Pyrotechnic Literature Series No. 10

Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 6 (2001 and 2002)

Table of Contents — Part 6

An earlier version appeared in *Fireworks Business*, No. 204, 2001.

Fire Sculptures Using FireRope

K. L. and B. J. Kosanke

Fire sculptures are not a true pyrotechnic effect, being produced simply by the burning of a liquid fuel in air. Nonetheless their use can contribute rather nicely to firework displays that include ground effects. Fire sculptures form continuous images in yellow fire that burn for 10 minutes or more. This is in contrast to lance work images, created using a series of points of variously colored fire that burn for about a minute.[1] As with lance work, it is probably more common for fire sculptures to form images of objects, ships or buildings, than lettering such as in the (self-serving) example below.

Fire sculptures, while relatively common in England[2] and Australia, are virtually unknown in the U.S. Presumably this reflects more of a difference in heritage rather than taste. However, perhaps another reason is the general unavailability of effective materials with which to assemble fire sculptures. One convenient material is called FireRope, a product that makes fire sculptures quite easy to produce. (Advanced Pyrotechnics, the Australian manufacturer of FireRope, is apparently seeking to export FireRope to the U.S.[3])

FireRope is available in 50-meter (160-foot) coils, is approximately one inch in diameter, and is made mostly of compressed absorbent paper. It holds its shape because of a central wire for stiffening, and it has an external wrap of strong thread to hold it together. In addition to its normal configuration, it is also available with an outer sleeve of thin plastic. This provides a significant degree of weather protection while also acting to retard loss of liquid fuel by evaporation during the time prior to its firing.

The thin plastic sleeve proved quite effective for the example shown in Figure 1. The fire sculpture was erected on a sunny and pleasant November afternoon. However, because of the unpredictability of late fall weather in western Colorado, it was constructed using the plastic sleeved FireRope. This proved to be a good thing, because before it could be fueled and ignited that same evening, a heavy wet snow started to fall. After two days, the weather cleared and the now solidly frozen snow could simply be broken off leaving the fire sculpture in perfect condition.

Fire sculptures are made by simply forming the FireRope into the shape of the image to be created (in this case, forming the letters for "JPyro", the abbreviation of the Journal of Pyrotechnics) and attaching them to a fire resistant

Figure 1. An example of a fire sculpture using FireRope.

frame. This is conveniently accomplished using the same twist ties often used to close plastic bags. Prior to igniting, the FireRope is thoroughly soaked with fuel, typically diesel fuel or kerosene. For the 1-½ by 4-foot "JPyro" example, the 1-½ quarts of fuel was quickly loaded into the plastic sleeving of the FireRope from used (empty) mustard dispensers. In cases where the non-sleeved FireRope is used the fuel can be applied directly to the FireRope, using a suitably sized dispenser.

Using diesel fuel or kerosene obviously produces an opaque yellow flame. However, one experiment was conducted using methanol applied to non-sleeved FireRope, to determine whether a mostly colorless (transparent light blue) flame would be produced. During the early period of the burning, the flame was sufficiently colorless to suggest that a suitable colorant could be added to produce a non-yellow colored flame.[4] However, the duration of the flame effect was only about 5 minutes and, when the methanol was mostly consumed, the flame gradually turned increasingly yellow.

The authors gratefully acknowledge Jack Moeller, of Advanced Pyrotechnics, for providing free samples of FireRope. Thanks also to G. Barchenger for supplying the frame (metal mesh) used in these tests. Finally, the authors wish to acknowledge John Bennett, publisher of *Fireworks*, for providing the references to fire sculptures produced in the UK.

References

1) B. J. and K. L. Kosanke, "Lance Work: Pictures in Fire", *Pyrotechnica*, No. XV, 1993; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996.

2) Various articles appearing in *Fireworks* mention the use of fire sculptures; Issue 36, p 10; Issue 29, p 16; Issue 25, p 6; Issue 24, pp 9 and 38; Issue 23, p 22; and Issue 17, p 24.

3) Jack Moeller, Advanced Pyrotechnics, 3/21 Church St., Abbotsford, Victoria, Australia; e-mail address, pyrohead@onthe.net.au.

4) C. Jennings-White and S. Wilson, "Lithium, Boron and Calcium", *Pyrotechnica*, No. XVII, 1997.

An earlier version appeared in *Fireworks Business*, No. 206, 2001.

Electric Matches: Physical Parameters

K. L. and B. J. Kosanke

Introduction

A major study of electric match sensitiveness was recently completed.[1] This article continues that work and presents a compilation of the physical parameters (as measured and/or provided by the suppliers) for the same collection of 10 electric match types as in the previous article.

Nominal Tip and Shroud Size

For each electric match type, five matches were selected at random, and their dimensions (maximum thickness, width, and length) were measured using a caliper. However, because of the limited number of matches measured and because of the variability in the size of the electric match tips, the averages of these values are only reported to the nearest 0.01 inch in Table 1. For those electric match types provided or available with shrouds, the measured diameter and length of those shrouds are also reported.

The size of the electric match tips fall roughly into three groups. The largest tips are the Aero Pyro, all three Daveyfires, the Luna Tech OXRAL, and the Martinez Specialty E-Max and Titan electric matches. Slightly smaller are the Luna Tech BGZD and Flash electric matches. Smaller still are the Martinez Specialty E-Max Mini electric matches. While the lengths of the shrouds (where provided by the supplier) varied, all but one had a diameter of approximately 1/4 inch. A smaller shroud, a little less than 3/16 inch is available for the Martinez Specialty E-Max Mini electric matches.

Table 1. Average Electric Match and Shroud Dimensions.

Supplier Name	Product Designation	Tip Dimensions (in.)[(a)]			Shroud Dimensions (in.)	
		Thick.	Width	Length	Diameter	Length
Aero Pyro		0.13	0.16	0.50	n/p	n/p
Daveyfire	A/N 28 B	0.11	0.14	0.46	0.24	0.71
	A/N 28 BR	0.13	0.15	0.50	0.24	0.71
	A/N 28 F	0.11	0.14	0.47	0.24	0.71
Luna Tech	BGZD	0.10	0.13	0.47	n/p	n/p
	Flash	0.10	0.13	0.45	n/p	n/p
	OXRAL	0.09	0.19	0.42	0.25	1.03
Martinez Specialties	E-Max	0.09	0.15	0.46	0.22[(b)]	0.60
	E-Max-Mini	0.08	0.11	0.34	0.16[(c)]	0.61
	Titan	0.11	0.15	0.45	0.22[(b)]	0.60

"n/p" means the electric match was "not provided" with a shroud from the supplier.

(a) Electric match tip size is the average of measurements made on 5 tips and is reported to the nearest 0.01 inch.

(b) This shroud is a short length of soft rubber (plastic) tubing. The stated diameter (0.22 inch) is that of the tubing before the electric match is inserted. Upon insertion of the electric match, the tubing takes a somewhat oval shape with the minor and major diameters of 0.22 and 0.26 inch, respectively.

(c) This shroud is a short length of soft rubber (plastic) tubing. The stated diameter (0.16 inch) is that of the tubing before the electric match is inserted. Upon insertion of the electric match, the tubing takes a somewhat oval shape with the minor and major diameters of 0.16 and 0.17 inch, respectively.

Composition Mass and Bridgewire Configuration

The mass of composition, including the protective coating, was determined for the electric match types. This was accomplished by selecting a single, typical match tip, weighing it, soaking the match tip in acetone and agitating until all of the composition was removed, and then reweighing the match tip after drying. The composition mass results are listed in Table 2. Because only a single electric match tip of each type was examined, it was felt to be appropriate to report the results to only one significant figure.

Table 2. Electric Match Composition Mass and Tip Design.

Supplier Name	Product Designation	Comp. Mass (mg)[(a)]	Tip Type[(b)]
Aero Pyro		80	1
Daveyfire	A/N 28 B	40	1
	A/N 28 BR	80	1
	A/N 28 F	80	1
Luna Tech	BGZD	10	1
	Flash	20	1
	OXRAL	40	3
Martinez Sp.	E-Max	20	2
	E-Max-Mini	6	1
	Titan	20	2

For conversion to English units, 1 grain equals 65 mg.

(a) Composition mass was determined for only one electric match tip and is reported to only one significant figure.

(b) Tip types 1, 2 and 3 are illustrated in Figure 1.

Three basic bridgewire configurations were found for the electric match tips. The numbers indicating the three configurations are designated in Table 2 and correspond to the numbers in the three illustrations in Figure 1. Figure 2 is a series of electron micrographs of the three bridgewire types. In Types 1 and 2, the bridgewire is soldered to the copper cladding. In Type 2, a small portion of the end of the electric match tip has been removed by milling, prior to the addition of the bridgewire. In Type 3, the bridgewire is held (crimped) under a fold of two brass support posts.

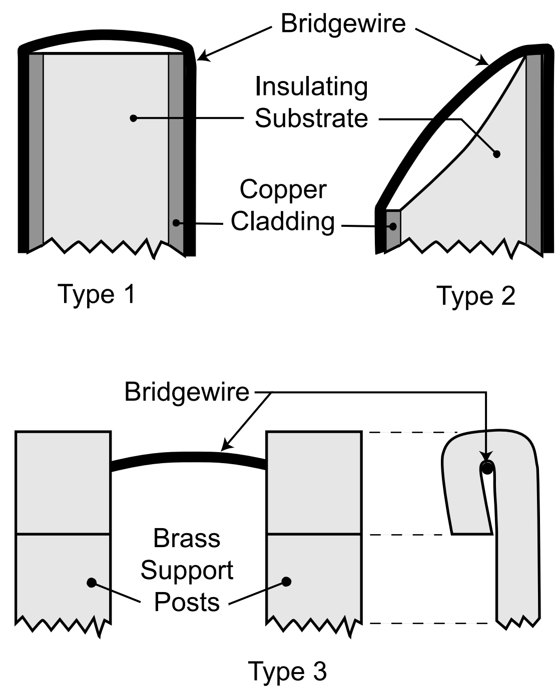


Figure 1. Illustrations of the basic bridgewire configurations of three styles of electric matches (not to scale). Types 1 and 2 are side views shown in cross section; type 3 is shown in both a frontal and a side view.

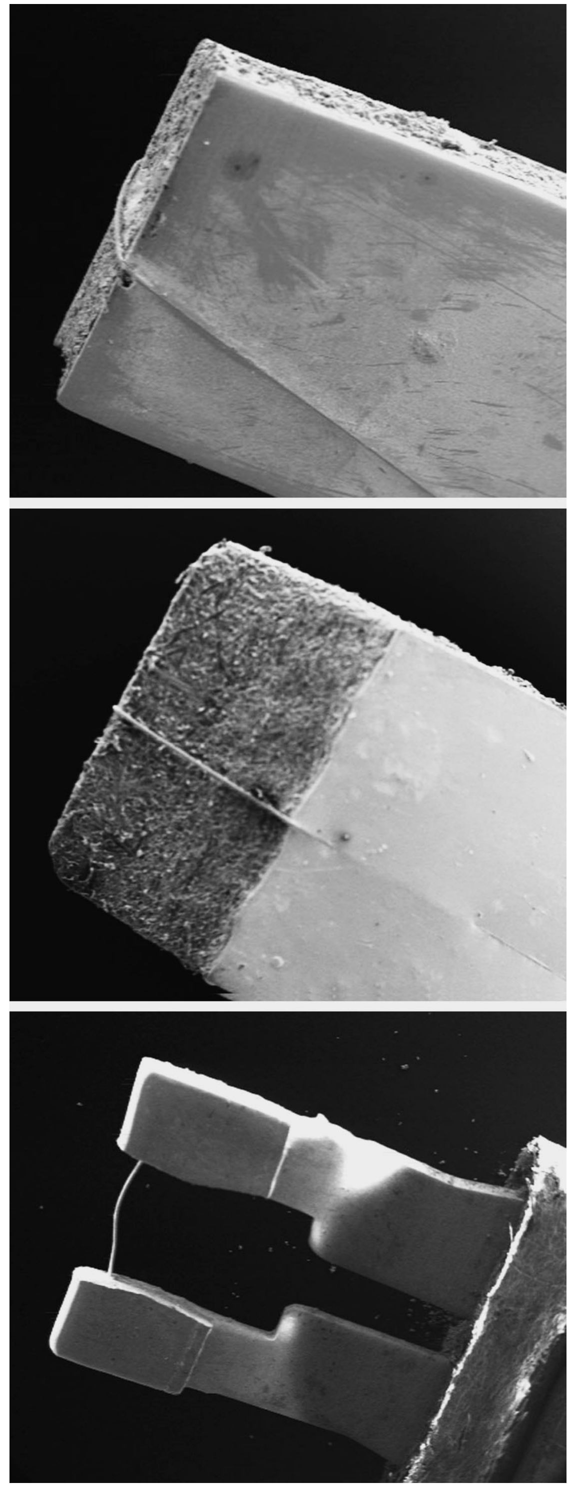
While the amount of composition on electric match tips is potentially related to its ability to produce ignitions, often it is not a good indicator. This is because there can be large differences in the density and effectiveness of the various compositions. Further, it is thought that the configuration of the electric matches (Types 1, 2, or 3) has little if any bearing on their performance. Information on the electric match's ability to produce ignitions will be presented in a subsequent article.

Electrical Parameters

Resistance measurements were made on a collection of 10 match tips, each with 5-inch leg wires attached tightly to the measuring instrument. The instrument used produced results to 0.1 ohm, was nulled for 0.0 ohm and produced a correct reading for a 1.00-ohm NBS calibrated resistance. The results of these resistance measurements are reported in Table 3. The suppliers were asked for information about the no-fire, all-fire, and recommended firing currents for their electric matches. Where provided, these data are also presented in Table 3, along with notes giving additional or qualifying information.

Most often, electric match tip resistance is of little concern; however, an exception is when many matches are to be fired in a series circuit. In that case, for electric matches requiring approximately the same firing current, the higher the individual match resistance, the fewer matches that can be reliably fired with a given firing unit (firing voltage). The lowest electric match resistances (0.9 to 1.2 ohms) were found for the Aero Pyro, Luna Tech Flash, and Martinez Specialty E-Max Mini matches. The next higher resistances (1.6 to 1.7 ohms) were found for all three of the Daveyfire and the Luna Tech BGZD and OXRAL matches. The highest resistances (2.5 to 2.7 ohms) were found for the Martinez Specialty E-Max and Titan matches, which are the two types of electric match tips that were milled (Type 2).

In a subsequent article, one discussing the performance of the various electric matches, more information will be presented on their firing characteristics. Nonetheless, it is worth mentioning that the suppliers' recommended firing currents fall into two groups. One group (firing currents of 0.5 to 1.0 ampere) includes most of the matches; the other group (firing currents of 2.0 to 3.5 amperes) consists of the Daveyfire A/N 28 F, the Luna Tech Flash and the Martinez Specialty Titan matches. Note that in the previous article,[1] these were the three electric match types that tended to be significantly less sensitive to ignition by impact, friction and electrostatic discharge. This serves to illustrate that it is generally true that pyrotechnic materials that are less sensitive to accidental ignition also tend to be less easy to ignite intentionally.



Electron micrographs of the three electric match bridgewire types: Top, Type 1; Middle, Type 2; Lower, Type 3.

Acknowledgments

The authors gratefully acknowledge that the four electric match suppliers provided samples of their products, at no cost, for testing. Further the American Pyrotechnic Association provided a grant to help cover some of the costs of this study. Finally the authors appreciate the technical comments provided by L. Weinman and M. Williams on an earlier draft of this article. Note that while many of the company and product

Table 3. Electric Match Electrical Parameters.

Supplier Name	Product Designation	Resistance (ohms)[a]		Current (ampere)[b]		
		Average	Range	No-Fire	All-Fire	Recom.[c]
Aero Pyro		1.2	1.1–1.2	[d]	[d]	[d]
Daveyfire	A/N 28 B	1.6	1.5–1.6	0.20[e]	0.37[f]	≥0.90[g]
	A/N 28 BR	1.6	1.5–1.7	0.20[e]	0.37[f]	≥0.90[g]
	A/N 28 F	1.6	1.5–1.6	0.40[e]	1.20[f]	≥2.00[g]
Luna Tech	BGZD	1.6	1.5–1.7	n/p	n/p	≥0.5[h]
	Flash	1.0	0.9–1.0	n/p	n/p	≥3.5[h]
	OXRAL	1.7	1.7–1.8	n/p	n/p	0.5 / 0.8[i]
Martinez Sp.	E-Max	2.5	2.4–2.8	0.20[j]	0.35[k]	0.5 / 0.9[l]
	E-Max-Mini	0.9	0.8–1.1	0.30[j]	0.50[k]	0.75 / 1.0[l]
	Titan	2.7	2.5–2.9	0.35[j]	0.50[k]	1.0 / 2.0[l]

"n/p" means data was "not provided" by the supplier.

(a) Tip plus 5-inch leg wire resistance for a collection of 10 electric matches.

(b) These values were not determined in this study; they were provided by the suppliers of the electric matches.

(c) "Recom." means firing currents recommended by the electric match supplier.

(d) Due to the untimely death of the owner of Aero Pyro, these values were not provided.

(e) This is the 10-second maximum no-fire current.

(f) This is the 40-millisecond minimum all-fire current.

(g) This is the recommended series firing current.

(h) This is the 50-millisecond specified minimum firing current.

(i) These are the "rated" and "series" firing currents.

(j) This is the 30-second maximum no-fire current.

(k) This is the 1/2-second minimum all-fire current.

(l) These are the recommended "minimum" and "normal" firing currents.

names are apparently registered trademarks, they have not been specifically identified as such in this article.

References

1) K. L. and B. J. Kosanke, "Studies of Electric Match Sensitiveness", *Journal of Pyrotechnics*, No. 15, 2000; also appearing in this collection of articles.

An earlier version appeared in *Fireworks Business*, No. 207, 2001.

Electric Matches: Ramp Firing Current

K. L. and B. J. Kosanke

Introduction

A major study of electric match sensitiveness was recently completed.[1] This article presents the results of a test to reveal aspects of the firing characteristics for the same collection of 10 electric match types as in the previous articles.

Ramp Firing Current Test

The ramp firing current test was selected because it was thought to be able to reveal much about an electric match's performance in a relatively small number of trials (typically about 25 match firings). In these tests, electric matches are subjected to a rapidly increasing electric current while being monitored to detect the moment the match ignites (as evidenced by the production of light). The setup for these tests is shown in Figure 1. The ramp current power supply provides the firing current; however, that current starts at zero and increases progressively. Further, the rate of increase is adjustable (i.e., the current can be set to rise relatively slowly, rise rapidly, or anywhere between). The current is monitored as a voltage drop across an NBS calibrated resistor, using one channel (A) of a digital oscilloscope. The electric match under test is located inside a light-tight enclosure along with a photo detector. When the match fires, the light produced is sensed by the photo detector and, after conditioning, the signal is directed to the second oscilloscope channel (B).

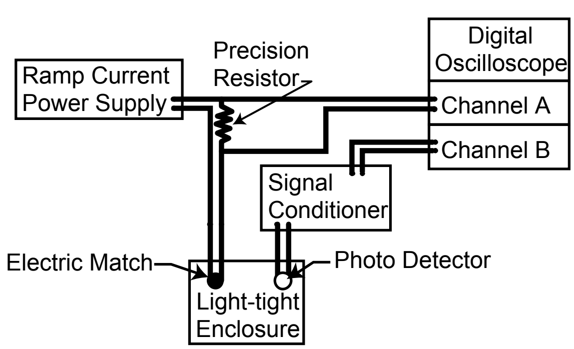


Figure 1. The configuration of equipment used to make the ramp current measurements.

Figure 2 presents data typical of that produced during the ramp firing current test of a single electric match. The electric match firing current starts to increase from zero at time t_0. At time t_1 (18.9 ms) the photo detector firsts senses light from the firing electric match. (The photo detector is adjusted to be extremely sensitive to light, such that it rapidly saturates and holds a constant value as the electric match burns. Also, to make the two traces in Figure 2 easier to see, the trace of the photo detector was shifted downward slightly.) At the time of first light output, the firing current I_f has risen to 418 mA. The firing current continues to rise reaching approximately 650 mA at time t_2 (29.9 ms), when the bridgewire fuses (melts) to open the circuit, thus dropping the electric current back to zero. (In Figure 2, the minor fluctuations seen in the oscilloscope traces are background noise mostly pickup from a nearby commercial radio transmission tower.)

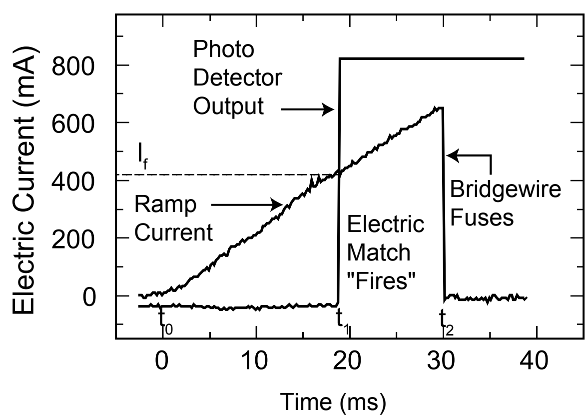


Figure 2. Typical ramp firing current test data from a firing electric match (Daveyfire A/N 28 B), showing both firing current and photo detector output.

In Figure 2, the time of electric match firing is equated with the first light produced by the match. Actually, the ignition of the electric match composition adjacent to the bridgewire must occur slightly earlier. For gas producing compositions, the time between the ignition and external light production is relatively small. Previous testing by the authors suggests that the interval for one type of gas producing composition is no more than a small fraction of a millisecond. One electric match manufacturer suggests that the time between ignition and light production may be as much as 2 ms for some gas producing compositions.[2] However, for mostly gasless compositions, the time interval could be considerably greater still.

