HAZARDS ASSOCIATED WITH THE LARGE-SCALE STORAGE OF FIREWORKS – HUMAN FAILURE AND ITS CONSEQUENCES†

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Large quantities of a wide range of materials, including fireworks, are shipped around the world in steel ISO-containers. In recent years, manufacturers and retailers have increasingly used such containers to store a large proportion of their fireworks. Each container can be large enough to store tonnes of different types, ranging from small fireworks for indoor use to large fireworks for professional display operators only.

While the most likely time for a firework incident to occur is when they are being used, some of the most catastrophic incidents have occurred during storage. Generally, this is because more fireworks are available to become involved in the explosion. An example, which is the major firework storage incident in Europe over the last 30 years, is without doubt the violent and devastating explosion that occurred at Enschede, in 2000. However, smaller but no less dangerous explosions have occurred during this period. This paper aims to provide an overview of the most significant of these incidents and discusses the underlying causes and the consequences.

INTRODUCTION

In contrast to high explosives (HE), which explode instantaneously, most fireworks tend to produce their effects over a few seconds or even minutes. Because of the behaviour of HE (instantaneous effects), emergency planning deals with the consequences of the explosion. With fireworks the emphasis needs to be shifted to take account of actions that can be taken during the escalation of a firework explosions as well as the aftermath. This paper describes a number of firework incidents to demonstrate events that can occur and to suggest actions to help prevent accidental firework explosions and mitigate their effects.

Fireworks have been used in entertainment for centuries and they have developed many different forms. They range from small relatively safe indoor fireworks such as party poppers, to shells with diameters in excess of 400 mm or Roman candles which eject effects at high velocity and to heights in excess of 100 m. All employ mixtures of fuels and oxidisers to generate pyrotechnic effects that are used mainly for entertainment purposes ranging from small back garden displays to large, spectacular shows designed for national celebrations. Individual fireworks of whatever size pose a limited threat to society, although there are many instances of lethal accidents to individuals. This situation can change dramatically once large numbers of fireworks are stored together and while thousands of tonnes of fireworks are stored safely each year, experience has shown that a relatively small ignition source can escalate to a large explosion capable of damaging buildings over large distances and resulting in many fatalities and injuries.

EXAMPLES FROM THE PAST

CULEMBORG 1991 (NL)

Approximately 4.4 tonnes gross of display fireworks containing an estimated 1500–2000 kg Net Explosive Content (NEC) were being stored at a display firework assembly plant and its associated storage facilities(1). Two explosions occurred that destroyed the site. A crater 2 m deep, 5 m wide and 10 m long was produced and buildings were damaged up to 900 m away.

After the incident it was established that two people were working in the store who are believed to have been modifying fireworks or processing blackpowder. It was also established that the site was licensed for UN 1.4 fireworks (those that present only a slight risk of explosion) and UN 1.3 fireworks (those that have a fire hazard and either a minor blast hazard or a minor projection hazard or both, but not a mass explosion hazard), and a limited amount of blackpowder. Blackpowder is defined as UN Hazard Division (HD) 1.1, meaning that it poses a mass explosion hazard. Investigations concluded that some of the fireworks stored at the site, while classified as HD 1.3, showed HD 1.1 properties in the incident. This was attributed to either some fireworks types being incorrectly classified or a boostering effect of HD 1.1 material on the HD 1.3 fireworks causing the compositions of the HD 1.3 fireworks to be consumed all together to produce a violent explosion. It was suggested that a third possibility might be that the bulk fireworks displayed a different behaviour in large-scale than was expected from the smaller quantities used in the UN series 6 tests. Clearly, an understanding of the products being stored would have helped to prevent this incident,

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not least because any mis-labelling of transport packs by manufacturers could have easily been identified. The processing of explosives in a storage area is considered to be inappropriate and suggests that the operators may have been working in the area in contravention of procedure.

FERRENSBY 1998 (UK)

As mentioned in the introduction the effect of fireworks on their surroundings can change dramatically when many articles are stored together. The quantity of fireworks that constitute 'a large quantity' varies depending on the type of firework being stored and the compositions they contain. A lack of appreciation of the hazards posed by the fireworks is demonstrated in this example. Although it was not a true storage situation it emphasises the need for a clear understanding of the article being stored and its mode of operation.

