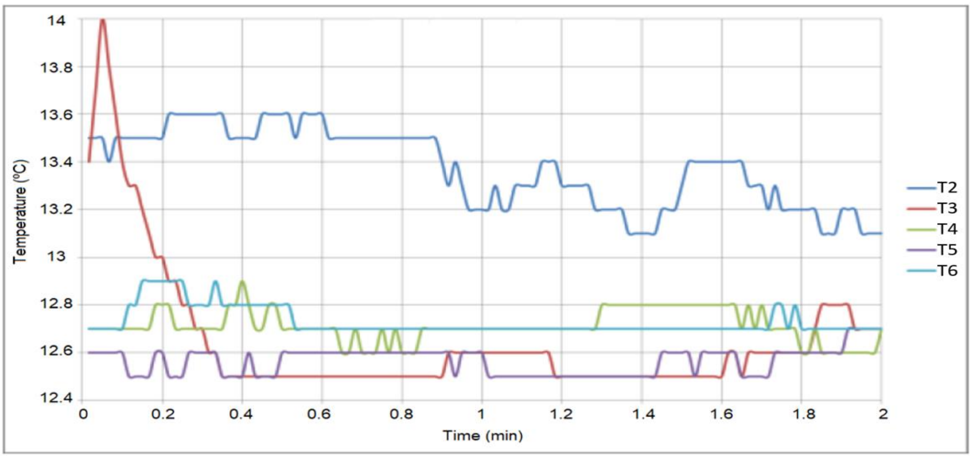


Figure 12. Temperature recording in the foam test.

3.4.3. Hi-Fog Water Mist. MAU-150 Equipment

The results of the test are shown in Figure 13. The maximum temperature is reached in T5 thermocouple approximately 2 min after the start of the fire, with a value of 18.6 °C. From that moment, the temperatures begin to decrease, which indicates that the extinguishing agent begins to act, and it can be noticed that, around minute 7, the fire is completely extinguished. The ambient temperature during the test was 11.8 °C. It is visually verified that, with this extinguishing agent, there is no spread to the surrounding boxes and only one article from box 1 ignites, in addition to the article that is intentionally started. These results indicate that it is also an extinguishing agent suitable for use in automatic fire extinguishing systems in establishments selling pyrotechnic products.

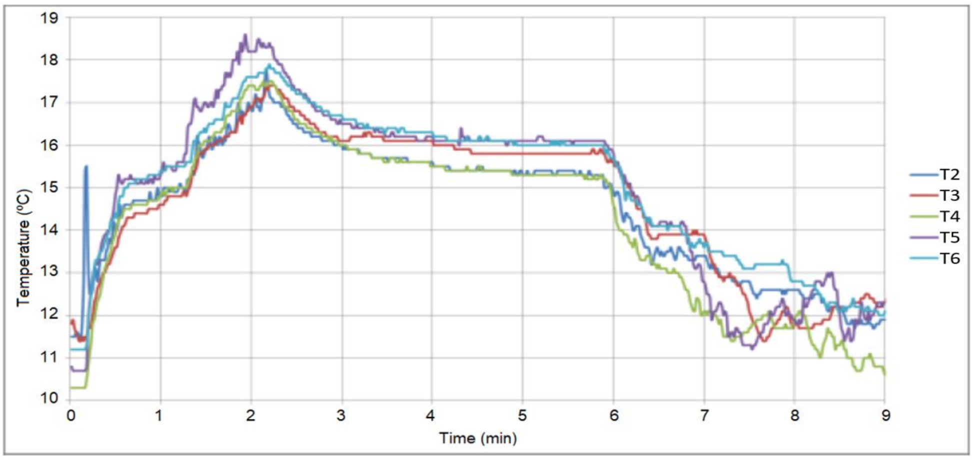


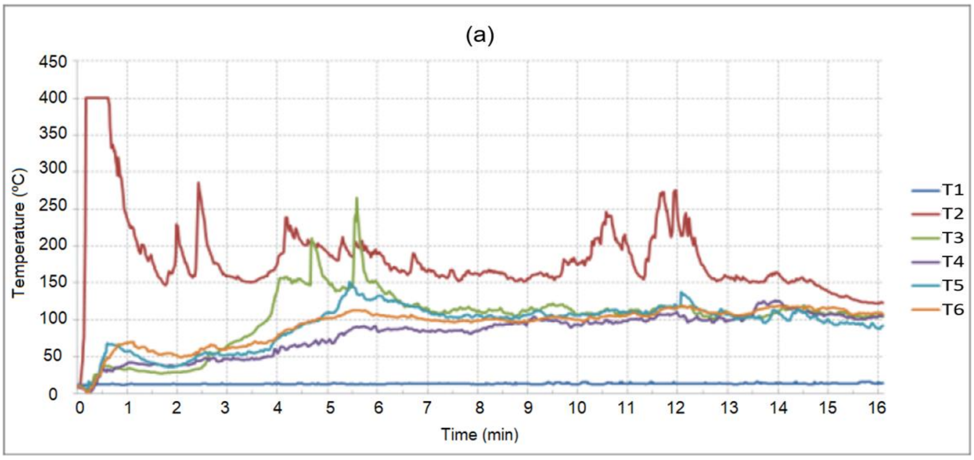
Figure 13. Temperature recording in the water mist Hi-Fog test.

