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Production Team

Publisher
Tom Smith
Davas Ltd
8 Aragon Place, Kimbolton
Huntingdon, Cambs
PE28 0JD, UK

Phone: +44 1480 878620
Fax: +44 1480 878650
email: toms@davas.co.uk

Production Editor
Helen Saxton
Davas Ltd
8 Aragon Place, Kimbolton
Huntingdon, Cambs
PE28 0JD, UK

Phone: +44 1480 878620
Fax: +44 1480 878650
email: helens@davas.co.uk

Publishing Consultant
Bonnie Kosanke
1775 Blair Road,
Whitewater
CO 81527, USA

Phone: +1-970-245-0692
Fax: +1-970-245-0692
email: bonnie@jpyro.com

Blue Flame Pyrotechnic Compositions: A Concise Review

Alessandro E. Contini
Department of Applied Science, Security and Resilience,
Cranfield University, Defence Academy of the United Kingdom, Shrivenham, Swindon SN6 8LA, UK
Tel: +44 1793 785394, email: a.contini@cranfield.ac.uk

Abstract: *A brief historical background to the development of effective pyrotechnic blue flame compositions, including strobing formulas, from the 19th century to the present day, is presented. The latest prevailing theories on blue flame generation are discussed and a list of some effective modern formulations is given.*

Keywords: *Pyrotechnic illumination, blue flame, copper salts, copper oxides.*

Introduction

Despite the continuous development of improved green, red and yellow fire compositions due to an increasingly demanding fireworks and distress-signals market, there is nothing more fascinating to some pyrotechnic chemists than a long-lasting, intense, deep blue pyrotechnic flame. Regrettably, blue flame compositions have not been exploited to the same extent as other colours, primarily because the human eye is more sensitive to longer wavelengths of the visible spectrum, notably yellow, green and red, which are the colours of choice for military and civilian signalling. As a consequence, blue flame compositions are now almost exclusively employed in the production of ground and aerial fireworks and mostly in the form of pellets ('stars') of blue-light producing composition. Although a badly formulated blue firework may still be described as 'beautiful' by the average unskilled observer, those skilled in the art would agree that the creation of a saturated, deep blue flame 'still represents a challenge to the pyrotechnic chemist' as stated by Conkling,[1] because of the required delicate balance between ingredients purity, flame temperature and the concentration of the right copper-based molecular emitter.

This paper aims to present a concise review of the main developments of blue-light producing pyrotechnic formulations throughout the last century and to highlight the latest theories on blue flame generation.

Historical background

The Ruggieri brothers, famous Italian pyrotechnists of the early 18th century, seem to have been the first who tried to impart blue and green hues to their black powder-based stars and other aerial effects by adding ammonium chloride and copper sulphate.[2] However the history of 'modern' blue flame compositions is invariably linked to the discovery of potassium chlorate. Thus, the likely first reference to the manufacture of more effective blue lights dates back to 1836, when a Belgian artillery officer published a pyrotechnics treatise including a section devoted to a composition based on '*chlorate of potash*, ivory, bismuth, alum, zinc and copper sulphate…'[2] Following this early work, an English pyrotechnician disclosed[3] in 1878 a compilation of formulae for blue stars and blue lancework which were also based on potassium chlorate whereas the copper-containing ingredient was copper oxychloride. It is likely that similar or more effective compositions had already been in use as early as the late 18th century, particularly in France, where potassium chlorate had been first prepared in 1786 by C. L. Berthollet, during one of his fabric-bleaching experiments involving aqueous potassium hydroxide and chlorine gas.[4]

Apart from fireworks, a number of civilian (railway) signalling devices[5] including blue lights were also developed during the late 19th century in the US and Europe. These did not always contain conventional oxidisers and may not be classed as pyrotechnic illuminating devices in the modern

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sense i.e. mixtures of oxidiser, fuel and coloured light producing agent. For example, a patent[6] was filed in 1895 describing the manufacture of a 'pyrotechnic' blue signal based on a mixture of zinc powder, selenium and carbon disulphide. Due to the absence of an oxidiser, the intensity of the signal, which was designed to be lit in the open air in slurry form, would not have been comparable to that of the fiercer chlorate-based blue compositions that would have been used in firework displays by some pyrotechnicians of the time.

Despite the early beginnings, the first scientifically rigorous publications concerning blue lights were not to appear until the 1950s, long after the discovery of the more stable perchlorates and the development of modern spectroscopic methods for flame emission observation.[7–13] At this time two classic text-books of military pyrotechnics[14,15] also dealt with the chemistry and physics of coloured flames including blue ones. Arguably, some of the blue light compositions developed during this time were still dangerous to manufacture. For example, Shidlovskiy[15] describes an 'improved' blue flare of good colour purity containing a pressed mixture of potassium chlorate, sulphur and basic copper carbonate to neutralise the acidity of the sulphur. Other Russian workers were active developing blue formulations during the 1960s, their research eventually culminating in a series of patents describing improved blue flares based on ammonium perchlorate, hexamine, copper(I) chloride, copper(II) oxide, copper(I) thiocyanate and stearic acid. [16–18] These mixtures, which exhibited low impact sensitivity, were capable of producing blue emission of high spectral purity, due to the presence of ammonium perchlorate. A few years after the Russian patents had been published, the American army developed a blue-burning tracer composition capable of providing a smoke trail after the blue flame was no longer visible.[19] As the composition contained metal fuels, it was not capable of producing a saturated, deep blue emission. One mixture is reported to have contained potassium perchlorate, magnesium powder, anhydrous copper(I) chloride, barium nitrate, sulphur and hexachlorobenzene. Nevertheless, modern tracer compositions rely on green and red flames, to which the human eye is far more sensitive.

More recent developments

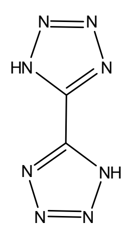
Despite these initial breakthroughs, the first systematic study of new, less sensitive and less toxic blue formulations was not published until 1980,[20] when the flame colour and intensity of a series of compositions based on potassium perchlorate mixed with copper powder, cupric oxide or basic copper carbonate were compared with those of a standard composition based on Paris green (copper acetoarsenite), an excellent blue light-colouring agent which was widely used at the time but known to be highly toxic. In that work the chlorinated polymers PVC (polyvinylchloride), Parlon (chlorinated isoprene) and hexachlorobenzene were explored as suitable chlorine carriers. The author did not assess the quality of the new compositions using conventional spectroscopic techniques, relying instead on his and his colleagues' naked eye, which was described as the 'best sensor for identifying subtle differences in the blue light colour' when in a dark room. This work demonstrated that each of the alternative blue colour-producing agents (with the exception of copper powder) was able to yield as good an effect as Paris green and that the burning rates and ignition characteristics were satisfactory. A series of effective purple flame compositions were also developed.

An interesting more recent development in blue flame technology came about in the 1990s in the form of *'strobing'* formulations. The strobing effect is caused by the cyclical or oscillating combustion of the composition due to the formation and then co-existence after ignition, of a smoulder- and a flash-type reaction. To give a practical example, a pressed pellet of a composition containing magnesium and a sub-stoichiometric amount of ammonium perchlorate in the presence of a metal sulphate can ignite and self-sustain flameless combustion whilst accumulating heat in the slag layer. When the temperature in the slag reaches the melting point of the sulphate, which can now also act as a second oxidiser, the mixture bursts into a brilliant auto-extinguishing flash, but one which is not violent enough to extinguish the 'dark' smoulder reaction. The process repeats itself with frequencies varying between 3 and 10 Hz, depending on the stoichiometric ratio and particle size of the ingredients, until the composition is consumed. Several compositions are known to be capable of strobing[21] and an excellent review of strobe chemistry has been published.[22]

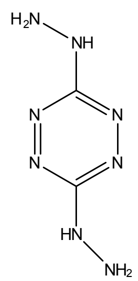
Among first strobe pioneers, it was Jennings-White who developed low smoke, high-performance blue strobes[23] based on ammonium perchlorate, copper metal and either guanidinium nitrate or tetramethylammonium nitrate (TMAN). Because of the high nitrogen content, these compositions, which were suitable for pressing into stars, produced excellent colour purity and strobed reliably during combustion. More work followed by McCaskie, who published a method[24] for the production of blue strobe stars capable of flashing at 10 Hz. The new compositions were based on guanidinium nitrate, ammonium perchlorate, PVC and a copper(I) oxide.

Although no further reports on blue strobes have appeared since McCaskie's work, research into continuous-burning blue lights for improved fireworks continues to this day in many countries, including China,[25] the Czech Republic,[26] the Netherlands,[27] the US[28,29] and Russia.[30] A whole variety of high-nitrogen ingredients are currently being explored, among which are simple energetic organic compounds like nitroglycerin (NG), diethylene glycol dinitrate (EGDN), nitroguanidine (NGu) and nitrocellulose (NC). Some of these formulations have been patented on the grounds of the reduced smokiness and good luminous intensities. However, during scale up operations involving nitroglycerin there would be safety issues as some of these formulations require up to 10 wt% of NG.[30]

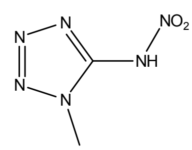
As for other coloured lights, the latest trend in blue light research involves developing smokeless compositions[31] capable of highly saturated emission, which may be used for indoor and special effects fireworks. These typically require the addition of insensitive fuels of very high nitrogen content (typically ≥80 wt%) which often have a highly positive heat of formation but low impact and friction sensitivity. The larger volume of nitrogen released during combustion and the increased burn rate when compared to ordinary fuels (like red gum or hexamine) act to enhance colour purity by reducing broadband emission. Promising high-nitrogen fuels include 3,6-dihydrazino-1,2,4,5-tetrazine (or some of its salts),[32] 5,5′-bis-1*H*-tetrazole and bis(1*H*-tetrazol-5-yl)amine monohydrate (or some of their salts)[33], 1-methyl-5-nitraminotetrazole[34] and 5-aminotetrazole (or some of their salts).[35] The chemical structures of these neutral compounds are shown in Figure 1. Their copper salts have also



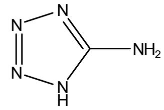
5,5'-Bis-1H-tetrazole



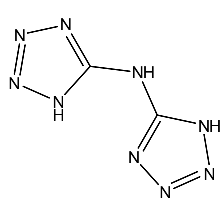
3,6-Dihydrazino-1,2,4,5-tetrazine



1-Methyl-5-nitraminotetrazole



5-Amino-1H-tetrazole



Bis(1H-tetrazol-5-yl)amine

Figure 1. *Structures of selected high-nitrogen fuels.*

been investigated as substitutes for conventional blue colour producing agents. For example, the copper salt of bis(1*H*-tetrazol-5-yl)amine has been reported[33] to produce intense, deep blue colour in an area of the spectrum not previously observed using conventional colouring agents.

Although most of the above-mentioned high-nitrogen fuels are expensive or laborious to prepare other than on a small laboratory scale,[33] 1-methyl-5-nitraminotetrazole and 5,5′-bis-1*H*-tetrazole would seem good choices at present, as their synthetic procedure appears to be less involved.[31,34] In addition to these two compounds, a series of relatively inexpensive metallic and organic salts of 5-aminotetrazole has been recently synthesised and these may also be ideal high-nitrogen fuels and excellent reviews describing the chemical and physical properties are available.[36,37] Hydrazinium 5-aminotetrazolate is the latest addition at the time of writing (2009).[38] Easily and safely synthesised from 5-aminotetrazole and hydrazinium hydrate, with a calculated enthalpy of formation of +373 kJ mol^{-1}, but with low sensitiveness to impact, friction and electrostatic discharge, this compound would seem a promising candidate fuel for new smokeless blue light formulations.

Another recent development towards new smokeless blue lights involves the synthesis[39] of a nitrogen-rich copper complex derived from 1-(chloroethyl)-5-nitriminotetrazole (Figure 2), which effectively contains its own source of molecular chlorine as well as a single energetic nitrimine group. Although not oxygen-balanced, the compound essentially possesses the necessary ingredients for blue fire generation, i.e. the blue colouring agent, a nitrogen-rich fuel and an oxidising moiety. When admixed with a secondary oxidiser, this compound may serve well for the intended task. However, although easily prepared in good yields, the starting material, 1-(2-chloroethyl)-5-nitriminotetrazole, would appear to be shock and friction sensitive, which may preclude future industrial application.

In line with the increasing global awareness for health and safety policies, coloured light-producing fireworks, including blue devices, have been identified[40] as generators of polychlorinated dibenzodioxins and dibenzofurans. As such, conventional formulations are not entirely safe

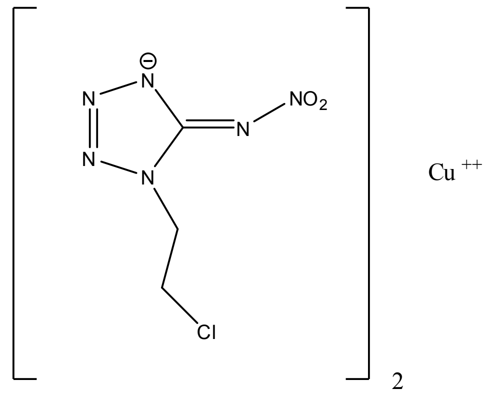


Figure 2. *Structure of the (anhydrous) copper complex of 1-(2-chloroethyl)-5-nitriminotetrazole.*

from an operational and environmental point of view if the devices are designed to function indoors. Since the presence of chlorine in the composition is required to produce deep coloured light, it is unlikely that the use of chlorine carriers will be completely phased out in future. However the use of low-carbon, high-nitrogen fuels should drastically reduce the formation of toxic airborne chlorinated species. Future efforts in blue (and other colours) light research may therefore benefit from combining high-nitrogen, insensitive oxidisers with high-nitrogen fuels. New continuous-burning and blue strobe compositions of high spectral purity may be accessed by systematically screening the performance, ageing profile and sensitivity of a number of such new formulations.

Oxidisers for blue light compositions

Although ammonium and potassium perchlorate are currently universally-favoured choices for both continuous-burning and strobe formulations due to the relatively low price and inherent thermal stability, high energy, appreciable chlorine content and good compatibility with organic and metallic fuels, these oxidisers have been identified as water pollutants exhibiting high residence times in lakes and rivers. Perchlorates in particular are known to inhibit iodide uptake by the thyroid gland and their presence in drinking water causes concern.[39]

Despite the high cost and potential scale-up safety concerns, new ‘green oxidisers’ may be accessed by admixture of the nitrogen-rich, hygroscopic ammonium dinitramide (ADN)[41] with relatively small amounts of established insensitive energetic molecules of lower hygroscopicity but high-nitrogen content and relatively high oxygen balance (~-20%) such as guanylurea dinitramide (FOX-12), 1,1-diamino-2,2-dinitroethene (FOX-7) and 3-nitro-1,2,4-triazol-5-one (NTO). These should act as hydrogen-bonding donors for the ADN, thus minimising its affinity for atmospheric moisture. It is the intention of the author to investigate the oxidising effectiveness of such mixtures in blue flame compositions.

Chemistry of pyrotechnic blue flame

Pyrotechnically-generated coloured light is the result of electronic excitation and the subsequent photonic decay of specific metal monochlorides (molecular emitters) which are transiently formed in the flame.[1,42] It has long been accepted that emission of blue light requires the formation of electronically excited copper(I) monochloride, CuCl,[43] which decays to the ground state emitting in the visible region of the electromagnetic spectrum between approximately 430 and 450 nm. However, there are significantly-intense emission lines well beyond 450 nm with weaker lines tailing to 550 nm (detailed analyses of the emission lines of CuCl have been published).[9,11,44] This results in CuCl being only 88% pure in its emission in contrast to the preferred emitters for the non-blue colours which are at or near 100% purity, which makes 'the production of a high purity blue flame much more difficult (and from a practical standpoint perhaps impossible) than producing the other colours'.[45]

CuCl is formed by the reaction of atomic copper or copper oxide with radical chlorine or HCl, which derive primarily from combustion and/or pyrolysis of the chlorine carrier (or donor), which may be a chlorinated polymer or non-polymeric compound. Commonly used polymers include polyvinylchloride (PVC) and chlorinated polyisoprene (Parlon). Examples of non-polymeric chlorine carriers, which are used less frequently than the polymers, include hexachloroethane (HCE) and hexachlorobenzene (HCB), although the latter is now forbidden as it violates regulations on persistent organic pollutants. Despite intuition, thermodynamic modelling demonstrates that, with the exception of ammonium perchlorate, the production of radical chlorine from potassium perchlorate is minimal, as the reaction is not favoured energetically. In early times, chlorates worked well without a chlorine carrier because they were used in combination with sulphur, whose reaction with $KClO_3$ does indeed release chlorine gas.[44]

As for the source of copper, this is normally introduced with the colour light-producing agent in the form of a salt (copper sulphate or basic copper carbonate), an oxide (cupric oxide, cuprous oxide or copper oxychloride), a sulphide (copper sulphide), an organic compound (like copper acetoarsenite, 'Paris green'[20], which is now considered obsolete due to its toxicity) or even as copper metal powder.

It is generally assumed that in the strongly oxidising environment of a pyrotechnic flame, at temperatures above 1500 K, CuCl decomposes to CuO and CuOH,[1,15] which emit in the green region of the visible spectrum between 500–530 nm. Since the green light contaminates the blue emission of copper chloride, a temperature value of ~1500 K has for years been accepted as the upper limit for effective blue light generation. This statement has recently been disputed in two papers[46,47] which focussed on the nature of the blue emitter in pyrotechnic flames.

In the first paper,[46] the identity of the emitter has been reassessed as the trimeric form of copper monochloride, or Cu_3Cl_3. This conclusion was based on an extensive review of previous work involving mass spectrometric detection[48,49] of the headspace gases found above sealed, heated (700–1800 K) crucibles containing CuCl or above the solid surface of laser-ablated CuCl targets.[50] It was shown that below 1360 K virtually no gaseous CuCl was present, with only the trimeric and tetrameric species being detected. As the temperature was increased, the concentration of 'monomeric' CuCl also increased, eventually predominating over the trimeric species above 1900 K (~1630 ºC). Although undoubtedly informative, this review was based on experimental observations of simple *non-pyrotechnic* systems. The fact that the gas phase above molten CuCl or above a laser-ablated surface of solid CuCl is rich in trimeric and tetrameric CuCl does not guarantee that at similar temperatures, the same species would be thermodynamically favoured in a highly oxidising pyrotechnic flame, where a number of reactive radicals exist.