A display operator undertook to dispose of rockets for a fireworks wholesaler. The rocket heads contained a flash composition consisting of barium nitrate, sulphur and finely divided aluminium powder. Such mixtures are used when a bright flash and loud explosion are required. They are extremely energetic[(2)], have TNT equivalencies in the range 0.4 to 1.3[(3)] and to a bystander would appear to explode in a similar manner to High Explosives, i.e. instantaneously. As individual rockets stored together the potential hazards from mass explosion were small. However, these items had been partly dismantled and segregated into boxes of rocket motors and rocket heads. In this arrangement all the flash composition was exposed simultaneously to an ignition source. In the incident 100 rocket heads and motors were placed in a large steel kiln and ignited by a firework fountain thrown in by the operator as he closed the kiln doors. The flash composition (in total 2.65 kg) ignited almost instantaneously causing the 2 kiln doors (total mass approximately 255 kg) to be ripped from their hinges. One door (144 kg) struck the operator, who died instantly; a relative standing nearby suffered hearing damage.

During HSL's investigation[(4)] on behalf of HSE, a reconstruction of the incident showed that a fireball was projected 18 m in front of the kiln (Figure 1), and an overpressure of 264 kPa (38.4 psi) was generated inside it. This caused the entire kiln (approx. 2 tonnes) to recoil 0.7 m as the gas vented through the doors before its motion was arrested by a grassy bank.

In this incident the wholesaler had failed to identify the increase in hazard brought about by the partial dismantling of the articles and had passed them on to an operator who was competent to perform firework displays but had only a superficial understanding of explosives disposal. His lack of appreciation of the construction of the rockets and the behaviour of their contents resulted in an inappropriate disposal technique being used. What this incident demonstrates is that training of staff to enable them to make correct decisions is vital to reduce the risk of serious incidents. In this instance the operator strayed outside his competency, knowledge and experience in undertaking the disposal work. As well as errors on the part of the operator, there were errors by a number of people in the management chain who failed to ensure that appropriate personnel were adequately trained.

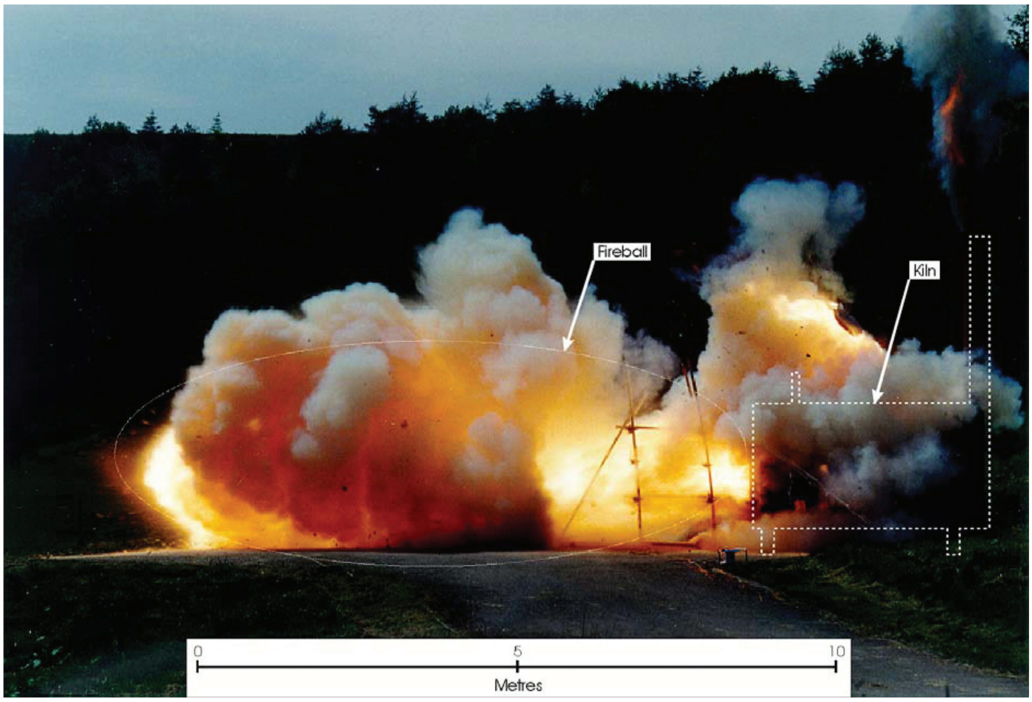

Figure 1. Ignition of 100 partially broken down rockets in a steel kiln

UFFCULME 1998 (UK)
Failure to follow procedures is another area which has lead to explosive incidents involving fireworks. In this example significant damage was inflicted to buildings surrounding a fireworks storage depot in Uffculme, Devon[5] when a fire started in one of the storage containers. This led to an explosion in which, fortunately, no one was killed.