3.4.4. FE-13 (HFC-23) Gas and HFC-200 Gas

Figure 14 plots the results obtained for the fire tests using both gases as extinguishing agents. It is observed how both tests follow a similar evolution in terms of temperature. The ambient temperature in both cases is approximately 12 °C. Once the fire has started, the temperature measured at T2 thermocouple (thermocouple located above the box where the pyrotechnic article starts) exceeds the measurement range of 400 °C in both cases. Despite the action of the extinguishing agent approximately 1 min after the start of the fire, it was not possible to suffocate the fire and high temperatures were still observed 15 and 20 min later. In all the thermocouples located in the areas close to the pyrotechnic material, temperatures exceed 100 °C. Once the test was finished, it was visually observed that, with both extinguishing agents, the fire spreads to all the existing boxes in the warehouse. Therefore, both extinguishing agents are considered unsuitable for use in automatic fire extinguishing systems in establishments selling pyrotechnic products, so the warehouses where these agents are used are unprotected against a fire.

3.4.5. Carbon Dioxide CO_2

Figure 15 shows the results obtained in this test. The ambient temperature at the time the test was carried out was 12.6 °C. The first thermocouple to register an increase in temperature is T2 thermocouple due to its proximity to the source of the fire. After just over a minute, the measurement limit of 400 °C is reached, which allows to foresee, due to the high temperatures, that the fire has not been extinguished in time and has spread to the rest of the surrounding boxes. This is confirmed with the data recorded by the rest of the thermocouples close to the pyrotechnic charge since, in all cases, temperatures exceed 100 °C. The high temperatures are maintained over time despite the action of the extinguishing agent, which indicates that this extinguishing agent is not suitable for use in automatic fire extinguishing systems in establishments selling pyrotechnic products. In other words, the warehouses where this extinguishing agent is used are unprotected against fires. Once the test was completed and by visually reviewing the warehouse, it was confirmed that the fire had spread to the rest of the adjacent boxes, having started all the pyrotechnic articles.



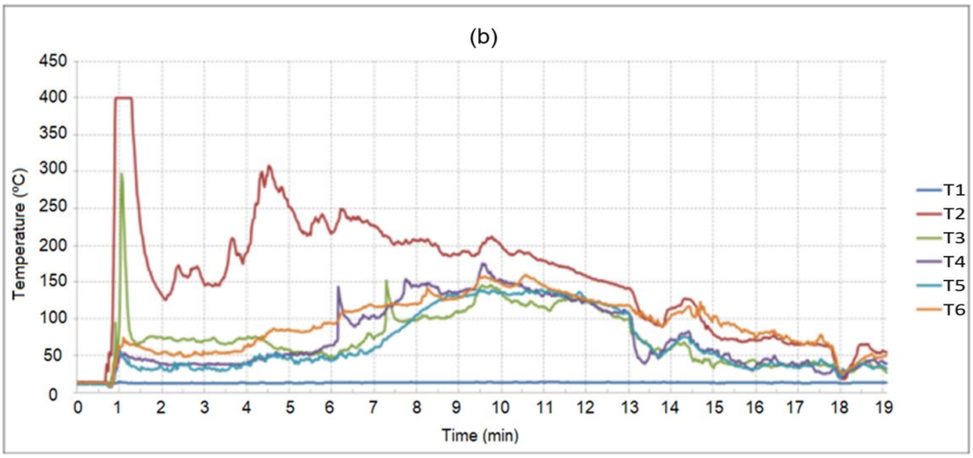


Figure 14. Temperature recording in the gas tests. (**a**) FE 13 gas test. (**b**) FM 200 gas test.