Not surprisingly, the hypothesis of the trimeric nature for the blue emitter was challenged in a second publication.[47] This work employed a thermodynamic code developed by NASA to model the calculated adiabatic temperature and mole fraction of the copper species predicted to form at equilibrium in the flames generated by eight continuous-burning compositions taken from the literature. For all of the compositions, the calculated equilibrium concentrations of CuCl turned out to be much higher than those of Cu_3Cl_3, which was predicted to form only in trace amounts, indicating that CuCl would be the main emitter. In addition, the calculated adiabatic flame temperatures were all above 1500 K which further discredited statements that flame temperature must be kept below 1500 K to generate CuCl effectively. Whilst the modelling results indicated that substantial amounts of CuCl can still be generated at ~2500 K, it was stated that at these higher temperatures broadband radiation from incandescent solid and liquid particles would interfere with the weaker blue emission of copper chloride, which may explain the often reported inefficacy of 'hot', metal-based blue formulations. In addition, it must be remembered that any trace impurity, and in particular sodium-containing impurities, in the fuel(s) and/or oxidiser is likely to contaminate the blue emission with the D line emission of elemental sodium (589 nm), to which the human eye is far more sensitive than blue light.

Component (parts by weight)	Compositions								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	CB	CB	CB	CB	S	S	S	CB	CB
Ammonium perchlorate	—	—	—	—	55	40	25	—	46.25 to 49.50
Potassium perchlorate	64.7	66.1	75.1	67.3	—	—	—	—	—
Microcrystalline nitrocellulose	—	—	—	—	—	—	—	87	—
Potassium nitrate	—	—	—	—	—	—	—	5	—
Paris green	11	—	—	—	—	—	—	—	—
Hexachloroethane	—	—	—	—	—	—	—	4	—
PVC	6	—	—	—	—	—	7.5	—	—
Accroides resin (red gum)	15	9.8	11.5	10	—	—	—	—	—
Glutinous rice starch	5	4.5	4.8	4.5	—	—	—	—	—
Cupric oxide	—	13.4	—	—	—	—	5	4	—
Parlon	—	10.7	3.8	9.1	—	—	—	—	—
Copper powder	—	—	9.6	—	15	10	7.5	—	—
Basic copper carbonate	—	—	—	13.6	—	—		—	—
Tetramethylammonium nitrate (TMAN)	—	—	—	—	30	—	—	—	—
Ammonium sulphate	—	—	—	—	—	10	—	—	—
Guanidine nitrate	—	—	—	—	—	25	55	—	—
Magnalium 50:50	—	—	—	—	—	15	—	—	—
3,6-Dihydrazino-1,2,4,5-tetrazine	—	—	—	—	—	—	—	—	46.25 to 49.50
Copper salt of 5,5′-bis-1*H*-tetrazole dihydrate	—	—	—	—	—	—	—	—	1.0 to 7.0

CB = continuous-burning type; S = strobing type. Composition **1**: Shimizu's excellent reference, but toxic blue.[20] Composition **2**: Shimizu's CuO blue.[20] Composition **3**: Shimizu's Cu powder blue.[20] Composition **4**: Shimizu's basic copper carbonate blue.[20] Composition **5**: Jennings-White's TMAN-based best blue.[23] Composition **6**: Jennings-White's best ammonium sulphate-based blue strobe.[23] Composition **7**: McCaskie's best blue strobe.[24] Composition **8**: Nickel's ultra-low smoke blue.[29] Composition **9**: Hiskey's low smoke high nitrogen blue.[31]

Examples of blue flame compositions

Table 1 lists a selection of continuous-burning and strobing blue flame compositions taken from the modern literature (1980–2009). During screening, particular emphasis was given to insensitiveness and low toxicity (with the exception of composition **1** which contains Paris green). All formulations were developed to function as pressed pellets (stars). The particle size of the components can be found in the individual references to which the formulae refer. Composition **9** was taken from the patent literature. Although it was also our intention to include a high-nitrogen blue recipe based on the copper salt of 5-aminotetrazole, no actual formula could be found in the relevant patent,[35] which listed only examples for other colours. The list should provide a simple and useful reference guide for practising pyrotechnic chemists and teachers of pyrotechnics.

Conclusions

Although modern pyrotechnic compositions that generate continuous or strobing blue light have undoubtedly come a long way from the days of the dim bluish stars made by the Ruggieri brothers, there is still much scope for improvement. Most current effort in blue-light research seems to be devoted towards the development of new smokeless, high-nitrogen compositions capable of producing deeply saturated blue flames. Because of the environmental and health & safety concerns of our time, we can expect this trend to continue for next decade and beyond.

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What is a "Safety Distance" for a Shell?

Tom Smith
Davas Ltd, 8 Aragon Place, Kimbolton, Huntingdon, Cambs, UK PE28 0JD
Email: toms@davas.co.uk

Abstract: *This paper outlines the risk assessment methodologies and calculates the risks affecting the audience from the malfunctioning of shells. Risks may arise from premature functioning of shells, from stars falling on the audience from low bursting shells, and from shells bursting in or near the audience. Two mathematical approaches are taken using* S*HELLCALC*© *derived data to determine the distances from the firing point of a shell that lead to an individual risk to a member of the audience.*

Keywords: *shells, risks, fallout, debris*

Introduction

In developing the European Standards[1] for "professional" fireworks and other pyrotechnics the question of what is the "safety distance" is frequently posed by experts and enforcing authorities. Unfortunately no activity involving pyrotechnics is ever "safe", not for operator and not for audience, and in many cases the nationally prescribed and often fixed "safety distances" may be regarded by others as overly draconian or too lenient. The major problem with fixed "safety" distances is that they do not provide a guarantee of safety – they tend to be arbitrary distances based on local custom and practice, and do not consider any risk control measures that have been adopted by the firer.

But in fact the question (and the answer) is wrong – what we really need to know is what fireworks can be fired at a given site, under the conditions prevailing and the methods and techniques adopted by the firer and hence provide an acceptable level of risk to those exposed to the risks. Any human activity poses some level of risk – it is just that we, both as individuals and as a society, tolerate some levels of risk more than others.

This paper illustrates the risk assessment process for, predominantly, shells at a variety of sites under a variety of conditions which leads to an assessment of the distances required from the point of firing to the audience under the specified conditions.

It does necessarily concentrate on the use of aerial shells at firework displays as these inevitably pose the greatest hazards, but the principles employed would also be suitable for outdoor displays not involving shells, or for events using theatrical or other pyrotechnics.

Safety and risk

Unfortunately, as practitioners of a occupation involving the use of hazardous materials we have to face two basic facts:

- The public are not good at statistics
- The public do not understand the concept of risk

Given these hurdles it is not surprising that the firework industry, and indeed any other industry that presents any form of risk to the public, battles to justify even their normal operation, and faces a barrage of criticism when something goes wrong.

Unfortunately we are not assisted by the law here. Most regulatory regimes require a person creating a risk to identify, assess and manage that risk – this is the basis of the, often abused, Risk Assessment approach to safety management.[2] This approach is the correct approach though – it simply is not realistic to consider only hazard, especially if hazard is considered in isolation to benefit.

Using a non-firework situation, for instance, the

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potential hazards from nuclear power generation are enormous – accidental meltdown after unauthorised experimentation, aerial contamination following a leak, long term mutagenic effects from exposure to radiation, potential terrorist threat at the plant or from its products, massive waste disposal issues, the potential rendering of large areas radioactive and contamination of the food chain – all are realistic potential hazards. What allows the world to even consider using nuclear power is firstly the benefits (electricity generation, lack of acidic or greenhouse gas emissions for such generation, independence of security of supply) but more importantly the control of all the hazards by rigorous application of risk analysis and the resulting extremely low frequency of any of the identified hazards arising.

The difference between risk and hazard

Hazard is the intrinsic harm that may be done by a particular sequence of events – for instance IF a shell bursts in the crowd people will be injured or killed. It does not relate to the likelihood of that event happening – if a shell bursts in the crowd it makes no difference how the shell came to be there!

Risk relates the intrinsic hazard to the likelihood of that event occurring and thus equates the frequency of an event (or series of related events leading to the eventual hazardous outcome) with the hazard of that event to provide a perception of the risk. In essence

$$\text{Risk} = \text{Frequency} \times \text{Hazard}$$

In the case of the shell bursting in the crowd the intrinsic hazard is very high, but the likelihood is normally extremely low – and thus the perceived risk (and the calculated risk – see later) remains acceptable.

Unfortunately when a very rare incident does occur the public and the press react as if that occurrence were actually commonplace, and worse, if the case comes to court, the court will tend to dismiss the frequency and hence the risk arguments and effectively state that in the particular case the frequency was one – it happened – and therefore and measure of the likelihood is now irrelevant and that as a consequence that only the hazard should be considered.

Until the discrepancy between the law makers and the courts is resolved, and until the public appreciate the difference, it is a battle that will continue to have to be fought – not only by the pyrotechnics industry.

Individual and societal risk

In considering risk we need to address the risk of several different classes of people:

- The risks to a single person in the audience or a display firer – usually taken to be the risks to a specified individual
- The risk to a group of people

Assessing the risk to a specified individual is both relatively straightforward and relates to the experience that individual has of risk, whether they are benefiting from the activity causing the risk (e.g. they are a paid display operator), whether they might be aware of the risks being posed to them (again a display operator) and those who neither gain, nor can realistically be expected to understand the potential risks they are being exposed to (in most cases this is the situation of a member of the audience).

Assessing and justifying the risks to a group of people is much more difficult. Society has an understandable aversion to incidents that injure many people – which is not proportionate to the number of people injured. We generally, as an example, are much more averse to a road accident that kills ten people than we would be to ten accidents each killing a single person. This may appear callous, but it is a demonstrable fact borne out, not least, by the media reporting of such incidents.

Many authors have used the *F–N* curve approach[3] to attempt to quantify the societal risk to members of the public affected by an incident. In this approach *N* is the number of fatalities and *F* is the frequency of *N* or more fatalities, and the resulting plot may typically look like either a step function or a smoothed curve.

It is sometimes appropriate to attempt to superimpose on such a plot the public aversion to the risks identified but there are also more sophisticated[4] ways of determining such aversion.

Societal risk[5] is difficult to quantify in a simple, unambiguous and objective way, and for the remainder of this paper we will concentrate on quantifying individual risk. Where appropriate, however, illustrations of societal risk factors will be made.

Risks and benefits

At firework displays it is important to consider that alongside potential individual and societal risks there are individual and societal benefits associated with the display. For instance for the firers and others involved in the event:

- Income for the firers
- Income generation for other performers

and for those witnessing or benefiting from the event:

- Getting people outdoors
- Income for charities at fund raising events
- Socialising
- General individual "feel good" factor of witnessing a spectacular display
- Enjoyment of a spectacle by a very large number of people, often for no charge, at extended distances

Just because there are associated societal risks doesn't mean that such events should be banned! There are plenty of examples where people, as groups or individuals, are prepared to accept significant risks for their benefit – even when the risks are not directly under their control – for instance:

- Flying away on holiday (risk of plane crash by mechanical or pilot error or by hijacking)
- Taking part in sports (risk of injuries or death)
- Watching a film in a cinema (risk of building fire or collapse)
- Driving (risk of crash caused by mechanical failure, or by driver error or by accident)
- Walking to a bar (risk of accident on the way, or as a result of drinking)

Any meaningful risk assessment process needs to address the costs of identified risk reduction measures, and thus to determine whether such costs are justified. Basing a paper Risk Assessment on unachievable or unaffordable control measures is not helpful or informative to anyone.

Cost–benefit analysis

For instance, in deciding if the risks arising from firing shells can be reduced it is necessary to consider

- How many mortars are used
- How many times they are reused
- How many shows are fired in a year
- How much the control measure would reduce the risk
- How much each control measure would cost
- What cost is placed on a life or on injuries

The last parameter may seem flippant, but without equating benefits and costs a risk assessment approach is almost meaningless. It simply is not practical or sensible to consider that ALL identified control measures are justified. It may be possible to reduce the risk of fatality from, say, one in one million to one in two million – but is such a reduction statistically significant, and is the cost of such a control measure justified? If the cost is, for instance in the case of mortars, comparable to the cost of a mortar the answer is probably "yes" – if the cost is 100 times the cost of a mortar it is almost certainly "no".

In general we believe that any control measure that decreases risk by a factor of less than ten is probably not worth contemplating in isolation.

We will examine this area in more detail later and attempt to equate the risk reduction to the costs of that managing the risk

The simple mathematical treatment of risk

As we have seen, in simple terms, risk is calculated as follows:

$$\text{Risk} = \text{Frequency} \times \text{Hazard}$$

Low risk events may occur if either the frequency or the hazard (or both) is low; the highest risk events

Table 1. *Very simple risk assessment methodology.*

	Low frequency	Medium frequency	High frequency
Low hazard	Very low risk	Low risk	Medium risk
Medium hazard	Low risk	Medium risk	High risk
High hazard	Medium risk	High risk	Very high risk

occur when the hazard and the frequency are high. In the simplest terms it is useful to illustrate the inter-relationship between frequency, hazard and the resulting risk – this is shown in Table 1.

In most cases we simply do not engage with high risk events at firework displays – it would be morally wrong, and commercially suicidal, to do so. However, as a consequence of only dealing with relatively low risks and especially with very low likelihood events there is a danger of complacency on the part of the operator, an assumption that "low risk" equates to "safe" and often a reluctance to comprehend the actual risks posed.

Somewhat more complex approaches to risk assessment include ranking of both likelihood and hazard on a suitable scale and treating the product of the two numbers as the risk.[6] We generally use the approach where hazard and likelihood are both rated on a 0–10 biased scale – because the resulting product has a maximum value of 100, and because there are situations where either the likelihood or frequency is truly zero and zero times anything is still zero! Biasing the scale puts greater emphasis on the highest frequency or highest hazard events and means, for instance, where a number of related events are considered together these high frequency or high hazard occurrences are not ignored.

There are occasions, however, where the simplistic approach is not appropriate and a simple quantified risk assessment (QRA) leads to better understanding (and therefore potentially better mitigation) of the risks.

This is the approach we will take in this paper.

The risks at firework displays

The risks at firework displays can be broadly separated into two areas

- Risks from the normal functioning of the fireworks (e.g. expected debris)
- Risks from the abnormal functioning of the fireworks (by product failure or operator error)

Both are important in determining the choice of fireworks and the suitability of site and the inter-relationship between the two. If the site has inbuilt flexibility (e.g. a barge that can be moved to maximise the fallout area under any wind conditions) then the choice of fireworks for the display may be much more extensive than if the site is fixed (e.g. a rooftop). Furthermore on the rooftop there may have to be various contingency plans to curtail or cancel the display in adverse conditions which may not need to be mirrored for the display on a barge.

If we take a typical firework display mix of products we can determine which are likely to pose the greatest risks as shown in Table 2.

The potential risks from "normal" debris from shells are relatively low (although the frequency of "normal" debris falling on the audience is surprisingly high, the hazard is low and hence the risk is low) and most firework companies have developed tables equating shell burst height and wind strength with fallout distance.

The SHELLCALC© programme, developed by Harradine and revised by Smith,[7] calculates the trajectories of shells and comets depending on a variety of user-inputs including:

- calibre
- firing angle
- wind direction and strength
- "barrelling" or "tumbling" effects (which add a realistic variation in shell dispersion)
- muzzle velocity (if known)
- mass of the shell or comet if known (and calculates comets having a decreasing mass during flight)
- shell delay (for determining if the shell

Table 2. *Potential risks from various firework types.*

Firework type	Subtypes	Potential risks
Shells	Colour shells	Normal debris (especially long burning stars) Risks from subcomponents Abnormal firing angles (from mortar disruptions) “Blinds” Blast/fragments from bursts
	Maroons	As above plus Increased blast/fragments from bursts
	Aqua shells	Unpredictable range
Roman candles	All types	Projectile effects
Rockets	Flight rockets	Random flights
	Display rockets	Blast/fragments from bursts Debris (sticks)
Mines	All types	Minor projectile effects Risks from subcomponents
Fountains	All types	Sparks Failure of casing – unintended explosion
Set pieces	Lancework	Relatively minor
	Wheels and set pieces	“Throwing” driver from wheel Failure of support

reaches the ground or bursts in the air)

In general Shellcalc© is not particularly useful in determining “normal” debris from the functioning of shells. For this, analysis of wind speed and direction from the burst point (which of course may itself be estimated by using Shellcalc©) and the time for fallout to reach the ground (or other areas) are more useful.

In the case of shells, in general it is the largest calibre shells, fired from displaced mortars, that pose the greatest risks. However lower hazard, higher frequency, events may actually pose the same or at least significant risks to both operators and the audience. For instance the main “normal” debris from rockets (their sticks) can travel significant distances downwind of the firing site and has the potential to cause significant harm.

For a display with several different calibres of shells, which is the norm, the high hazard/low frequency failure of the largest calibre shells may be outweighed by less hazardous but more frequent failures of lower calibre shells. This arises for four main reasons:

- In general large calibre shells are manufactured to a higher quality than small calibre shells (for instance they may contain dual or multiple internal delay fuses)
- There is usually a higher number of smaller calibre shells than large calibre shells in a display – indeed the numbers of shells fired are usually inversely related to their calibre (because of cost and aesthetic features)
- Smaller shells are more usually fired at greater deliberate angles than large calibre shells
- Smaller shells are more usually fired from “racks” than larger calibre shells

However, as will be seen, the risks from the largest calibre shells are usually the ones considered in risk assessments. This is because

- Larger shells generally rise to a greater height – therefore “normal” debris is likely to travel further downwind than debris from smaller calibre shells

- If the mortar is disrupted the range of the shells is greater
- The burst charges of larger calibre shells are greater and hence likely to cause greater injury if a larger calibre shell bursts in/near the audience

Mathematical evaluation of risk

The remainder of this paper will address a more complex mathematical evaluation of the risks posed from shells to the audience at firework displays – a so-called “Quantified Risk Assessment” (QRA). The principles applied are also valid for other firework types, and for use of other pyrotechnic devices (for instance indoors).

To evaluate the risks to individuals in the audience from shells, we first need to consider what are considered the benchmarks for the acceptability of risk.

In general the following are the UK accepted guidelines for risk of fatality

- 1×10^{-6} – broadly acceptable
- 1×10^{-5} to 1×10^{-4} – the so called “ALARP” region (1×10^{-5} to 1×10^{-3} for workers)
- $>1 \times 10^{-4}$ – unacceptable ($>1 \times 10^{-3}$ for workers)

This means that a member of the public should consider broadly acceptable the chance of being killed at a firework display as one in a million – about ten times the chance the same individual has of winning the UK lottery on any one week. This seems at least reasonable – no one expects to win the lottery, no one should expect to be killed at a firework display!

In general we will use the 1×10^{-6} “broadly acceptable” criterion for determining the risk to an individual.