The ramp firing current tests for each electric match type were repeated a number of times, using a collection of different rates of current increase. For each test, the firing time t_1 (first light production) and the current flowing at that time I_f were recorded. Figure 3 (for Daveyfire A/N 28 B matches) is typical of the data produced. Note that under the condition of a rapid ramp current increase, the minimum firing time of approximately 15 ms is produced with a ramp firing current of approximately 500 mA. At the other extreme, using more slowly increasing currents, when the ramp firing currents were as low as approximately 250 mA, a wide range of firing times was produced. Further, under these conditions, some match tips failed to ignite (shown in Figure 3 as open data points and are arbitrarily plotted at 500 ms). The scatter of data points about the curve plotted in Figure 3 is thought to reflect a combination of the normally expected uncertainties in the ignition process, plus minor manufacturing variations between the electric matches. This amount of scatter is fairly typical of that seen for most other electric match types tested.

For some electric match types and under some conditions, the bridgewire fuses before the match fires (i.e., before light is emitted). The types of electric matches experiencing fusing before firing and the conditions under which this occurred are discussed briefly below; see Table 1 and its notes. When fuse-before-firing occurred, the firing current I_f was taken to be what was flowing at the moment of fusing, whereas the firing time continues to be the time to the first light output, t_1.

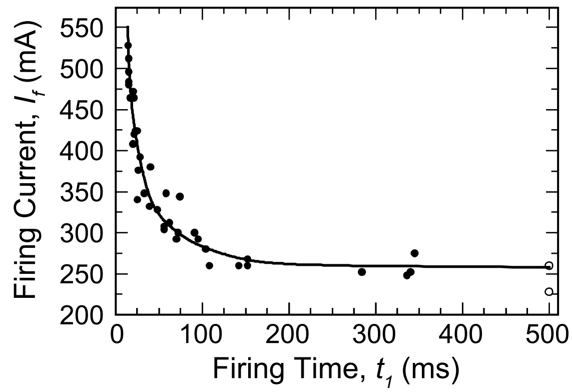


Figure 3. Ramp firing current data for Daveyfire A/N 28 B electric matches.

Results

The results of the ramp firing current tests are summarized in Table 1. The approximate minimum firing time gives some indication of the rapidity with which the electric match types fire. In actual application, with approximately constant applied currents, the firings will occur more rapidly than in these tests. However, even if typical firing times were as long as those listed in Table 1, they would all be rapid enough to be of no concern in designing a fireworks display. Of somewhat more interest is the corresponding ramp current for these firing times. These give an indication of the minimum reliable firing current for the electric matches. Note that for the normal sensitiveness electric matches, these currents all range from 500 to 600 mA. In contrast, the low sensitiveness electric matches require greater firing current. For example, the Martinez Specialty Titan matches require about 50% more current, and the Luna Tech Flash matches require at least 300% more current, than the normal sensitiveness matches. The ramp firing data for a collection of Daveyfire A/N 28 F matches is presented in Figure 4. The scatter in the data is such that no reliable estimate could be made for the minimum firing time and its corresponding ramp firing current; however, it is apparent that it too requires significantly more firing current than electric matches of normal sensitiveness.

An estimate of the average minimum ramp current resulting in firing of each type electric match is also presented in Table 1. While this estimate is related to no-fire current, it is some-

Table 1. Ramp Current Firing Results.

Supplier Name	Product Designation	Minimum Firing Time / Current[a] (ms)	(mA)	Ave. Min. Firing Current[b]	Statistical Spread[c]	First Light Versus Fusing Time[d]	Other Notes
Aero Pyro		14	600	325	Slightly Broader	Before	
Daveyfire	A/N 28 B	15	500	250	Average	Before	
	A/N 28 BR	15	500	250	Average	Before	
	A/N 28 F	(e)	(e)	(e)	Much Broader	Slightly After (f)	
Luna Tech	BGZD	27	600	300	Average	Variable (g)	
	Flash	35	1900	1250	Slightly Broader	After	(h)
	OXRAL	19	600	200	Slightly Narrower	Before	
Martinez Specialties	E-Max	17	500	300	Average	Before	
	E-Max Mini	15	600	375	Slightly Broader	Before	
	Titan	28	900	450	Much Narrower	Near Same	(h)

a) Minimum firing times and the corresponding currents are approximations and only apply for the conditions of these tests. These values were determined subjectively by examination of the plotted results for each electric match type in the area where the curves (like that shown as Figure 3) become near vertical. (Firing times are actual times to first light production.) It was felt appropriate to report those ramp-firing currents to only the nearest 100 mA. These currents are not the same as "All-Fire" currents for the electric matches.

b) Average minimum firing currents are approximations and only apply for the conditions of these tests. These values were determined subjectively by examination of the plotted results for each electric match type in the area where the curves (like that shown as Figure 3) become near horizontal. It was felt appropriate to report those ramp-firing currents to only the nearest 25 mA. These currents are not the same as "no-fire" currents for the electric matches.

c) The statistical spread in the data is a subjective estimate of the degree to which the collection of each type electric match produced consistent ramp firing results. This is an estimate of how close on average the data points fell to the curve fit line. See Figure 3 for example, which is defined as having an average data spread.

d) "Before" indicates that the electric match produced light before its bridgewire fused, as in Figure 2. "After" indicates that the electric match produced light after the bridgewire fused, as in Figure 5.

e) These results varied so widely (See Figure 4) that it was not felt to be appropriate to attempt to assign values.

f) At higher ramp currents, light production occurred after the bridgewire fused, whereas at somewhat lesser currents the firing and fusing were essentially simultaneous.

g) Two production lots of Luna Tech's BGZD electric matches were used in this study and insufficient care was taken to identify exactly which matches were used in these ramp-current tests. While the firing times and currents seemed to be consistent between the two lots, the fusing times seemed to be different. Most electric matches produced light before their bridgewires fused; others fired at about the same time the bridgewire fused. The reason for the difference was not discovered.

h) Occasionally when using minimal firing current, there was an incomplete ignition of the electric match composition, with only the tip igniting (Luna Tech) or one side igniting (Martinez Specialty). See Figure 6.

what greater as a result of the statistical spread (uncertainty) found in the data. The data for normal sensitiveness electric matches ranged from about 200 to 375 mA, suggesting that no-fire currents for these electric matches probably are in the range of 150 to 300 mA.

Perhaps the most interesting ramp current results are the statistical spreads observed during the testing. For the purposes of this study, the spread demonstrated in Figure 3 for the Daveyfire A/N 28 B electric matches was considered to be typical (average). Note in Table 1 that most electric matches were designated as being average, or only slightly narrower or broader than average. However, one electric match type, Martinez Specialty Titan matches, had a statistical spread significantly narrower than average, and one electric match type, Daveyfire A/N 28 F matches, had a statistical spread significantly broader than average. (See Figure 4). As in Fig-

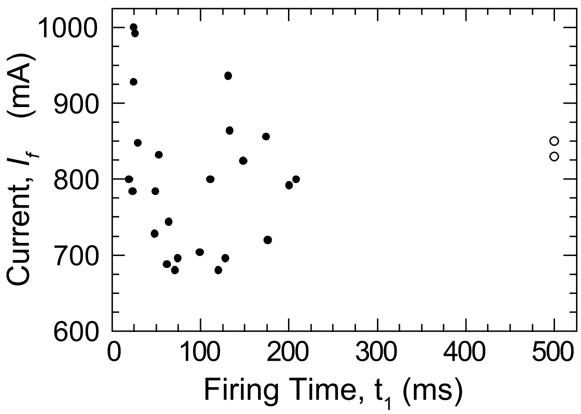


Figure 4. Ramp firing current data for Daveyfire A/N 28 F electric matches.

ure 3, the two data points shown as open dots in Figure 4 were instances where the electric matches did not ignite and are arbitrarily plotted with a firing time of 500 ms. It would seem that matches with lesser spreads might prove to be more reliable (predictable) in their performance, while those with wider spreads would be less predictable in their performance. This could possibly translate to their being less reliable in series firing of many matches. However, this has not been proven, and it is not known the extent to which such differences would be noticeable in actual use.

In those cases when electric matches fired (produced light) significantly after their bridgewires fused, there is a potential concern that un-

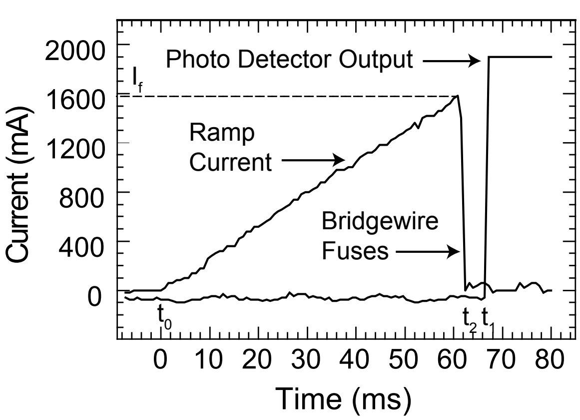


Figure 5. An example of the ramp current test data when the bridgewire fuses shortly before there is light output (Luna Tech Flash match).

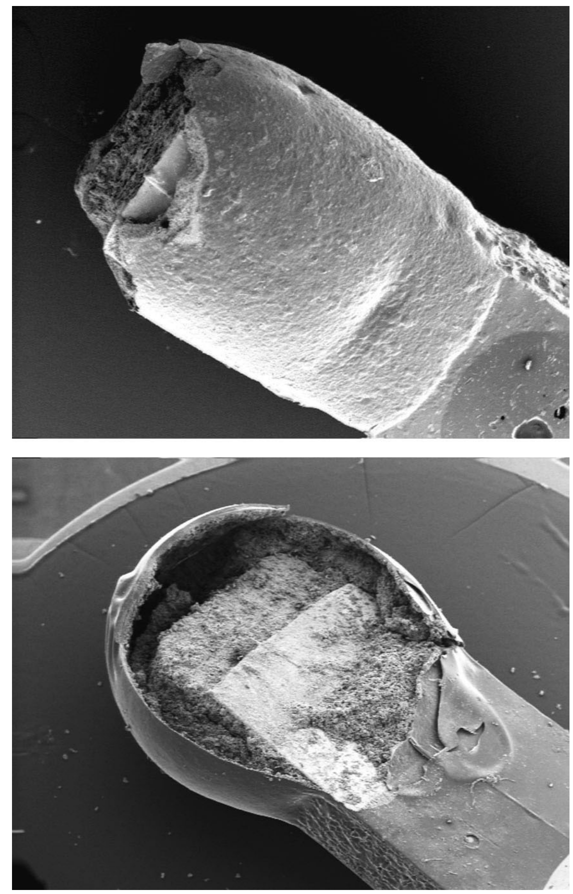


Figure 6. Electron micrographs of a Luna Tech (upper) and a Martinez Specialty (lower) electric match with incomplete ignition..

der some circumstances, they could conceivably fail to fire at all, especially if fired in a series circuit with many electric matches. However, this has not been confirmed by testing, and it may merely be the result of the electric matches burning internally prior to their external light emission. However, for two of the more rapidly rising ramp currents used in the testing of Luna Tech Flash Matches, it was observed that the bridgewires fused without successfully producing an ignition of the electric match. The reason for this was not determined. (The fire after fuse question will be considered further in the next article of this series.)

Acknowledgments

The authors gratefully acknowledge that the four electric match suppliers provided samples of their products, at no cost, for testing. Further, the American Pyrotechnic Association provided a grant to help cover some of the costs of this study. Finally, the authors appreciate the technical comments provided by L. Weinman, M. Williams, and P. Martinez on an earlier draft of this article. Note that while many of the company and product names are apparently registered trademarks, they have not been specifically identified as such in this article.

References

1) K. L. and B. J. Kosanke, “Studies of Electric Match Sensitiveness”, *Journal of Pyrotechnics*, No. 15, 2000; also appearing in this collection of articles.

2) P. Martinez, private communication, 2001.

An earlier version appeared in *Journal of Pyrotechnics*, No 13, 2001.

Pyrotechnic Reaction Residue Particle Identification by SEM / EDS

K. L. & B. J. Kosanke

PyroLabs, Inc., 1775 Blair Rd., Whitewater, CO 81527, USA

and

Richard C. Dujay

Mesa State College, Electron Microscopy Facility, Grand Junction, CO 81501, USA

ABSTRACT

Today the most reliable method for detecting gunshot residue is through the combined use of scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) of the resulting X-rays. In recent years, this same methodology has found increasing use in detecting and characterizing pyrotechnic reaction residue particles (PRRPs). This is accomplished by collecting particulate samples from a surface in the immediate area of the pyrotechnic reaction. Suspect PRRPs are identified by their morphology (typically 1 to 20 micron spheroidal particles) using a SEM, which are then analyzed for the elements they contain using X-ray EDS. This will help to identify the general type of pyrotechnic composition involved. Further, more detailed laboratory comparisons can be made using various known pyrotechnic formulations.

Keywords: pyrotechnic reaction residue particles, PRRP, primer gunshot residue, PGSR, scanning electron microscopy, SEM, energy dispersive spectroscopy, EDS, morphology, X-ray elemental analysis, forensics

Introduction

The combined use of scanning electron microscopy (SEM) and X-ray energy dispersive spectroscopy (EDS) for use in the detection of primer gunshot residues (GSR) was introduced in the mid-1970s.[1] This GSR analytic method has become so well established that it has been defined through an ASTM standard.[2] In essence, the method uses SEM to identify particles with the correct morphology and X-ray EDS to determine whether those particles have the elemental constituents of PGSR. The sought after GSR particles have a morphology that is nearly spherical in shape and range in the size from approximately 0.5 to 5 microns. These residue particles, which originate from the primer composition, are spheroidal in shape because they are formed at high temperature, where the surface tension of the molten residue droplets contracts them into spheroids before they solidify upon cooling. The particles are relatively small because they are created under near explosive conditions, first at high pressure inside the firearm, then suddenly expanding to atmospheric pressure. The sought-after GSR particles most commonly have lead, antimony and barium present (or some combination thereof), often in conjunction with a small collection of other chemical elements. This is because GSR particles have essentially the same elements present as in the formulation used in the primer for the cartridge, where compounds containing lead, antimony and barium are common.[3] In addition, materials from the projectile, cartridge case and barrel of the weapon may be present in GSR particles. The chemical elements present in smokeless powder are the same as are generally present in organic matter and are thus not unique to GSR. (However, these materials can often be chemically detected by other means.[4])

The requirement for both the correct morphology and the correct elemental composition, all within the same individual particle, provides high specificity. Certainly this methodology provides much higher specificity than the previously accepted technique for GSR analysis based on atomic absorption spectroscopy of washes taken from the hands or clothing of an individual. In fact the SEM / EDS technique is considered so specific that in a recent survey, one forensic laboratory considered finding even a single particle meeting the GSR criteria sufficient to report that a person was near a discharging firearm.[5] (Note, however, essentially all laboratories surveyed did not provide the specific number of particles required for positive GSR identification. Presumably because the answer is more complicated, requiring consideration of things such as whether there may be natural or industrial materials present that have similar attributes.) The same high degree of specificity that SEM / EDS offers in GSR detection, also applies to the identification of pyrotechnic reaction residue particles (PRRPs); however, there are two important differences. First, the chemical elements present in PRRPs are mostly different (and potentially more varied) than those most commonly found in GSR. Second, generally the quantity of PRRPs produced is several orders of magnitude greater than that for GSR. The first difference makes performing PRRP analysis somewhat more difficult, but the second makes it much easier.

Although using the combination of SEM / EDS is well established from decades of use in GSR analysis, and although the same methodology applies equally well to the analysis of PRRPs, relatively little information regarding its use for PRRP analysis has appeared in the literature. While the first reports of the application of the SEM / EDS methodology to pyrotechnic residue analysis also appeared in the 1970s,[6–7] most of the articles are recent and in the context of pyrotechnic residues that may be found to meet the criteria of GSR.[8–11] The one recent exception known to the authors is a single article produced at the Forensic Explosive Laboratory in the UK.[12] The sparseness of published information is unfortunate, because this is a powerful investigative tool about which too few people are aware. Granted, the number of pyrotechnic and fireworks incidents whose investigations can benefit from this technique is not large. However, in those instances where it can be beneficial, probably no other methodology can produce comparably useful results. Accordingly, this paper was written to increase awareness of the use of SEM / EDS for the analysis of pyrotechnic reaction residues for the purpose of accident investigation. Since many investigators may not be familiar with SEM / EDS, this article includes some basic information about these techniques. However, it should be noted that many details and subtleties of SEM / EDS methodology are beyond the scope of the present article.

Basic SEM / EDS Methodology

Most of what is described in the remainder of this article is independent of the type of instrument used. However, it may be instructive to describe the instrument most often used by the authors. The SEM is a manually operated AMRAY 1000, recently remanufactured by E. Fjeld Co.[13] For this work, the instrument is most often used in the secondary electron mode, but it is occasionally used in the backscatter mode when that is needed. The instrument provides software driven digital imaging. The X-ray spectrometer is energy dispersive, using a Kevex Si(Li) detector[14] with a beryllium window in conjunction with an American Nuclear System[15] model MCA 4000 multichannel analyzer and its Quantum-X software (version 03.80.20). Most typically, samples are collected on conductive carbon dots and are not coated. However, to improve the image quality of some of the micrographs in this article, some specimens were lightly sputter coated with gold. It should be noted that some additional information on the techniques used is included in a subsequent article.[16]

Much of the information presented in this section is based on standard texts dealing with the subjects of scanning electron microscopy and X-ray energy dispersive spectroscopy.[17,18] In its simplest terms, the operation of a SEM can be described as follows. An electron gun produces high-energy electrons that are focused and precisely directed toward a target specimen in a vacuum (see Figure 1). As a result of this bombardment, among other things, low energy secondary electrons are produced through interactions of the beam electrons with the atoms in the specimen. In the most commonly used SEM mode, these secondary electrons are collected and used to generate an electronic signal. The amplitude of that signal is dependent on the nature and orientation of the portion of the specimen being bombarded at that time. The impinging electron

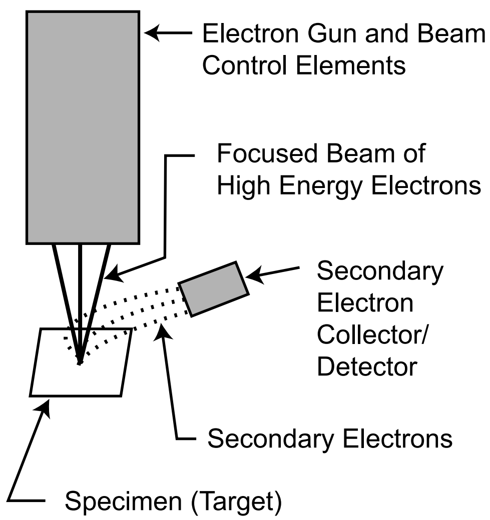


Figure 1. Illustration of some aspects of the production and collection of secondary electrons in a SEM.

beam can be systematically moved over the specimen in a rasterized pattern of scans (see Figure 2). The resulting secondary electron signal can then be used to create an overall (television-like) image of that portion of the specimen being scanned. Because the incident beam of electrons is highly focused and because the pattern of scans across the specimen can be precisely (microscopically) controlled, the image produced is of high spatial resolution and can be highly magnified (easily to 20,000×).

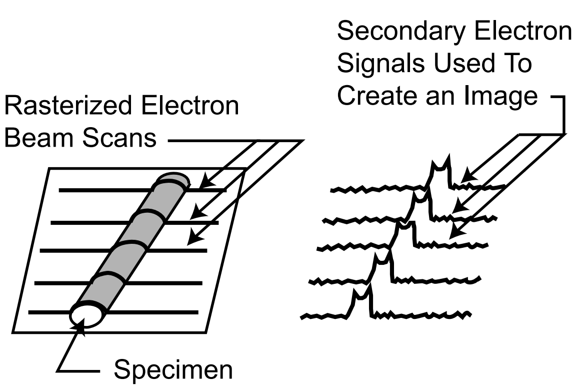


Figure 2. Illustration of some aspects of rasterized SEM scanning to produce an image.

Along with the production of secondary electrons, much higher energy backscatter electrons are also produced. Because of their high energy, only a relatively few will be detected and can be used for imaging with the instrument being used. Nonetheless, there are times, discussed later in this article, when using backscatter electrons for imaging will be a useful tool in identifying the origin of some types of particles found within samples.

In addition to the production of secondary and backscatter electrons, another result of the interaction of the electron beam with the target specimen is the production of X-rays. These X-rays are uniquely characteristic of the type of atoms (the chemical elements) that produced them. By detecting and analyzing the energies of the X-rays that are generated, the identity of chemical elements in the target specimen can be determined with great specificity.

The most common method for analyzing the X-rays produced by the specimen is described as energy dispersive spectroscopy (EDS). This uses a solid state [Si(Li)] X-ray detector. The output of this detector consists of voltage pulses that are proportional to the X-ray energies being deposited. Using a multichannel analyzer (MCA), the signal pulses are sorted according to voltage (X-ray energy) and the results stored for subsequent interpretation (i.e., the identification of the atomic elements present). There are some limitations on the range of energies of the X-rays that are produced and detected using a SEM / EDS instrument. The maximum energy of the X-rays will be a little less than the energy of the electron beam (which typically is 20 or 30 keV). However, as a practical matter, good X-ray yields require a beam energy approximately 1.5 times the X-ray energy. Further, there is an energy threshold below which the X-rays will not be detectable. For those instruments that use a vacuum isolating beryllium window, this threshold is approximately 0.5 keV. This has the effect of preventing the detection of the X-rays from elements below oxygen in the periodic table. (As a practical matter, for such instruments, X-rays from elements below sodium are difficult to detect.)

As the primary beam of electrons penetrates and interacts with the specimen, there is a loss of their initial energy, and with that, a loss in the electron's ability to stimulate the production of higher energy X-rays. While it depends on the electron beam energy and the nature of the specimen, for the X-ray energies of interest in PRRP analysis, the depth of interrogation should be considered to be no more than approximately 5 μm.