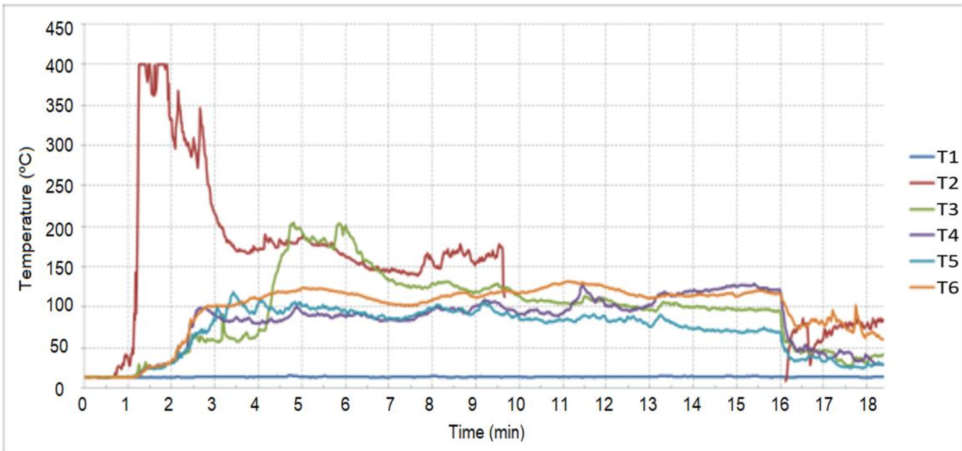


Figure 15. Temperature recording in the CO_2 test.

The storage and handling of pyrotechnic products can be dangerous due to the high risk of fire and explosion. Pyrotechnic mixtures contain their own oxidizer, making them highly reactive and more prone to catching fire. Once a fire starts, it can be difficult to extinguish as it can spread quickly and easily to nearby packages, resulting in a larger fire and greater danger.

To prevent fires in pyrotechnic warehouses, it is crucial to have effective fire prevention measures in place, such as rapid detection and automatic extinguishing systems. Extinguishing agents play a crucial role in controlling and extinguishing fires in pyrotechnic warehouses. However, not all extinguishing agents are equally effective in extinguishing fires caused by pyrotechnic products.

In tests carried out to evaluate the effectiveness of different extinguishing agents, water and foam were found to be the most effective in extinguishing fires caused by fountain-type pyrotechnic articles. Water, in the form of automatic sprinklers and bottled water mist, was particularly effective in preventing the spread of fire to nearby packages. The higher the water supply pressure, the better the results in extinguishing the fire. Nebulized water was also effective, but it is important to ensure proper sizing in relation to the amount of bottled water and the type of nozzle installed.

Other extinguishing agents, such as gases, were found to be insufficient in preventing the spread of fire inside the premises. These systems do not have enough refrigeration capacity to prevent the spread of fire inside pyrotechnic warehouses and should not be considered as effective fire prevention measures.

In conclusion, it is essential to have appropriate fire prevention measures in place to prevent fires in pyrotechnic warehouses. Rapid detection and automatic extinguishing systems, combined with effective extinguishing agents, such as water and foam, can help to control and extinguish fires caused by pyrotechnic products. However, the use of insufficient extinguishing agents, such as gases, should be avoided as they do not have the necessary cooling capacity to prevent the spread of fire.

4. Conclusions

Due to the large number of accidents caused by fires inside these warehouses, national regulations must be unified globally in order to achieve more appropriate regulations to reduce the consequences in the event of an accident. In the present study, overpressure and risks derived from a fire inside warehouses containing pyrotechnic material have been assessed. Pyrotechnic articles of different risk divisions and generic type are tested, as well as different amounts of NEC. The design of the test warehouses also varies, as well as the installed fire detection and extinction systems.

According to the UN Series 6 tests to assign a substance the corresponding risk division, most pyrotechnic articles do not generate a mass explosion. These tests are performed outdoors, without taking into account the overpressure due to confinement. When a fire breaks out inside the pyrotechnic warehouse, due to the overpressure generated, it is shown that risk division articles 1.4 G (materials that supposedly present a low risk in case of ignition) can explode simultaneously, even causing the destruction of the building as in the test case, where structural fragments of the building were found up to approximately 200 m. As the assigned risk division is taken into account for the storage and transport of the substance, Series 6 tests should simulate real cases in enclosed environments.

The reduction in the load density inside a warehouse would lead to a decrease in the pressure reached in the event of an accident, and, therefore, the consequences of a fire are reduced. However, the measurements of the pressure generated inside a warehouse, without a fire prevention and extinction system, due to the fire caused by flash bangers indicate that, for a quantity of 56 g of NEC, a reflected pressure of 183.27 kPa is generated. This indicates that the load density admissible for a pyrotechnic store must be so low that its use is impossible to put into practice. Because of that, tests are carried out installing detection and extinction systems in the warehouses to reduce the probability of fire events. Once a fire spreads to the rest of the containers, due to the high burning rate of the pyrotechnic compositions, it is very difficult to extinguish the fire. It means that rapid detection is required, which is achieved with smoke, ion and optical detectors. The most effective extinguishing agents have turned out to be those that have a greater refrigeration capacity and prevent the reignition of the articles, such as water and foam. These ignition systems were the only ones capable of extinguishing the fire, before it spread to the rest of the articles, during the tests, although new tests are required for other types of extinguishing agents.