The so called “ALARP” region (discussed below) is where the level of risk is still permissible, but that measures should (if at all possible and practical – especially when related to cost) be implemented to reduce the risk still further.

It is accepted that people who directly benefit from an activity involving risk (i.e. firers) may be subject to a greater range of ALARP than would the audience and this is reflected in the figures given above. However neither should ever be exposed to risks in the “unacceptable” region.

ALARP “As Low As is Reasonably Practical”

The UK Health and Safety Website[9] includes the following observations (our emphasis) on ALARP:

> *Thus, determining that risks have been reduced ALARP involves an assessment of the risk to be avoided, of the sacrifice (in money, time and trouble) involved in taking measures to avoid that risk, and a comparison of the two.*
>
> *This process can involve varying degrees of rigour which will depend on the nature of the hazard, the extent of the risk and the control measures to be adopted. The more systematic the approach, the more rigorous and more transparent it is to the regulator and other interested parties. However, duty-holders (and the regulator) should not be overburdened if such rigour is not warranted. The greater the initial level of risk under consideration, the greater the degree of rigour HSE requires of the arguments purporting to show that those risks have been reduced ALARP.*

It is clear that the costs are critical in determining the proportionality of any risk control measures. Demonstration, by means of analyses such as presented in this paper, should be enough to satisfy that the the risks have been reduced to ALARP and hence that they should be accepted by operators, the audience and, if necessary, the courts provided, of course, that they truly represent the risks involved and that operator error or disproportionate ratios of product failure have not been a contributing factor.

Risk to the operator vs risk to the audience

In all assessment of risks it is essential to consider all consequences of the identified hazard. For instance in firing shells it is important to consider:

- The effects on the audience AND
- The effect on the operators

Some things that reduce risk for operators MAY increase risk to audience (and *vice versa*). For instance, it is often (correctly) stated that electric firing of shells is safer for the operator – but it possible that electric firing of shells actually poses a greater risk to the audience than manual firing. It could conceivably be that the firing of one shell (as discussed below) displaces an adjacent mortar so that it is directed at the audience – if the firer is "merely" pushing a button 100 m away along a piece of wire they will fire the second shell unaware that it is lying in a displaced mortar. A person manually firing would simply not fire the second shell! This is NOT to say electric firing is bad – just that the consequences of one risk reduction method might actually increase the risks to another party and therefore appropriate measures to control the additional risk should be taken.

For simplicity, for the remainder of this investigation we will concentrate on the effects to the audience only.

Hazards from shells

There are several major hazards from the firing of shells as shown in Table 3. Of course, the risks arising from these hazards depend on the frequency of each event occurring. In the remainder of this paper we will concentrate on fatality hazards, and risks to the audience.

It is important to identify the critical events to consider, and where possible to separate key events leading to various scenarios.

For example

- What is the overall rate of shell failures (of any type)
- What proportion of general failures could affect the correct functioning of an adjacent mortar
- If a mortar is fired at an undesirable (and unplanned) angle – what proportion of those could affect the audience (i.e. are "shot" towards the audience
- What proportion of shells fired from disrupted mortars could actually impact on the audience, and which will function "normally" without affecting the audience – for instance by bursting at sufficient height that the stars do not reach the audience
- What proportion will function "abnormally" (e.g. fail to burst in the air) and thus present a different hazard to the audience
- How many people may be affected by each failure mode

Table 3. *Potential hazards from shells.*

Type	Hazards	Comments
"Normal" functioning of a shell	Lit debris drifting downwind, especially from long burning stars	General unlikely to cause fatalities by direct action – although may impact on structures leading to fire
"Abnormal" functioning of a shell when fired in designed orientation	"Blind" shells	Obviously worst if the mortar is angled
Premature functioning of a shell	Flowerpot, muzzle breaks or in mortar explosion – especially if it leads to disruption of adjacent mortars	See below
Disruption of the mortar from external event and subsequent "normal" functioning	Low bursting shells at unplanned firing angles – risk if stars reach the audience	If mortar is fired near vertical then the risk of stars impacting the audience is very low
Disruption of the mortar from external event and subsequent "abnormal" functioning (e.g. "blind")	Shells at unplanned firing angles – risk if shell lands in or adjacent to the audience	Impact or close-proximity effects from fragments and blast

Table 4. *UK shell accidents from EIDAS database.*

Date	Location	Injuries	Fatalities	Cause/Comments
5/11/2005	Kettering, UK	1 major, 10 minor		Rack collapse, shell burst near crowd
1/11/2004	Middleton, UK	1		Shell or stars fired into leg
3/11/1996	Wilmington, UK		1	Incorrectly fired (Cat 3)
2/11/1996	Hazelmere, UK		1	Head over mortar (Cat 3)
1927	Unknown		1	Head over mortar
25/6/1910	Leeds, UK	7	3	Shell detonated in steel tube
19/9/1898	Folkestone, UK	1		Mortar burst
2/6/1896	Doncaster, UK	3	1	Mortar lands in audience
5/8/1895	Brighton, UK	25	1	Mortar burst
24/12/1886	Bately, UK	5	1	Mortar tipped over prior to firing
25/9/1882	Hull, UK	3	2	Mortar burst
19/7/1882	London, UK		1	Mortar burst

- What is the frequency of injuries/fatalities from the postulated shell failure mode

We have made some very general assumptions on the basis of data regarding shell failures collated from informal and formal surveys of the UK firework industry.

For injury and fatality data we have examined the UK Explosives Incidents (EIDAS)[10] database for reported accidents involving shells and the results are shown in Table 4.

Note that in several cases identified in EIDAS it appears that fragments of the mortar were the cause of the injuries/fatalities – rather than the shell itself. This is obviously an important factor, particularly when using metal mortars, but we have not considered it further here for 3 main reasons:

- The use of metallic mortars (particularly steel) is decreasing
- The injuries are most likely to occur to operators not the audience
- There has been a general trend to move fireworks further from the audience for aesthetic and practical reasons, as well as for general perceived safety reasons.

It is also relevant to note that the number of accidents is actually very low – the data spans 1882 to 2005 and includes the period (up to 1996) when shells were available for the general public to purchase and use.

Where a shell lands in the crowd, the apparent outcome is most likely to be a single fatality (if a fatality occurs) – so we have set the likelihood of such a fatality to be 1. For shells that do not burst in the crowd we have set the fatality likelihood as 0.1 (see Table 5).

All the above information is collated in Table 6.

The nature of the display site and the scale of the display also affect the likelihood of a particular shell reaching the audience.

Most significant is the angle that the audience subtend, that is they occupy, at the perimeter of a circle drawn around the display site and examples are given in Table 7. It is often the case that smaller professionally fired displays subtend relatively small angles to the audience – a private function for example is likely to have a relatively

Table 5. *The failure modes of shells involving fatalities.*

Failure mode	No and likelihood of fatalities	Comments
Shell bursts above the audience so that stars reach the audience	Multiple injuries Single fatality (hazard = 0.1)	
Shell busts in or near the audience so that people are affected by impact or by bursting of the shell, or by fragments of the shell	Multiple injuries Single fatality (hazard = 1)	It is possible for multiple fatalities to occur in this situation – a brief examination of the societal risk aspects will be made below

small audience in a relatively small area – and the display itself to be fired some distance away.

Larger displays often are fired from positions where the audience may subtend significant angles – up to situations where the audience, in effect, surrounds the display site. However, in general, as the display gets larger the proportion of shells that can reach the audience decreases as the audience is beyond the design range of the smaller calibre shells, and hence the risks from the smaller

Table 6. *Individual components of frequencies and hazards of shell failures.*

Failure	Estimated frequency	Comments
Frequency of failure of a shell in any manner	0.01	This is pessimistic – and improvements in manufacture are reducing this. However we have considered ANY failure of a shell
Frequency of above shell failure leading to mortar failure	0.01	
Frequency of disruption of adjacent mortars	1	We have assumed ANY failure of a mortar will cause disruption of adjacent mortars in a rack or trench. This is overestimating significantly.
Frequency of adjacent mortar containing a shell being ignited	0.5	The adjacent tube may be empty or non-existent (failure of last shell in a rack) – and the evidence from accidents (e.g. Kettering) is that some shells remain unfired in mortars even after having been disrupted.
Angle factor – adjacent shell fires towards audience	0.1	This is variable – see text.
Frequency of fatalities occurring from shell bursting above audience	0.1	Measure of hazard to a person standing within the star burst radius of a shell
Frequency of fatalities from blast occurring from shell bursting in/near audience	1	Measure of hazard to a person standing within the immediate burst radius of a shell where they will be affected by blast
Frequency of fatalities from fragments of a shell bursting in/near audience	1	Measure of hazard to a person standing within the immediate burst radius of a shell where they will be affected by fragments
Frequency of shell bursting adjacent to mortar	0.01	For instance muzzle break or flowerpot. In most cases this affects the operator only.
Frequency of fatalities occurring from shell bursting in/near operator	0.1	

Table 7. *Effect of the nature of the display site.*

Type	Description	Typical angle subtended
Where the audience only subtend a small fraction of a circle around the firing site	Typically an event where the number of people are small and are well controlled – e.g. a wedding where the audience are assembled on the steps of a hotel	36° 0.1 of a circle
Where the audience are on one side of the display site	Typical of many shows	180° 0.5 of a circle
Where the audience are all around the display site	Large displays, or displays from rooftops	360° A complete circle

shells bursting in the crowd are reduced to near zero. This can be used to calculate the likely risks in one of two ways:

- By only performing calculations on the largest shell calibres and counting only those largest calibre shells
- By applying a "show factor" for the show – but counting all shells fired – for instance as shown in Table 8

We have used both methods and find they yield similar results. However where the normal pattern of distribution of shell sizes is inappropriate then calculations may have to be made across a variety of shell calibres/numbers and the results combined to give a value of the total risk.

Proportionality factors

HSE in the UK recognise that any work required to mitigate a particular risk must be proportionate to the reduction in risks achieved. The higher the original (unmitigated) risk, and the greater the risk reduction, the more affordable are the mitigation measures.

For instance, taking the "cost" of a life as £1 million a reduction in risks from the "broadly acceptable" (1×10^{-6}) risk to lower would be justified if the benefits exceeded £1 million (i.e. there is a proportionality factor of 1 in this case). For a risk of ca. 1×10^{-5} the proportionality factor would be arbitrarily set at about 4, i.e. measures would be justified if the benefits exceeded £250 000 or in essence one-quarter of a life, or significant numbers of major injuries.

The costs associated with such benefits can be

Table 8. *Show factors applied to the total number of shells fired in a display.*

Type of show	Shells used	Typical value for show factor
Small – e.g. private wedding	Several 75 mm Several 100 mm 1 × 150 mm	0.2
Medium – e.g. public concert	Many 75 mm Many 100 mm Many 125 mm Many 150 mm A few 200 mm	0.1
Large show – e.g. national event	Very many 75 mm Very many 100 mm Very many 125 mm Many 150 mm Many 200 mm	0.05

spread over many mortars and many uses of the mortars and effectively amortised over the lifetime of the mortar. For instance for a medium sized company

- Doing 100 displays each year
- Holding 2000 mortars in stock
- An average number of shells fired per show is 125
- With a total number of shells fired over a 4 year period of 50 000
- Where each mortar is reused 6.25 times a year and 25 times in a 4 year lifetime
- Assuming shows have an audience of 1000, of which 100 are at risk and that the audience subtend 1/10 of a circle

and then examining four possible risk reduction measures:-

- Tinfoil over mortars to prevent ignition from stray sparks – if the mortar is, for instance, disrupted by an adjacent mortar explosion
- Waterproofing mortars to boost structural integrity (e.g. for fibreboard or GRP mortars to prevent freeze-cracking)
- Replacing each mortar each year
- Redesigning and implementing new mortar racks

illustrates the measures that are sufficient r necessary.

For a large display company firing multiple displays on the same site (or a very large display for a single event) the calculations are somewhat different. Assuming that the display

- is repeated 10 times each year
- 2000 shells are used per display (or 20 000 per year)
- and assuming multiple shows have 100 000 audience, of which 1000 are at risk and that the audience subtend at least 1/2 of a circle, or a single very large display has a 1 million audience subtending a full circle.

leads to a differnt set of conclusions.

Where there are many displays each year (for instance at theme parks) more elaborate control measures may be justified, but in general some measures are justified for all shows and relatively simple "housekeeping" is essential for all. Mortars and racks should be checked regularly to ensure the integrity of both.

The results are shown in Tables 9 and 10.

The risks from firing shells range from "broadly acceptable" to lower risks – they DO NOT pose unacceptable risks. Larger displays merit greater "in depth" analysis than smaller shows and can justify additional expenditure on risk reduction measures.

Individual risk model

The remainder of this paper looks at the use of SHELLCALC© data to investigate the individual risk to persons in the audience of a firework display. This approach could be applied generally, but for the purposes of this paper we have made the following assumptions for inputting data into SHELLCALC©.

- Ignore wind
- Factor in "typical" tumbling and/or

Table 9. *Risk reduction for medium shows.*

Risk reduction method	Cost per mortar	Total cost over 4 year period	Estimate of risk reduction	Cost benefit analysis indicates control method worth doing
Tinfoil to protect shells from sparks	£0.10	£5000	5×10^{-6} to 1×10^{-6}	Yes
Waterproof mortars (renew each year)	£1.00	£8000	5×10^{-6} to5×10^{-7}	Yes
All new mortars each year	£10.00	£80 000	5×10^{-6} to 2.5×10^{-7}	No
Redesigned mortar racks (each with 5 mortars)	£20 (i.e. £100 per rack)	£40 000	5×10^{-6} to 1×10^{-7}	No

Table 10. *Risk reduction for multiple large displays (or single very large display).*

Risk reduction method	Total cost for 10 shows (or single very large display)	Risk reduction	Cost benefit analysis indicates control method worth doing
Tinfoil to protect from sparks	£2000	5×10^{-5} to 1×10^{-5}	Yes
Waterproof fibreboard mortars	£20 000	5×10^{-5} to 5×10^{-6}	Yes
Additional sand barriers, new racks etc	£200 000	5×10^{-5} to 2×10^{-6}	Marginal – may be justified for large budget productions
"Catchers"[a]	£500 000	5×10^{-5} to 1×10^{-6}	Generally no

[a] Disney style "catchers" are barriers erected to stop low trajectory shells reaching the audience.

barrelling

- Assume standard mortars, shell weights etc
- Run the SHELLCALC© model using 150 mm shells.

We have also made the assumption that if a mortar falls over there is an equal likelihood of the shell firing at any time, and therefore at any angle, as it falls to the ground.

We have then calculated the range and likely effect of firing a shell towards the crowd at 5° increments and investigated whether a shell

- Bursts over the audience at such a height that the stars impact on the audience
- Bursts at or near ground level so that persons may be affected by blast or fragments

The raw data derived from from SHELLCALC© are given in Table 11 and illustrated in Figures 1 to 3.

Table 11. *Data for 150 mm shell derived from SHELLCALC©.*

Angle of firing	BLIND Burst range	NORMAL Burst range	NORMAL burst height	Stars reach the ground between distances[b]	
0					
15	188	118	207		
20	226	147	195		
25	259	173	180		
30	286	199	162		
35	309	222	143		
40	325	243	121		
45	334	262	98		
50	339	278	74	270	290
55	336	292	49	240	350
60	327	303	22	230	370
65	310	310	0[a]	230	390
70	282	282	0	210	360
75	236	236	0	180	310
80	169	169	0	90	250
85	33	33	0	−40	110
90	11	11	0	−80	80

[a] Star functions on the ground even if burst time is "normal". [b] See Figure 2 and Figure 3 for examples.

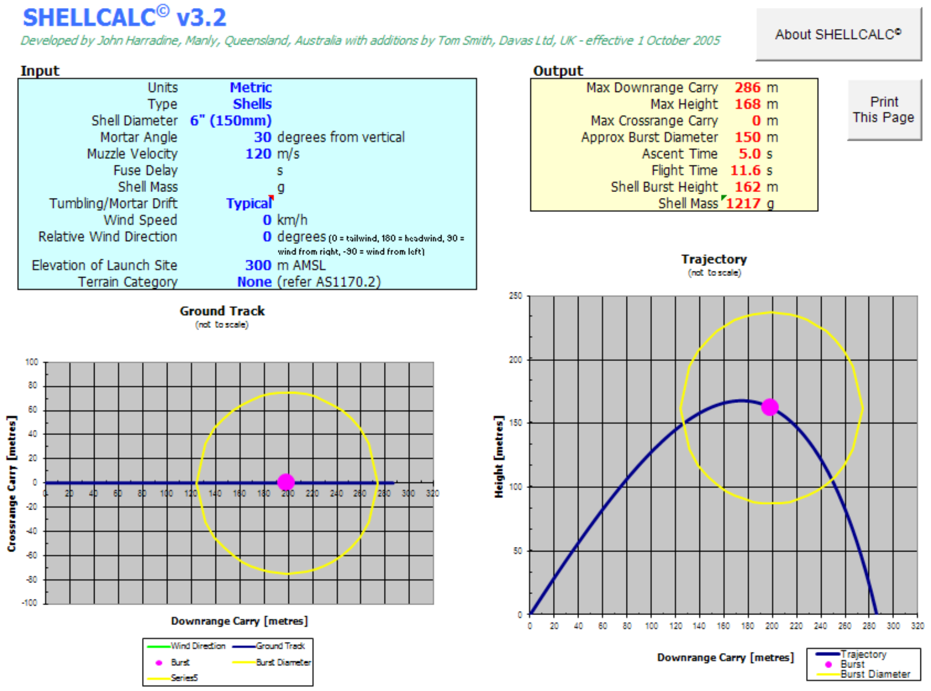

Figure 1. *SHELLCALC output for 150 mm shell fired at 30 degrees – note that the stars from a "normal" burst do not affect the audience.*