Accordingly, the combination of SEM / EDS allows (with some limitations) the microscopic imaging of specimens and the determination of the chemical elements present in those specimens. It is this powerful combination of abilities that allows for the rapid identification and characterization of PRRPs.

Pyrotechnic Reaction Residue Particle Morphology

In essentially every case, pyrotechnic reactions produce sufficient thermal energy to produce molten reaction products. Further, in the vast majority of cases, some temporarily vaporized reaction products are also generated—usually along with some permanent gases. Assuming the pyrotechnic reaction is somewhat vigorous, the temporary and permanent gases act to disperse the molten and condensing reaction products as relatively small particles. The size of these residue particles varies from several hundreds of microns down to considerably less than one micron. The distribution of particle size depends on the nature of the pyrotechnic composition and the conditions under which they were produced. Explosions tend to produce only relatively small particles (smoke), whereas mild burning tends to produce a wider particle-size distribution, including many larger particles. Because of surface tension, those pyrotechnic reaction residue particles (PRRPs) that were molten and then solidified while airborne will generally be spherical (or at least spheroidal) in shape. The collection of electron micrographs in Figure 3 demonstrates the appearance of some PRRPs. The selected particles range from approximately 10 to 20 microns in diameter. These particles were collected from a surface that was one foot (0.3 m) from an explosion produced using a type of fireworks flash powder. In this same test, in addition to particles of pyrotechnic origin, soil particles were present that were mobilized as a result of the explosion. For comparison, see Figure 4, which is a collection of micrographs of typical soil particles of geologic origin. Again, all selected particles range from approximately 10 to 20 microns.

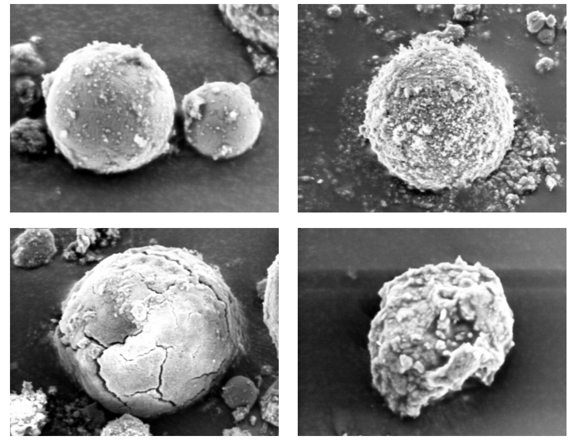


Figure 3. Examples of 10 to 20 micron spheroidal pyrotechnic reaction residue (PRR) particles.

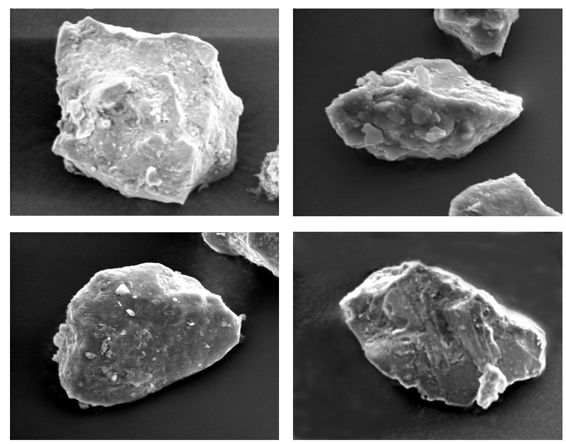


Figure 4. Examples of typical 10 to 20 micron particles of geologic origin (soil).

As illustrated in Figures 3 and 4, most often there are discernable differences between PRRP morphologies and those of geologic soil particles; however, this cannot be absolutely relied upon. Pyrotechnic residues often include particles that are non-spheroidal, and some geologic particles can be spheroidal. The non-spheroidal particles of pyrotechnic origin can be unreacted components of the pyrotechnic composition or reaction residues that are not spheroidal, apparently the result of their still being molten when they collided with the collection surface. Occasionally soil particles appear nearly spherical in shape, apparently the result of their being mobile in the environment for a long time, during which abrasive action removed their sharp, angular features.

Another potential complication in identifying PRRPs is that occasionally particles of unreacted pyrotechnic composition can be spheroidal in shape. This can be a result of their method of manufacture or processing. For example, the left image in Figure 5 is a type of atomized aluminum occasionally used in pyrotechnic formulations.[19] The right image is a particle of potassium nitrate that has been prepared for use by ball milling to reduce its size.[20] If any particles such as these are left unreacted after an incident, it is possible a few could be found interspersed with PRRPs.

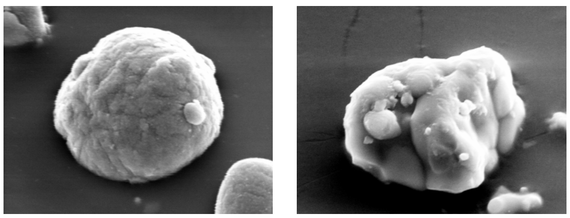


Figure 5. Examples of 10 to 20 micron spheroidal or nearly spherical particles sometimes found in pyrotechnic compositions: left, atomized aluminum; right, ball-milled potassium nitrate.

Other types of non-pyrotechnic particles are spheroidal and fall in roughly the same size range as PRRPs. The two images in Figure 6 are examples of spherical particles of biologic origin: blood cells and grass pollen. Although the explanation is beyond the scope of this article, the yield of secondary electrons is virtually independent of atomic number (Z), whereas the yield of backscatter electrons depends highly on the Z of the target atoms, see Figure 7. Accordingly, the use of the backscatter mode of the SEM operation is useful in differentiating between organic particles (low Z) and PRR or geologic particles (typically higher Z). Similarly, in those instances when there is sufficient difference in atomic number between PRR and geologic particles, the use of backscatter mode can be useful. The two images in Figure 8 illustrate the difference between operating in secondary and backscatter electron modes. Note in the image on the right how the two high Z lead particles clearly appear brighter than the many particles of organic material. Finally, Figure 9 demonstrates two more spheroidal particles that can be found in the environment that are of non-pyrotechnic origin. These are a particle produced by grinding metal and a cigarette smoke particle.

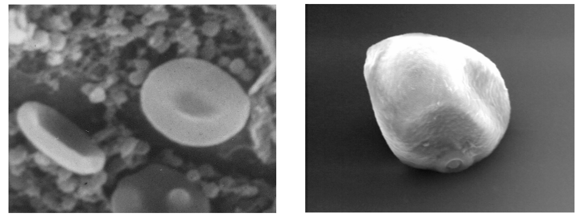


Figure 6. Examples of 5 to 20 micron spheroidal particles of biologic origin: left, red blood cell; right, grass pollen.

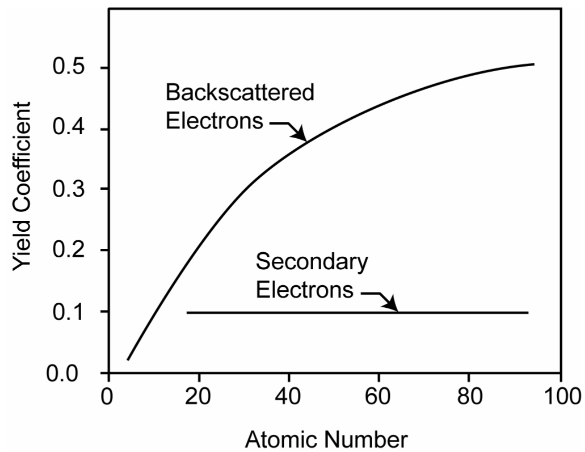


Figure 7. A graph illustrating the number of secondary and backscatter electrons produced from targets as a function of atomic number. (Based on references 17 and 18.)

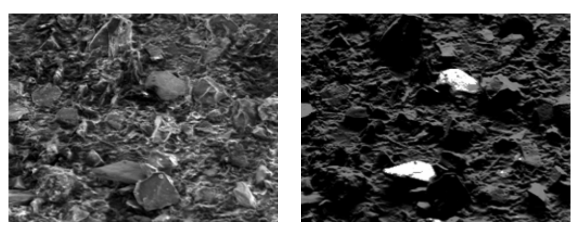


Figure 8. These two images demonstrate the difference between operating the SEM in the secondary electron and backscatter modes with a mixture of organic and high atomic number particles. (This specimen had been coated using a conductive carbon spray.)

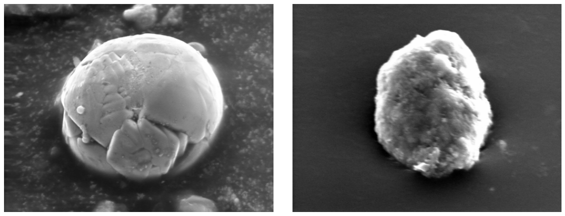


Figure 9. Examples of 10 to 20 micronspherical particles in the environment: left,particle from metal grinding and right, cigarette smoke particle.

All these various particle shapes for both PRRPs and non-PRRPs not withstanding, keying on spheroidal particles for analysis is still quite useful, as this fairly quickly targets those particles that have the best chance of being PRRPs.

Suspect Particle X-ray Signatures

Table 1 is a list of those chemical elements somewhat commonly found in pyrotechnic compositions. Included is an attempt to estimate the relative overall frequency of each chemical element's presence in civilian and/or military compositions. Also included are the energies of the X-ray peaks that are most often used to establish the presence of that element in PRRPs. Because many instruments commonly in use have difficulty detecting X-rays from the elements below sodium in the periodic table, those elements have not been included in Table 1.

Of course, all of the chemical elements present in the unreacted pyrotechnic composition will be present in the combustion products. However, not all of the elements will be present in the solid residues to the same degree that they were in the unreacted composition. For example, when sulfur is used as an ingredient in a high-energy flash powder, it is generally not found in the PRRPs. Most likely this is because it has reacted to form sulfur dioxide, a gas, which is lost.

In Figure 10, the three upper X-ray spectra are from individual particles in an unreacted flash powder with the formulation: 60% potassium perchlorate, 30% magnesium:aluminum alloy 50:50 (magnalium), and 10% sulfur. Below them is the spectrum from a "gross" sample of the unreacted flash powder, collected such that the X-rays originate from a large collection of individual

Table 1. Most Common Chemical Elements Present in Pyrotechnic Compositions.

Element[(a)]	Z[(b)]	F/P[(c)]	X-ray Energies (keV)[(d, e)]
Sodium	11	1	1.04
Magnesium	12	1	1.25
Aluminum	13	1	1.49
Silicon	14	2	1.74
Phosphorous	15	3	2.01
Sulfur	16	1	2.31
Chlorine	17	1	2.62
Potassium	19	1	3.31, 3.59
Calcium	20	3	3.69, 4.01
Titanium	22	2	4.51, 4.93
Chromium	24	3	5.41, 5.95
Manganese	25	3	5.90, 6.49
Iron	26	2	6.40, 7.06
Copper	29	1	8.04, 8.90
Zinc	30	3	8.63, 9.57
Strontium	38	1	1.82, 14.14, 15.84
Zirconium	40	2	2.06, 15.75, 17.71
Antimony	51	2	3.60, 3.86, 4.10
Barium	56	1	4.46, 4.84, 5.16
Lead	82	2	2.36, 10.55, 12.62
Bismuth	83	3	2.44, 10.83, 13.02

a) Only those elements producing characteristic X-rays with energies above 1.0 keV are listed. The elements are listed in order of increasing atomic number.

b) Z is atomic number.

c) F/P means the frequency of presence of this element in pyrotechnic compositions. Rankings range from 1 to 3, with 1 indicating those elements most frequently present, and 3 indicating those elements only occasionally present. No attempt was made to differentiate between their presence in civilian versus military pyrotechnics.

d) Energies (in keV, reported to 0.01 keV) for the X-rays between 1 and 20 keV that are most frequently used to identify the presence of the element.

e) When using an energy dispersive X-ray spectrometer, sometimes there will be overlaps of some of the X-rays listed. However, in most instances these cases should not result in their misidentification. This will be discussed in a future article.[16]

particles, which produce a spectrum representative of the average composition of the unreacted flash powder. The lower most X-ray spectrum is typical of that produced by a PRRP. In the lower two spectra, note the difference in the sulfur peaks; while it is quite prominent in the unreacted gross spectrum, it is missing from the gross residue spectrum. The reduction of the potassium and chlorine peaks, and a small change in the ratio of magnesium and aluminum peaks will be discussed in a subsequent article addressing some of the finer points of PRRP analysis.[16]

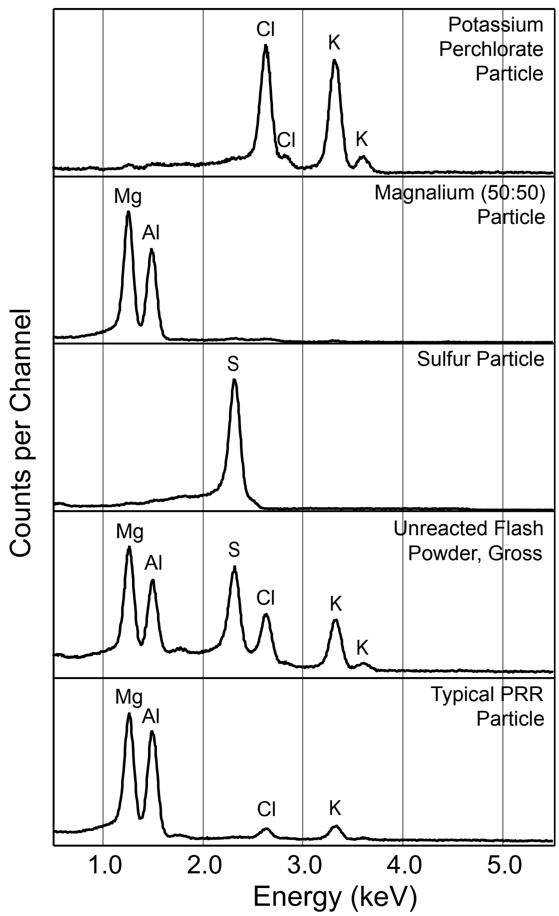


Figure 10. X-ray spectra from a pyrotechnic flash powder.

The vertical scales of the spectra were normalized such that the largest X-ray peak in each spectrum has the same, full-scale height. This method was chosen because it readily facilitates the comparison of spectra collected for different lengths of time, or for which different count rates were produced. Also, while data was collected to nearly 20 keV, the horizontal (energy) axis was truncated at a point shortly above the last significant X-ray peak found in any spectrum, in this case at about 5.5 keV. This provided a clearer view of the peaks that are present. Similarly, the portion of the spectrum below approximately 0.5 keV was not included.

The X-ray spectra in Figure 11 were produced as part of an accident investigation. In this case, an individual received burns when a firework allegedly exploded and sent burning pieces of pyrotechnic composition in his direction. Uppermost is the gross spectrum of the unreacted composition taken from the firework alleged to have been responsible for the injury. In the middle is a spectrum typical of a PRRP produced by burning this same pyrotechnic composition under laboratory conditions. Lowermost is a spectrum typical of PRRPs taken from the clothing of the burn victim. In comparing the two lower spectra, note that the spectrum of PRRPs from the victim is consistent with having been produced by the suspect firework.

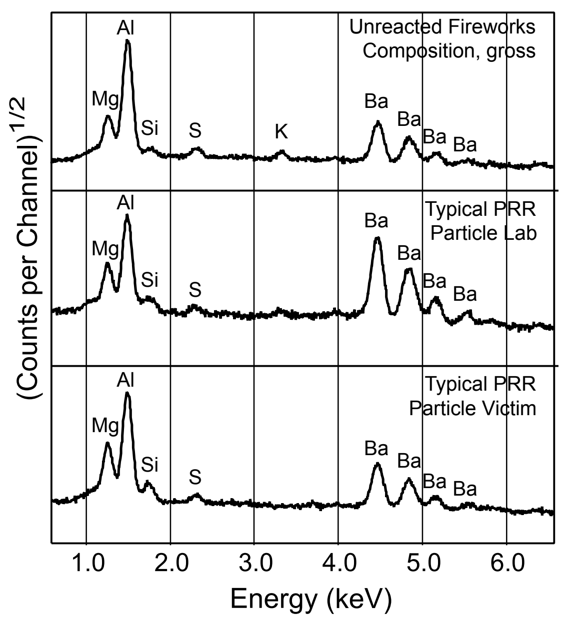


Figure 11. X-ray spectra produced during an accident investigation.

The spectra in Figure 11 were recorded for a relatively short time, approximately 1.5 minutes. It is often appropriate to use short collection times, from 0.5 to 2 minutes. Generally, data collection time only needs to be sufficient to confidently identify the significant elemental components of the particle. This allows the analysis of a greater number of PRRPs, thus increasing one's confidence in any conclusions reached. When needed, longer data collection times can be used when attempting to identify minor components of a suspect particle.

All of the spectra presented in Figure 11 (and Figure 13) use a vertical scale presenting the square root of the number of counts per channel. This scale was chosen because it readily facilitates the observation of both major and minor X-ray peaks in the spectrum (as well as giving an indication of their statistical precision). As in Figure 10, the vertical scales have been normalized to have the largest peak reach full scale, and the horizontal axis has been truncated at a point a little higher than the last peak observed.

For the most part, those particles of geologic origin, comprising the inorganic components of soil, can be eliminated from consideration based on their non-spheroidal morphology. (See again Figure 4.) In addition, those few geologic particles that appear roughly spheroidal can almost always be eliminated based on their X-ray signatures. To someone without a geochemistry and pyrotechnic chemistry background, this might not be readily apparent, especially after considering Table 2, which lists the abundance of the most prominent chemical elements in the Earth's crust. Note that of the ten most abundant crustal elements, all eight of those with atomic numbers from sodium and above also appear in the list of elements somewhat commonly present in pyrotechnic compositions. The non-morphologic basis for discriminating between geologic and PRRPs is discussed in the next few paragraphs.

Table 2. Average Crustal Abundance.[21]

Element	% (a)	Element	% (a)
Oxygen	46.6	Sodium	2.8
Silicon	27.7	Potassium	2.6
Aluminum	8.1	Magnesium	2.1
Iron	5.0	Titanium	0.4
Calcium	3.6	Hydrogen	0.1

a) Percent by weight, expressed to 0.1%.

Sometimes the presence of pyrotechnic residue is so abundant that it is clearly visible as whitish, grayish or blackish material adhering somewhat to the surface of items exposed during the incident. In that case, the samples taken from those locations are likely to contain a relatively high proportion of PRRPs. This combined with the relatively small number of geologic particles that fit the morphology criteria for residues, often allows the tentative identification of residue particles based primarily on statistical considerations. For example, consider the case of examining a total of 50 suspect particles selected because they meet the PRR morphology requirements. Suppose that 40 of these have elemental signatures consistent with being from the same source. Whereas the remaining 10 have one or another of a few other general signatures. In this case, based on probability alone, it is somewhat likely that the 40 particles are of pyrotechnic origin. The level of confidence significantly increases if the X-ray elemental signature for the 40 particles is consistent with having been produced pyrotechnically (even more so if there is an absence of such particles in background samples, discussed further below). Nonetheless, it must still be considered that some of the 10 other morphologically correct particles may also be of pyrotechnic origin, such as might have been produced in another event or from a different pyrotechnic composition.

Often the exposure to pyrotechnic residues is limited, either in duration of exposure, by distance from the reaction, or both. In addition, it is possible that the surface to be sampled was dirty at the time of the exposure, has become dirty since the exposure, or is of a nature that will produce an abundance of non-pyrotechnic material. In these cases, gross statistical considerations and general pyrotechnic knowledge may not be sufficient to produce results with a reasonable confidence level. In such cases, or to increase ones general confidence in the identification of residue particles, a combination of two other things will greatly aid in discriminating between PRRPs and those relatively few geologic particles with similar morphologies. First is the taking and analyzing of background samples, which can come from at least three different sources. Background samples can be taken of the soil (dirt) in the local area that is thought to be free of the pyrotechnic residues of interest. Background samples can be taken from the surface of items in the area of the incident, which are similar to those items of interest, but which were far enough away to be reasonably free of the pyrotechnic residues of interest. Background samples can also be taken from the primary items being sampled for PRRPs. In that case, an examination of non-spheroidal particles that clearly appear to be non-pyrotechnic in origin can also be useful in establishing the elemental signatures of geologic particles. Any of these various background samples are useful in establishing a list of elemental signatures for non-pyrotechnic particles that are likely to be found on the suspect items. Then, depending on whether the suspect particles have elemental signatures similar to background geologic particles, their origin can often be established with reasonable confidence. If not, the particles must be considered to be of indeterminate origin, at least until further information is developed.

A great aid in discriminating between geologic and PRRPs is knowledge of the likely elemental signatures for both types of particles. For example, for the most common EDS units, far and away the most abundant geologic element that can be detected is silicon, and the most common mineral is one or another form of quartz, silicon dioxide.[22a] Accordingly, it is not uncommon to find particles that produce essentially only silicon X-rays. Further, it is known in pyrotechnics that: silicon is not one of the more commonly present elements; silicon is primarily used in military formulations; silicon only tends to be used in the igniter portion of a device, which is generally only a tiny portion of the total amount of composition likely to be present; and silicon is essentially always used in combination with other readily detectable elements. Thus, when a particle is examined and found to exhibit only silicon X-rays, even when it has a morphology roughly consistent with PRRPs, one can be relatively certain that it is of non-pyrotechnic origin (especially if such particles have also been found in background samples). A similar argument can be made for particles exhibiting essentially only calcium X-rays, which may be one or another geologic form of calcium carbonate.[22b]

Geologic particles producing combinations of X-rays are a little more problematic, but most can also be identified with a reasonable degree of confidence. For example, feldspar refers to a group of minerals making up about 60% of the Earth's crust.[22c] Most commonly these are combinations of silicon, aluminum, and one or the other of potassium, sodium or calcium. While these specific combinations occur frequently in geologic particles, it would be unusual to find such combinations in PRRPs. Although a little too simplistic to make it a general rule, the most common geologic material will generally have silicon or calcium as the most prevalent X-ray peak, whereas pyrotechnic material will generally have few, if any, of these elements present. (For more complete information on the forensic analysis of soils using SEM, see reference 21.)