The fireworks were being stored in steel storage containers 6.1 m long and of 2.4 m cross-section. They are commonly called ISO-containers and are used for freight transport and increasingly for the storage of fireworks and other goods.

An operator was dismantling a string of firework shells in an open steel storage container when the shells ignited causing the fireworks in the container to catch fire and ultimately explode. In total eight containers used for the storage of fireworks were housed in the same building, which was constructed in a similar manner to many industrial units (i.e. concrete base, brick lower walls, and corrugated steel sheet construction above). Many of the containers subsequently exploded after the ignition of the fireworks in the first container. Buildings in the immediate area were destroyed (Figure 2) and others severely damaged. A portakabin 55 m from the explosion was also destroyed. Debris was scattered for hundreds of metres.

The account of the operator confirmed that the string of shells had been returned from a display and that he wanted to separate them to facilitate a stock check. Unfortunately, the matchead fuse that had been fitted at the display site had not been removed before the fireworks were returned to the store. The company had procedures instructing staff how and where the breakdown of fireworks should take place. Contrary to these procedures, the operator elected to cut the fuse between the shells using scissors (instead of using a sharp knife cutting onto a wooden block), while still inside the ISO-container (not the designated area for this activity).

Subsequent investigation showed that the crushing action of the scissors acting on a matchead fuse in the firework fuse system was sufficient to ignite the shell string and resulted in an explosion which scattered burning firework stars throughout the ISO-container causing more fireworks to ignite. As the fire and explosions continued they attracted the attention of the local population who gravitated towards the site, unaware of the danger in which they were placing themselves. Finally a large explosion occurred throwing debris into the air and destroying the magazine complex. ISO-container fragments were thrown up to 210 m[5]; in particular a steel ISO-container corner weighing 10 kg fell through an extension roof 140 m from the explosion, narrowly missing a child. Corrugated cladding from an adjacent mill (53 m) was ripped off and panes of glass were broken at distances of up to 100 m. Directly beneath the first container that exploded were two depressions in the 163 mm thick concrete base. The largest was approximately 113 mm deep and 4 m in diameter. The smaller depression was 3 m from the first and was 50 mm deep and 3 m in diameter. From the available data it was calculated that the explosion was equivalent to 200–250 kg TNT. As a result of the large explosion and ensuing fire, the office area was damaged and all magazine records were destroyed thereby making analysis of the incident more difficult.

Research into firework storage in ISO-containers that was being performed at HSL[6] at the time of the incident produced visual effects similar to those observed at the incident scene (Figure 3). A total of 2.6 tonnes NEC of firework

Figure 2. Uffculme fireworks complex after incident (Reproduced by permission of Aerial Photos)