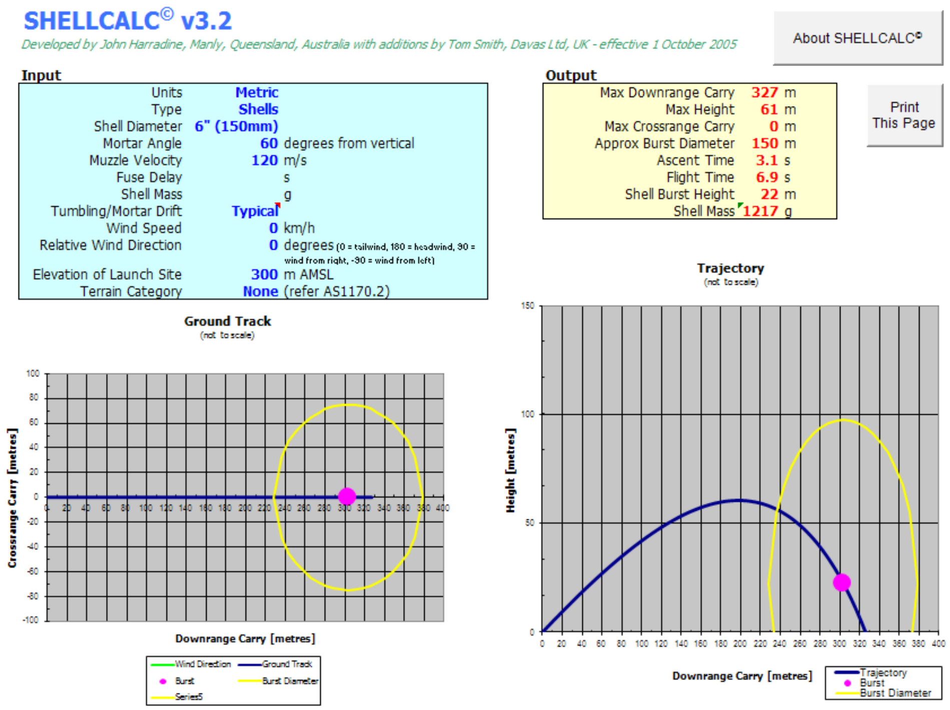

Figure 2. *SHELLCALC output for 150 mm shell fired at 60 degrees. Note that the stars from the "normal" burst affect the audience. Note that the elongation of the shell "burst" is a function of automatic axis fitting in Excel and is not intended to indicate aspherical bursts.*

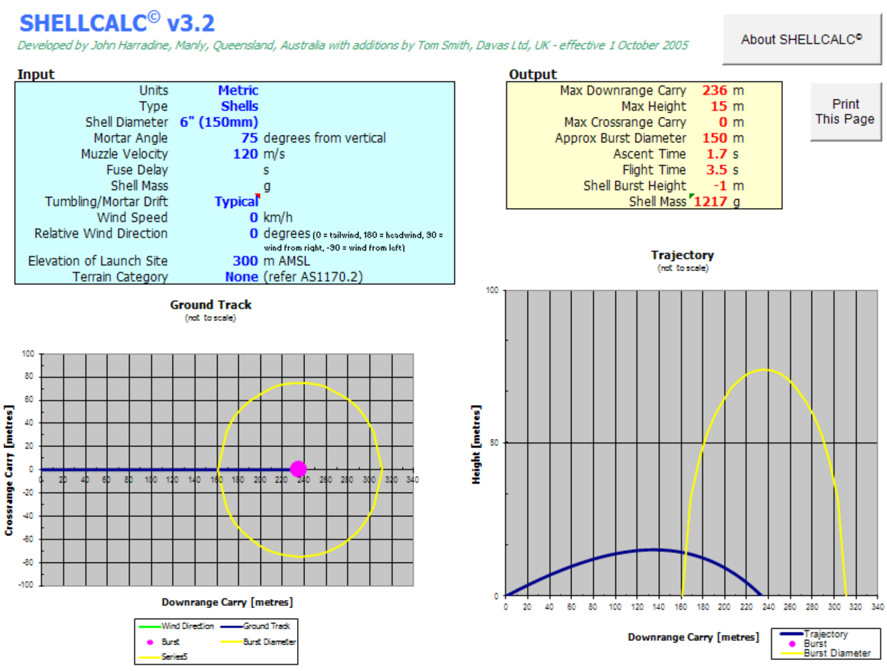

Figure 3. *SHELLCALC output for 150 mm shell fired at 75 degrees. Note that the shell bursts at ground level.*

From these data we have applied the risk calculations outlined above to calculate the individual risk for persons standing at distances of 0 to 500 m from the firing point relating to

- Very early bursts (e.g. muzzle breaks)
- Displaced mortars firing shells that burst "normally"
- Displaced mortars firing shells that function abnormally

In each case we also examine hazards from

- The effects of burst at very close distances (2 m – taken as fatal at this distance)
- The effects of fragments of shells at extended distances (10 m – taken as fatal at this distance) – this, in general, combines with the burst hazard so that we have calculated anyone within 10 m has a fatality frequency of 1
- The effects of stars (taken to the burst radius of the shell – taken as 80 m – with a fatality of 0.1)

The risk calculations relate to the number of shells fired according to the formula

$$Risk_n = 1 - (1 - Risk_1)^n)$$

and not simply

$$Risk_n = n \times Risk_1$$

where $Risk_n$ is the risk from n shells and $Risk_1$ is the calculated risk from a single shell. Tossing a coin 10 times does not mean you will get 5 "heads" (10 × 0.5 = 5) – it doesn't even mean you will get any "heads". The likelihood you will get at least one head in this case is 1-(1/1-024) or approximately 0.99. For very small probabilities the two formulae tend to coalesce.

Figure 4 shows the distribution of distances where either a "blind" shell may fall or the stars from a "normally" functioning shell might reach the ground. The distribution was calculated by analysing the SHELLCALC© derived data in an Excel spreadsheet and analysed according to the following criteria:

- That if a mortar is displaced there is equal probability of it firing at any angle of displacement
- That a "blind" shell is considered to affect an area of its impact point on the ground and 10 m either side of it

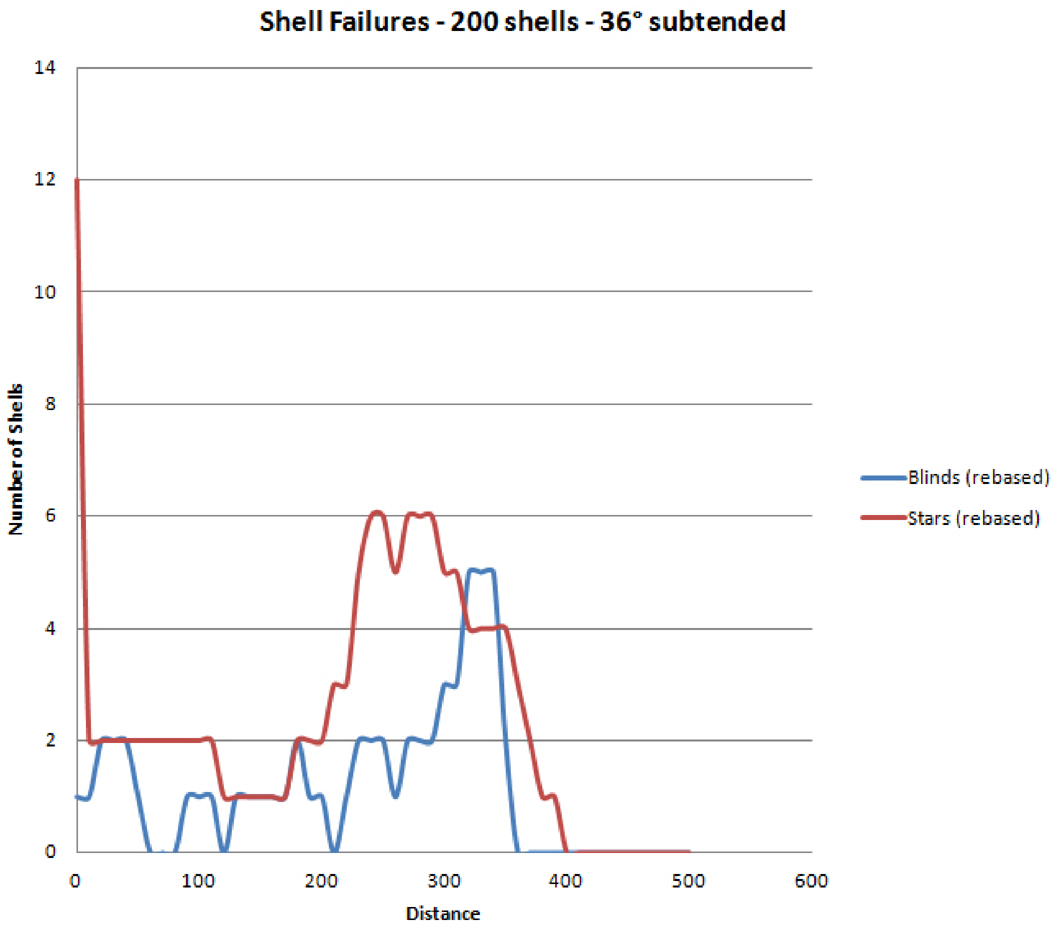

Figure 4. *Ranges where shells may fall "blind" and where stars from shells fired from displaced mortars may reach the ground.*

- That the analysis is carried out using 10 m increments of distance – up to 500 m from the firing point
- The likelihood of a shell failing in either mode is then applied to the range distribution, and the overall risk calculated
- The risk is then rebased because the Excel analysis overcounts shells – it effectively counts all possible times a shell affects the audience whereas the audience will only be affected once per single shell.

Figure 4 does not imply that, for instance 5 shells reach the ground at approximately 250 m, rather that if stars from a "normally" functioning shell reach the ground they are 5 times more likely to reach the ground at 250 m than they are at 150 m. This is entirely in concordance with real life observations and the SHELLCALC plots. If a shell is fired at a small deviation from the vertical and functions normally then the stars do not reach the ground.

The "jagged" nature of the plot reflects the mathematical analysis used and does not mean that there are particular distances where the likelihood of a "blind" shell falling or the stars reaching the ground is particularly high or low. We have chosen to ignore this "jagged" anomaly

The plot for a show containing 200 150 mm shells and subtending an angle of 36° (i.e. 1/10 of a circle) is shown in Figure 5.

Excel also allows an estimated regression to be made, which is also shown in Figure 5, and which is a more realistic evaluation of the risk at any particular point.

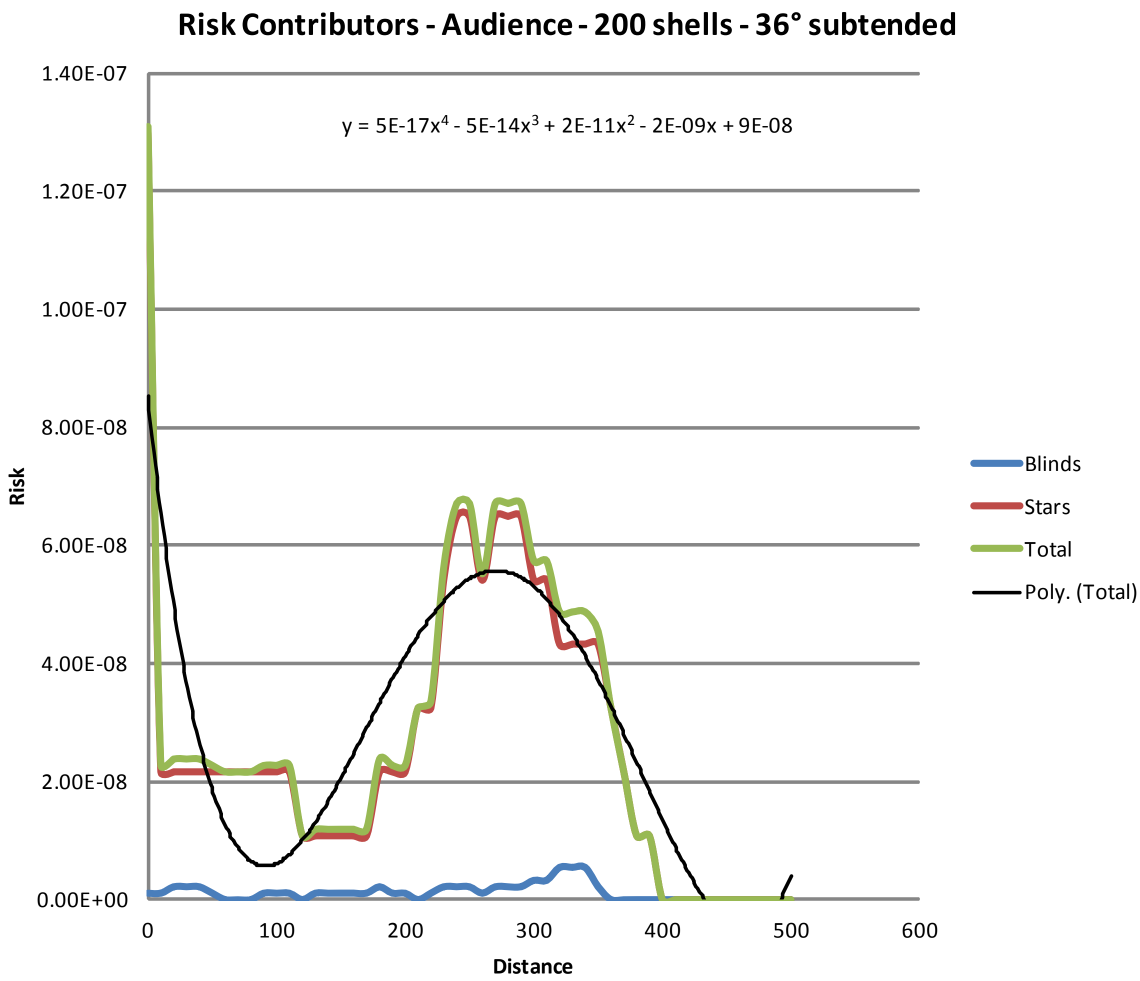

Figure 5. *Individual risk from 200 shells – audience 36°.*

A similar plot for a show containing 500 shells where the audience subtend 360° is shown in Figure 6.

From these plots it is possible to calculate

- The distance at which an individual is subject to more than a "broadly acceptable" – i.e. 1×10^{-6} risk.
- The total risk for persons at all distances

In the case of 50 shells subtending 36° there is no position away from immediately adjacent to the firing point at which the individual risk is greater than 1×10^{-6}.

In the case of 500 shells fired at 360° then the distance at which an individual is subject to the same risk is approximately 360 m. There is a area nearer the firing point at which the risk is the same – but this is discounted for obvious reasons.

Overall the risks remain extremely low – even in the second case the risks do not approach twice the

Table 12. *Total risk to the audience for a number of display scenarios.*

No of shells	Angle subtended/degrees 36	180	360
50	3.5×10^{-7}	1.8×10^{-6}	3.5×10^{-6}
100	7.1×10^{-7}	3.5×10^{-6}	7.1×10^{-6}
200	1.4×10^{-6}	7.1×10^{-6}	1.4×10^{-5}
500	3.5×10^{-6}	1.8×10^{-6}	3.5×10^{-5}
1000	7.1×10^{-6}	3.5×10^{-6}	7.1×10^{-5}

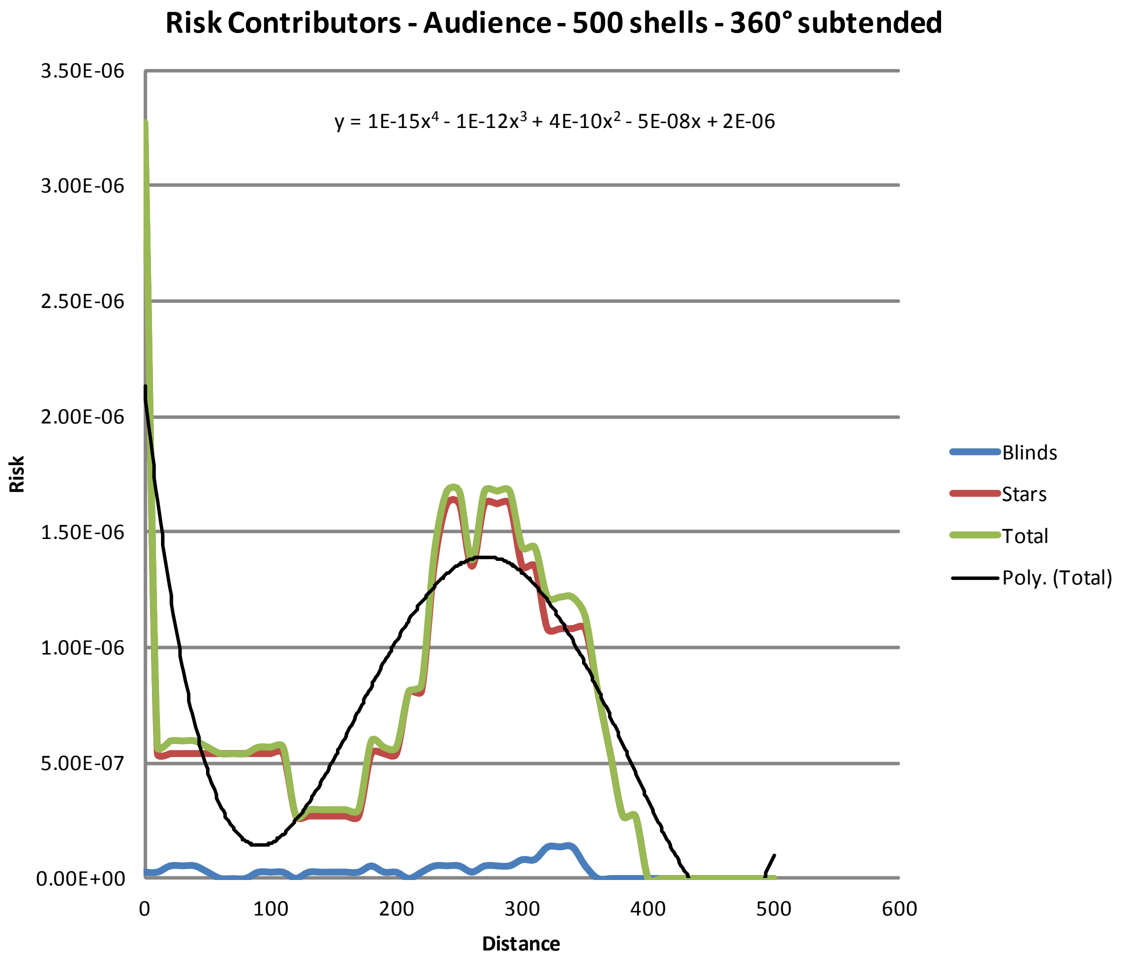

Figure 6. *Individual risk from 500 shells – audience 360°.*

"broadly acceptable" risk at any point.

Table 12 shows the total risk for a variety of numbers of shells fired and angle the audience subtends. Even for the most extreme case (1000 shells, audience at 360°) the risks are still within the ALARP region and therefore merit additional control measures – they do not pose unacceptable risks.

Table 12 also gives an indication of the societal risk, albeit not precisely. An alternative approach would be to sum the total risks to individuals between two specified distances and relate this to the number of people occupying such a range of distances given a specific angle that they subtend.