Like particles of geologic origin, those that are organic in nature (biologic or manmade) generally will not have morphologies mistakable for PRRPs. Also, similar to geologic particles, organic particles will have X-ray characteristics that greatly aid in their identification. One of these characteristics is their low rate of production of X-rays with energies greater than 0.6 keV. This is a result of biologic particles being mostly comprised of compounds with elements no higher than oxygen. Thus, it is common for biologic particles to produce no more than about 1/3 the number of X-rays above 0.6 keV than will geologic or PRRPs. Further, the elemental signatures of organic particles are likely to be significantly different from PRRPs. Finally, operating the SEM in the backscatter mode offers the potential to discriminate against biologic particles because of the reduced intensity of their images. However, this generally requires applying an electrically conductive coating to the specimen. Further, because the difference in Z between organic and geologic or PRRPs is not very great, the image intensity contrast may not be sufficient to allow their easy differentiation.

Generally, it will not be possible to establish the identity and origin of each particle analyzed, and these should be characterized as being "Indeterminate". However, in most cases the sheer number of PRRPs produced is so great (generally at least a thousand times more than for GSR) that there is no need to positively characterize each particle. Further, there is no need for the search for PRRPs to be exhaustive. Rather a statistical approach is taken in which analysis continues only until the degree of certitude reaches the level desired.

Analytical Example

This example comes from the same case mentioned earlier, wherein an individual was burned when a firework was alleged to have exploded sending pieces of burning pyrotechnic composition in his direction. Figure 12 is an electron micrograph of a small portion of a sample taken from the inside the individual's clothing, from the general area where the burn occurred. (This specimen was sputter coated with a thin layer of gold to help produce a satisfactory image for publication.) In this image, a series of six items are identified for use as examples of the way the analysis was performed. (In the actual investigation, several additional particles seen in this image were also analyzed, as well as many other particles from other portions of this and other samples.) Figure 13 is the collection of the X-ray spectra collected from the six particles (items) identified in Figure 12.

Table 3 presents the results from the analysis of the particles identified in Figure 12 and illustrates a typical methodology used in performing an analysis of PRRPs. However, the categories and classifications will often need to be adjusted for specific investigations. In Table 3, particle *Morphology Type* is basically divided into two categories, *Spheroidal* (in this case meaning near spherical) and *Non-Spheroidal*, with *Fibrous* as a subcategory of non-spheroidal. The reason for including the fibrous subcategory is that organic materials (both biologic and manmade) often have this appearance, while PRRPs do not. (In this example, since the specimen was taken from clothing, many fibrous items were found.) When the appropriate category for a particle is not reasonably clear, it is assigned as being *Indeterminate*.

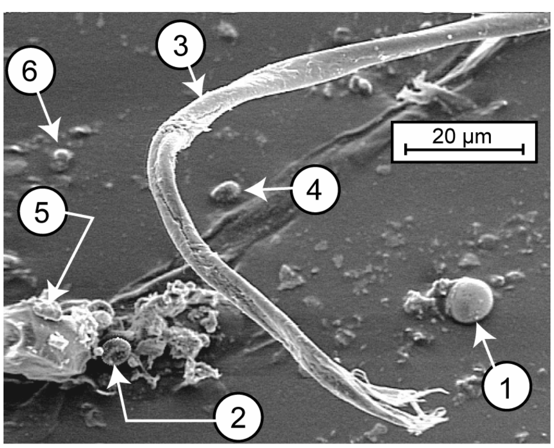


Figure 12. An electron micrograph identifying a series of particles (items) analyzed during an accident investigation. (See Table 3.)

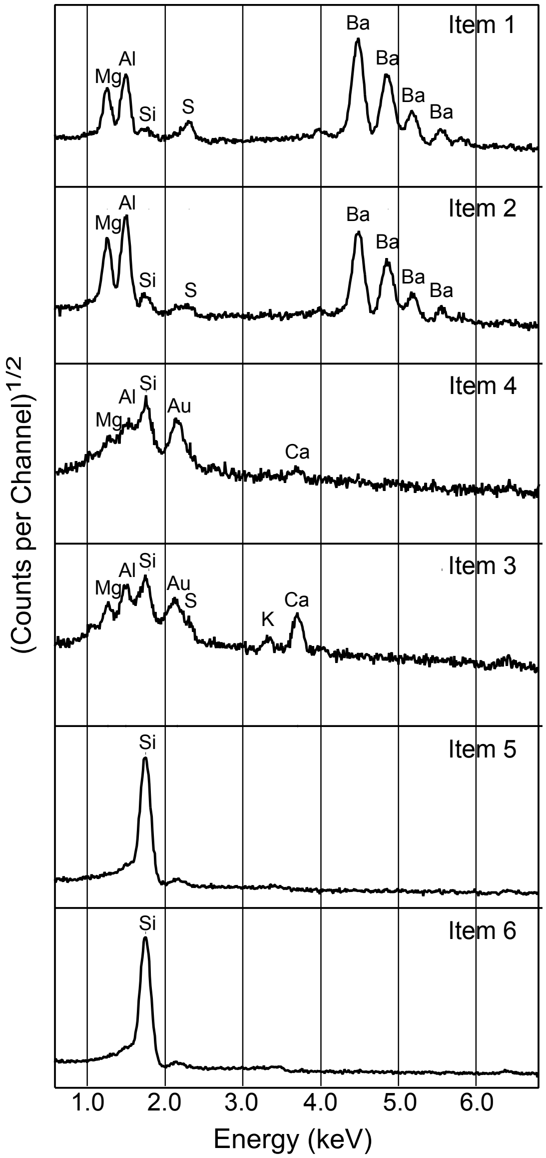


Figure 13. X-ray spectra collected from the six particles identified in Figure 12.

Multichannel analyzer (MCA) *Dead Time* is the percent of time the MCA is occupied sorting the electronic pulses from the X-ray detector. All things being equal, MCA dead time is a useful indication of the rate at which X-rays from the specimen are being detected. For many systems, the X-rays from elements with atomic numbers (Z) less than approximately 11 (sodium) are es-

Table 3. Analytical Results for the Particles Identified in Figure 12.

Particle Number	Morphology Type	Dead Time (%)	Peak-to-Background Ratio	Chemistry Type	Particle (Item) Identification
1	Spheroidal	16	3.8	Pyrotechnic	PRRP
2	Spheroidal	18	3.4	Pyrotechnic	PRRP
3	Fibrous	4	1.0	Organic	Organic
4	Indeterminate	4	0.8	Indeterminate	Non-PRR
5	Non-Spheroidal	12	13.	Geologic	Geologic
6	Spheroidal	14	16.	Geologic	Geologic

sentially not detected. Nevertheless, MCA dead time will often provide a useful indication of the extent to which the specimen is composed of elements with Z less than 11. This is of interest because it will aid in determining whether a particle is organic in nature (whether manmade or biologic). Many things affect the rate of production and detection of X-rays from the specimen. However, for the instrument and the configuration used in this article to produce the spectra in Figure 13, when the dead time is less than approximately 5 percent, it is likely that the vast majority of the atoms in the portion of the specimen being scanned have atomic numbers less than 11. For this reason, spectra dead times have been included in Table 3. As further indication that a recorded spectrum is from organic material, it will generally not contain any peaks of major intensity. Usually a visual inspection of the spectrum is sufficient to reveal this; however, for the purpose of this example, a quantitative measure of the peak-to-background ratio for the most prominent peak(s) in the spectrum was produced. For the instrument and its configuration used in this article, purely organic material generally produces peak-to-background ratios less than 2. Thus, as a further aid in characterizing particles, Table 3 includes the value for the maximum peak-to-background ratio found in each spectrum.

While the use of approximate MCA dead times to infer something about the predominant atomic numbers of a particle is useful, it is not completely reliable. Even for the same instrument, operated under the same conditions, there are a number of factors that can give false low dead times. For example, for the very smallest particles (those significantly less than the interrogation depth of the electron beam) the count rate (dead time) will be reduced. Similarly, when there is shadowing of the X-ray detector by another portion of the specimen, the count rate will be reduced. These effects are expected and manageable; however, a more complete discussion must be deferred to a subsequent article.[16] Similarly, peak-to-background ratios are not a completely reliable indicator of prevalent atomic number. When there is a mixture of several moderate to high Z materials in the particle, such that there are many prominent peaks in the spectrum, peak-to-background ratios are reduced (in Table 3, compare particles 1 and 2, with particles 5 and 6). Further, sometimes particles are mixtures of organic material with other material having higher Z components. For example, white paper has calcium carbonate added to make it whiter and more opaque, and organic material may have inorganic material imbedded within or adhering to its surface.

Identification of organic particles can often be aided using the instrument in the backscatter electron mode. However, this is also not always reliable. If there is not a sufficient difference between the atomic number of the PRR and organic particles, the difference in the backscatter yield coefficients may not be sufficient. In that case, the contrast between PRR and organic particles may not be readily apparent given the normal variation in contrast between particles in the image (flaring or excessive contrast), especially when the sample has not been coated.

In Table 3, particle *Chemistry Type* is basically divided into two categories (*Pyrotechnic* and *Non-Pyrotechnic*, with subclasses of *Organic* and *Geologic* for non-pyrotechnic particles). Assignments are made based on the types and ratios of chemical elements present. For the most part, the basis for assigning particles (items) to these classifications was described in the previous section on X-ray signatures. Another non-pyrotechnic subclass is often used for particles that are removed from the substrate from which the sample was collected. This might include paint flecks from a painted surface or rust particles from an iron or steel surface. In the example being discussed, clothing fibers could have been assigned to that category. When the appropriate category for a particle is not reasonably clear, it is assigned as being *Indeterminate*.

Particles one and two have the correct morphology and reasonably high count rates. Further, their chemistry is consistent with that of a PRRP, which has been confirmed through the production of effectively identical (matching) PRRPs in the laboratory using the suspect pyrotechnic composition (see again Figure 11). Further, many more particles with the same elemental signature were found in the same area of clothing where the injury occurred. Finally, no similar particles were found on background areas of clothing remote from the area of the injury. Accordingly, with a high degree of confidence, particles one and two are identified as PRRPs.

Item three has the obvious appearance of a fiber; most likely from the individual's clothing itself. Further, its counting dead time and peak-to-background ratio are quite low, suggesting it consists mostly of low Z atoms, and its chemistry is essentially devoid of those major elements associated with geologic or pyrotechnic materials. Accordingly, with a high degree of confidence, this item is identified as being organic material. (The presence of an X-ray peak from gold is the result of the specimen having been sputter coated with gold for the purpose of facilitating the taking of a high resolution electron micrograph for this article. The same gold X-rays were produced by all of the particles being analyzed; however, when those particles produce higher X-ray count rates, the gold peak becomes much less prominent.) Particle four is roughly spheroidal, although it is elongated with a fairly pointed end. Accordingly, it has been conservatively designated as having a morphology that is indeterminate. Its counting dead time and peak-to-background ratio are quite low, suggesting it consisted of mostly of low Z atoms. While its chemistry appears to be much like that of particle (item) three, it has been conservatively designated as indeterminate because of the somewhat increased prominence of X-ray peaks most consistent with geologic material (calcium, silicon, magnesium and aluminum). Taking everything into consideration, with a reasonable degree of confidence, this particle could have been identified as being organic in nature; however, it was more conservatively designated as being *Non-PRR*.

Particle five is of non-spheroidal morphology, has a relatively high dead time, has a very high peak-to-background ratio, exhibits chemistry consistent with being silica sand, and has a chemistry that is quite inconsistent with being pyrotechnic. Further, samples taken from the cuff area of the clothing, well beyond the area of likely deposition of PRRPs contain many particles of the same chemistry. Accordingly, with a high degree of confidence, this particle is identified as being of geologic origin. Except for its spheroidal shape, particle six is like that of particle five. However, geologic particles, that have been mobile in the environment for a prolonged time, tend to become near spherical in shape. Accordingly, with a high degree of confidence, this particle is also identified as being of geologic origin.

In the case of this example, most of the particles cataloged were not PRRPs. As a practical matter, during an investigation it would be unusual to bother to document the nature of a high percentage of non-PRRPs. Typically, only enough of these particles would be analyzed and documented such as to reasonably represent the range of different non-PRRPs found. Instead, most of the time would be devoted to finding and analyzing PRRPs. In this way, while a few particle assignments may be less than certain, collectively, conclusions can be drawn with a high degree of confidence.

Conclusion

The use the SEM / EDS methodology to analyze PRRPs in the course of investigating accidents involving pyrotechnic materials can provide information with a degree of sensitiveness and specificity that is unavailable with other commonly used techniques. Given the wide spread availability of SEM / EDS instruments and the long history of the successful use of the same methodology in GSR analysis, it is somewhat surprising that the technique is not used more often in investigating accidents involving pyrotechnics. Obviously one reason for its infrequent use is that most accident investigations would benefit little, if any, from the type of information that could be developed. However, even for those accidents where PRRP analysis would be of great benefit, often that analysis is not performed. After speaking with pyrotechnic researchers and investigators, the authors have conclude the likely reason for its under use is simply that many investigators working outside of forensics are not sufficiently aware of the PRRP analysis methodology and the information it can provide. Therein lies the purpose of this introductory article, to disseminate some basic information about PRRP analysis to the scientifically oriented pyrotechnic community. Toward this same end, at least two additional articles are planned. One article will present much more information about the mechanics of specimen production, collection, and their subsequent analysis.[16] A second article will further demonstrate the nature and utility of the information produced by considering a series of investigations of actual and staged incidents.

Acknowledgments

The authors are grateful to M. J. McVicar, J. Giacalone and S. Phillips for providing technical comments on an earlier draft of this paper. The authors also acknowledge J. Conkling and R. Cole for commenting on portions of a draft of this paper.

References

1) R. S. Nesbitt, J. E. Wessel, and P. F. Jones, "Detection of Gunshot Residue by Use of the Scanning Electron Microscope", *Journal of Forensic Science*, Vol. 21, No. 3, 1976, pp 595–610.

2) ASTM: E 1588-95, "Standard Guide for Gunshot Residue Analysis by Scanning Electron Microscopy / Energy-Dispersive Spectroscopy", ASTM, 1995.

3) J. S. Wallace, "Chemical Aspects of Firearms Ammunition", *ATFE Journal*, Vol. 22, No. 4, 1990, pp 364–389.

4) H. H. Meng and B. Caddy, "Gunshot Residue Analysis—A Review", *Journal of Forensic Science*, Vol. 42, No. 4, 1997, pp 553–570.

5) R. L. Singer, D. Davis, and M. M. Houck, "A Survey of Gunshot Residue Analysis Methods", *Journal of Forensic Sciences*, Vol. 41, No. 2, 1996, pp 195–198.

6) J. Andrasko, "Identification of Burnt Matches by Scanning Electron Microscopy", *Journal of Forensic Science*, Vol. 23 No. 4, 1978, pp 637–642.

7) B. Glattstein, E. Landau, and A. Zeichner, "Identification of Match Head Residues in Post Explosion Debris", *Journal of Forensic Science*, Vol. 36, No. 5, 1991, pp 1360–1367.

8) P. V. Mosher, M. J. McVicar, E. D. Randall, and E. H. Sild, "Gunshot Residue-Similar Particles by Fireworks", *Canadian Society of Forensic Science Journal*, Vol. 31, No. 2, 1998, pp 157–168.

9) J. R. Giacalone, "Forensic Fireworks Analysis and Their Residue by Scanning Electron Microscopy / Energy-Dispersive Spectroscopy", *Scanning*, Vol. 20, No. 3, 1998, pp 172–173.

10) P. Mosher, "Fireworks as a Source of Gunshot Residue-Like Particles: An Overview", *Proceedings of the 4th International Symposium on Fireworks*, 1998, pp 275–281.

11) J. R. Giacalone, "Forensic Particle Analysis of Microtrace Pyrotechnic Residue", *Scanning*, Vol. 21, No. 2, 1999, pp 100–101.

12) S. A. Phillips, "Analysis of Pyrotechnic Residues—Detection and Analysis of Characteristic Particles by SEM / EDS", *Proceedings of the 2nd European Academy of Forensic Science Meeting, Sept. 2000*.

13) E. Fjeld Co., N. Billerica, MA, USA.

14) Kevex, Inc. Foster City, CA, USA.

15) American Nuclear Systems, Inc., Oak Ridge, TN, USA.

188) K. L. & B. J. Kosanke and R. C. Dujay, "Characterization of Pyrotechnic Reaction Residue Particles by SEM / EDS", *Journal of Forensic Science*, Vol. 48, No. 3, 2003.

16) J. I. Goldstein, D. E. Newbury, P. Echlin, D. C. Joy, A. D Roming, C. E. Lyman, C. Fiori, and E. Lifshin, *Scanning Electron Microscopy and X-Ray Microanalysis*, 2nd ed., Plenum Press, 1992.

17) R. E. Lee, *Scanning Electron Microscopy and X-Ray Microanalysis*, Prentice Hall, 1993.

18) K. L. & B. J. Kosanke and R. C. Dujay, "Pyrotechnic Particle Morphologies – Metal Fuels", *Journal of Pyrotechnics*, No. 11, 2000, pp 46–52; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

19) K. L. & B. J. Kosanke and R. C. Dujay, "Pyrotechnic Particle Morphologies – Low Melting Point Oxidizers", *Journal of Pyrotechnics*, No. 12, 2000, pp 5–15; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

20) D. L. Holmes, *Holmes Principles of Physical Geology*, John Wiley, 1978, p 46.

21) *Van Nostrand's Scientific Encyclopedia*, 5th ed., Van Nostrand-Reinhold, 1976, [a] p 1857; [b] p 400; [c] p 1012.

22) M. J. McVicar, "The Forensic Comparison of Soils by Automated Scanning Electron Microscopy", *Canadian Society of Forensic Science Journal*, Vol. 30, No. 4, 1997, pp 241–261.

An earlier version appeared in *Journal of Pyrotechnics*, No 14, 2001.

Hypotheses Regarding "Star-Shell-Detonations"

K. L. and B. J. Kosanke

PyroLabs, Inc., 1775 Blair Rd, Whitewater, CO 81527, USA

ABSTRACT

Fireworks star shells occasionally explode upon firing while they are still inside the mortar. Most often, this occurs with approximately the same level of violence as when the shell explodes after having left the mortar, and often even relatively weak mortars survive the experience intact. While unnerving to the firing crew, this represents relatively little hazard for crew or spectators. However, on rare occasion, the in-mortar star shell explosion achieves a level of violence substantially greater than normal. These more powerful explosions represent a potentially life-threatening hazard for both the firing crew and spectators. Unfortunately, the cause for these more violent explosions has not been definitively established, and without knowing the cause, relatively little can be done to prevent them from happening. In this article, two hypotheses are suggested as possible explanations for these dangerous malfunctions. Basic information and some empirical evidence are presented in support of two potential theories.

Keywords: aerial shell explosion, aerial shell malfunction, in-mortar explosion, flowerpot, star-shell-detonation, VIME

Preface

A large number of explanatory notes are included in this text. These are indicated in the text using superscript letters. (Literature references are designated by superscript numerals.) Hopefully putting the supporting and supplemental information at the end of the article will make the text easier to read by allowing readers to skip this information if they wish.

Introduction

Occasionally upon firing, a fireworks aerial shell explodes while it is still within the mortar. Of course, when the shell in question is a salute (maroon), the result is always a powerful explosion, generally with the potential to fragment even a steel mortar. However, for star shells, the vast majority of in-mortar explosions produce the malfunction generally known in the US as a flowerpot. This results in a relatively mild explosion with an eruption of the burning contents of the shell projected upward from the mouth of the mortar. Typically, for small diameter, single-break shells the mortar remains intact and produces a display appearing much like a fireworks star mine. For large diameter, single-break star shells, depending on the strength of the mortar,[a] the display may again appear much like a normal star mine. (However, if a relatively weak mortar fails to withstand the explosive forces, a mortar failure may allow some of the burning stars to proceed in directions other than primarily upward.)

For star shells, another more malevolent in-mortar explosive malfunction may occur, fortunately only on fairly rare occasions. In this case, the power of the explosion is much greater than that produced by a flowerpot, and most mortars will fail to withstand the explosive force, thus potentially producing dangerous mortar fragments. Traditionally, the accepted term for this malfunction is a *star-shell-detonation*. However, it is unlikely such explosions technically are detonations in the true high explosive sense. In recognition of this, some pyrotechnists are beginning to refer to this malfunction as a VIME (violent in-mortar explosion). In an attempt to be more generally correct, that usage has been adopted for this article. It is generally believed that the reason for the great power of these explosions is that most of the pyrotechnic content of the star shell is consumed in a much shorter span of time than is the case when the same type of shell flowerpots.[b] Because the shell's stars are apparently consumed in producing the explosion, they are not seen as a display being projected from the explosion.[c]

Some information in the literature[3,4] suggests that the cause of star shell flowerpots is the fairly catastrophic failure of the shell's casing upon firing, due to the reactive forces produced by the shell's rapid acceleration.[d] Unfortunately, however, little information suggesting the cause of VIMEs has appeared in the literature. There is the important suggestion by Brock,[6] based on research conducted in the late 19th century, that at least one cause for VIMEs was the result of using "badly made" ("crumbly") stars made with a chlorate oxidizer. The implication that chlorate-based stars can contribute to the cause of VIMEs is consistent with much of the speculation regarding their cause even today. Potassium and barium chlorate oxidizers decompose exothermally, a property shared with explosives in general.[e] Further, potassium chlorate has been used to produce truly detonable explosives in simple combination with small percentages of organic fuels.[f]

In contrast to potassium and barium chlorate, the decomposition of potassium perchlorate is approximately energy neutral, and the decomposition of potassium, sodium, barium and strontium nitrate are all substantially endothermic.[7] Nonetheless, there have been anecdotally reported VIME incidents thought[g] to have been produced by shells containing stars made using potassium perchlorate, and still other incidents were thought to have involved stars made using a nitrate oxidizer with a metal fuel. Accordingly, while chlorates may make it somewhat more likely that a mild in-mortar explosion (flowerpot) may transition into a much more violent explosion (VIME), it would seem that the presence of a chlorate is not essential.