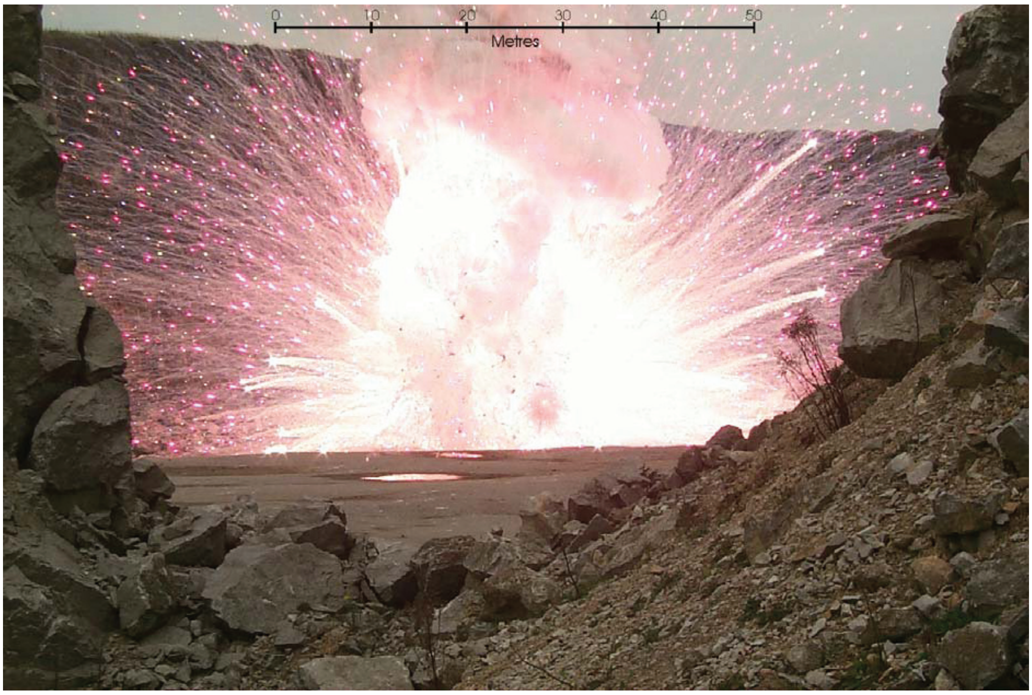

Figure 3. Effects of ignition of 2.6 tonnes NEC of firework shells in a 20 ft steel ISO transport container

shells, caused the doors of the container to burst open and the container sides to bulge. The shells ignited sequentially over a 20 second period and produced a sphere of stars in excess of 100 m diameter. An inner core of flame 36 m diameter was estimated to have an effective surface temperature of 400°C and exceeded 800°C over a diameter of 22 m.

ENSCHEDE 2000 (NL)

The most notable firework storage incident that has occurred in Europe over the last 10 years was at Enschede(7) on 13 May 2000.

S.E. Fireworks were operating from buildings originally used for bulk paper processing in a residential area. The complex had several reinforced concrete bunkers that were used to store the fireworks. Over time, the need for more storage space led to the licensing of 17 concrete bunkers, 7 MAVO boxes (a brand of pre-fabricated garage), and 14 large ISO-containers (steel containers used primarily to transport goods via cargo ship or lorry). To facilitate efficient processing of fireworks' orders the MAVO boxes and ISO-containers were next to each other and less than 50 m from the main bunkers.

On the day of the incident five employees were working at the site packing fireworks for dispatch, which resulted in the doors on a number of stores being left open. During the afternoon a fire, allegedly started deliberately, caused some fireworks in one of the reinforced concrete bunkers to ignite. Fire-fighters were called to the scene and onlookers gathered to watch. After about 2.5 minutes a large explosion occurred which knocked people to the ground. Over the next few minutes two further large explosions occurred which broke windows and ripped tiles from the roofs of nearby homes hurling them hundreds of metres. The explosions also spread lighted fireworks over a large distance, which facilitated a rapid spread of fire. In all, 23 people were killed including four fire-fighters and hundreds more were injured.

Examination after the incident revealed that the complex and 400 buildings within a 400 m radius were destroyed and that many buildings within a 1 km radius caught fire. In addition, the aftermath left a crater 1.35 m deep and 13 m in diameter. Analysis of the glazing damage at different distances from the explosion point indicated that the explosion was equivalent to that of 4000–5000 kg of TNT.

The incident demonstrated the potential problems associated with storing large quantities of the more powerful firework types near residential areas. As a result it was recommended that the larger the quantity of fireworks stored, the greater the separation distance between the store and such settlements.

Another consideration was the proximity and orientation of the stores to each other and nearby buildings. In the incident the stores were close together and doors from one store often faced those of stores opposite. It would be safer for stores to be further apart and for doors to face open ground wherever possible. Related to this aspect would be a drive to train personnel to close store doors each time they leave to help prevent escalation.

It has also been suggested that the use of strong stores such as reinforced bunkers and ISO-containers may compound the explosive risk by providing containment and confinement.

A Dutch government investigation into the incident[8] concluded that the company had been storing quantities of fireworks in excess of their licence, that some were knowingly of a more hazardous classification than the site permits allowed and that some fireworks may have been stored inappropriately due to failures in the explosives classification scheme or because manufacturers were assigning classifications based on expediency rather than on hazard.

CARMEL 2002 (AUSTRALIA)

Similar events to those at Uffculme occurred in Carmel, Australia[9,10]. Two operators were removing electric matchead fuses from a batch of 30 mm diameter 25 shot Roman candle combinations in a light commercial building. After removing the electric fuse one of the combinations was placed on a table and is reported to have ignited. The other effects in that firework functioned and ignited a wide range of other fireworks that were in the shed. The operators fled leaving the shed door open, which allowed fireworks' effects to escape. Some landed around a reputedly closed ISO-container 16 m from the doors of the shed. Combustible materials such as cardboard boxes and wooden stakes that were piled up outside the container subsequently ignited. The fire that ensued resulted in an explosion of such force that an operator was blown over 35 m from the blast. Fragments from the explosion of the ISO-container punctured the walls of other magazines causing two to ignite and explode, resulting in damage to building structures and windows. In addition, a large area of scrub was destroyed by fire. In total the event took 14 minutes from the first ignition to the explosion of the last container. Fortunately, no one was killed or injured.