A second approach to risk assessment

We have also interrogated the SHELLCALC© derived data in a different manner. In this case we have examined the likelihood of fatality at each distance (again from 0–500 m in 10 m increments) and calculated that if a "blind" shell falls to the ground or the stars from a "normally" functioning shell reach the ground at any distance greater than the specified distance then a potential fatality will occur.

The results for the same situations as outlined above are shown in Figures 7, 8, 9 and 10.

Distances calculated for an individual risk of less than 1×10^{-6} from this method for the two given scenarios are approximately 80 m and 320 m respectively.

These differ from, but are consistent with, the first method. The appropriateness of each method

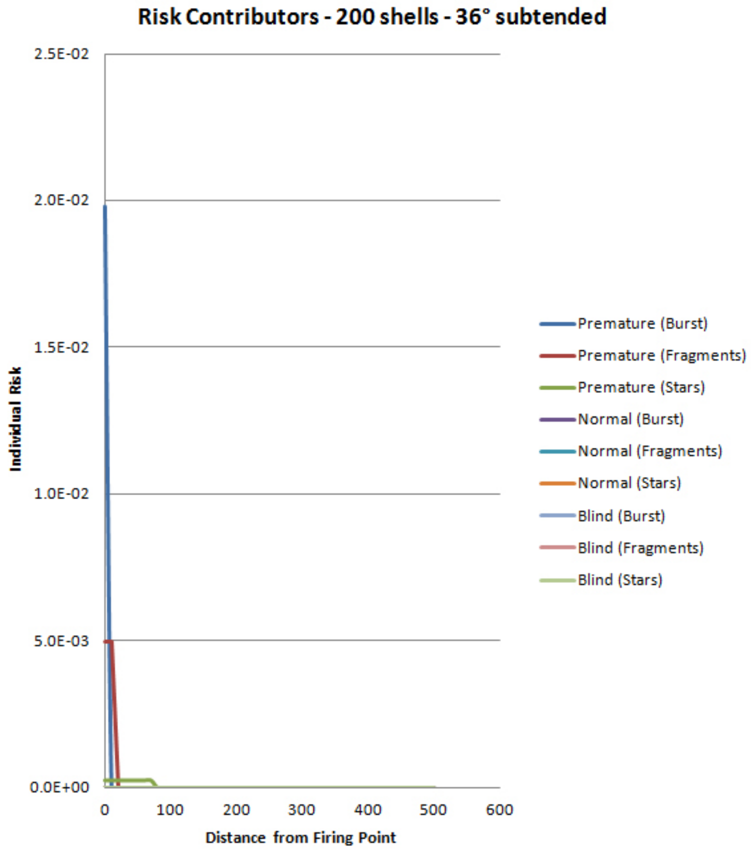

Figure 7. *Calculation of individual risk by method 2 for 200 shells subtending 36°.*

should be chosen on its merits for a particular display at a particular venue on the basis of the likely distribution of the audience.

Further work

The methods illustrated in this paper relate to a relatively narrow range of hazards to the audience. Although "normal" debris is unlikely to produce a fatality hazard, none the less it is an important factor to be considered when siting a fireworks display – especially because "normal" debris (card or composite fragments of the shell case, unburnt stars or long burning stars reaching the ground) is significantly affected by the wind strength and direction after the shell (or other firework) bursts.

This will be the study of further papers in due course dealing with societal risks of both fatality and injury to audience members and to operators at both firework displays and where other pyrotechnic items are used in proximity to the audience.

Conclusions

Modelling of individual risk by knowledge of the likely failure rates and likely hazards and applying this over the possible failure modes for shells allows distances to be estimated where the individual risk is approximately 1×10^{-6}. The procedures demonstrate that it is essential to recognise the angle subtended by the audience, the number of shells fired and the possible mechanisms by which such shells could cause injury or fatality to members of the audience.

Although we propose that, in general, the estimates of frequency and hazard have been quite pessimistic, the overall risks to audience members remain extremely low – which concurs with the observed accident statistics. Form other studies[11] we estimate that in the UK some 12 million people attend an organised firework display annually and the number of fatalities remains extremely low.

Finally, it is apparent from the analyses carried out that it is not appropriate, for professionals, to apply set "safety distances" for shells of a

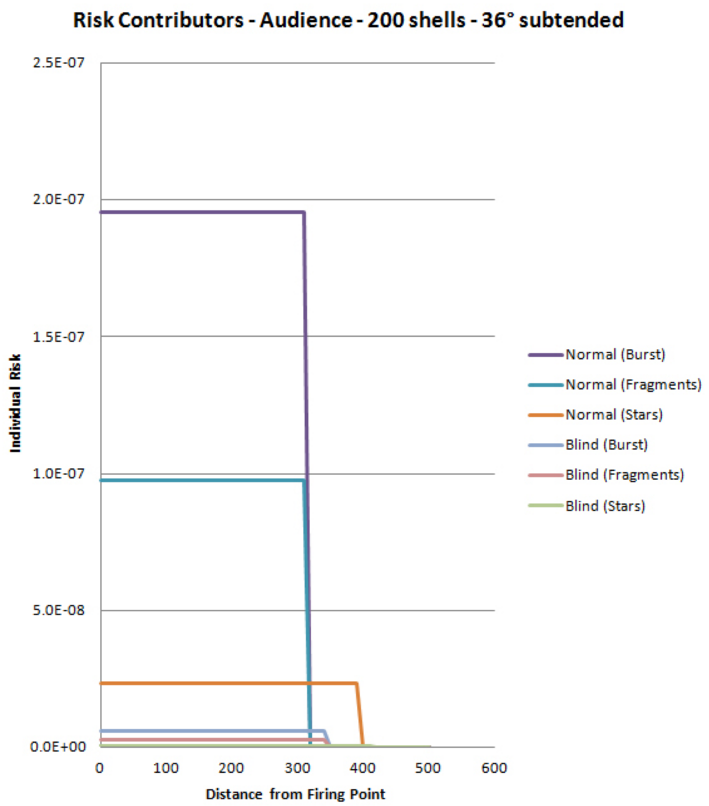

Figure 8. *Individual risk (zoomed in) area from Figure 7.*

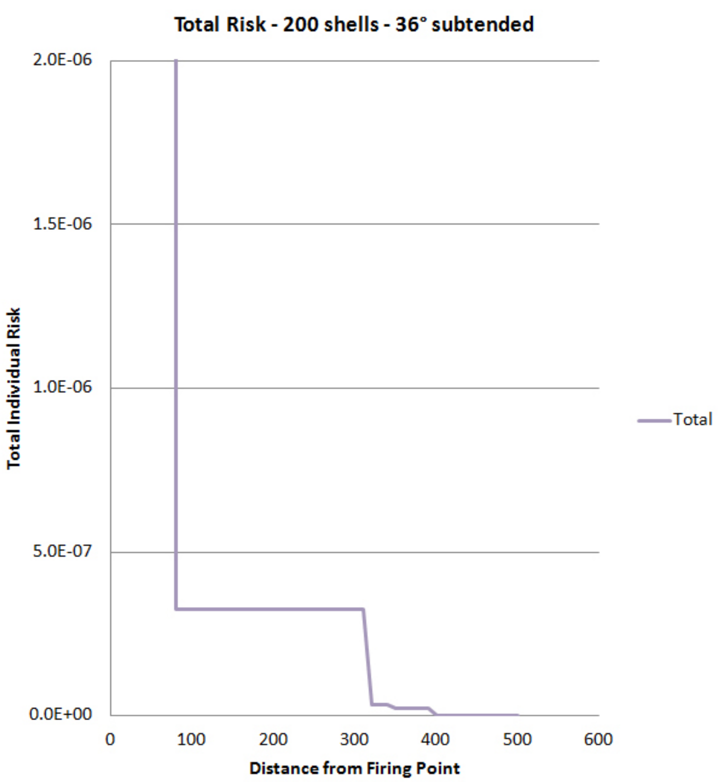

Figure 9. *Individual risk (zoomed in) from Figure 8.*

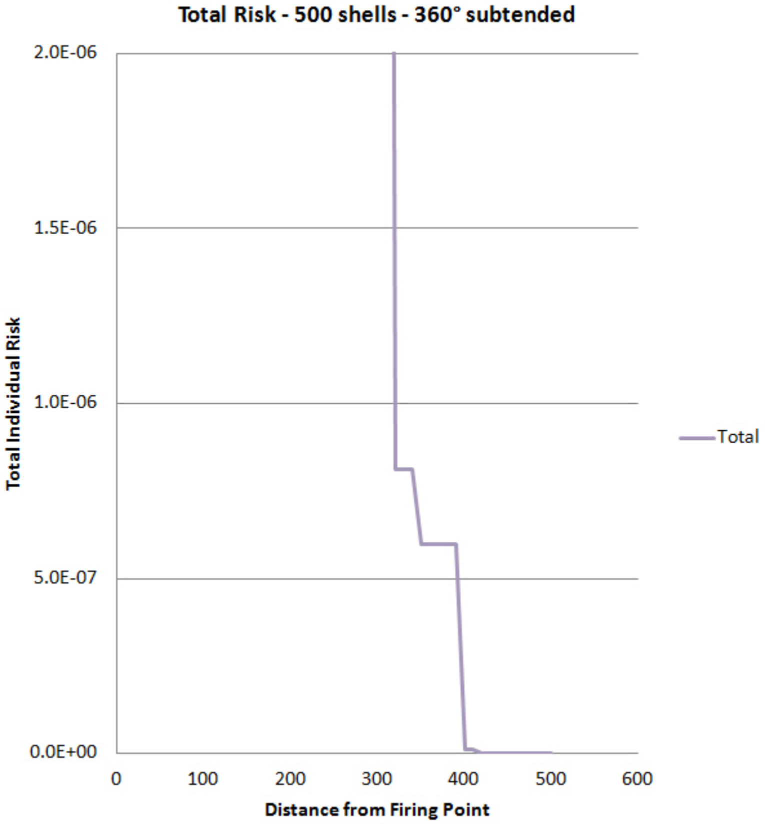

Figure 10. *Individual risk from 500 shells subtending 360°* .

particular calibre – even if the shells are always fired in the same manner. The nature of the site and the display has a critical role in determining appropriate distances where the risks are reduced to an acceptable level.

References

1 For details of the CN Standardisation work see http://www.cen.eu/cen/Sectors/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Pages/default.aspx?param=6193&title=CEN/TC%20212

2 For a definitions of terms see http://www.iacs.org.uk/document/public/Publications/Other_technical/PDF/FSA_Glossary_pdf437.pdf

3 See for example http://home.att.net/~d.c.hendershot/papers/pdfs/riskland.pdf

4 Societal Risk: Initial briefing to Societal Risk Technical Advisory Group, http://www.hse.gov.uk/research/rrpdf/rr703.pdf

5 Societal risk – Estimating the chances of people being harmed from an industrial incident, http://www.hse.gov.uk/societalrisk/ and links to papers therein.

6 T. Smith, *Journal of Pyrotechnics*, Issue 18, 2003, pp. 32–42 (http://archives.jpyro.com/?p=158).

7 J. Harradine and T. Smith, *Journal of Pyrotechnics*, Issue 22, 2005, pp. 9–15 (http://archives.jpyro.com/?p=23).

8 Principles and guidelines to assist HSE in its judgements that duty-holders have reduced risk as low as reasonably practicable, http://www.hse.gov.uk/risk/theory/alarp1.htm

10 The Explosives Incidents (EIDAS) database is available at http://www.hse.gov.uk/explosives/eidas.htm. Although this is the HSE official database of incidents, the data appear not to be complete and concerns have been expressed about the validity of some of the data provided.

11 Explosive Industry Group survey, results to be published.

Defining Flash Compositions: Modifications to UN Time/ Pressure Test

D. Chapman and K. Howard
Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire, UK SKI7 9JN.

Abstract: *The Time/Pressure Test from the UN Manual of Tests and Criteria has been modified to define flash compositions in the default classification lists for fireworks in the UN Model Regulations. This modified test is known as the HSL flash composition test. This paper summarises the history of this change from a composition-based to a performance-based definition and describes more recent work to improve the method when testing pyrotechnic compositions. A modified test method has been developed with a new firing plug that has been designed to improve reliability and reproducibility by changing the sample geometry and removing the primed cambric. The system has been manufactured and tested and was presented as a proposal to the UN Subcommittee of Experts on the Transport of Dangerous Goods as an additional test method for the Manual of Test and Criteria specifically for defining hazardous compositions with flash-like properties. The method and apparatus is now incorporated into the UN scheme for the classification of dangerous goods, specifically for fireworks.*

Keywords: *Flash Composition, UN Default List, Time/Pressure Test.*

Introduction

There are numerous instances of fireworks being involved in major incidents that have resulted in damage to storage premises, homes, ships and manufacturing sites. Probably the worst such incident was that at Enschede in the Netherlands which occurred in May 2000.[1] This incident was one of the main driving forces for a European Project entitled “Quantification and Control of the Hazards Associated with the transport and storage of Fireworks” with the acronym ‘CHAF’ for short.[2] The project provided a number of results, ranging from small-scale (single and multiple fireworks),[3,4] medium-scale (transport package(s))[5–7] and large-scale (ISO container).[8,9] The project culminated in an international conference[10] organised by the International Symposium on Fireworks, attended by world pyrotechnic experts. Discussion during the conference suggested that one major omission was work at the composition level and that this could lead to a more cost effective means of testing potentially hazardous fireworks.[11]

Traditionally, explosives undergo a series of tests from the UN Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria[12] to classify them as UN hazard division 1 substances and articles, and to assess their hazard in transport. This transport classification is often used as a guide to assess hazard in storage without additional experimentation. For pyrotechnic items, the defining tests are series 6, which comprises tests under confinement and in a fire. One of the firework types tested in the CHAF project was subjected to the standard UN series 6 tests, giving results typical of a UN hazard division 1.3 material; that is a major fireball was produced in the UN series 6(c) test and it did not give a mass explosion in the 6(a) or (b) test. However, when the fireworks were tested in large-scale trials undertaken by the CHAF project, a large mass explosion took place in an ISO container full with these fireworks.[13] The CHAF project undertook testing on transport packages of fireworks in a medium sized pressure vessel. This approach differentiated between the fireworks that mass exploded in the large-scale trials and those that did not.[7]

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The UN Recommendations on the Transport of Dangerous Goods – Model Regulations has developed a default classification scheme for the classification of fireworks.[14] This "default list" uses the amount (either absolute amount or percentage) of flash composition within fireworks or components of the firework. Flash composition was defined in the Model Regulations, Editions 13 and 14 as a mixture of oxidiser and powdered metal. However, this definition did not capture all mixtures being employed to function as a flash composition and a performance-based test was thought to offer a more objective means of assessing the potential hazard. The UN Manual of Tests and Criteria does contain a test that can offer an objective means of determining differences between flash, flash-like and other pyrotechnic compositions, the Time/Pressure Test. This paper outlines the main features of the existing test and describes the work undertaken to develop and improve the test into a practical means of quantitatively testing fireworks compositions to be able to differentiate between highly hazardous and those less so.

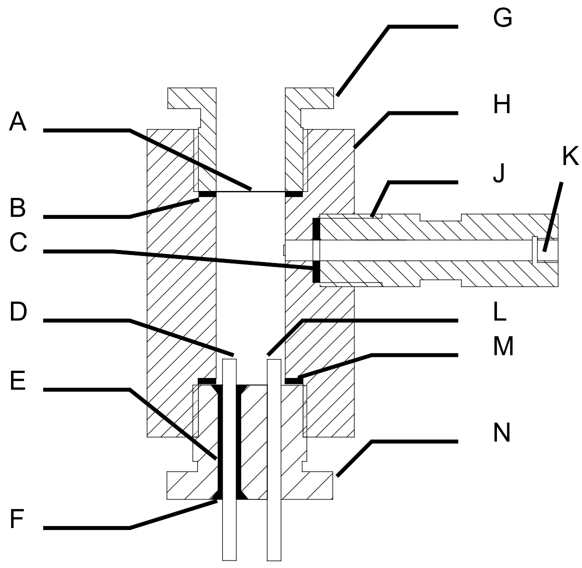

Figure 1. *Time/pressure test equipment. A: bursting disc; B: soft lead washer; C: copper washer; D: insulated electrode; E: insulation; F: steel cone; G: bursting disc retaining plug; H: pressure vessel body; J: side arm; K: pressure transducer; L: earthed electrode; M: soft lead washer; N: firing plug.*

The UN test method

The Time/Pressure Test is part of the United Nations scheme for the assessment of the hazard during transport of dangerous goods and is found within the United Nations Transport of Dangerous Goods, Manual of Tests and Criteria.[12] The test method is used in Test Series 1 to determine if a substance has explosive properties, and Test Series 2 to determine how explosive a substance is. The test methods are Test 1(c)(i) and Test 2(c)(i) respectively.

The method as described in the UN test normally uses 5 g of substance, unless the material is suspected of being particularly energetic, when the sample size may be reduced to as little as 0.5 g. The ignition system in use at HSL employs an electric fuse head attached to a firing plug, with a 13 × 13 mm piece of primed cambric tied around the fuse head. A diagram of the original apparatus is shown in Figure 1.

A 5 g sample of substance is subjected to an incendive flame from the ignition source in a pressure vessel fitted with a pressure recording device and a bursting disc. The vessel has a volume of 20 ml and the bursting disc is designed to burst at approximately 2200 kPa. The test substance is regarded as capable of presenting a risk of an explosive deflagration if the time taken for the pressure to rise from 690 to 2070 kPa is less than 30 milliseconds. The procedure is performed three times using the same mass of sample, and due to the variability, the result is the fastest time taken for the pressure inside the vessel to rise from 690 kPa to 2070 kPa. The UN Manual of Tests and Criteria does not state any limits of repeatability or reproducibility. In the standard test, HSL uses a slightly modified version of the UN firing plug, with threaded bars with small nuts to secure the fuse head rather than soldering the fuse head on to points located on the firing plug. This system was developed after a number of accidental ignitions of the fuse head during soldering. The bar and nuts also eliminate the need for removing all of the insulation on the Testex fuse head.

Summary of reported data on pyrotechnic samples in the unmodified Time/Pressure Test

Pyrotechnic compositions from fireworks have been tested in the Time/Pressure Test, following the original method with primed cambric/Testex fuse as the initiating system and 0.5–5.0 g of sample. These results have been reported in a paper to the UN[15] and in a report for HSE.[16] These tests showed that different types of pyrotechnic composition have markedly different rise times in the existing test, and showed promise as a test method to distinguish between the sample types. A summary of the results carried out on 1 g samples is provided in Table 1.