The storage and handling of pyrotechnic products pose significant fire and explosion risks. Once a fire starts inside a package of pyrotechnic products, it can be difficult to extinguish, especially due to the presence of an oxidizer in the pyrotechnic mixtures. Therefore, it is crucial to have effective fire prevention measures in place, including rapid detection and automatic extinguishing systems, combined with appropriate extinguishing agents, such as water and foam. These measures can help to control and extinguish fires in pyrotechnic warehouses and prevent their spread to nearby packages.

Some of the national regulations do not accept many of the tested extinguishing agents, but it is important to study them in order to have all the necessary information to be able to establish a global standard. This is crucial because some countries have lax regulations that can lead to fatal accidents.

The data provided in the present study can be used to properly address the associated risk and develop a safe standard that allows the use of only capable extinguishing systems. Indeed, the tests carried out have shown that NEC significantly influences the generated pressure; therefore, standards should consider using NEC value instead of gross weight.

As a consequence of this study, mandatory requirements were incorporated into the current Spanish legislation. Therefore, the tests carried out could also be useful to establish guidelines at a global level on the location, design and security measures to be installed in the stores of pyrotechnic products, thus avoiding future accidents due to fire and explosion of the material.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13106181/s1, Table S1: Shockwave results of overpressure tests; Table S2: Detailed information on the store capable of supporting the simultaneous explosion.

Author Contributions: Conceptualization, D.L. and J.G.-T.; methodology, D.L.; software, B.C.; validation, D.L., J.C. and I.A.; formal analysis, D.L. and J.C.; investigation, J.C. and I.A.; resources, I.A. and B.C.; data curation, D.L.; writing—original draft preparation, B.C.; writing—review and editing, J.C. and I.A.; supervision, J.G.-T.; project administration, D.L. and J.G.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Industry, Energy and Tourism of Spain (Collaboration agreement between the Secretary of State for Energy of the Ministry of Industry, Energy and Tourism and the Universidad Politécnica de Madrid (Laboratorio Oficial J. M. Madariaga–LOM)).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Russell, M.S. *The Chemistry of Fireworks*; Royal Society of Chemistry: Cambridge, UK, 2009.
2. Chen, S.; Jiang, L.; Liu, W.; Song, H. Fireworks regulation, air pollution, and public health: Evidence from China. *Reg. Sci. Urban Econ.* **2022**, *92*, 103722. [CrossRef]
3. The Observatory of Economic Complexity. Pyrotechnic Articles | OEC—The Observatory of Economic Complexity. *Pyrotechnic Articles* 2018. Available online: https://oec.world/en/profile/sitc/pyrotechnic-articles (accessed on 19 January 2023).
4. Guzii, S.; Tsapko, Y.; Kravchenko, A.; Remenets, M. Fire Protection of wooden storage containers for explosive and pyrotechnic products. *EUREKA Phys. Eng.* **2016**, *2*, 34–42. [CrossRef]
5. Witsaman, R.J.; Comstock, R.D.; Smith, G.A. Pediatric Fireworks-Related Injuries in the United States: 1990–2003. *Pediatrics* **2006**, *118*, 296–303. [CrossRef] [PubMed]
6. Canner, J.K.; Haider, A.H.; Selvarajah, S.; Hui, X.; Wang, H.; Efron, D.T.; Haut, E.R.; Velopulos, C.G.; Schwartz, D.A.; Chi, A.; et al. US emergency department visits for fireworks injuries, 2006–2010. *J. Surg. Res.* **2014**, *190*, 305–311. [CrossRef] [PubMed]
7. CHAF. Quantification and Control of the Hazards Associated with the Transport and Bulk Storage of Fireworks. Grant Agreement ID: EVG1-CT-2002–00074. 2002. Available online: https://cordis.europa.eu/project/id/EVG1-CT-2002-00074 (accessed on 14 July 2022).
8. Basco, A.; Salzano, E. The Analysis of Explosion of Storage Plants Containing Display Pyrotechnics. In Proceedings of the Processes and Technologies for a Sustainable Energy, Ischia, Italy, 27–30 June 2010. [CrossRef]