Another clue to a possible cause of VIMEs was revealed recently during the investigation following a serious fireworks accident. During the course of testing, the open burning of some large comets occasionally produced powerful explosions.[10,11] These comet stars had previously been radiographed to confirm that they were composed of a single, substantially solid block of pyrotechnic composition (i.e., they did not contain internal explosive elements such as might be present in an intentionally exploding comet such as a crossette). The explosion of these comets while burning completely unconfined, and in particular the violence of these explosions, was quite unexpected. While attempting to formulate an explanation for these observations, an additional possibility regarding possible causes of VIMEs was formulated.[11]

These two possible causes of VIMEs are presented below, along with brief supporting discussions. About 10 years ago, the necessary test equipment and rough protocol for testing the first of these hypotheses were developed; however, to date, time constraints and other research projects have prevented pursuing this project. In addition, current research interests make it unlikely that the causes of VIMEs will be studied in this laboratory in the near future. Accordingly, and in the hope that someone else may be encouraged to pursue such a study, this article was written.

Weak Star Collapse Hypothesis

Most commonly, the individual particles in a fireworks star composition adhere to one another as a result of a binder that has been activated by the addition of a suitable solvent.[h] As a practical matter, all fireworks stars contain void spaces between the individual grains of the components in the mixture.[i] Figure 1 illustrates the porosity of two typical fireworks stars. The upper micrograph is of a rolled spherical color star; below that is a pressed aluminum comet star. Even though the two stars are substantially different in both their composition and method of manufacture, note the grain structure and void spaces (dark recesses) in both.

If something were to happen that would suddenly collapse these void spaces, the gas within the spaces would increase in temperature as a result of the mostly adiabatic compression.[j] (This is the same process that causes the ignition of the fuel in the cylinder of a diesel engine.) If the increase in void gas temperature were great enough, it is possible for this high temperature gas (*local hot-spot*) to cause an ignition of at least some of the surrounding pyrotechnic material.[k]

During the collapse of the star, frictional forces (shear) could also contribute to thermal

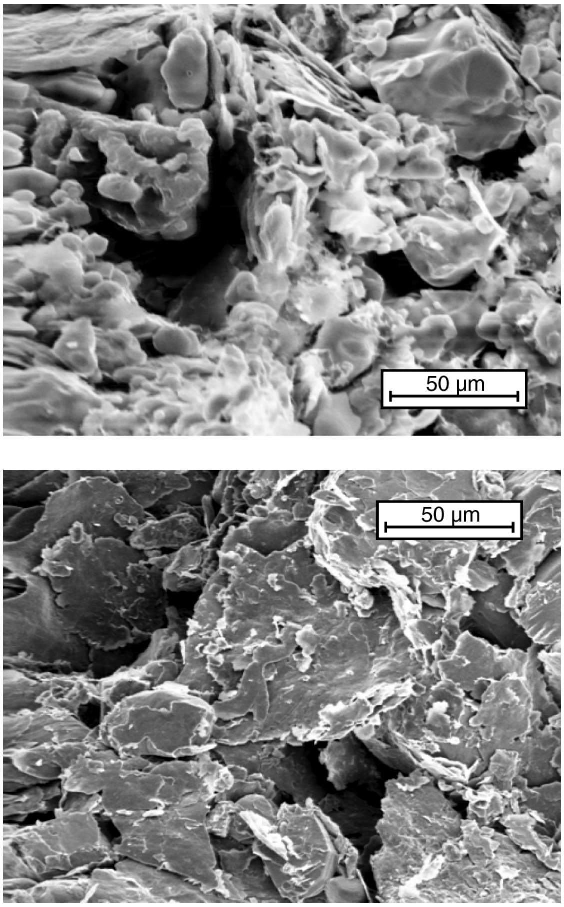


Figure 1. Electron micrograph of the internal structure of two substantially different firework stars. (Upper: rolled color star. Lower: pressed aluminum comet star.)

ignition as the grains of composition grind against each other. In addition, the penetration of burning gases from the burst charge, as the star is collapsing under the extreme pressure, must also contribute to the internal ignition of the star composition. In that way, the combination of adiabatic heating of void gas, plus the frictional heating from shear, plus the penetration of burning gas, might reasonably produce nearly simultaneous ignition of composition throughout much of the volume of the star.

When a star shell bursts (explodes) normally in the air, the peak internal pressure reaches a fairly high level before the casing fails and the contents are projected outward. However, based on the observation that most fireworks stars exit a bursting aerial shell in one piece, this peak pressure is obviously one that most well-made stars successfully withstand without being crushed.[l] If, instead, the shell explosion takes place within a mortar, the additional confinement provided by the mortar, must result in significantly greater pressure being produced within the exploding star shell. If this greater pressure is sufficient to cause the collapse of some of the stars in the shell, this might trigger a VIME. (This is the combined effect of the adiabatic heating of the gas in the pore-spaces, the frictional energy of the grains of composition grinding against one another, and the penetration of burning gases from the shell's burst charge into the interior of the stars.) As a result of the essentially simultaneous ignition of the entire mass of a few stars, the total pyrotechnic energy of those stars might then be released in a matter of milliseconds, instead of their normal several-second burn time. As a consequence of the additional, near instantaneous, release of energy from the collapse of a few stars, still greater pressures could result, which might then induce other stars to collapse, increasing the pressures even further, causing still more stars to collapse. In such a manner, essentially all of the stars in the shell might fail in a small fraction of a second, adding substantially to the power of the explosion, thus producing a VIME.

Weak Star Collapse Discussion

As explained above and in the notes, there is at least a theoretical basis to believe that the weak star collapse hypothesis could be one explanation for VIMEs. Further, the star collapse theory is consistent with Brock's observations about "crumbly" stars, along with anecdotal accounts of non-chlorate stars being capable of producing these powerful explosions. In considering the likelihood of an in-mortar star shell explosion producing a VIME, in addition to those things affecting a star's tendency to collapse, all of the other factors affecting pyrotechnic ignition and propagation must be considered. For example, ignition temperature, friction sensitiveness, heat of reaction, the degree of acceleration of burn rate with pressure,[m] etc., all are expected to play a role in determining whether an in-mortar shell explosion will be a flowerpot or a VIME.

With the weak star collapse theory as background, a couple of related areas deserve a little more attention. One topic relates to voids. The size of voids is important. This is because larger voids contain a greater mass of gas, thus offering the ability to produce and transfer more heat to the surrounding composition and in turn offering a greater potential for the internal hot-spot ignition of the collapsing star.[n] Larger voids also offer greater potential for frictional heating and ignition upon collapse. This is because, for a star with larger void spaces, there will be greater internal movement as the star collapses.

While the size of voids is a prime consideration, attention must also be directed toward the pressure acting to cause the star's collapse. With greater pressure, the amount of adiabatic heating, the shear forces, and the extent of penetration of burning gas from the burst charge will all be greater. Accordingly, smaller voids, under greater pressure, should produce similar results. In much the same way, the number of voids should be relevant, with a large number of voids offering a greater combined ability to produce and transfer heat. Accordingly, with both the size and number of voids as concerns, probably it is porosity (the percent void space) that is most important.

For cut stars, probably the amount of water present in the composition and the degree of consolidation of the *loaf* (block of moistened star composition) collectively play a role in determining the porosity of the stars. In this case excess water and poor consolidation would be expected to produce high porosity stars. For pressed stars, while the amount of moisture added must have an influence on porosity, the loading pressure (compacting force) is expected to have the greatest effect, with low loading pressure producing high porosity stars.

For rolled stars, the amount of water used must be kept fairly low, to keep the stars from sticking together during their manufacture. Nonetheless, there is a range of moisture content that is possible and that should also result in a range of porosities. Further, the degree of consolidation of rolled stars seems to depend on the amount of water being used, the amount of star composition added in each layer of the star, and the amount of time the stars tumble between additions of composition.[o]

This star collapse hypothesis is based on the premise that the cause of VIMEs may be the result of sufficiently weak stars with sufficiently great porosity. Accordingly, another topic deserving discussion relates to the structural strength of stars. The crush strength of the star will depend on both the type and amount of binder, as well as the solvent, used. Obviously, when too little binder is used, the star will be weak as a result of the individual particles not being well secured to one another. While the strength of the binder is important, and certainly not all binders are equally strong, there is little useful information in the pyrotechnic literature on this subject. Also the nature of the solvent used to activate the binder will affect star strength. For example, for water-soluble binders, sometimes a water and alcohol mixture is used to decrease the time needed for star drying. However, while drying times are reduced, it is suspected that using a water and alcohol mixture may result in reduced structural strength of the star because of a reduced effectiveness of the binder.

Strong Star Explosion Hypothesis

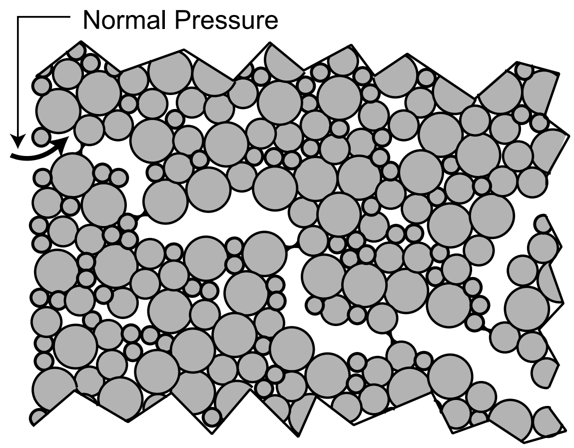
Imagine a situation where one has a fairly large star that is constructed such that the particles adhere to one another with great strength, producing a star that is quite hard and structurally very strong. In addition, assume that the star has features that under the right circumstances could produce fire paths to its interior. Such features might be the star having marginal permeability, such that its pore spaces are not sufficiently well connected to constitute effective fire paths to its interior when ignited under the pressures[l] experienced within a normally exploding aerial shell (i.e., when the shell is not exploding while still within a mortar). In that case, when the star is ignited on its exterior surface it will burn normally (non-explosively). However, if that same star is ignited during an in-mortar shell explosion, and if the greater pressures are now sufficient to force open the connection of the pre-existing void spaces, those void spaces might then become effective fire paths leading to the interior of the star. In that case, very quickly fire will race down the fire paths into the interior of the star producing ever increasing internal star pressure. Given the great structural strength of the star, the resulting internal burning might then be sufficient to cause the explosion of the star when the internal pressure finally exceeds the structural strength of the star. Further the power of the star's explosion will be greater if the star composition is sufficiently fast burning or if it has a sufficiently large pressure exponent,[m] such that the gas pressure inside the star rapidly accelerates to catastrophic (explosive) levels.

Strong Star Explosion Discussion

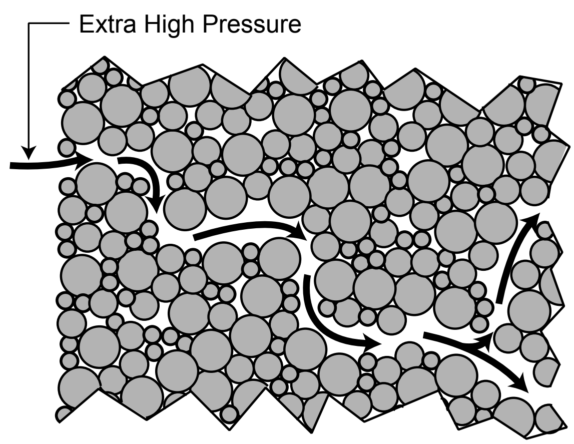
As explained above and in the notes, there is at least a theoretical basis to believe that the strong star explosion hypothesis might be another explanation for VIMEs. Further, this theory seems to be supported by some of the testing performed following a recent accident, wherein a number of incredibly violent comet star explosions were observed to occur during their unconfined burning.[10] A close examination of the interior of these comet stars revealed a level of porosity perhaps sufficient to be consistent with this strong star explosion theory. In addition, when properly functioning (non-explosive) comets were modified by increasing their permeability by drilling tiny channels into the center of the star, the stars exploded violently upon their unconfined ignition.

If the fire paths within a star such as described above are sufficiently well developed so as to allow the powerful explosion of the star when burning unconfined at one atmosphere, then it would surely do so under the conditions of a normal (not-in-the-mortar) shell explosion. Thus, it would not require the additional high pressures that must occur during an in-mortar shell explosion, and it would not seem to be a potential explanation of VIMEs. However, if the degree of permeability is not sufficient under these normal shell explosion pressures but could become sufficient during an in-mortar shell explosion, then it remains a potentially viable explanation. There would seem to be at least two ways this might happen.

The first way would be if the connection between the pre-existing pores is marginally blocked, such as might be caused by a relatively thin film of binder at various points along the length of the channel, see the upper illustration in Figure 2. If that were the case, the pores might not function as fire paths under the normal shell functioning pressures. However, under the higher in-mortar shell explosion pressures, these thin barriers to gas penetration might be breeched to then become continuous (fire paths), see the lower illustration in Figure 2. If so, these stars could behave properly during normal shell explosions but might still be the cause of VIMEs. Note that this scenario becomes more likely as the pressure exponent of the composition increases towards unity. This is because there would be a rapid further increase in pressure inside the channels themselves. As a minimum, this could act to force even greater penetration of fire into the star. Further, in general, the



[Channel with Blockages]



[Channel Forced Open]

Figure 2. Illustration of a possible star interior that initially (upper) has its pores blocked by thin films of binder, but which are forced to open (lower) upon exposure to the high pressures during an in-mortar shell explosion.

higher the pressure exponent, the less pressure is required to initiate explosive burning.

The second way stars might have such a dual mode of functioning has to do with the effectiveness of fire paths as a function of their diameter. Shimizu reports that the effectiveness of fire paths is a maximum for some diameter, but decreases to approach a constant value for large diameter fire paths,[p] and decreases to zero as the diameter of the fire path approaches zero,[15] see Figure 3. Based on general physical principles, a developing pressure gradient accelerates flame propagation down a fire path. Accordingly, consider the case where pores are minimally connected via tiny paths so narrow that they are ineffective as fire paths at the normal shell explosion pressures. However, the same minimally connected pores might serve as effective fire paths at the higher in-mortar explosion pressures. Note that a similar argument might be made for stars that have microscopic cracks in them, perhaps produced during drying or curing.[q]

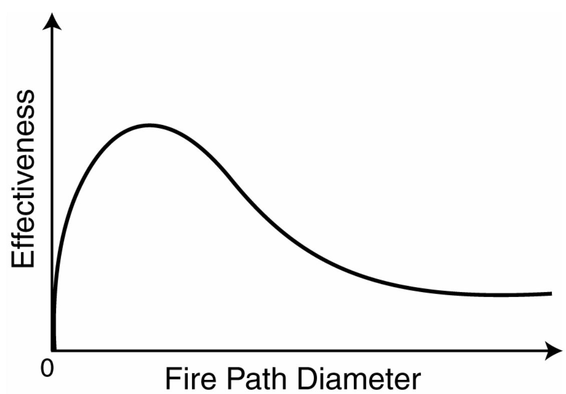


Figure 3. The effectiveness of fire paths as a function of diameter.[14]

Conclusion

Fortunately, VIMEs are considerably less common than the substantially less explosive (and thus less dangerous) flowerpot malfunctions. Nonetheless, because they can produce such powerful explosions, apparently rivaling those from salutes and salute containing shells, VIMEs continue to be a serious display crew and public safety concern. It is hoped that this article will provoke further discussion of the causes of VIMEs, possibly resulting in research to identify the actual causes of VIMEs.[r] Once the causes are determined, it should be possible for manufacturers to eliminate these most horrific of star shell malfunctions.[s]

Acknowledgments

The authors gratefully acknowledge E. Contestabile, B. Sturman, L. Weinman, and G. Laib for commenting on an earlier draft of this article. Also, the authors wish to thank Malcolm Smith for suggesting one of the references used in this article.

Notes

a) The pressure safety margin for many large diameter mortars is less than for small diameter mortars made of the same material. For example, the most commonly used 3-inch high density polyethylene (HDPE) mortars, firing typical spherical shells, have a pressure safety margin estimated to be perhaps as much as a factor of 16, whereas 12-inch (300-mm) HDPE mortars may have a pressure safety margin of no more than 2.[1]

b) Power is equal to the amount of energy produced during a given time interval. Thus, if roughly the same energy is produced, but it is produced in a much shorter period of time, this corresponds to much greater power. For a flowerpot, much of the pyrotechnic energy is produced over a number of seconds as the stars continue to burn after the explosion. For a VIME, while the duration of explosion has not been measured, it appears to be on the order of no more than a few tens of milliseconds (and possibly only a very few milliseconds). Accordingly, if the same total amount of pyrotechnic energy is produced by both the flowerpot and the VIME, the power contributed by the stars in the VIME will be on the order of at least 100 times greater than that from the stars in a flowerpot. (Presumably, the power produced by the shell's burst and lift charges will be mostly unchanged.)

c) While it is generally assumed that all of the stars within a shell are consumed during a VIME, it is possible that some (many?) of the stars are not consumed, but rather are "blown blind" (i.e., traveling so fast that they are not capable of remaining ignited as they leave the area of the explosion).[2]

d) Calculations, based on simple physics and the measured pressures during the firing of aerial shells, indicate that the peak acceleration of a shell is approximately 1000 times the acceleration due to gravity.[5] Inertial forces in response to such high acceleration rates, produce large and partially unbalanced forces on the casings of aerial shells. These forces can produce a more or less complete failure of the shell casing.

e) The energy produced upon the decomposition of potassium and barium chlorate are 0.34 and 0.38 kJ/g, respectively.[7] The energy produced by the explosive decomposition of tritnitrotoluene (TNT) is 4.4 kJ/g.[8] Thus the decomposition of these chlorate oxidizers, on their own without any fuel, produce roughly 10 percent of the energy that is produced by a common high explosive.

f) The typical formulation of some of these chlorate explosives (called "Cheddites") was approximately 9 parts potassium or sodium chlorate and 1 part hydrocarbon (often paraffin), and they produced detonation velocities of approximately 3000 m/s.[9]

g) The reason for including the word "thought" is that rarely is one completely certain of the actual contents of an aerial shell. For example, often when an aerial shell malfunctions, it is not known with certainty what type of aerial shell was involved. Further, even when it is thought that the type if shell can be identified by recalling the identifying label, there is no guarantee as to the actual contents of the shell. That is to say, it is a common experience of those performing fireworks displays to find that Chinese shells have been incorrectly labeled (e.g., shells labeled as producing one color display are found to actually produce some other color display).

h) The most commonly used binder in the US is dextrin. It is present as approximately 5% of the star composition and is activated by the addition of water. The water dissolves the dextrin, which, upon drying, then holds together the other ingredient particles in the composition. However, the first hypothesis for VIMEs applies equally well to non-aqueous binders and to pressure activated plastic flow binders.

i) Based on measurements of typical fireworks stars, the density of a star may be approximately 1.6 g/cm^3, whereas its maximum theoretical density (MTD) might be 2.0 g/cm^3. This means that such a star has about 20% void space (porosity). Although not well reported in the literature, the average percent MTD of cut stars is probably the lowest for stars made using common manufacturing methods; while the MTD of rolled stars is somewhat greater. For pressed stars, the percent MTD probably ranges from as low as for cut stars to more than that for rolled stars, depending in how forcefully the stars are compressed.

j) The temperature of a gas heated by adiabatic compression is given by

$$T_2 = T_1 \left({P_2}/{P_1} \right)^{(\gamma-1)/\gamma}$$

where T is absolute temperature, P is pressure, γ is the heat capacity ratio for the gas ($\gamma \sim 1.4$ for air), and subscripts 1 and 2 refer to the initial and final states, respectively.[12] While this equation is most useful, it is only an approximation, in that it assumes the process of compression is thermodynamically reversible and that it is for an ideal gas.[13]

k) Based on the equation in Note j, compression from atmospheric pressure to about 10 atm is sufficient to raise the temperature of air to over 450 °C. While many star compositions would easily be ignited at this temperature, that is not to say that a small mass of gas could transfer sufficient heat to raise the much larger mass of surrounding star composition to this temperature. However, compressions ranging up to 50 to 100 atm should be capable of transferring sufficient heat to a few tiny particles of star composition to cause their ignition.

l) One published value for the peak pressure inside a hard breaking Japanese style spherical aerial shell is approximately 4 MPa[14] (about 600 psi). At this pressure, a fireworks star that was a 1-centimeter (about 0.4-inch) cube would experience a force of 400 N (about 100 lbs) on each surface of the cube. Note that this is likely to be somewhat different from just squeezing a star on its two opposing sides with a 400 N force. It seems likely that a star pressed equally on all six sides at once is likely to be able to withstand a somewhat greater force than if that force is only applied to its two opposing sides. Consideration also needs to be given to the rapidity with which the gas pressure is applied and to the permeability of the star. If the pressure is increased somewhat gradually, over a sufficiently long interval, and the permeability of the star is sufficiently high, the externally applied pressure and that within the voids will more nearly have a chance to equalize, and the star is not likely to collapse.

m) The burn rate equation (also called the Vieille equation) expresses the relationship between pyrotechnic burn rate and local pressure.

$$R = A\,P^b$$

where R is linear burn rate, P is the pressure in the vicinity of the burning surface, and typically A and b are approximately constant over a moderate range of pressures. (However, these "constants" themselves are commonly pressure dependent when considering a wide range of burning pressures.) Further, if b (the pressure exponent) is sufficiently large, the increase in burn rate with pressure may easily accelerate to catastrophic (explosive) levels, even under conditions of minimal confinement.

n) The volume, and thus the mass, of gas in a void space is proportional to the cube of the effective radius of the void. Whereas the mass of composition immediately surrounding the void is proportional to the square of its effective radius. Thus the ratio of gas to surrounding composition mass increases with increasing void size.

o) While measurements of rolled star porosity were not actually made, the statements about those factors affecting the porosity (density) of rolled stars is based on the authors' significant past experience manufacturing rolled stars.

p) For large diameter fire paths, the rate of flame propagation drops to the rate of propagation across a normally exposed surface.[15]

q) Some binders shrink upon setting. For example, based on recollections of work performed by the authors in the distant past, polyester resins typically shrink by about 6% upon curing. As a result, upon drying or curing, some stars could possibly develop microscopic stress cracks. It would seem that the production of such stress cracks may be more likely to occur for large stars, with their larger dimensions and greater aggregate shrinkage. Further, for large stars there is a greater potential for differential drying to occur, wherein the exterior portions of the star dry (and shrink) before the center of the star dries. Based on more recent star manufacturing experiences of the authors, differential drying was observed to occur and did act to greatly increase the burn rate of the stars.

r) It is not intended to imply that the two hypotheses are necessarily mutually exclusive. It is possible that both could be occurring to some extent at the same time or at different stages of the same VIME. Also, it is certainly possible that there are other explanations of VIMEs that have not occurred to the authors at this time.

s) Experience suggests that fireworks mine effects experience VIMEs at least as frequently as do star shells. There is little reason to think that the mechanisms suggested for star shell VIMEs would not also apply to mines. On the one hand, the in-mortar pressures produced by normally functioning mine effects must certainly be less than the pressure within star shells functioning inside mortars (flowerpots). This fact potentially makes mine VIMEs less likely. However, all mines function within their mortars, whereas relatively few star shells flowerpot. This fact makes mine VIMEs more likely. The net result seems to be that mine and star shell VIMEs occur with approximately similar frequency.