Tests to show reproducibility of result using the existing primed cambric/fuse head initiation were conducted and these proved to be disappointing with some large variation in results. This is illustrated in the cluster analysis, Figure 2. The issue of the variation in rise time was raised and discussed at the UN committee on the transport of dangerous goods.[19–23] It was decided that a modification to the initiation system was desirable to reduce this variation, the rationale being that with a small sample, the pyrotechnic material may not be in contact with the primed cambric. A large proportion of the rise time was thought to be due to the variation in time taken for the burning cambric to fall onto the sample and initiate sufficient of the pyrotechnic surface to achieve the upper pressure (2070 kPa). Thus, a more consistent method of initiation was required.

Modification of the test apparatus

Primed cambric is used as a secondary source of ignition for substances that may be difficult to ignite in the original UN Time/Pressure Test method (1(c)(i) & 2(c)(i)). With a 5 g sample this will be in good contact with the test sample, however with the smaller sample used for pyrotechnic materials this is not necessarily the case. In simple laboratory tests with pyrotechnic compositions at HSL it was shown that the compositions would ignite from a single electric fuse head without the primed cambric. In removing the primed cambric, it is necessary to ensure that the composition to be tested is close to the fuse head and directly in the path of a spark. Additionally, the sample must not be "blown out" and dispersed by the small explosion of the initiating electric fuse head. Thus, the fuse head needed to be above the sample but not in direct contact.

Several efforts were made to retrofit the UN test equipment with sample holders to hold the small sample mass in contact with the fuse head, or increasing the size of the chamber to allow larger samples to be tested. However, none of these

Table 1. *Time/pressure rise times for 1 g pyrotechnic mixtures taken from fireworks.*

Composition	Physical form	Source[a]	Minimum rise time (ms)	Mean rise time (ms)	Standard deviation
Black powder lift charge	Granular	WP9, 150 mm star burst shell	6.1	6.7	0.9
Black powder burst charge	Granular	WP9, 150 mm star burst shell	5.1	6.0	0.9
Black powder from rocket motor	Powder	WP9, unsticked rocket	8.6	12.2	3.1
Flash composition	Powder	WP9, unsticked rocket	<1	<1	—
Waterfall composition	Powder	WP9 waterfall	<1	<1	—
Waterfall composition	Powder	WP6 waterfall	4.8	6.4	1.7
Star fragments	Chips	WP9, 150 mm star burst shell	8.2	9.2	1.5
Whistle composition[b]	Powder	Wheel driver unit	1.7	1.9	0.3

[a] WP6 and WP9 are work packages in the CHAF project. Details of the materials can be found in the work package reports.[17,18] [b] Potassium perchlorate/sodium benzoate.

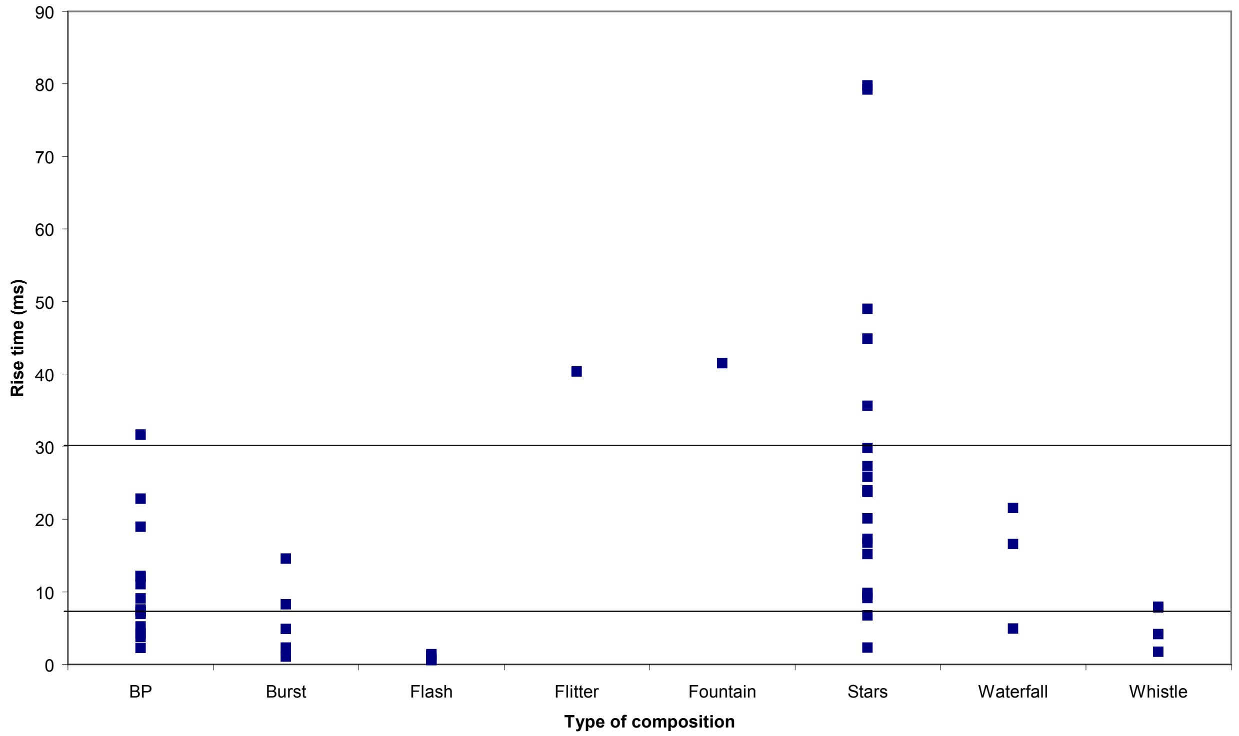

Figure 2. *Cluster analysis of rise time results***.**

proved successful, either due to repeatability, time or cost issues and a revised "cone in plug" design was adopted.

The new firing plug with a central recess to hold the sample, as shown in Figure 3, was manufactured using mild steel, with Tufnol™ as the insulating material. This new "cone in plug" firing system accommodated an inverted Vulcan™ fuse head with a length of insulated wire in the chamber as shown in Figure 4. Other suitable electric fuse heads could be used if they had similar igniting power. The cone was 1 mm narrower than the internal diameter of the time/pressure vessel to allow the plug to fit into the vessel.

The non-insulated section of each lead wire from the fuse head had to be accurately measured on the 'insulated' terminal to prevent short circuits. The leads from the fuse head are twisted just below the foils to strengthen the fuse head, and to avoid breaking the soldered connection on the foils.

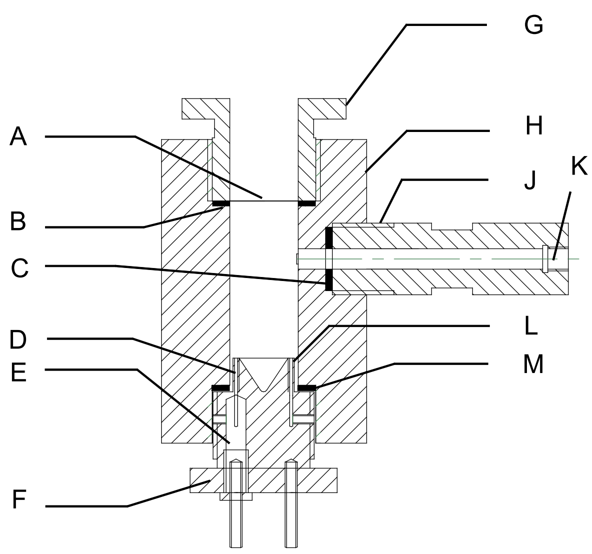

Figure 3. *"Cone in plug" time/pressure apparatus***.**
A: bursting disc; B: soft lead washer; C: copper washer; D: insulated electrode; E: insulation; F: firing plug; G: bursting disc retaining plug; H: pressure vessel body; J: side arm; K: pressure transducer; L: earthed electrode; M: soft lead washer.

Results

The 'cone in plug' firing plug was validated by comparing results obtained from the original test

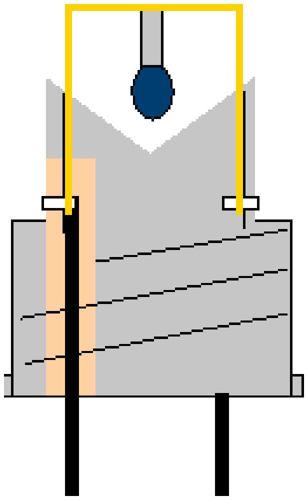

Figure 4. *Location of Vulcan fuse head in the "cone in plug".*

equipment using the original test method (0.5 g of sample with 3 repeats (unless stated otherwise) with those from the "cone in plug" apparatus. Two types of commercial flash powder were tested along with a commercial black powder. The results obtained are detailed in Table 2. Composition data are given in Table 3.

Additional validation data has been obtained from the black powder sample used. The results are tabulated in Table 4. Since validating the modified apparatus additional samples have been tested. Specimen results are presented in Table 5.

Discussion

Original UN series 1 and 2 apparatus

The initial attempts to investigate pyrotechnic compositions in the UN Series 1(c) and 2(c) apparatus using primed cambric and an electric fuse, were designed to investigate material that may have energetic properties. That is, it is intended to be part of the preliminary tests to ascertain properties below the severity of explosives but none the less posing hazard in transport. It is intended that a 5 g sample will normally be used for the test but does allow for lower sample size down to 0.5 g. With many pyrotechnic material (which do have explosive properties) the 5 g sample was found to be excessive for the test to differentiate between samples, the upper burst pressure being achieved rapidly for many different samples. Thus lesser amounts of pyrotechnic were tried. Within the existing UN series 1 and 2 apparatus 1 g samples were the lowest practical amount to ensure reliable ignition. These results (Table 1) showed differentiation between different pyrotechnic types but with a relatively high variation as measured in the standard deviation. Typically this ranged from 10 to 25% of the mean. There were additional difficulties in ignition with some materials that may be caused by the lack of direct contact of the pyrotechnic with the primed cambric in the ignition system. This variation in result and problems with initiation led to the development of a different plug body, the main aims being to provide reliable initiation and better reproducibility.

Cone in plug development

The cone in plug assembly has developed through a number of modifications; initially, placing a cone within the existing base plug, through to redesign and production of an integral cone. All designs require that there be an insulated path to allow a circuit to the electric fuse to be formed. This has presented a number of technical challenges. The corrosive nature of pyrotechnic compositions and their products has caused difficulties with the grub screws used to form the circuit. Ceramic grub screws were sourced for test to ascertain if they overcome this difficulty. While they would be resistant to corrosion they were found to be too brittle and broke too readily when being inserted or removed. Currently a plastic insert attached to the end of the metal grub screw is being trialled to see if it reduces corrosion of the metal grub screw. This has been found to be successful and is now standard on the apparatus used at HSL.

The use of an inverted conical cup to hold the pyrotechnic has ensured that there is a large pyrotechnic surface close to the initiating fuse. This has given more reliable initiation of the pyrotechnic compared with the original UN series 1 and 2 plug.

Reproducibility of result has also been improved. Table 2 shows all samples having a lesser standard deviation, both in absolute value and as a percentage of the of the mean value. Typically this has reduced from greater than 20% to less than 15% of mean.

Table 2. *Comparison of original test method and new firing plug – 0.5 g samples.*

Composition	Original method		Cone in plug method	
	Mean rise time (ms)	Standard deviation	Mean rise time (ms)	Standard deviation
Flash powder 1 (5 repeats)	0.78	0.14	0.70	0.10
Flash powder 1 (second set)	0.74	0.17	0.84	0.08
Flash powder 2	3.11	3.31	1.51	0.47
Black powder (10 repeats)	5.10	1.18	4.98	0.65

Table 3. *Composition data.*

Composition	Composition (% mass)						
	Potassium perchlorate	Magnalium	Sulphur	Aluminium	Carbon	Potassium nitrate	Titanium
Flash powder 1	45	22	11	22	—	—	—
Flash powder 2	60	—	—	25	—	—	15
Henry Crank fine black powder	—	—	10.4	—	15.6	74.0	

Validation testing

The validation results for 0.5 g samples in Table 2 show reduced standard deviation compared with the original apparatus utilising primed cambric. The original large variation in results was a major criticism of the test at the UN[19–23] and was the major driver for the development of the current test apparatus. "Flash powder 2" appears to have had initiation difficulties when using the original plug system. This may be due to a higher ignition temperature of the material caused by the lack of sulphur (see Table 3 for composition data). Certainly, with the plug in cone system more reliable ignition of this sample was achieved. With all the materials tested in this comparative investigation of the two plugs (original vs. modified) the cone in plug reduced the measured standard deviation in rise time.

Reproducibility testing

The UN Default table permits the use of black powder in some fireworks, e.g. rocket burst charges for a UN HD 1.4G classification. HSE/HSL had originally proposed a ≥4 ms rise time in the modified cone in plug apparatus as the differentiation point between materials that were considered to be as hazardous as flash and those that were considered less hazardous than flash. A commercial black powder (Henry Crank fine black powder) was used as the "standard" material for investigating this aspect. A series of trials over a 6–7 week period (Table 4) was used to ascertain reproducibility. In general, results for this black powder were in the range 4–6 ms with the occasional outlier. Standard deviation was, as expected, found to be less for sets of 10 than for sets of 3, however, sets of 3 are more practical and

Table 4. *Black powder study.*

Date	Minimum rise time(ms)	Average rise time (ms)	Standard deviation	No. of tests
08/07/2009	4.57	5.46	0.63	10
23/07/09–28/07/09	4.38	6.18	0.81	10
31/07/2009	4.22	5.62	1.26	3
25/08/2009	3.63	4.98	1.23	3

Table 5. *Sample testing results.*

Sample/description	Min rise time (ms)	Average rise time (ms)
Potassium perchlorate fireworks report flash composition	<1.0	<1.0
Potassium perchlorate theatrical flash composition	2.7–4.2	2.8–5.3
Potassium nitrate theatrical flash composition	3.2	4.6
Strontium nitrate theatrical flash composition	2.7	3.0
Meal powder theatrical gerb composition	2.8–12.1	6.7–16.4
Rocket motor black powder[a]	8.6	12.2
Black powder[a] burst charge	5.1–6.1	6.0–6.7
Potassium perchlorate enhanced black powder	2.44–3.46	2.69–3.35
Fireworks whistle composition	1.7	1.9

[a] Black powder as defined: "a mixture of potassium nitrate and carbon with or without sulphur".

give sufficient reproducibility to be a practical test method.

Day to day testing

Numerous different pyrotechnic compositions have now been tested and the results summarised in Table 5. Some of this work has been undertaken as part of an HSE programme for compliance with the UN default classification scheme[24] and some in an ongoing programme on the HSL flash composition test. True black powders (potassium nitrate, carbon and sulphur) from fireworks have generated rise times greater than 4 ms and are generally well differentiated from true flash (metal/oxidiser) which have generated rise times. Whistle and potassium perchlorate enhanced black powders have been found to consistently have a rise time less than 4 ms. Theatrical gerb compositions based on meal powders have shown the largest variation in rise time. This is most likely due to the wide range of size in the metal powders depending on the effect desired in the devices. It could be argued that 4 ms is the best rise time to differentiate between the more hazardous pyrotechnic compositions and those deemed to pose a lesser hazard.

Conclusions

The cone in plug apparatus has achieved the aims of the project and a modified test has been developed. Certainly, the modification has produced a reduction in the variability of rise time compared to the original UN apparatus. While the UN default scheme for firework classification uses a cut-off of 8 ms rise time to differentiate between acceptable compositions for a UN HD 1.4G and those deemed to be too hazardous for this classification without UN series 6 data, this programme has found that true black powders generally lay in the rise time range 4–8 ms. Thus where black powder burst charges are not allowed for a UN HD 1.4G classification (e.g. shells) the test results is likely to result in a default classification of UN HD 1.3G, which may not have been the original intent of this work.

Disclaimer

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UK Fireworks Surveillance for Compliance with ADR and the UN Default Classification of Fireworks

D. Chapman,[a] S. Dennis,[a] B. Joyce,[a] A. C. Donalds[b] and M. J. C. Sime[b]
[a] Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire, UK SK17 8JN
[b] Explosives Inspectorate, Health and Safety Executive, Redgrave Court, Merton Road, Bootle, Merseyside, UK L20 7HS

Abstract: *Fireworks compositions have been examined for a range of different fireworks. These compositions have been tested and measured to ascertain compliance (or otherwise) with the United Nations (UN) Default Fireworks Classification Table criteria for UN Hazard Division (HD) 1.4G classification.*

Non-compliance with the requirements of UN HD 1.4G criteria have been found. These have constituted exceeding the total net explosive content (NEC), time–pressure rise times of less than 8 ms for non-black powder formulation burst charge compositions, metal based flash compositions being used as burst charge, and greater than 5% flash content in shot tubes.

Fireworks that comply with the requirements of the UN default classification scheme have also been found.

Keywords: *Compliance, default classification, UN, ADR*

Introduction

The majority of fireworks imported into Great Britain (GB) are classified for transport purposes using the criteria set down in the United Nations (UN) Default Fireworks Classification Table at paragraph 2.2.1.1.7.5 in the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR).[1] Importers classify fireworks by this method and those classifications must be approved by the GB Competent Authority responsible for classification, i.e. the Health and Safety Executive (HSE)'s Explosives Inspectorate, in order to comply with legal duties under the Classification and Labelling of Explosives Regulations 1983[2] as amended (CLER), and the Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations (latest version)[3] (The Carriage Regulations).

The latest versions of ADR are brought into GB law via updates to The Carriage Regulations. Chapter 1.8 in ADR allows Competent Authorities to carry out compliance checks to ensure safety requirements concerning the transport of dangerous goods are met. In accordance with paragraph 1.8.1.3 of ADR, HSE ensures that duty holders comply with the UN Default Fireworks Classification Table as a means of addressing these safety concerns. This is achieved through HSE taking transport packs of fireworks as samples and having their contents examined by the Health and Safety Laboratory (HSL).

Summary of the UN default classification criteria for UN HD 1.4G fireworks

Most of the fireworks imported to the UK for consumer use require a UN hazard division (HD) of 1.4G for transport and by extension storage at retail premises. The UN default scheme gives a

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Table 1. *UN default criteria for UN HD 1.4G fireworks.*

Firework type	UN DH 1.4G criteria
Roman candle and shot tube	An inner diameter of the Roman candle tube of ≤30 mm, a pyrotechnic unit of less than 25 g and any flash burst charge ≤5% of the total NEC
Rocket	A total NEC ≤20 g, a black powder bursting charge and if report units are present these must be ≤0.13 g flash and their total amount must be ≤1 g
Mine	A total NEC of ≤150 g pyrotechnic containing ≤5% as flash composition as loose powder and/or report units. Any report units present must be ≤2 g and any whistle units present must be ≤3 g
Fountain	A total NEC of <1 kg
Wheel	A total NEC of <1 kg, with no report effects and if present any whistle units ≤5 g with a total NEC per wheel of 10 g of whistle
Batteries, combinations and selection packs	The default classification is determined by the firework having the most hazardous classification

series of criteria for such fireworks of most types, certainly all the fireworks currently available for retail sale to the general public.