Subsequent investigation showed that the explosion of the first ISO-container created metal shrapnel that penetrated two other magazines that contained 725 kg and 941 kg NEC of fireworks, respectively. It is believed that the contents of these two magazines were ignited by the impact, friction or heat from the shrapnel. After approximately 5 minutes, one of these magazines exploded by failing at its welded seams which tends to indicate either a partial detonation or a rapid deflagration as the mechanism of the explosion. 11 minutes later the other magazine exploded violently producing a fireball 100 m in diameter and radiating shrapnel up to 500 m from the explosion. The door (170 kg) was found 370 m away from the explosion and the roof (380 kg) was projected 295 m. Structural damage was inflicted on buildings up to 2.5 km away and window glass was damaged to a distance of 4.5 km. In addition, fires were started which destroyed 40 hectares of land around the site.

LEWES 2006 (UK)

The most recent large-scale fireworks incident in the UK occurred at the premises of Festival Fireworks Ltd near Lewes, East Sussex, where fireworks capable of mass explosion were being illegally stored in a 6.1 m long steel ISO-container.[11]

An operator was weatherproofing single-shot batteries outside the designated factory building for use at a display that evening and had some electric igniters close by. While moving the igniters the operator alleged that they burst into flames and ignited the single shot batteries. A fire ensued that spread through the site and eventually impinged on the ISO-container resulting in a violent explosion causing the deaths of two fire-fighters and injuring Police Officers, other fire-fighters and members of the general public. Fragments of the container were thrown hundreds of metres, windows in domestic premises nearby were broken and tiles on roofs were dislodged. An aerial view of the site after the incident is given in Figure 4.

Subsequent investigation demonstrated that fireworks were being stored in unlicensed areas of the site and that some of these fireworks posed a mass explosion hazard. This was in contravention of the site licence, which allowed storage of predominantly HD 1.4G fireworks and a small quantity of HD 1.3G fireworks in a separate store.

Between the licensed stores were areas set aside for the storage of non-explosive materials in order to act as 'buffers' to prevent propagation from one explosive store to another. However, buildings had been extended, which defeated the buffer provision and allowed the fire to spread across the site. Video evidence also showed that fireworks effects were ejected from these areas indicating firework storage in inappropriate locations.

The container that ultimately exploded was not licensed for the storage of fireworks and had no labelling on it to indicate the hazardous nature of its contents. When it exploded the container was ripped into relatively small fragments (1–4 m^2) that were found up to 350 m from the explosion point. In addition, a 10 m^3 crater was formed beneath the container, window damage was incurred up to 240 m from the explosion point and tiles on nearby dwellings were dislodged. A report by the Home Office calculated that the window damage and crater size suggested an explosion equivalent to 200–250 kg of TNT.

The investigation concluded that the single shot batteries were being processed outside the process building in contravention of the licence and that once lit, some of the ejected stars entered the load area of a near-by van by way of the open doors and ignited the 150 mm diameter shells and transport packs of ground maroons that it contained. These exploded causing the destruction of the van and scattering burning stars over a wide area causing fires to break out in combustible material stored between firework storage areas. Eventually the fires progressed through the site and impinged on the unmarked ISO-container, which the fire service was attempting to cool when the contents mass exploded with fatal consequences.

DISCUSSION

The conclusions of investigations at Culemborg and Enschede suggested that the behaviour of fireworks in

Figure 4. Festival Fireworks Ltd storage complex after incident

large-scale storage might have reacted more violently than would have been expected from the standard UN classification tests, where limited quantities are tested. Similar concerns applied after the Uffculme incident. HSE had already commissioned work with HSL[(6)] before that incident occurred and as a result both organisations were instrumental in bringing about a multi-national European Union funded research programme referred to as 'CHAF' (**Q**uantification and control of the **H**azards **A**ssociated with the transport and bulk storage of **F**ireworks), which was set up between Germany (BAM), The Netherlands (TNO) and the United Kingdom (HSL) after the Enschede incident. This collaborative work concluded that in the vast majority of cases the Hazard Division predicted by the UN tests correctly predicted behaviour in large-scale stores but identified some significant exceptions.