9. McIntyre, F.L.; Rindner, R.M. *A Compilation of Hazard and Test Data for Pyrotechnic Compositions*; Computer Sciences Corp Stennis Space Center MS; Defense Technical Information Center: Fort Belvoir, VI, USA, 1980.
10. Rajathilagam, N.; Rajathilagam, N.; Azhagurajan, A. Accident analysis in fireworks industries for the past decade in Sivakasi. *Int. J. Res. Soc. Sci.* **2012**, *2*, 170–183.
11. Ajith, S.; Sivapragasam, C.; Arumugaprabu, V. A review on hazards and their consequences in firework industries. *SN Appl. Sci.* **2019**, *1*, 120. [CrossRef]
12. Arce-Palomino, J.L. Grandes Incendios Urbanos: Mesa Redonda, Lima 2001. *Rev. Peru Med. Exp. Salud Publica* **2008**, *25*, 118–124.
13. Weeth, C.P. Enschede: Lessons to Relearn. In Proceedings of the 6th International Symposium on Fireworks, Orlando, FL, USA, 3–7 December 2001; pp. 345–366.
14. Myatt, S.G.; Bale, E.W. Hazards Associated with Large-Scale Storage of Fireworks-Human Failure and its Consequences. In *Hazards XXII: Process Safety and Environmental Protection*; Liverpool, UK, 11 April 2011; Available online: http://www.icheme.org/media/9268/xxii-paper-56.pdf (accessed on 14 December 2022).
15. Lynam, D. Fireworks Stand Test Burn. *Fire Technol.* **2001**, *37*, 153–166. [CrossRef]
16. Myatt, S.G. The effects of external fire on fireworks stored in steel ISO transport containers. *J. Pyrotech.* **2002**, *16*, 59–70.
17. DDESC (Danish Defense Explosives Safety Commission). AC/258 NATO Work Group. 'Storage of Fireworks', Report AC/258 (ST) (DA) IWP 01-2002, 27 January 2002. Available online: http://www.rasrinitiative.org/pdfs/AASTP-1-Ed1-Chge-3-Public-Release-110810.pdf (accessed on 13 July 2022).
18. Basco, A.; Salzano, E.; Cammarota, F. The risk of storage plant of pyrotechnics. *Chem. Eng. Trans.* **2010**, *19*, 231–236. [CrossRef]
19. DIRECTIVE 2012/18/EU on the Control of Major-Accident Hazards Involving Dangerous Substances. *Off. J. Eur. Union L* **2012**, *197*, 1–37.
20. DIRECTIVE 2013/29/EU on the Harmonisation of the Laws of the Member States Relating to the Making Available on the Market of Pyrotechnic Articles. *Off. J. Eur. Union L* **2013**, *178*, 27–65.
21. Wharton, R.K.; Bagley, M.J. Review of threshold quantities for the control of explosives in health and safety legislation in The Netherlands. *Saf. Sci.* **2004**, *42*, 621–626. [CrossRef]
22. Yao, X. The Application of Artificial Intelligence-Based Fireworks Recognition Technology in Fire Detection. In Proceedings of the 2022 IEEE Asia-Pacific Conference on Image Processing, Electronics and Computers (IPEC), Dalian, China, 14–16 April 2022; pp. 1371–1374. [CrossRef]
23. United Nations. *Committee of Experts on the Transport of Dangerous Goods and on the Globally Harmonized System of Classification and Labelling of Chemicals*; Manual of Tests and Criteria. Amendment 1; United Nations: New York, NY, USA, 2021.
24. Mohanty, B. Physics of explosions hazards. In *Forensic Investigation of Explosions*; Beveridge, A., Ed.; Taylor and Francis: London, UK, 1998; pp. 33–62. [CrossRef]
25. Department of the Army; Department of the Navy; Department of the Air Force. *Structures to Resist the Effects of Accidental Explosions (ARMY TM 5-1300)*; National Institute of Building Sciences: Washington, DC, USA, 1990; Chapter 2; pp. 49–136.
26. Alonso, F.D.; Ferradás, E.G.; Pérez, J.F.S.; Aznar, A.M.; Gimeno, J.R.; Alonso, J.M. Characteristic overpressure–impulse–distance curves for the detonation of explosives, pyrotechnics or unstable substances. *J. Loss Prev. Process Ind.* **2006**, *19*, 724–728. [CrossRef]
27. Williams, M.A. Modern rack and mortar designs for professional fireworks displays. *J. Pyrotech.* **1995**, *2*, 6–14.
28. Duan, L.; Hou, X. Review of automatic fire water monitor system. *J. Phys. Conf. Ser.* **2021**, *1894*, 012013. [CrossRef]