References

1) PyroLabs, Inc., unpublished results from the test firing of massive and over-lifted shells from HDPE mortars, ca. 1990.

2) K. L. and B. J. Kosanke, “Stars Blown Blind”, *American Fireworks News*, No. 160, 1995; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999.

3) B. Ofca, *Fireworks Safety Manual*, B&C Associates, 1991, pp 13 and 32.

4) K. L. and B. J. Kosanke, “Hypothesis Explaining Muzzle Breaks”, *Proceedings of the Second International Symposium on Fireworks,* 1994; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996.

5) K. L. and B. J. Kosanke, “Peak In-Mortar Aerial Shell Accelerations”, *Journal of Pyrotechnics*, No. 10, 1999 ; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

6) A. H. Brock, *A History of Fireworks*, George G. Harrap, 1949, pp 179–180.

7) A. A. Shidlovskiy, *Principles of Pyrotechnics*, reprinted by American Fireworks News, 1997, pp 22–23.

8) R. Meyer, *Explosives*, VCH Verlagsgesellschaft, 1987.

9) T. L. Davis, *The Chemistry of Powder and Explosives*, 1943, reprinted by Angriff Press, pp 357–364.

10) *Investigation Report - Bray Park Fireworks Tragedy*, Queensland Government, Department of Natural Resources and Mines, 2001.

11) K. L. & B. J. Kosanke, G. Downs and J. Harradine, “Roman Candle Accident: Comet Characteristics”, *Fireworks Business*, No. 228, 2003.

12) F. P Bowden and Y. D. Yoffe, *Initiation and Growth of Explosion in Liquids and Solids*, Cambridge University Press, 1952, pp 33 & 35.

13) *Mark’s Standard Handbook for Mechanical Engineers*, McGraw Hill, 1978, p **4**-10.

14) Y. Takishita, H. Shibamoto, T. Matsuzaki, K. Chida, F. Hosoya, and N. Kubota, “Burst Process of Spherical Aerial Shells”, *Journal of Pyrotechnics*, No. 10, 1999, p 3.

15) T. Shimizu, *Fireworks, From a Physical Standpoint, Part I*, reprinted by Pyrotechnica Publications, 1981, p 16.

An earlier version appeared in *Fireworks Business*, No 213, 2001.

Chlorate Compositions in Quick Match

K. L. and B. J. Kosanke

After the 1999 PGI convention, the authors were told about a type of quick match that had been sold at the convention and which was suspected of being made using a chlorate oxidizer. The individual's suspicion was based on his perception of its extremely fast burn rate. Subsequently, a sample of that fuse was spot tested and found to contain a nitrate but not a chlorate. Sometime later, the authors were given a sample of quick match thought to be of the same type. The burn rate of the quick match was observed to be most vigorous; however, there was not a sufficient amount for the authors to make a usefully quantitative measurement of its burn rate. Small amounts of the composition were removed from the black match portion of this fast burning quick match, and two tests for the presence of chlorate were performed. The first test was the concentrated hydrochloric acid test, in which a few drops of the acid are placed on the composition. The presence of a chlorate is revealed by a modest rate of chlorine dioxide gas production, with its characteristic color and odor.[1,2] The second test was the analine-HCl spot test, in which some of the composition is dissolved in a tiny amount of water, the water is decanted and treated with a drop of analine-HCl test reagent.[1,3] The presence of a chlorate is revealed by the appearance of first a red then blue color. Again, both test results were negative for the presence of a chlorate. Accordingly, another possible explanation for the vigorous burn rate of the quick match was sought.

The design of the quick match was typical of the fuse seen in recent years being used on some higher quality products from China. The fuse had a series of 5 individual strings, each of which was well coated with a pyrotechnic composition that remains noticeably more flexible than that of traditional products. These strands were laid side by side and surrounded with match pipe that was quite flat. This configuration is illustrated in Figure 1 and identified as *Recent Chinese*. This manner of construction is in contrast to the configuration most commonly used in the US (also illustrated in Figure 1 and identified as *Typical US*), in which the collection of strings are coated as a group with a Black Powder slurry and forming a somewhat rounded grouping of the strings.

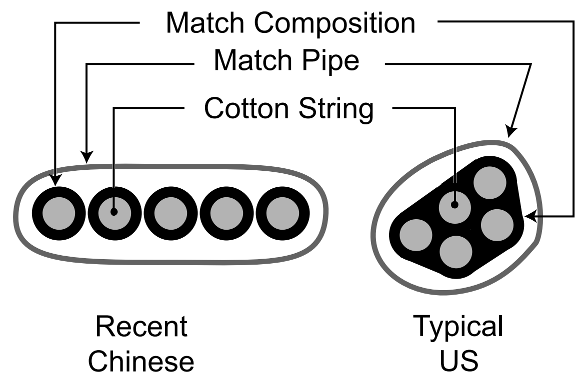


Figure 1. Illustration of the configuration of two types of quick match.

One significant difference between the two configurations is the total amount of surface area of exposed black match composition. For the Recent Chinese fuse, the surface area is proportional to $5\pi D$, where D is the diameter of each individual black match strand. Based on measurements of typical US black match, the overall diameter for the group of threads is typically no more than about $3D$, thus giving a surface area proportional to no more than about $3\pi D$. Accordingly, the Recent Chinese fuse has nearly twice the burning surface area. If it is assumed that the compositions are otherwise effectively the same in their burning characteristics, the Recent Chinese fuse will produce nearly twice the quantity of flame as does Typical US black match. Based on our understanding of the manner of functioning of quick match,[4,5] the greater volume of flame produced will result in a greater *initial* rate of burning for the quick match. (Ultimately, the rate of burning of unobstructed quick match is mostly determined by the strength of its match pipe.)

The Recent Chinese quick match has another property that may cause it to appear to be especially fierce burning. The method generally used to slow the burning of quick match is to close the fire path between the black match and the match pipe. This is found to work well for the Typical US quick match, where the closure of the match pipe around the central black match can easily be made with a moderately tight wrap of string, and which causes approximately a ¼-second delay.[6] On the other hand, when the same method is attempted with the Recent Chinese style of quick match, it will be most difficult to get a complete closure of the fire paths. This is because small spaces (fire paths) between the individual strands of black match will persist (see Figure 2), unless the composition on the black match strands is sufficiently crushed to completely fill the gaps. Accordingly, this type of quick match will be quite difficult to slow using the normal methods of fire path closure. Accordingly, this also probably suggests to users that its burning is especially fierce.

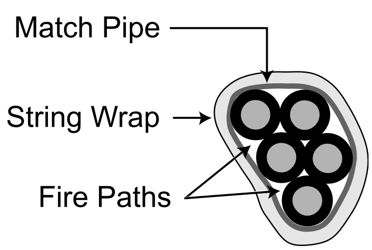


Figure 2. Illustration of the difficulty of closing fire paths to slow the burn rate of the Recent Chinese quick match.

Although it is somewhat understandable that this Recent Chinese quick match was suspected of having been made using a chlorate oxidizer, both its high burn rate and the difficulty with slowing its burn rate can be explained based on its manner of construction. Over the years, the authors have tested many suspect samples of quick match. However, except for a type of quick match used on Horse Brand shells for many years (and possibly still today), none of the others was found to contain chlorates. (Note that is not to say that no quick match ever has been or is being made using a chlorate oxidizer, just that we have not found any except for Horse Brand shell leaders.)

Figure 3 is an illustration of one form of the Horse Brand fuse found to contain a chlorate oxidizer. The quick match shell leader contains two fuse elements. One is a somewhat conventional strand of black match, although it tends to be made of a single thicker strand of fairly coarse cord and to which the powder coating tends to adhere only poorly. This powder coating is found to contain no chlorate, but it is found to contain sulfur and presumably is hand-made Black Powder. (In some cases, especially on larger shells, this quick match has two strands of black match.) The second fuse element is a single (but sometimes double) strand of so-called Chinese fuse, made with a powder core wrapped in tissue paper, which is similar to the type of fuse typically used on small firecrackers. It is in this Chinese fuse that the chlorate oxidizer is found to be present.

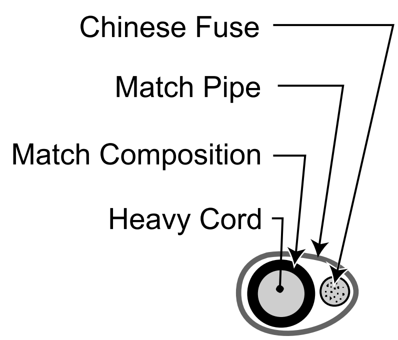


Figure 3. Example of one type of Horse Brand quick match shell leader found to contain a chlorate oxidizer.

The problem with the presence of chlorate in one element of this Horse Brand fuse is exacerbated by the presence of sulfur in the other element. When this fuse is cut or the Chinese fuse becomes sufficiently damaged through handling, there will be a commingling of the chlorate and sulfur compositions, with all the sensitiveness problems that are known to result.[7,8] (For example, in some recent testing of the impact sensitiveness of these Horse Brand fuse compositions, the combination of the two compositions was found to be 2.5 times as sensitive as the rough Black Powder composition alone.) Over the years, there have been a number of serious accidents thought to have been caused by this fuse.

Acknowledgment

The authors are grateful to S. Majdali for initially identifying the suspect quick match (sold at the 1999 PGI convention) and for performing the initial spot tests that identified the lack of chlorate and the presence of nitrate in the fuse composition. We also wish to thank R. Fullam for providing a sample of quick match for our laboratory testing.

References

1) R. Winokur, "Some Easy Spot Tests for Qualitative Analysis of Pyrotechnic Compositions", Pyrotechnics Guild International Convention Seminar, 1985, p 1.
2) F. A. Cotton and G. Wilkenson, *Advanced Inorganic Chemistry*, Interscience Publishers, 1966, p 566.
3) W. S. Majdali, "A Selection of Spot Tests for Qualitative Analysis of Pyrotechnic Compositions", *Pyrotechnica XVII*, 1997, p 30.
4) T. Shimizu, *Fireworks, From a Physical Standpoint, Part I*, Pyrotechnics Publications, 1981, pp 11–16.
5) K. L. & B. J. Kosanke, "Quick Match: Its Construction and Manner of Functioning", *American Fireworks News*, No. 221, 2000.
6) K. L. & B. J. Kosanke, "Quick Match: Methods of Slowing its Burning", *American Fireworks News*, No. 222, 2000.
7) C. Jennings-White and K. L. Kosanke, "Hazardous Chemical Combinations", *Journal of Pyrotechnics*, No. 2, 1995, pp 23 and 26; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999..
8) J. A. Conkling, *The Chemistry of Pyrotechnics*, Marcel Dekker, 1985, pp 56, 59 and 109.

An earlier version appeared in *American Fireworks News*, No. 242, 2001.

Faversham's Gunpowder Mills

B. J. and K. L. Kosanke

Recently, while in the United Kingdom and between teaching pyro-chemistry short courses, we took a side trip to visit the restored Chart gunpowder mill. This is the only restored mill from what was once a collection of approximately ten powder mills near the town of Faversham in Kent county. When operating at their peak in 1792, these mills produced over 25,000 barrels of powder.

The first of the Faversham powder mills was established near the head of Faversham Creek sometime in the 1500s. The number of mills in Faversham increased over the years because of a combination of favorable factors. Faversham was already an established coastal port, located at the head of its tidal creek. This allowed relatively easy access to the imported components of the powder; sulfur from Italy and Sicily and potassium nitrate from Italy and India. Because Faversham Creek is a tributary of the Thames, this location also provided for the safe delivery of the completed powder, via a water route, to the Royal Arsenals in London. Faversham had an ample supply of water power and the local terrain was reasonably flat to facilitate the construction of the diversion channels, ponds, sluices and their control mechanisms needed to deliver a reliable supply of water to the mills' water wheels. Finally, there was a local forest to provide suitable wood for making charcoal and to provide a level of blast protection to nearby structures.

The general design of the incorporation mills was all somewhat similar. Most commonly, there was a central water wheel, to which water was delivered from below. The water wheel fed power via an arrangement of overhead gears to two edge-runner incorporation mills, one on each side of the central water wheel, thus tending to balance the load and resulting forces. A fairly typical arrangement is illustrated in Figure 1, where the water wheels (W), incorporation mills (I), water flow control structures (C), and blast walls (B)

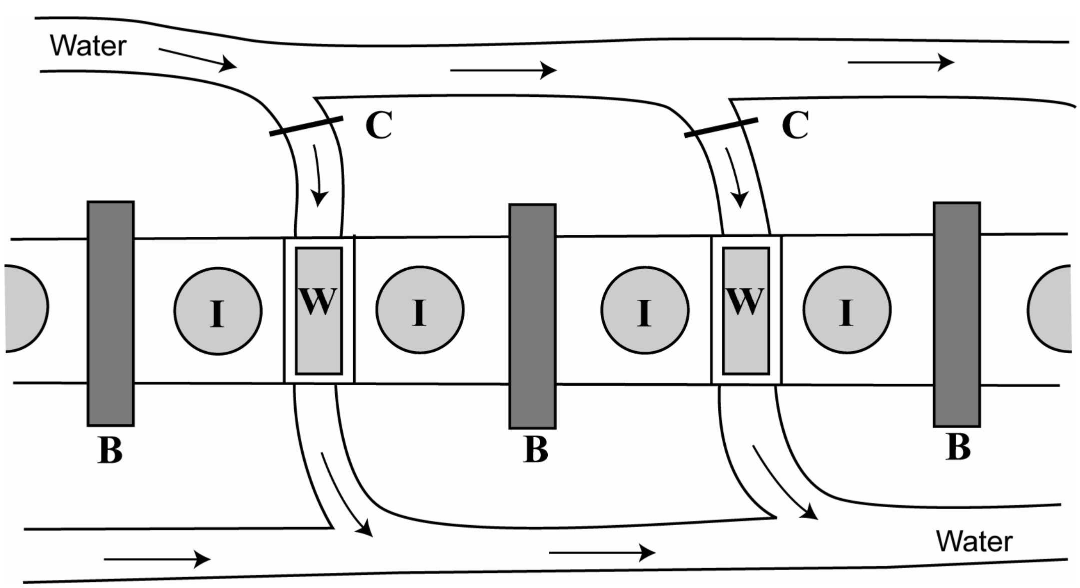


Figure 1. An illustration of a somewhat common layout of incorporation mills, where the W's are the central water wheels (fed from below), the I's are the individual incorporation mills, the B's are heavy stone blast walls, and the C's are water flow control structures.

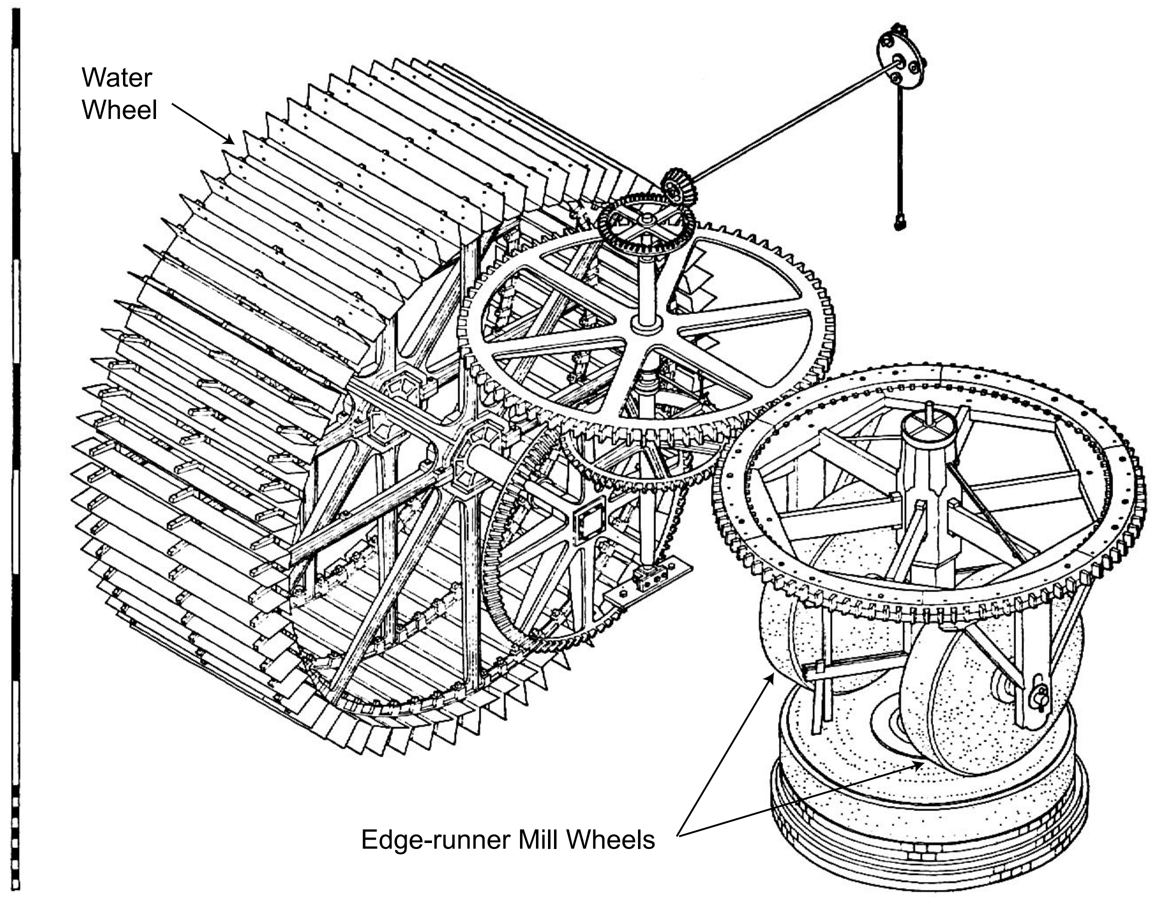


Figure 2. A detailed illustration of the mechanics of the reconstructed Chart incorporation mill in Faversham, England. (Each large scale unit to the left in the drawing is one meter.)

are shown. (Note that in some designs, blast walls were also located on either side of each central water wheel.) The wooden buildings of the mills then extended between the heavy stone blast walls.

A more detailed view of a water wheel, the overhead arrangement of gears and one incorporation mill with its pair of mill wheels is shown in Figure 2. The edge-runner mill wheels are suspended slightly above the lower surface of the mill (a heavy iron pan) with the load of powder caught and worked in the narrow space between the wheels and the pan. The wheels are mounted slightly asymmetric with respect to the angles with which their individual central shafts (horizontal) meet the main vertical shaft of the incorporation mill. This arrangement forces the charge of powder slightly toward the outside edge of the mill with each pass of the wheels. The powder is continually brought back under the mill wheels using wooden plows (not well illustrated in Figure 2). The overall action of the milling is a combination of particle size reduction and intimate mixing (i.e., incorporation) of the dampened powder.

Although impressive, the incorporation mills are only a small part of the powder manufacturing operation. To begin with the raw materials must be prepared. In the 18th century, the raw potassium nitrate needed refining through recrystalization; however, eventually the purity of the material supplied improved to the point where it could be used just as it came from the refineries. The needed charcoal was manufactured on site, using the normal destructive distillation process. Also, the raw sulfur was refined on site in a distillation process.