The majority of the examples discussed involve explosions of fireworks that were being stored in ISO-containers. The incident at Ferrensby is different in this regard since it was essentially a disposal incident. However, it clearly shows the catestrophic results of dealing with fireworks without having a clear understanding of their construction, how they function and what compositions they contain. It is likely that if the complete rockets had been put in the kiln rather than being broken down the mass explosion described would not have occurred. It is clear that for this incident and the others described, that all relevent staff should be trained to ensure the safe handling of fireworks and have sufficient background knowledge of the theory behind fireworks in order to make informed judgements about their storage.

The fireworks' storage incidents described (Enschede, Uffculme, Carmel and Lewes) clearly demonstrate that large-scale storage of fireworks can potentially lead to large explosions and destruction. The human failings in these incidents can be summaried as:

1. Operators being unaware of, or chosing to ignore, the real hazards associated with the fireworks they were handling;
2. Operators failing to comply, either knowingly or unknowingly, with the constraints placed on them by regulations; and
3. Operators failing to observe basic precautions, either consciously, or sub-consciously, that would have eliminated or mitigated the effects of the incident. These would include:
   - ensuring that fireworks are only stored in the areas designated by the explosives licence,
   - ensuring that stores are adequately spaced to reflect the quantity and hazard of the contents,
   - ensuring that, where multiple stores are used, the doors of one store do not directly face those of another,
   - complying with the explosive limit for the stores,
   - ensuring that where dismantling or modification/fusing of fireworks is allowed by the licence, that these activities are performed in a designated building. In the UK modification/dismantling of fireworks is legally regarded as manufacture and requires licensed premises and a designated production area,

- ensuring that the quantities of fireworks present in buildings designated for dismantling or modification/fusing of fireworks are kept to a minimum.

Some of these failings can be overcome by training and the others by robust supervision and strong management. The question is to what extent are these failings due to operators deluding themselves that 'it won't happen to me'. The message that needs to be reinforced when handling fireworks, or any explosives, is that 'it can happen to you, and in all probablity it will happen to you if you take liberties with safety.'

As a regulator HSE expects people handling dangerous substances to be aware of the hazards associated with those materials, both under normal and abnormal conditions and take the appropriate precautions to protect people from the potential effects. Where there is doubt or uncertainty, we expect investigation to provide clarity and understanding.

As a general observation most of the incident examples start with a fire that spreads to fireworks' stores prior to the fireworks exploding. It is a legal requirement in the UK to take measures to prevent the spread of fire through non-explosive vectors, i.e. good housekeeping to prevent flammable material building up between explosive stores.

It was clear from the court case that followed the Lewes incident that the fire-fighters that arrived at the site were unaware of the scale of the fireworks' storage at the site and did not consider fireworks to be explosives. It is evident that close liason between a fireworks' company and the fire service is essential and that familiarisation visits to the storage sites by fire-fighters would significantly reduce the possibility of misunderstandings in the event of an incident.

At Enschede, Uffculme, and Lewes there was clear evidence that the noise of the fireworks exploding led to members of the general public congregating in areas too close to the sites. Companies should take account of this when considering their emergency planning in order to encourage people to move further away into safer areas.

Once an explosion has occurred and hazards have been controlled the aftermath will need to be inspected to obtain evidence of the cause and also to provide information on the severity of the explosions. To assist in estimating the latter it would be beneficial if all debris was undisturbed until investigating officers had completed their surveys. Associated with these surveys would be a requirement to inspect the stock levels of the magazines prior to the incident. From the examples given, it is clear that such records are not always kept in an appropriate manner. Consideration should be given to storing such documents in protected storage areas, fireproof safes etc. or keeping back-up copies at alternative sites.

The measures outlined above should be common sense for anyone working within the pyrotechnics industry however it seems that the over-riding human failure present in all the incidents is complacency. The operators were familiar with the general procedures and regulations but chose to underestimate/ignore the hazards, overestimate their own competence, ignore safe working practice or deliberately flout the law. These observations highlight the need for managers *and* supervisors to carry out effective monitoring of the workplace to ensure that correct procedures are being followed, particularly after procedural change. Only by identifying and correcting deviations from the standards expected will safe behaviours be maintained and failure to do so can quickly lead to serious degradation of working practices to the detriment of all.

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