The UN default classification scheme allows for fireworks that comply with a set of limits to be classified without carrying out UN Series 6 tests, as prescribed in the UN publication entitled "Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria". The criteria for achieving a UN HD 1.4G using the default system are given in Table 1 and these are a mixture of dimensions, masses and net explosive content (NEC).

Scope of the study

Previous experience of compliance checks indicated that rockets had the largest number of non-complying items following examination against the UN default table for a 1.4G classification. These were:

- Over-Net Explosive Content (NEC) i.e. >20 g total pyrotechnic mass,
- Flash powder burst charge i.e. metal and oxidiser substance,
- Non-black powder formulations i.e. potassium perchlorate based compositions.

No rockets with the allowed ≤0.13 g individual report units were found during the surveillance programme.

Shot tube batteries also produced some non-compliance issues with the UN default table for a 1.4G classification. These centred on:

- Oversized cardboard tubes i.e. >30 mm tube inside diameter,
- Total NEC of the pyrotechnic unit i.e.>25 g,
- Percentage of flash powder burst charge in the total pyrotechnic i.e. >5% of NEC.

Rockets

Basic considerations

For UN HD 1.4G rockets these limits are:

1. Total pyrotechnic NEC 20 g or less,
2. A black powder bursting charge (defined as potassium nitrate and charcoal with or without sulphur),
3. Individual report units (if present) limited to no more than 0.13 g with a total NEC for the report units being 1 g or less,
4. Any burst charge that is not black powder as defined above in point 2 would require that its time–pressure rise time[4,5] is 8 ms or greater.

Rockets tend to be transported as rocket packs within a transport carton; they can also be found within some of the larger selection packs. The rocket pack may contain rockets of the same size with different effects or a set of different sized rockets each size with different effects. The different effects within a given sized rocket may result in different total NEC. If the different NECs by effect type are known from the information provided to the UK Competent Authority then it may be possible to focus on the effect with supposed highest NEC. However, past experience has suggested that this may not always be that useful in identifying which effect has the greatest variation in NEC and hence those most likely to be over the NEC limit.

Methodology

Sampling under ISO2859-1:1999 (BS6001-1:1999)[6] relates to production inspection. The level of samples taken is determined by the lot size from the production run and ideally should be used by the manufacturer in their quality assurance programme. This level of sampling is not appropriate for surveillance sampling. A more practical sampling number was needed. The numbers chosen were in line with revised fireworks standard BS EN14035[7] in which sets of 10 fireworks articles are used for type testing.

Rockets, for example, can be considered as two basic pyrotechnic units, the rocket motor and the payload consisting of stars and burst charge or report. The payload is more easily measured as it can be removed from the rocket much more readily. Where there is clear evidence of the burst composition being a metal/oxidiser flash composition, analysis is performed by ion chromatography (perchlorate and nitrate) and inductively coupled plasma emission spectroscopy (metals, metal ions and sulphur). Similar analysis (ion chromatography) is performed for non-black powder burst charges where potassium perchlorate is the sole oxidiser or has been used in conjunction with potassium nitrate in an oxidiser/sulphur/charcoal formulation.

Where a non-black powder burst or a report charge is found the composition is tested using the HSL Flash Composition Test[8,9] (a modified UN Series 1/2 time–pressure test). The results from this test, carried out on a 0.5 g sample, regard a composition that has a rise time of less than 8 ms for a pressure rise from 690–2070 kPa as being pyrotechnic flash for classification purposes.

The rocket motor composition requires careful removal to avoid contamination with clay from the choke. There are two methods that have been used to determine rocket motor NEC, break-out and burn-out. In the break-out method this is preferably achieved by removal of all the clay with a trace amount of black powder before the black powder to be weighed is removed. Where this is not practicable due to the design of the rocket motor black powder is carefully removed until no more can be retrieved without clay contamination. To achieve removal of the pressed rocket motor composition the motor is removed from the rocket, any cardboard separated from the (usually) plastic rocket motor body and the body carefully crushed in a modified vice. Both methods (removal of clay then black powder or just removal of black powder) will slightly underestimate the amount of black powder present in the rocket motor. The alternative method, burn-out, has been shown to give almost identical results in a study at HSL. This method is considerably easier and takes the weighed rocket motor, burns the composition by igniting the fuse and reweighing after the motor cools down.

Shot tubes are generally easier to assess NEC than rockets. Comets, for example, are only lift and star. Disassembly of the article readily allows access to the lift charge and effects. If there is a bombette found rather than a comet then further disassembly will be required to access the internal compositions, and there may be a readily accessible tracer composition present. With a bombette there will be a burst charge; this is separated from any stars and weighed to ascertain if it exceeds the 5% of NEC limit. Batteries of shot tubes have the same considerations as the individual tubes and once the tubes are separated can be treated in the same way. This is also the case for Roman candles and mines.

Results

Rocket A

Rocket A was sampled as part of a surveillance programme in conjunction with Suffolk Trading Standards which ran from 2006–2008. The classification information supplied to HSE indicated that the rockets were close to the 20 g NEC limit for a UN HD 1.4G rocket under the UN default classification scheme and that the burst charge was black powder. Sampled examples had a recovered pyrotechnic content in the range 16.22–

Table 2. *Summary of rockets.*

Rocket	NEC range (g)	No. >20.0 g	t–p rise time (ms)	UN Default classification 1.4G failure mode
A	16.22–20.92	5	—	NEC over 20 g
B (2 sets of 10)	16.30–20.23	1	—	None
C	≈12	0	0.82–0.92	t–p rise time and/or composition classes the burst charge as flash – i.e. not a black powder burst plus for rocket H an NEC over 20–g
D	≈12	0	0.61–1.00	
E	15.48–16.96	0	3.18–3.46	
F	15.36–16.36	0	2.44–2.83	
G	13.85–18.71	0	2.70–3.26	
H	16.28–20.80	1	<3	
J	11.28–12.14	0	<3	
K	11.57–13.72	0	<3	
L, M, N, O, P, Q, R and S	<20	0	—	None

20.92 g and there were 5 rockets with greater than 20.0 g. Of these 3 were over 20.5 g. Analysis indicated that the burst charge was potassium nitrate, sulphur and carbon, i.e. black powder.

Rocket B

Rocket B was similarly sampled as part of the 2006–2008 surveillance programme. Again the classification information supplied to HSE indicated that the rockets were close to the 20 g NEC limit for a UN HD 1.4G rocket under the UN default classification scheme and that the burst charge was black powder. One rocket was found with an NEC of greater than 20.0 g and a second batch was sampled. This identified no further rockets with an NEC of greater than 20.0 g and again the burst charge was black powder.

Rockets C and D

Rockets C and D were sampled in 2009 as part of HSE's classification surveillance programme due to the information supplied indicating a flash powder burst charge. The recovered pyrotechnic composition indicated that the rocket NEC was well below the 20.0 g NEC limit for a UN HD 1.4G rocket under the default scheme. The burst charge was analysed and shown to be a potassium perchlorate, magnesium/aluminium composition (no check was made to ascertain if the metals were separate or as the alloy magnalium). The HSL Flash Composition Test gave a rise time in the range of 0.82–0.92 ms for Rocket C and 0.61–1.00 ms for Rocket D. For these small rockets the burst charge was less than 0.5 g and composition had to be aggregated for testing.

Rockets E, F and G

Rockets E, F and G were similarly sampled as part of HSE's classification surveillance programme due to the information supplied indicating non-black powder burst charge. The recovered pyrotechnic composition indicated that the rocket NEC was well below the 20.0 g NEC limit for a UN HD 1.4G rocket under the default scheme. The burst charges were analysed and shown to be a potassium perchlorate, potassium nitrate, sulphur and carbon composition. The HSL Flash Composition Test gave a rise time in the range of 3.18–3.46 ms for rocket E, 2.44–2.83 ms for rocket F and 2.70–3.26 ms for rocket G, all well below the 8 ms limit for a UN HD 1.4G rocket under the default scheme.

Rockets H, J and K

Rockets H, J and K were similarly sampled as part of HSE's classification surveillance programme due to the information supplied indicating a non-black powder burst charge. The recovered pyrotechnic composition indicated that the rocket NEC was well below the 20.0 g NEC limit for a UN HD 1.4G rocket under the default scheme for most examples. However, an example of a 20.80 g NEC rocket was identified. The burst charges were analysed and shown to be a potassium perchlorate, potassium nitrate, sulphur and carbon composition. The HSL Flash Composition Test gave a rise time of less than 3 ms (note insufficient material for a full set of 3 firings), all well below the 8 ms limit for a UN HD 1.4G rocket under the default scheme.

Rockets L, M, N, P, Q, R and S

Rockets L to S were sampled as part of HSE's classification surveillance programme due to having been declared as containing a flash burst. The importer had the specification changed to a black powder burst charge and HSE wanted this checked prior to allocating a UN HD 1.4G classification. Total NEC was not an issue for these rockets. Analysis indicated that the burst charge was indeed black powder.

Shot tubes and shot tube batteries

Results

Shot tube A

A set of individual shot tubes that were a comet (various colours) with an added mine effect (again various colours) were examined against the requirements for shot tubes. Of these, 3 examples exceeded the 25.0 g unit NEC limit for shot tubes. There was no burst charge within the device and hence no need for analysis of any of the compositions.

Shot tube battery B

This was a large multi-shot battery with both star and whistle units. The tube internal diameters were below 30 mm and NEC ranged from 3.32–4.94 g, well within the NEC limits for a UN HD 1.4G. However, the bombette units contained a flash burst charge and this ranged from 5.8% to 10.0% of total NEC.

Shot tube batteries C, D, E and F

These shot tube batteries were well within the limits for total NEC and diameter for all tubes examined. They did, however, contain a flash burst charge that exceeded the 5% limit of NEC. This ranged from 5.8–10.0% for shot tube battery C, 7.7–14.4% for shot tube battery D, 3.9–4.9% for shot tube battery E and 3.8–6.8% for shot tube battery F.

Mines

Results

Mine A was sampled as it had declared burst charges of silver fulminate, which seemed very unlikely. Analysis of the burst charge showed it to be a potassium perchlorate/aluminium flash. Additionally the flash constituted less than 2% of the total NEC and the total NEC was 120 g. This allowed the mine to be classified under the UN default classification scheme as a UN HD 1.4G firework.

Discussion

Rocket NEC

A protocol for acceptance for UN HD 1.4G classification has been developed. This uses sets of 10 fireworks taken at random from a transport pack. All sampled fireworks should be below the limits set within ADR and the UN default classification scheme. If all these 10 rockets were under 20.0 g then the UN HD 1.4G classification would be allowed subject to them not contravening one of the other requirements. If one rocket was found marginally over the 20.0 g limit then a second batch of ten was examined and the combined results considered by HSE. A number of rockets

Table 3. *Summary of shot tubes.*

Firework	NEC range (g)	No. >25.0 g	% flash	UN Default classification 1.4G failure mode
Shot tube A	24.44–25.54	3*	N/A	NEC over 25 g
Shot tube battery B	3.32–4.95	0	5.8–10.0	Flash >5% of total NEC
Shot tube battery C	3.32–4.94	0	5.8–10.0	Flash >5% of total NEC
Shot tube battery D	3.29–4.42	0	7.7–14.4	Flash >5% of total NEC
Shot tube battery E	4.03–4.80	0	3.9–4.9	None
Shot tube battery F	3.96–4.89	0	3.8–6.8	Flash >5% of total NEC

* Batch of 5 samples provided, level of non-compliance was such that an additional set of 5 was not requested to make up to the normal set of 10.

that were over the 20 g limit were found (Rockets A, B and H); of these B was allowed a UN HD 1.4G as only one rocket in 20 was marginally over the limit and this was accepted as a "rogue".

Rocket burst charge

The UN default classification scheme does not allow for a flash burst charge in a UN HD 1.4G rocket. Similarly, a non-black powder burst (i.e. a composition that is not potassium nitrate, sulphur and carbon) is not allowed if the HSL Flash Composition Test gave a rise time of <8.0 ms. Rockets that had a burst charge that was not black powder and had a t–p rise time of <8 ms were found (rockets C and D, E, F, G, H, J and K failed). Clearly from these limited surveillance results there are a large proportion of rockets being supplied in the UK where the burst charge is not black powder.

Shot tube NEC

Small diameter shot tube batteries have not been found to exceed the NEC limit within the UN default classification scheme. The only large diameter (i.e. approaching 30 mm) items examined for classification purposes were shot tubes with mine effect, having both a large comet and a bag of small stars with a lift charge under the effects. However, the payload NEC was pushed over the 25 g limit by the added mine effect precluding a UN HD 1.4G classification under the default scheme.

Shot tube percentage flash

By far the greatest problem with shot tubes was from bombettes that had a flash burst charge. The UN default scheme sets a 5% limit on the proportion of pyrotechnic composition that can be a flash burst charge in any tube. The bulk of the shot tube batteries that failed to achieve the UN HD 1.4G classification were due to these flash burst charges. This is clearly a concern to importers as such items are now a major element in selection packs and display packs. The smaller items with low total NEC are the more likely to fail to meet this UN default criterion than larger items with a higher total NEC. The importers are free to undertake UN Series 6 testing on these smaller batteries with the possibility of attaining a UN HD 1.4G classification by this route. Results from suitable examples could then provide evidence for classification by analogy for other examples with similar tube size, similar effects, percentage flash composition and NEC.

Misleading information

Information provided by the importer of a mine initially indicated that the composition contained potassium perchlorate and silver. When this was questioned the importer contacted his Chinese supplier who then declared the composition as containing silver fulminate. Analysis showed the composition to be a perchlorate/aluminium flash composition, thus the originally declared silver metal was aluminium. As all the tubes tested had the flash burst at less than the limit of 5%, the properly declared flash burst charge would have generated a UN HD 1.4G under the UN default scheme. This incident does raise concerns regarding the declared compositions which may suggest that surveillance of product should be carried out by the importers.

Conclusions

The surveillance reported has found a number of items that do not comply with the requirements of the UN default classification scheme. Clearly it is of legal importance that such surveillance be carried out to maintain safety in transport of fireworks. Many of the fireworks examined have complied with the requirements of the UN default classification scheme for a UN HD 1.4G hazard code assignment. Where fireworks have failed to meet the criteria the problems of non-black powder burst charges and total NEC have predominated. This paper has dealt with the surveillance of fireworks where classification was sought through the use of the UN default table. There remains the alternative option for importers to suggest a classification based on actual performance of the products in UN Series 6 tests.

Disclaimer

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Quality Control Testing Of Pyrotechnic Articles For The Beijing 2008 Olympic Games

Andrew Tang, BSc, MPhil, CChem, FRSC
Tian Cheng Pyrotechnics Laboratory, Liuyang, Hunan, China
Email: atang@tcpyrolab.org, web: www.tcpyrolab.org

Abstract: *Firework displays are commonly used to celebrate special events. They have been used in Olympic Games opening and closing ceremonies for years. During the 29th Olympic Games – Beijing 2008 Olympic Games Opening and Closing Ceremonies, firework displays were therefore used as part of the program. Due to the Chinese traditional culture and the demands of the location, the technical director demanded special requirements of all pyrotechnic articles. A working committee of the Beijing 2008 Olympic Games Opening and Closing Ceremony had been created to develop the main four firework display shows that were part of the opening and closing ceremonies of the Olympic Games and Paralympic Games. To ensure all pyrotechnic articles performed safely and as intended, technical guidance was developed for the control of all pyrotechnics used in the event. It specified the terms, product type, product classification, safety quality requirements, testing methods and acceptance criteria for testing and inspection of pyrotechnic articles used in the 29th Olympic Games. The technical document was used for the first time and referred to many GB Standards (Guo Biao Standards – China National Standards). This paper describes the requirements and control programs for all pyrotechnic articles from design, manufacturing, transportation and usage.*

Introduction

Fireworks have been used in celebration of great events around the world for many years. Similarly there are many years of experience using fireworks to celebrate national events in China, such as the China National Day on October 1, the Chinese Lunar New Year, Fireworks Festivals, local and private ceremonial celebrations or graduation etc. Usually fireworks or pyrotechnic articles are directly sourced from manufacturers by the display organization or company. The quality of fireworks or pyrotechnic articles solely or mainly relies on the internal quality control of the manufacturer and/or with the addition of experience of display personnel. Since fireworks and pyrotechnic articles are still, in the majority, dependent on labor intensive manufacturing processes, there is always the potential excuse of fireworks not being properly made or containing natural defects.

Since the announcement of the hosting of the Olympic Games 2008 in Beijing, the organizing committee started to investigate the best possible ways and means to perform an excellent firework display show during the Opening and Closing ceremonies of the Beijing 2008 Olympic Games. It was not as simple as having a performance oriented pyro-display but there was also a higher safety requirement because the sites were large and near to the audience. In addition, those places were important and historical scenes themselves. It was not possible to adopt normal practices to prohibit the audience from going into the venues.

With a lack of experience in shooting so many pyrotechnic articles within such large areas and time, quality in terms of performance and safety was critically important to ensure excellence of both. Therefore the Committee demanded and the working committee developed the first of its kind of quality control testing of pyrotechnic articles – *Acceptance of Inspection Criteria for Pyrotechnics used in Olympic Games*,[1] and started the trial in 2007. All the pyrotechnic articles were selected,

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modified, manufactured and tested according to the planned design, then completed and passed the test inspection prior to transport to Beijing for the Olympic Games 2008 in August.

Standard reference

Due to the lack of such large scale display experience and the complex pattern designed, most of the pyrotechnic articles were newly developed or modified to suit the purpose. These included smokeless formulation, red color enhancement, new shooting techniques, construction techniques and manufacturing processes, etc. All such processes and products demanded a high level of quality testing and inspection. The whole quality control adopted a cradle-to-grave approach to ensure all manufactured articles were made to design, packed to transport, set to shoot, recorded and any found to be defective were destroyed.