The charcoal and refined sulfur were first milled together, and then combined with the refined potassium nitrate. This *green powder* was moistened and charged into the edge runner mills. The process of incorporation took two hours for blasting powder and eight hours for the finer sporting powders, during which time the moisture content was maintained between approximately one and six percent, depending on the stage of the processing and the type of powder being produced. Following this milling, the *mill cake* (more commonly called *wheel cake* in the US) was removed using wooden implements and placed in trays to form layers of powder, which were then pressed to higher density using a mechanical press. The resulting *press cake* was then broken into the near final granulations in a process called *corning,* wherein the powder was passed between a pairs of wooden rollers with a gap between them. Following the corning process the powder was dried in a chamber heated by the backside of an iron fireplace. The next process was *glazing.* Prior to the 1800s, glazing merely consisted of tumbling the powder to remove its sharp edges and to have some of the dust being produced pack into exposed pores in the powder. Later glazing often included the use of graphite to lightly coat the powder grains, making the powder flow more freely and also providing a greater degree of moisture protection for the powder. The final process before packaging was the sieving of the powder into the various granulations. (It might be of interest to note that the largest number of employees in the mills were not used in making powder, but rather they worked in the cooperage, making the barrels into which the powder was loaded for shipment.)

Figure 3. An example of an advertisement of Black (gun) Powder from one of the oldest mills at Faversham.

During the period from the construction of the first mill at Faversham in the 1500s until 1759, all of the mills at Faversham were operated by private manufacturers. (See the advertisement included as Figure 3.) In 1759 the British government ceased relying on the private sector for its supply of powder and acquired all of the Faversham mills. In the half century thereafter, the government acquired much of the country's remaining private powder mills. Based on accounts of fatalities in the country's gunpowder industry, this would seem to have been a good thing. During the period of government acquisition, the annual number of fatalities in the gunpowder industry decreased from approximately 43 to 7 per year. While the greatest number of accidents occurred in the incorporation mills, the most serious accidents and the greatest loss of life occurred in the pressing and corning operations.

The authors gratefully acknowledge the Faversham Society for supplying some of the information for this article and for granting permission to reproduce the figures in this article. In addition, a large amount of the information in the article has come from the booklet, *The Gunpowder Industry*, by Glenys Crocker, Shire Publications, 1991.

An earlier version appeared in *Fireworks Business*, No. 214, 2001.

Floating Dud Aerial Shells

K. L. and B. J. Kosanke

Introduction

Over the past 25 years, the percentage of spherical aerial shells that fall to the ground as duds after firing has substantially decreased. (This is especially true for shells from China.) Obviously this is a good thing, and it is a result of such things as improvements in the quality of the time fuses being used and the methods of their priming, and because of the near universal adoption of redundant fusing techniques.[1] However, the improvement has not been so great as to reduce the percentage of dud shells to zero. Nonetheless, the reduction in the number of dud shells, in conjunction with the use of substantially increased separation distances introduced approximately 15 years ago,[2] combine to afford a high level of spectator protection from dud shells during typical displays.[3,4] Further, the increased attention to dud searches both immediately following and at first light on the morning after land-based displays has mostly eliminated accidents resulting from dud shells left behind to be found by children.

With the reduction in the number of dud shells and the virtual absence of accidents from unrecovered dud shells from displays fired over water, it is appropriate to ask why a study of floating dud shells was undertaken. In part the answer is that: nearly all dud shells do float for a period of time after landing in water; dud searches are essentially never done for displays fired over water; most dud shells are virtually impossible to find in water at night, and by the next morning they will have drifted some distance from where they fell; and even after a shell eventually sinks, its pyrotechnic contents will generally remain viable or will become viable again after minimal drying. Thus, in part the answer is that there is potential for a serious accident resulting from unrecovered dud shells from displays fired over water, and it is hoped that this study and article will raise awareness of this potential.

However, it must be acknowledged that a significant impetus for this study was simple curiosity. It was of interest to determine, for typical non-plastic spherical aerial shells: the percentage of shells that initially float; for those floating shells, how much of their volume remains above the water's surface and how long before they eventually sink; and even after sinking, how likely is it that their contents have remained pyrotechnically viable? According, a brief study was undertaken in an attempt to satisfy this curiosity.

Results

A collection of 26 aerial shells (3 inch through 6 inch) were devoted to this study, none of which had a plastic casing. Of these 26 shells, only one sank immediately (i.e., was initially more dense than water). For those shells that initially floated, the percentage of each shell's volume above water was determined by comparing its volume, as calculated by its average diameter, with its measured mass. The result was that the 25 shells floated with 1 to 34 percent of their volume above the water's surface. The average volume above water was 17 percent, with a one-sigma standard deviation of 10 percentage points. Accordingly, with relatively little of the shells' volume above the water, such floating shells will be difficult to spot, even in completely calm water.

The first group of 19 shells to be tested had their time fuses intact, as though their time fuses had failed to ignite when the shells were fired, or had only burned for a short portion of their length before extinguishing. These shells were placed in water in an environmental chamber held at 70 °F, a temperature thought to be reasonably representative of northern lakes in early to mid summer. In this study, for the most part, the shells were not agitated during the period of their floating, contrary to what would typically occur because of wave action on real bodies of

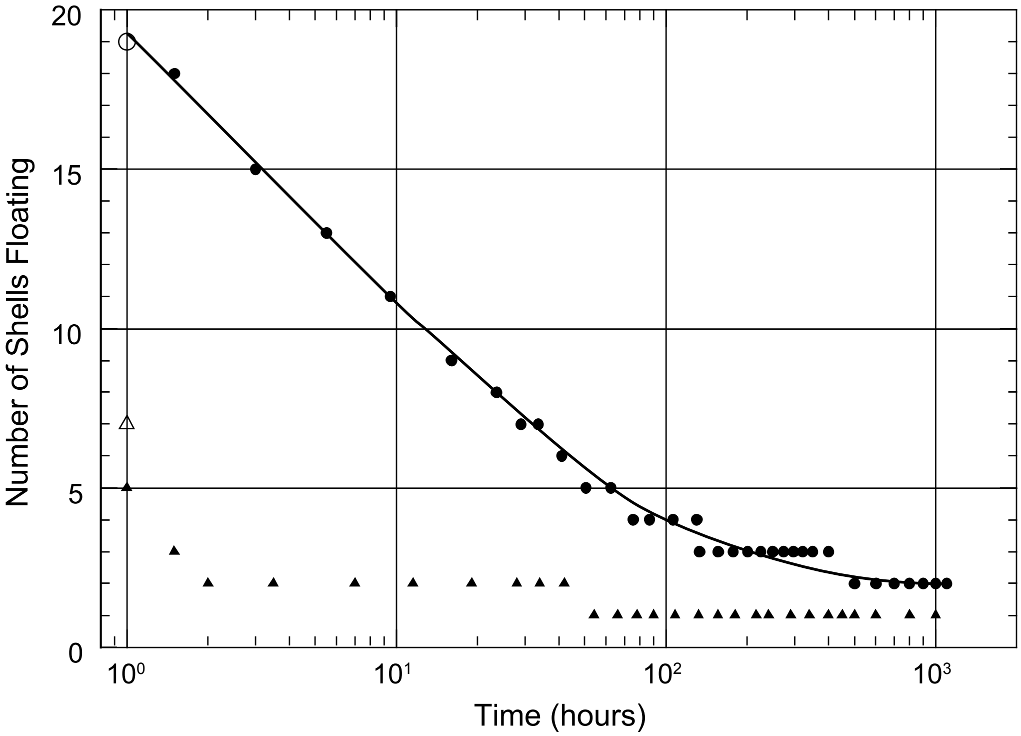


Figure 1. Number of shells floating as time progressed. (Note that time is plotted using a logarithmic scale.)

water. However, at the time of each shell inspection, each floating shell was momentarily submerged a few times using simple hand pressure. For the most part this bobbing of the shells was to confirm that they were still freely floating, but it was also done to introduce a minimal amount of agitation. It must be expected that the near total lack of agitation slowed the process leading to the shells' sinking. Further, for these tests, the total volume of water used was approximately 4 times that of the shells being tested. Although not as significant as the lack of agitation, this too must have slowed the process of sinking, because of a slightly reduced rate of glue dissolution. Finally, the relative humidity in the chamber was 100 percent. This, combined with the occasional dunking of the shells, possibly hastened their sinking slightly. While it is unfortunate that the conditions in this study were not those for shells actually floating in large bodies of water, this was mostly necessitated for practical reasons. Nonetheless, the results from this study still provide a useful approximation of typical shell float times, albeit somewhat of an upper limit.

The float times found for these test shells, under the conditions of this study, are presented in Figure 1 (solid dots). However, since the shells were not being monitored continuously, the precise times of their sinking are not known. The times reported in Figure 1 are for the midpoint between pairs of observations. Accordingly, when 18 shells were found to be floating one hour into the test, but only 17 were floating at two hours, the sinking was reported as happening at 1.5 hours into the test. Also in Figure 1, as a matter of convenience, the number of shells at the start of the test is plotted as an open dot at a time of one hour (10^0), even though one shell sank immediately. During the first couple of days of the testing, the number of floating shells decreases logarithmically. Also note that approximately 10 percent of the shells never did sink, even after 48 days at which time the test was ended.

In general, the shells that sank within the first day or two, more-or-less came totally apart, with the pasted wraps coming completely free from the inner hemispherical casing. Those shells that floated longer, for at least a couple of days, generally stayed mostly intact and seemed to have sunk because of moisture penetrating to their interior and accumulating there. A few of these shells appeared to have been coated with a water resistant coating, but most seemed to have been made using a somewhat water resistant adhesive for the pasted wraps.

Not shown in Figure 1 is the fact that one shell, which sank approximately 500 hours into the test, surfaced again within approximately another 100 hours. The resurfacing of the shell seemed to be fairly obviously the result of gas production within the shell as evidenced by the appearance of tiny bubbles. Also the two shells that never did sink appeared to be producing gas internally. For several of the floating and sunken aerial shells, gas production seemed to be the result of biologic activity, presumably from bacterial growth within the paste wraps of the shell. While not confirmed, this is consistent with previous electron microscope observations of what appeared to be several forms of microbial entities, frequently seen associated with the paste on completed aerial shells. In other cases, gas production seemed to be the result of water reactions with metal fuels in the stars of the shells.

A second smaller set of 7 aerial shells was also tested. These shells had the powder core of their time fuses carefully drilled out, in an attempt to simulate dud shells for which their time fuses had burned completely, but the fuse had failed to successfully ignite the contents of the shell. Other than the drilling of their time fuses, the remaining test conditions were not changed from those reported above. The results of this second test are also reported in Figure 1, this time as solid triangular points. As expected, these shells seemed to sink at a faster rate than those with intact time fuses. However, because the number of shells tested was rather small, how much faster the sinking would typically occur it is not clear. Nonetheless, one clear result is that, as for the first series of tests, some shells must still be expected to float for extended periods of time.

The condition of the pyrotechnic content of several shells was inspected after their sinking, and the contents were tested for viability. The inspections took place anywhere from a few hours to 4 days after the shell's sinking. In essentially all cases, the contents remained pyrotechnically viable, either immediately or after a relatively short interval of drying. The viability test consisted of attempting to ignite the stars or break charge with a propane torch. In a few cases, the contents were readily ignitable (ignited after less than one second of exposure to the flame). In other cases the contents failed to ignite within a second but ignited within a few seconds. Even when the contents would not initially ignite, they returned to a viable state after a day of air drying. The above observations were for stars were made using a water-soluble binder. In a few cases, it appeared that the stars had been made using a nonaqueous binder. Of course, the viability of these stars was not significantly affected by their exposure to moisture.

Conclusion

Thankfully, it cannot be said that the failure to search for and retrieve dud shells from fireworks displays fired over water, represents a major safety problem. Because so little of the shells remain above water, it cannot be seriously argued that a nighttime marine search is likely to find many (any?) dud shells. Further, those dud shells that do not sink overnight are likely to be relocated some distance from the fallout area of the display as a result of wind and water currents. Thus, a first light search the morning after a display is also not likely to find many (any?) dud shells in the fallout area. Nonetheless, because there is potential for a problem with non-sinking dud shells, it is difficult to argue that absolutely nothing should be done.

One possibility, at least for non-river fired displays, is to search the shoreline in the downwind direction on the morning after the display. (For ocean-fired displays, consideration will need to be given to the direction of any along shore currents.) At least, such a search could be performed fairly quickly, because any dud shells will tend to be concentrated immediately along the shore and because of the relatively limited length of shore line needing inspection. For river-fired displays, there seems to be little that might be done to locate floating duds. However, one potential solution for any over-water display would be to only use shells that can be expected to sink well before dawn. Accordingly, any shells with a painted or varnished exterior would not be suitable. Further, shells that are pasted with water resistant adhesives would not be suitable. Unfortunately, the only sure way to identify rapidly sinking shells is to test the shells (or fragments from their exploded casings) by soaking them in water for a few hours and observing the result.

References

1) K. L. and B. J. Kosanke, "Reduction of Shell Ignition Failures", *American Fireworks News*, No. 83, 1988; also in *Selected Publications of K. L. and B. J. Kosanke, Part 1 (1981 through 1989)*, Journal of Pyrotechnics, 1996.
2) *Code for the Outdoor Display of Fireworks*, National Fire Protection Association, NFPA-1123, 1990.
3) K. L. and B. J. Kosanke, "Dud Shell Hazard Assessment: NFPA Distances", *Fireworks Business*, No. 179, 1998; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.
4) K. L. and B. J. Kosanke, "Dud Shell Hazard Assessment: Mortar Placement", *Fireworks Business*, No. 180, 1999; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

An earlier version appeared in *Proceedings of the 6th International Fireworks Symposium*, 2001.

Study of the Effect of Leg Wire Attachment on the Burst Height of Aerial Shells

K. L. Kosanke
PyroLabs, Inc., 1775 Blair Road, Whitewater, CO, USA

and

B. J. Kosanke
Journal of Pyrotechnics, Inc., 1775 Blair Road, Whitewater, CO, USA

ABSTRACT

In many electrically discharged fireworks displays, it is a common practice to securely attach the electric match leg wires to both the aerial shell and to the firing mortar or mortar rack. When this is the case, it is necessary for the aerial shell to sever the attachment to the mortar or rack upon the firing of the shell. Usually this is accomplished by severing (tearing) the leg wires themselves. In this process, some of the kinetic energy of the shell is consumed, resulting in a reduction in the burst height that would otherwise have been achieved. This reduction in burst height will be greatest for those shells possessing the least kinetic energy (i.e., the smallest and lightest of the aerial shells). While experience has shown that the amount of reduction in burst height apparently does not present a significant safety hazard, the question remains as to how much reduction actually results. In a brief study of this question, it was concluded that for even the smallest and lightest aerial shells commonly used in displays (75 mm with a mass of 90 g) the reduction in burst height is on the order of 12%, and this decreases to about 1% for mid-sized aerial shells (150 mm with a mass of 1.1 kg).

Introduction

After loading fireworks aerial shells into their mortars for firing electrically, it is a common practice to firmly secure the electric match leg wires to the rack or mortar (a process often called *short wiring*). One purpose of this is to prevent the leg wires attached to one shell, from dislodging the leg wires attached to other shells, when the first aerial shell is fired. Further, to achieve a high degree of aerial shell burst time precision,[1] electric matches are often installed either into the quick match at a point close to where it enters the lift charge or directly into the lift charge itself. When this is done, it is common for the electric match leg wires to be securely attached to the aerial shell itself.

In those instances where solid leg wire attachments have been made to both the rack and the shell, it is necessary for the aerial shell to break the leg wire tether upon firing. Often this is accomplished by a breaking (tearing) of the leg wires themselves, a process that must reduce the shell's upward velocity and thus the height achieved by the aerial shell.

From time to time, pyrotechnists have pondered the extent of that burst height reduction. Obviously, the effect will be the greatest for small spherical shells that have lower amounts of kinetic energy. However, even for the smallest commonly fired spherical aerial shells (75 mm or 3 in.), common experience has shown that the reduction in height is not so great that it represents a substantial safety risk from low breaking shells. Nonetheless, the question remains as to the amount of reduction that occurs. Toward satisfying such curiosity, a brief study was conducted to determine the reduction in the height achieved by small caliber (75-mm or 3-in.) aerial shells that had to sever their electric match leg wires upon exiting the mortar after firing.

Table 1. Results from Time of Flight Measurements for Test Aerial Shells.

Leg Wire Attachment Method	Average Time of Flight (s)	Std. Dev.[(a)] (s)	Std. Error[(b)] (s)	Muzzle Velocity[(c,d)] m/s (ft/s)	Approx. Height Reached[(d)] 1400 m (4600 ft)[(e)] m (ft)	300 m 1000 ft[(e)] m (ft)	3 sec.[(f)] m (ft)
Wires Free	10.09	0.58	0.16	84.5 (277)	122.6 (402)	113.4 (372)	107.6 (353)
Wires Break[(g)]	9.38	0.65	0.17	72.6 (238)	106.4 (349)	98.8 (324)	95.1 (312)
Difference	0.71	—	—	11.9 (39)	16.2 (53)	14.6 (48)	12.5 (41)

a) The standard deviation was determined using the $n - 1$ method.

b) The standard error was reported as the standard deviation divided by the square root of the number of measurements.

c) The muzzle velocity was calculated to be that needed to produce the observed flight time for the test shells fired at 1400 m (4600 ft) above sea level, which is the elevation of the test facility being used.

d) More significant figures are being carried than might be justifiable. While it is thought that the relative accuracy of these data is fairly good (probably to within a percent or two), the absolute accuracy is not as good (perhaps no better than about 10 percent).

e) The approximate shell height attainable at the elevation above sea level indicated, assuming shell does not burst prior to that.

f) The approximate shell height attained after 3 seconds of flight at 300 m (1000 ft) above sea level.

g) The attachment of the leg wires was sufficiently strong to cause them to tear, as was confirmed by inspection after each firing.

Experimental

Typically, even for just one size aerial shell, there is a considerable range in shell characteristics (lift charge type and amount, shell diameter and mass, etc.). As a result, upon their firing, shells possess a considerable range of kinetic energy. The test shells used in this study had characteristics chosen to be representative of 75-mm (3-in.) aerial shells producing only relatively modest kinetic energy (such that they would be more greatly affected by having to sever their leg wire attachments).

The test shells used in this study were all 75-mm (3-in.) inert spherical plastic shells with an actual diameter of 66 mm (2.62 in.) and weighing 90 g (3.2 ounces). Each lift charge contained 14 g (0.5 ounce) of Goex[2] 4FA Black Powder and was ignited using a Daveyfire[3] SA2000 A/N 28 B electric match inserted into the approximate center of the lift charge.

For one collection of 16 aerial shells, the electric match leg wires were firmly attached to the body of the shell; for a second collection of 16 shells, the leg wires were not attached to the shell. In both cases, the other ends of the electric match leg wires were firmly attached to the mortar rack. (The attachments to shell and rack were sufficiently strong to cause the leg wires to tear upon firing the shell, as was confirmed by inspection after each firing.) For each test, the total flight time, from firing the shell to its eventual return to the ground, was measured by two observers using stopwatches and was recorded as the average of the two measurements. However, of these 32 firings, only 29 flight times were properly recorded (14 with leg wires free of the shells and 15 with wires attached to the shells). The averaged results from the test firings are reported in the first four columns of Table 1.

Results

After incorporating the parameters of the tests into an aerial shell ballistics model,[4] the computer model was used to convert the measured average flight times into the shell muzzle velocities that would be needed to produce those flight times. The computer model also produced maximum shell heights expected to be reached by those shells. (Note that the general accuracy of the computer model had previously been verified by comparisons between its predictions and actual test shell firings.) These muzzle velocities

Table 2. Expected Reduction in Burst Height for Typical Aerial Shells.

Spherical Aerial Shell	Muzzle Velocity m/s (ft/s)	Shell Weight kg (lb)	Shell Diameter mm (in)	Burst Height Reduction (%)
75 mm (3 in.), Modest Energy[(a)]	84 (277)	0.09 (0.2)	67 (2.62)	12
75 mm (3 in.), Typical	92 (300)	0.14 (0.3)	67 (2.65)	7
100 mm (4 in.), Typical	92 (300)	0.36 (0.8)	91 (3.60)	3
125 mm (5-in.), Typical	92 (300)	0.68 (1.5)	117 (4.60)	2
150 mm (6 in.), Typical	92 (300)	1.14 (2.5)	141 (5.55)	1

(a) See Table 1.

and maximum shell heights are presented in columns five and six of Table 1.

When the two sets of data were compared, the model predicted a reduction of approximately 11.9 m/s (39 ft/s) in the muzzle velocity for those shells that had to break their electric match leg wires. Further, this corresponded to a reduction of approximately 16.2 m (53 ft) in the maximum height reached by those test shells that had to break their electric match leg wires. In this case, the firmly attached shells were predicted to have reached only approximately 106.4 m (349 ft) on average, as compared with the shells that flew freely to have reached approximately 122.6 m (402 ft).

It must be considered that this testing took place in western Colorado at an elevation of approximately 1400 m (4600 ft) above sea level. Accordingly, the computer ballistics model was used to convert the shell height predictions to their corresponding values for an elevation of 300 m (1000 ft) above sea level (assumed to be a reasonable average for most display sites). This reduced the calculated maximum heights to approximately 98.8 and 113.4 m (312 and 353 ft) for the shells with attached and unattached leg wires, respectively.

Finally, it must be considered that typical 75-mm (3-in.) fireworks aerial shells burst approximately three seconds after their firing, which is typically before the shells will have reached their maximum achievable height. Accordingly, by consulting the time record of the ballistics model, it was determined that on average the shell height upon bursting will be 95.1 and 107.6 m (324 and 372 ft), respectively for shells (fired at 300 m above sea level) with attached and unattached leg wires, respectively. This corresponds to an approximate 12 percent reduction in burst height for these (modest kinetic energy) 75-mm (3-in.) aerial shells that must break their electric match leg wires upon being fired from their mortars.