The following key Chinese national standards[2] were adopted during the quality control processes:

GB/T2828.1: Sampling Procedures for Inspection by Attributes Part 1: Sampling schemes indexed by Acceptable Quality Limit (AQL) for batch-by-batch inspection

GB10631: Fireworks and Firecrackers – Safety and Quality

GB/T10632: Fireworks and Firecrackers – Rules of Sampling Inspection

GB/T15814.1: Fireworks and Firecrackers, Chemical Composition – Qualitative Determination of composition

GB19593: Fireworks and Firecrackers – Batteries and Combination

GB19595: Fireworks and Firecrackers – Fuses

GB/T20613: Fireworks and Firecrackers – Rules of Safety Performance Inspection for Storage and Transportation

NY/T757: Propellant Charge used in Fireworks

QB/T1941.5: Fireworks and Firecrackers, Chemical Composition – The determination of moisture absorption

SN0545-1996: Rules of Safety Inspection for pyrotechnic reagent of exporting fireworks and firecrackers

Discussion

The Quality Control Testing (QCT) is the first of its kind in the Fireworks Industry using systematic testing and inspection tools controlling the manufacture of the pyrotechnic articles used in such a great event. It is a big change and a big step towards quality control management for sourcing fireworks in China.

The QCT adopts different techniques and methods in controlling the processes of sourcing raw materials, designing items, manufacturing, packaging and transportation. These were all developed into a special set of requirements for fireworks used specially for the great event of the Beijing 2008 Olympic Games, DB11/Z 525 – 2008 *Acceptance of Inspection Criteria for Pyrotechnics used in Olympic Games.* The criteria are summarized and listed as below.

Labeling

The label includes external packing marking, product marking and special effect marking. All content must be in standard Chinese, clear, precise and legible. Labels for transportation packing should include the product name, product code, specification, type and classification, factory name and display company, address, telephone, production date, expiry date, content, net explosive content, volume, tracking number and wording of safety warning.

Packing

The product shall be packed in an inner packing poly bag for whistling composition, black powder or smoke composition. It should be damp proof material. Combination products and fountains should be sealed by a tin-fold sheet. Outer packing should use standard shipment corrugated boxes.

Appearance

Outer packing should be artistic, intact, not deformed or damaged. There should be no loose chemical composition or signs of mold/ contamination.

Design of ignition

The method of ignition could be an ignition fuse that complies with the requirements of GB19595

Table 1. *Bursting height of shells*

Item	Specification of shell							
	Size #3	Size #4	Size #5	Size #6	Size #7	Size #8	Size #10	Size #12
Shell diameter, mm	72	97	122	147	172	196	246	296
Shell tolerance, mm	+1, −2	+1, −2	+1, −2	+1, −3	+1, −3	+1, −4	+1, −4	+1, −4
Bursting height, m (min.)	80	90	110	130	170	200	240	300
Extinguished height, m (min.)	50	50	50	50	50	50	50	50
Fuse length, mm	650	750	1000	1100	1200	1400	1500	1600
Tolerance, mm	±20	±20	±20	±20	±20	±20	±20	±20

or an electric ignition head as recommended by the working committee. For both the firing ratio should be 100%.

Construction and dimensions of main component

The construction of the main component and its effect must be manufactured in accordance with the design. The dimensions must follow the design diagram. No metal or plastic is allowed for any aerial effects. No electric igniter may be installed but a propellant charge can be filled.

Construction and dimensions of auxiliary parts

The construction of auxiliary parts must be accordance with the design. Connection to the main component must support 100 grams weight for at least 1 minute. The should be no loosening or detaching during functioning.

Stability

The relevant articles should be stable during a 12 degree tilt testing and functioning, while auxiliary articles shall be subject to 30 degree tilt block testing.

Chemical composition

The chemical composition should comply with the design and should use no prohibited chemicals such as chlorate, arsenics, mercuric, gallic acid, magnesium powder, phosphorus, lead compounds and hexachlorobenzene (HCB).[3] Propellant charges must meet the requirements of NY/T 757. Standard methods and requirements refer to SN0545 and GB/T15814.1.

Net explosive content

The net explosive content must be in accordance with the design and requirements of class B & C of GB10631. The content does not include fuse and filler but must be marked.

Performance

The geometric figure, effect and shooting declination angle must be manufactured in accordance with the design. It must function at a designated height with no premature burst, and no sharp debris. Waterfalls, shells, mines, roman candles and combinations must comply with the requirements of GB10631. Smokeless items must obviously produce less smoke than regular items. An example of the specification of shells[4] is listed in Table 1.

Safety requirement

Some parameters were selected to be tested during production and these were mainly concerned with safety of handling and transportation, such as the thermal stability test which is set at 75 °C, the moisture absorption test[5] and 12 metre drop test.[6]

Acceptance criteria

After manufacturing and before loading into containers for transportation to Beijing, all products were subject to batch testing and inspection based on the sampling criteria according to the type and size of the articles. The sampling plan basically followed GB/T2828.1[7] and was modified to suit the specific needs of the event. The basic sampling plan is listed in Table 2. It required a sample size twice the basic sample size plus 3 cases more. All types of defect are clearly indicated with their acceptable levels.

The defect type (see Table 4) is also clearly defined

Table 2. *Basic sample size of pyrotechnic articles.*

Batch size, *N*	≤100	1 01–500	501–1000	≥1001
Sample size, *n*	10	10 + *N* × 2%	20 + *N* × 1%	30 + *N* × 0.2%

Note: The basic unit for waterfalls is a single item.

Table 3. *Rejection quantity according to batch size.*

Sample size, *N*	Defect classification									
	a		b1		b2		c1		c2	
	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re
≤100	0	1	0	1	0	1	1	2	1	2
101–500			0	1	1	2	2	3	3	4
501–1000			1	2	2	3	3	4	5	6
≥1001			2	3	3	4	5	6	7	8

in terms of its nature and acceptable levels, see Table 3.

Technical information

Suppliers or manufacturers must provide technical information to ensure the product and information match and are correct. This information includes (1) Construction diagram of the product and the effect components; (2) Pyrotechnic content and (3) Performance effect. The construction diagram shall include all product information such as product name, product code, specification model number, type, classification, total pyrotechnic content, supplier's name and address, structure of the fixture and its assembly, etc. If the product is a shell, a mortar[9] shall be provided together with material, dimensions of mortar, production date, and test report. The pyrotechnic content of the article shall be clearly and precisely stated in the information with its formulation. The performance effect shall include a video file of the article, performance time, method and time of ignition, bursting height, angle of trajectory if any, geometric pattern, color, effect of smoke and other instructions.

Figure 1. *Shooting 5 rings in the air.*

Conclusion

After years of experience, pyrotechnic articles used on different occasions of celebration are usually subject to loading inspection or simple shooting tests. It mainly relies on the internal quality control system that is implemented by the manufacturer, and sometimes on the quality demands from suppliers or buyers. The QCT is the first of its kind to have a complete and comprehensive quality control system enforced in the production of pyrotechnic articles in China, and probably in the world. Thus it is confirmed that through QCT, the challenging task of providing a perfectly safe and impressive display of pyrotechnic articles during the show at the Beijing 2008 Olympic Games can be successful.

Table 4. *Type of defects.*

No.	Inspection item	Defect descriptions	Defect Type
1	Label	No outside packing mark, no product label and no inner tube element label	a2
		The label is not tidy; the content of the label is not clear, covered or damaged.	c1
2	Packing	No inner packing. Whistling, black powder and smoke firework products should be confined in a poly bag; the combination and fountain products should be sealed with a tinfoil sheet; roman candles should be packed with a plastic cover; other pyrotechnic products should be packed with waterproofed plastic sheet or cardboard. The inner product is not placed properly, becomes loose and moves around.	a2
		The outside packing should be made of proper cardboard and sealed very firmly; the net weight not more than 30 kg. The strength or the waterproof resistance is not enough.	c1
3	Appearance	The product is not complete, is deformed or damaged. The tube and attachment are not stuck very firmly, or split and loose.	b1
		The tube paper is not stuck very neatly, is covered or exposed. The product is not tidy, the pyrotechnics is loose, moldy or damaged.	c2
4	Fuse and electric igniter	The ignition method and the connection method of each element of the effect does not comply with the design. The ignition head is not complete. No waterproof materials. It is damaged and does not function. There is no backup fuse for the combinations.	a2
		There is no electric ignition and fuse ignition method in the leading fuse location.	a2
		The fuse is moldy, damaged and blank.	b1
		The ignition fuse is not visible or has no protective cover.	c1
		It is not firmly assembled.	c1
5	Construction and dimension of main component	The product body and the effect element structure: size does not comply with the design. Metal materials and attachments should not be used in the lift product. It is not filled with propellant charge as per the design. The manufacturer installs the ignition head in the pyrotechnic product in advance. The fuse is not firmly installed and well connected; There is only 1 fuse cord for the shells of size over 5.	a1
		The variation of the propellant tube, inner diameter and the tube thickness for the lift product does not comply with the design.	b1
		The variation of the length, exterior diameter of the non-lift product does not comply with the design.	c2
6	Construction and dimension of auxiliary component	The attachment structure and size do not comply with the design. The attachment is not installed very firmly. The attachment becomes loose or detached during the display process.	a1
7	Fixture	The strength of the fixture is not sufficient. Under the circumstances of blowout and low breaking, the fixture may cause secondary damage.	a1
		The installation and dismantling is not convenient.	c2
8	Stability	The stability of the product is insufficient.	a2
9	Chemicals	Prohibited chemicals used in the product.	a1
		The pyrotechnic composition is not in accordance with the design.	a1
10	Net explosive content	The chemical content does not comply with the design and product label.	a1
		The chemical content of the propellant charge and the shells is different from the design.	b1
		The chemical content of the effect charge is different from the design.	c2

Table 4. *Contd.*

11	Performance	The product performance is different from the design.	a1
		The ignition method and ignition time are different from the design.	
		The geometric figure formed during the functioning process does not comply with the design.	
		The effect color is different from the design.	
		The firing sequence of each effect element is different from the design. For the elements which have several effects, the effect sequence does not comply with the design.	
		The product is blasting out and becomes loose during functioning.	
		Low break, burning or sharp debris of big mass is not allowed. Meanwhile, the attachment should not become detached at the designed time.	
		A smoke product should have smoke effects.	
		The 29th Olympic Games product with special requirements should meet the special requirements during the functioning.	
		The shell does not function or is dud. The explosion radius should not exceed the explosion height; the extinguished height should be lower than the standard figure.	
		The combinations become flameout.	
		The firing ratio, burning ratio and projection height for the shells, combinations and fountains is different from the acceptance criterion. The burning ratio of other pyrotechnics should comply with the requirements in GB 10631.	
		The projectile declination angle of the shells, combinations and fountains is different from the video documentations provided by the manufacturer.	b1
		The geometric figure formed during the functioning process is not clear and visible. It is defective and incomplete.	c2
		The purity of the effect color is not good.	
12	Safety function	The thermal conditioning, drop test and the moisture absorption ratio are not in accordance with the requirements.	a1

Figure 2. *"FUTURE" shoots into the air.*

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fax: +1-727-367-1407
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web: http://www.alliedspeciality.com

American Fireworks News
Jack Drewes
HC 67 Box 30
Dingmans Ferry, PA 18328, USA
phone: +1-570-828-8417
fax: +1-570-828-8695
email: afn@fireworksnews.com
web: http://www.fireworksnews.com

American Pyrotechnics Association
Julie Heckman
4808 Moorland Lane - Ste 109
Bethusda, MD 20814, USA
phone: +1-301-907-8181
fax: +1-301-907-9148
email: jheckman@americanpyro.com
web: http://www.americanpyro.com

Canadian Explosives Research Laboratory
Dr Phil Lightfoot, Manager
CANMET - 555 Booth St.
Ottawa, ON K1A 0G1, Canada
phone: +1-613-947-7533
fax: +1-613-995-1230
email: plightfo@nrcan.gc.ca
web: http://www.nrcan.gc.ca/mms/cerl

Combined Specialities International Inc.
John & Alice Allen
8362 Tamarack Village, Ste. 119
Woodbury, MN 55125, USA
phone: +1-651-855-0091
fax: +1-651-855-0088
email: jallen@combinedspecialities.com

Davas Ltd
Tom Smith
8 Aragon Place, Kimbolton, Huntingdon
Cambs. UK. PE28 0JD
phone: +44 1480 860124
fax: +44 1480 861125
email: toms@davas.co.uk
web: http://www.davas.co.uk

Daveyfire, Inc.
Alan Broca
2121 N California Blvd. Ste. 290
Walnut Creek, CA 94596, USA
phone: +1-925-926-6414
fax: +1-925-926-6439
email: info@daveyfire.com

European Pyrotechnic Arts Newsletter
Rob Driessen
Grenadierweg 55
Riemst, B 3770, Belgium
phone: +32-12-210-630
fax: +32-12-210-630
email: epan@pandora.be
web: htp://users.pandora.be/epan

Fire One
Dan Barker
863 Benner Pike
State College, PA 16801, USA
phone: +1-814-238-5334
fax: +1-814-231-0799
email: info@fireone.com
web: http://www.fireone.com

Firework Professionals
Anthony Leyland
PO Box 19-912
Christchurch, 8030, New Zealand
phone: +64-3-982-3473
fax: +64-3-982-3474
email: firework@firework.co.nz
web: http://firework.co.nz

Fireworks
PO Box 40
Bexhill, Sussex TN40 1GX, England
phone: +44-1424-733-050
fax: +44-1424-733-050
email: editor@fireworks-mag.org
web: http://www.fireworks-mag.org

Fireworks and Stage FX America
Joseph R. Bartolotta
PO Box 488
Lakeside, CA 92040, USA
phone: +1-619-938-8277
fax: +1-619-938-8273
email: info@fireworksamerica.com
web: http://www.fireworksamerica.com

Fireworks Business
Jack Drewes
HC 67 Box 30
Dingmans Ferry, PA 18328, USA
phone: +1-717-828-8417
fax: +1-717-828-8695
email: afn@fireworksnews.com
web: http://www.fireworksnews.com

Fireworks by Grucci
Phil Grucci
1 Grucci Lane
Brookhaven, NY 11719, USA
phone: +1-631-286-0088
fax: +1-631-286-9036
email: philgrucci@aol.com
web: http://www.grucci.com

Fullam's Fireworks Inc
Rick Fullam
PO Box 1808 CVSR
Moab, UT 84532, USA
phone: +1-435-259-2666
email: rfullam_3@yahoo.com

Goex Inc.
Donald McDonald
PO Box 659
Doyline, LA 71023, USA
phone: +1-318-382-9300
fax: +1-318-382-9303
email: email@goexpowder.com
web: http://www.goexpowder.com

Lantis Fireworks & Lasers
Ken Lantis
PO Box 491
Draper, UT 84020, USA
phone: +1-801-768-2255
fax: +1-801-768-2433
email: info@fireworks-lasers.com
web: http://www.fiireworks-lasers.com

MagicFire Inc
Paul McKinley
PO Box 896
Natick, MA 01760, USA
phone: +1-508-647-9645
fax: +1-508-647-9646
email: pyrotech@magicfire.com
web: http://www.magicfire.com

Martin-Baker Aircraft Ltd
David Chapman
Lower Rd, Higher Denham
Uxbridge, Middlesex UB9 5AJ
Great Britain
Phone: +44-1895-836-644
FAX: +44-1985-836-686
email: dchapman@martin-baker.co.uk
web: www.martin-baker.com

Martinez Specialities
Phil Martinez
208 Bossard Rd
Groton, NY 13073, USA
phone: +1-607-898-3053
fax: +1-607-898-3952
email: mr.squib@clarityconnect.com

Maratamaya Ogatsu Fireworks Co. Ltd.
1-35-35 Oshitate Fuchu
Tokyo, 183-0012, Japan
phone: +81 42-363-6251
fax: +81-42-363-6252
email: hanabi@mof.co.jp
web: http://www.mof.co.jp

MP Associates Inc.
PO Box 546
Ione, CA 94640, USA
phone: +1-209-274-4715
fax: +1-209-274-4843

Nitrotech Australia Pty. Ltd.
Chris Larkin
PO Box 349
Mount Isa, QLD 4825, Australia
phone: +1-617-47-44-2290
fax: +1-617-47-44-3998
email: nitrotech@smartchat.net.au

Precocious Pyrotechnics Inc.
Garry Hanson
4420 278th Ave NW
Belgrade, MN 56312, USA
phone: +1-320-346-2201
fax: +1-320-346-2403
email: ppinc@tds.net
web: http://www.pyro-pro.com

Pyro Shows Inc.
Lansden Hill
PO Box 1406
LaFollette, TN 37766, USA
phone: +1-800-662-1331
fax: +1-423-562-9171
email: info@pyroshows.com
web: http://pyroshows.com

Pyrodigital Consultants
Ken Nixon
1074 Wranglers Trail
Pebble Beach, CA 93953, USA
phone: +1-831-375-9489
fax: +1-831-375-5255
email: pyrodig@aol.com
web: http://www.infinityvisions.com/pyrodigital

PyroLabs Inc.
Ken Kosanke
1775 Blair Road
Whitewater, CO 81527, USA
phone: +1-970-245-0692
fax: +1-970-245-0692
email: ken@jpyro.com

RCS Rocket Motor Components Inc.
Gary Rosenfield
2113 W 850 N St
Cedar City, UT 84720, USA
phone: +1-435-865-7100
fax: +1-435-865-7120
email: garyr@powernet.net
web: http://www.rocketmotorparts.com

RES Speciality Pyrotechnics
Steve Coman
21595 286th St
Belle Plaine, MN 56011, USA
phone: +1-952-873-3113
fax: +1-952-873-2859
email: respyro@earthlink.net
web: http://www.respyro.com

Rozzi Famous Fireworks
Arthur Rozzi
PO Box 5
Loveland, OH 45140, USA
phone: +1-513-683-0620
fax: +1-513-683-2043
email: art@rozzifireworks.com
web: http://www.rozzifireworks.com

Service Chemical Inc.
Ben Cutler
2651 Penn Avenue
Hatfield, PA 19440, USA
phone: +1-215-362-0411
fax: +1-215-362-2578
email: ben@servicechemical.com
web: http://www.servicechemical.com

Spirit of 76 Fireworks
John Bechtold
6401 West Highway 40
Columbia, MO 65202, USA
phone: +1-573-477-1776
fax: +1-573-477-1786
email: marketing@76wholesale.com
web: http://www.76wholesale.com

Starburst Pyrotechnics & Fireworks Displays Ltd
Bonnie Pon
2nd Fl-Sui Hing Hong Bldg-17, Commissioner St
Johannesburg, Gauteng 2000, South Africa
phone: +27-11-838-7705
fax: +27-11-836-6836
email: info@starburstpyro.co.za
web: http://www.starburstpyro.co.za

Weeth and Associates
Charlie Weeth
122 S 17th St
LaCrosse, WI 54601, USA
phone: +1-608-784-3212
fax: +1-608-782-2822
email: czweeth@pyro-pages.com
web: http://www.pyro-pages.com

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