If it can be assumed that the results reported above are reasonably correct and that the energy consumed by more massive aerial shells breaking free is the same as for the test shells, then some additional inferences can be drawn. The first four columns of Table 2 present the salient parameters for "typical" 75-mm (3-in.) to 150-mm (6-in.) aerial shells. Reported measurements of aerial shell muzzle velocities typically range from approximately 75 to 110 m/s (250 to 350 ft/s), mostly independent of shell size. Accordingly, for this study, muzzle velocities of 92 m/s (300 ft/s) are assumed for the variously-sized shells. Shell weights and diameters are those the authors have used in previous studies; they are based on a series of measurements of a wide range of display shells made in the mid 1980s, and the values are assumed to still be typical of shells produced today. Using these input parameters, the ballistics modeling code was used to predict the heights of the typical attached and unattached aerial shells. The burst height reductions are presented in the last column of Table 2 and are rounded to the nearest percent.

Conclusion

The ballistics model used in these calculations has been tested and found to accurately reproduce the results of field trials. However, to obtain the greatest accuracy in its calculations, one must adjust for actual air density at the time of the shell firings and also fine tune the drag coefficients of the shells. This was not done for the calculations in this article. Accordingly, while the relative accuracy of the calculations should be quite good, the absolute accuracy may be considerably less. For example, when calculating the difference between pairs of predicted shell heights differing only because of a small change in muzzle velocity, the results are probably accurate to within a meter; whereas, when considering any one predicted shell height alone, the results may be no more accurate than perhaps ten meters. Considering the wide range of actual shell parameters and firing conditions, the uncertainties the in the shell heights reported in Table 2 must be small by comparison.

The reduction of burst height, for modest kinetic energy 75-mm (3-in.) spherical aerial shells when they must break free of their leg wire attachment (≈12%), is only minimally significant. The reduction for normal energy 75-mm (3-in.) shells (≈7%) is mostly insignificant, and that of larger shells (≤3%) is completely insignificant. Accordingly, the results reported in this article are consistent with the empirical observation that the reduction in aerial shell burst height, as a result of shells having to break free of their leg wire attachment, does not represent a safety problem for typical 75-mm (3-in.) and larger aerial shells.

Acknowledgments

The authors greatly appreciate the comments and technical input provided by L. Weinman on earlier drafts of this article.

References

1) K. L. and B. J. Kosanke, "Firing Precision for Choreographed Displays", *Fireworks Business*, No. 194, 2000; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.
2) Goex, Inc., Doyline, LA, USA.
3) Daveyfire, Inc., Walnut Creek, CA, USA.
4) K. L. and B. J. Kosanke, "Computer Modeling of Aerial Shell Ballistics", *Pyrotechnica* XIV, 1992; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)*. Journal of Pyrotechnics, Inc., 1995.

An earlier version appeared in *Proceedings of the 6th International Fireworks Symposium*, 2001.

Study of the Effect of Ignition Stimulus on Aerial Shell Lift Performance

K. L. Kosanke
PyroLabs, Inc., 1775 Blair Road, Whitewater, CO, USA

B. J. Kosanke
Journal of Pyrotechnics, Inc., 1775 Blair Road, Whitewater, CO, USA

ABSTRACT

It had been speculated that the replacement of fierce burning quick match shell leaders with electric matches might have contributed to the production of a significant number of low breaking aerial shells experienced by a small fireworks display company. A preliminary study of the effect of ignition stimulus level did not supporting the theory that the weaker stimulus provided by electric matches (possibly in conjunction with Chinese lift powder) was the reason for the low breaking shells. However, that study was thought not to be sufficiently conclusive to completely settle the question. Accordingly, a more extensive series of tests were subsequently performed. For these tests, because of the lack of sufficient Chinese lift powder, Goex (USA) Black Powder was used. The result of these tests was that again no effect was observed for the flight times of the test aerial shells. The average flight times for groups of approximately 30 of the 75-mm (3-in.) test shells was 9.65 ± 0.13 seconds and 9.58 ± 0.17 seconds for shells using quick match and electric match firing, respectively.

Introduction

A few years ago, a small fireworks display company was experiencing what they thought to be an unusually large number of low breaking aerial shells (a few percent). These shells appeared to be breaking low because of being weakly propelled from their mortars. The shells were of Chinese manufacture but were of moderate to high quality (Jumping Jack, Thunderbird, and Sunny). The fierce-burning quick match on these shells had been removed and electric matches inserted into their lift charges. Obviously, one possible reason for the low breaking shells was a deficiency in their Black Powder lift charges (e.g., the amount or its quality). However, a few displays had been performed in which the shell leaders had not been removed, and on which the number of low breaking shells seemed to be significantly less. Accordingly, this lead to speculation about other possible causes for the low breaks when using electric matches. Foremost among the possibilities was the lower level of ignition stimulus thought to be provided by the electric matches in comparison with the strong jet of fire produced by the burning quick match shell leaders.

A preliminary study of the possible effect of ignition stimulus on lift powder performance was conducted previously.[1] First, the relative performance of the lift powders from the suspect shells was tested in an apparatus specially built for such testing.[2] These lift powders were found to produce muzzle velocities approximately two-thirds that of the same granulations of Goex[3] powders. Following this, a series of nine test shell firings were conducted, three using each of three levels of ignition stimulus: that produced by a hot wire igniter, that provided by an electric match (Daveyfire[4] SA-2000, A/N 28 B), and that from a shell leader taken from one of the suspect Chinese shells (Jumping Jack, Thunderbird, and Sunny). So that the test shells would be as near to identical as possible, inert spherical plastic shells were prepared, each measuring 67 mm (2.62 in.) in diameter, weighing 130 g, and each using the same amount and type of lift powder as used by the three manufacturers of the suspect Chinese shells. In that preliminary study, the flight times of the shells, peak mortar pressures, and pressure impulses produced during firing were determined.[1] While no significant differences in lift performance as a function of ignition stimulus was observed, the number of test firings was not felt to be sufficient to be completely definitive. This current article is a report of a follow-on series of tests to further examine the effect of ignition stimulus on lift powder performance.

Background

McLain has reported[5] that varying levels of ignition stimulus can produce differences in pyrotechnic output. To some extent, Shimizu[6] also documents the effect of varying the level of ignition stimulus. He reports that the velocity of propagation for flash powders can be substantially greater when initiated using a detonator (blasting cap) in comparison to that produced by thermal ignition. For example, Shimizu reported[6] that a potassium perchlorate, aluminum, and sulfur flash powder (in a ratio of 70:27:3, respectively) propagated at approximately 870 m/s when an electric igniter was used, as compared with a rate of 1420 m/s when initiated using a number 8 detonator.

In addition to McLain's and Shimizu's reports, the authors' found indirect evidence suggesting that the internal ballistics of aerial shells are quite sensitive to relatively minor changes in ignition stimulus. During laboratory measurements, it was found that surprisingly large variations in peak mortar pressure and muzzle velocity occur for apparently identical shell and lift powder configurations.[2,7,8] One possible explanation for this observation is that small differences, occurring in the earliest stages of lift charge burning, are responsible for relatively large differences in the propulsion of the aerial shells. Limited support for this theory can be seen in the lift pressure profile (lift pressure as a function of time) in a mortar as a shell is fired. For approximately half of the time between igniting the lift powder and the expulsion of the aerial shell, there is no significant pressure rise. (See Figure 1.) Presumably this apparently quiescent period is the time taken for the fire to spread through the grains of Black Powder before the burning becomes vigorous enough to cause a measurable rise in pressure. If that is the case, it is certainly possible that changing the manner of ignition of the lift powder could change the dynamics of the early fire spread and thus produce a significant difference in the propulsion of aerial shells. More support for this theory was found when it was discovered that lift performance can be significantly affected by relatively small changes in the point of ignition within the lift charge with all else being constant.[2]

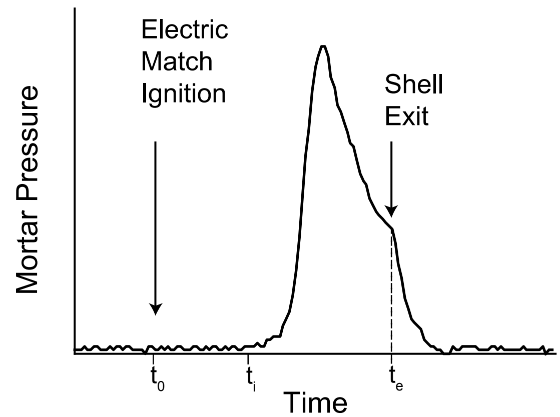


Figure 1. A fairly typical mortar pressure profile\during the firing of an aerial shell.

With the firing of an electric match, there is a sudden burst of fire, which is fairly limited in both amount and duration. With burning quick match, potentially a much more substantial and sustained jet of fire is produced. Thus it seemed reasonable to speculate that quick match, especially the quite vigorous burning quick match found on some Chinese shells, would provide a greater ignition stimulus for the lift charge than that provided by an electric match. Further, because the Chinese lift powders were found to be somewhat slow burning in comparison to domestically produced Black Powder, the Chinese powder might be expected to be more sensitive to differences in the level of ignition stimulus.

However, contrary to the above speculation, if a weak ignition stimulus was the cause of the low break problem, then why did the problem not occur in more of the Chinese shells being fired using an electric match? Further, why had other display companies, which also used electric matches installed directly into the lift charges, not been reporting similar problems? Despite these possible contrary indications, it seemed that the ignition stimulus hypothesis was worth further consideration; not only because it might be related to the low break problem, but also because it might help to explain the large variations in lift performance observed experimentally during the firing of what seemed to be identical aerial shells. Accordingly, a brief study was undertaken to investigate the effect of various levels of ignition stimulus on lift powder performance.[1] In that preliminary study, no support was found for the weak ignition stimulus hypothesis. However, due to the brevity of that study, it was thought that the results were not sufficiently conclusive to completely settle the question. Accordingly, this follow-on study was conducted.

Experimental

The test shells used in this study were all 75-mm (3-in.) inert spherical plastic shells with a diameter of 67-mm (2.62-in.) and weighing 90 g. The lift charges were each 14 g of Goex[3] 4FA Black Powder, ignited using either Daveyfire[4] SA2000 A/N 28 B electric matches or quick match from one of a collection of suppliers. In either case, the end of the igniter was placed in the approximate center of the lift charge. The test mortars were approximately 560-mm (22-in.) long HDPE with an ID of approximately 74-mm (2.93-in.). The test firings were conducted at an elevation of approximately 1400 m (4600 ft). For each test firing the effectiveness of lift charge performance was determined by measuring the time from firing the shell to its eventual return to the ground. This was used to determine the average maximum height reached by the shells.[9] The flight times were measured by two observers using stopwatches and recorded as the average of the two measurements.

A total of 64 test shells were fired. Of these 32 used electric matches; however, total flight times were successfully recorded on only 29 occasions. In addition, a total of 32 firings used quick match from a collection of manufacturers. The results from the test firings are reported in Table 1.

Table 1. Results from Time of Flight Measurements.

Ignition Method	Average Time of Flight (s)	Std. Dev.[a] (s)	Std. Error[b]
Electric Match	9.68	0.93	0.17
Quick Match	9.64	0.74	0.13

a) Standard deviation, determined using the $n - 1$ method.

b) Standard error, reported as the standard deviation divided by the square root of the number of measurements.

Conclusion

The time of flight results for both types of ignition stimulus were found to be statistically equal, and both correspond to a maximum shell height of approximately 110 m (370 ft). Thus, as in the preliminary study, the current tests provide no support for the theory that the low breaking shells were the result of a reduction in ignition stimulus because of the replacement of quick match with electric matches. However, in the current study only US produced Black Powder was used. Whereas it had been part of the initial speculation about the level of ignition stimulus affecting the lift charge performance, that perhaps the effect would be more noticeable when using Chinese Black Powder, which had been found to be less vigorous in its burning. Unfortunately, the authors did not have a sufficient supply of Chinese lift powder for use in the current study. However, even if the Chinese lift powder is more sensitive to varying levels of ignition stimulus than is the US powder, it is thought that some reduction in performance should still have been found in the current tests. Accordingly, it is concluded that a reduced level of ignition stimulus provided by electric matches, in comparison with that provided by fierce burning quick match, most probably was not the cause of the low breaking shells that originally prompted these tests.

References

1) K. L. and B. J. Kosanke, "Preliminary Study of the Effect of Ignition Stimulus on Aerial Shell Lift Performance", *Proceed-*

ings of the 5th International Symposium on Fireworks, 2000; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

2) K. L. and B. J. Kosanke, "An Instrument for the Evaluation of Black Powder as a Propellant for Aerial Shells", *Proceedings of the 3rd International Symposium on Fireworks*, 1996; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999..

3) Goex, Inc., Doyline, LA, USA.

4) Daveyfire, Inc., Walnut Creek, CA, USA.

5) J. McLain, *Pyrotechnics, From the Viewpoint of Solid State Chemistry*, Franklin Institute Press, 1980, pp 185–186.

6) T. Shimizu, *Fireworks, The Art, Science and Technique*, Maruzen, 1981, p 43–44. (Reprinted by Pyrotechnica Publications.)

7) K. L. and B. J. Kosanke, "Hypothesis Explaining Muzzle Breaks", *Proceedings of the 2nd International Symposium on Fireworks*, Vancouver, BC, Canada, 1994; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996.

8) K. L. and B. J. Kosanke, "Peak In-mortar Aerial Shell Accelerations", *Journal of Pyrotechnics*, No. 10, 1999; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

9) K. L. and B. J. Kosanke, "Computer Modeling of Aerial Shell Ballistics", *Pyrotechnica* XIV, 1992; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)*, Journal of Pyrotechnics, Inc., 1995.

An earlier version appeared in *American Fireworks News*, No. 245, 2002.

The Effect of Mortar Diameter on the Burst Height of Three-Inch Spherical Aerial Shells

K. L. and B. J. Kosanke

Background

A while ago, a small fireworks display company called seeking information about the effect of mortar internal diameter on the burst height expected to be achieved by aerial shells fired from them. It seems the company had received a large quantity of three-inch, high-density polyethylene (HDPE) pipe that they had cut into 18-inch lengths for mortars (including 1.5-inch thick plugs) before having checked the pipe's internal diameter. When it was checked, the HDPE pipe was found to have an internal diameter of 3.21 inches (i.e., it was significantly oversize). Because it was close to the July 4th holiday season, there was not sufficient time to replace the pipe. Accordingly, the question was, could these mortars be safely used?

Of course, one problem with mortar diameter being greater than expected is that this results in greater clearance between the shell and mortar, through which more than the usual amount of burning lift gas will escape. Typically, the gap between shell and mortar amounts to about 20 percent of the cross-sectional area of the mortar. (For example, with a 2.7-inch diameter shell and a 3.0-inch diameter mortar, the gap amounts to 19 percent of the cross-sectional area of the mortar.) However, for these oversized mortars, the gap was about 30 percent of the cross-sectional area, thus reducing the normal lift pressure and causing the shells to be propelled to less than full height.

Generally, shells can be propelled to a greater height by lengthening the mortar. This is because aerial shells normally exit the mortar while there is still significant lift pressure in the mortar. Accordingly, if a mortar is lengthened, some of this normally wasted lift energy will be used to increase the muzzle velocity of (and thus the height reached by) the exiting aerial shell. In this case, had the pipe not already been cut into short lengths, the effect of an oversize diameter might have been compensated for, simply by making the mortars somewhat longer. Since this was not an option, the question remained, would these mortars propel their aerial shells to a safe height?

However, there is another issue not addressed in the initial question about shells attaining a safe height. For the most part, all three-inch HDPE pipe is extruded with the same outside diameter, 3.50 inches.[a] Accordingly, as a consequence of this pipe having an oversize inner diameter, its wall thickness was less than expected. In this case, the wall thickness was approximately 0.15 inch as opposed to the expected thickness of approximately 0.25 inch. Thus, an additional question was, is this pipe sufficiently strong to be safely used. Fortunately, a previous study (unpublished) of the effective burst strength of HDPE mortars had demonstrated that even these thin-walled, three-inch mortars were still amply strong to be safely used.

Discussion

For the most part, the effect of mortar diameter has received relatively little attention in the literature. Some of the writings of T. Shimizu address the subject to some extent, and he has suggested a mathematical model incorporating the effect of shell-to-mortar clearance,[1] providing the clearance is not too great. However, neither Shimizu nor anyone else we are aware of has provided quantitative data based on field measurements. Because time was extremely short before the display company needed to use the mortars, only the briefest of investigations could initially be undertaken. A series of 12 shell firings, six from the oversized mortar and six from a 3.00-inch ID mortar, was conducted.

The burst height of these shells was determined by measuring the amount of time elapsing between the burst of the shell (as determined optically) and the arrival of the sound of the burst.[b] Unfortunately, only a limited number of shells were available at the time for testing. The only manufacturer for which there were a sufficient number of three-inch shells was Horse Brand, and even those were a variety of shell types. Nonetheless, the testing was performed while trying to match pairs of shells (for firing from both size mortars) as best as one could. The results were that the average burst height using the normal 3-inch mortar was 345 feet, while that for the oversized mortar was 277 feet, with both data sets producing a fairly wide range of burst heights. The difference corresponds to approximately a 14% reduction of burst height for these oversized mortars as compared with those achieved using 3.00-inch mortars.[c]

More than a year later, after performing some tests as part of another project, some of the 3-inch shells used in these later tests remained unused. These were Thunderbird, Color Peony-White (TBA-106) shells having an average mass of 136 g, an average diameter of 2.72 inches, and an average of 37 g of lift charge (apparently 4FA granulation). Five test shells were fired from each of three mortars with different internal diameters (2.93, 3.02 and 3.21-inches). Approximately 10 minutes elapsed between each use of a mortar, to allow time for the mortar to cool before its next firing. The average heights of the shell bursts were determined as described above[b] and found to be 530, 490 and 460 feet for the three mortar diameters, respectively.[c] If the burst height from the 3.02-inch mortar is defined as 100%, the mortar with the tight fit produced a burst height increase of approximately 8% and the mortar with the loose fit produced a reduction in burst height of approximately 6%.

In each case, the one-sigma coefficient of variation[d] was about 10% (approximately 50 feet) and the standard error[e] was about 5% (approximately 25 feet). Also, had the shells been fired at about 1000 feet of elevation above sea level, based on an increase in air density, the burst heights would have been reduced by roughly 50 feet.[f]

While the burst heights may be unexpectedly high for those using the 100 feet per shell-inch rule of thumb, this rule of thumb was found to under estimate actual burst heights.[5] Also, it must be recalled that the testing was performed at nearly a mile above sea level with a corresponding reduction in air density. Further, the test shells were a little larger (tighter fitting) than normal, and they had greater lift mass than is typical for 3-inch spherical aerial shells. Finally, the mortar was about 10% longer than the 15 inches recommended by the NFPA.[6] Accordingly, considering everything, it is thought that the measured burst heights are approximately correct.

The results from these two brief tests are summarized in the table below. Accordingly, it is concluded that the effect of using the oversized mortar is a reduction in burst height of approximately 10%. However, it must be considered that the statistical uncertainty in the combined measurements is a little more than 3%. Thus the effect on burst height resulting from the use of the oversized mortar could easily be anywhere in the range from about 5 to 15%. Certainly it would have been preferred to have results with better statistical precision, nonetheless it is clear that there was not an overwhelming decrease in the burst height of the shells fired from the oversized mortar in this instance. While this is not the preferred situation, neither does it represent a substantial safety concern. Also, in this instance, the reduction in burst height is small enough that it could have easily be compensated for by a modest increase in mortar length.[g]

Mortar	Percent Change in Burst Height(a)		
Diameter	Test 1	Test 2	Average
3.21 in.	–14	–6	–10%
2.93 in.	—	+8	—

a) The change in burst height is compared with shells fired from a 3.02-inch mortar.

It is hoped that these brief studies and this article have provided some useful (and perhaps interesting) information on the effect of mortar diameter on the burst height achieved by small caliber aerial shells.

Acknowledgements

The authors are grateful to L. Weinman for commenting on an early version of this article.

Notes

a) Typically, as HDPE pipe is extruded, it is drawn through a "vacuum sizer" which literally sucks (expands) the still pliable pipe up to the size of the vacuum sizer. The vacuum sizer is generally water-cooled and of sufficient length to maintain the pipe's diameter until the pipe has cooled sufficiently, so the pipe will retain the correct diameter.

b) If desired, see references 2 and 3 for discussions of two slightly different methods using the delay in arrival of the sound of the explosion to determine the distance to the explosion.

c) Testing was conducted in western Colorado at an altitude of 4600 feet above sea level. The reduced air density at this elevation results in lower drag forces, such that aerial shells travel faster for longer (i.e., shells will have greater burst heights) than when fired nearer sea level.

d) The coefficient of variation is the standard deviation expressed as the percent of the mean.

e) The standard error in this case is expressed as a percentage and is the coefficient of variation divided by the square root of the number of measurements.

f) Based on the use of a computer ballistics model for fireworks aerial shells.[4]

g) For example, for the same shells used in this study, fired from a minimum length mortar, 15 inches above the plug, the burst height can be increased by about 10% by simply increasing the mortar length to about 19 inches.[7] However, the reduced lift pressure would require a mortar length in excess of 19 inches to compensate fully.

References

1) T. Shimizu, *Fireworks, From a Physical Standpoint, Part III*, Pyrotechnica Publications, 1985.

2) K. L. Kosanke, "Determination of Aerial Shell Burst Altitudes", *Pyrotechnics Guild International Bulletin*, No. 64, 1989 ; also in *Selected Publications of K. L. and B. J. Kosanke, Part 1 (1981 through 1989)*, Journal of Pyrotechnics, 1996.

3) K. L. and B. J. Kosanke, "Simple Measurements of Aerial Shell Performance", *American Fireworks News*, No. 181, 1996 ; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999..

4) K. L. and B. J. Kosanke, "Computer Modeling of Aerial Shell Ballistics", *Pyrotechnica* XIV, 1992; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2*, Journal of Pyrotechnics, 1995.

5) K. L. Kosanke, L. A. Schwertly, and B. J. Kosanke, "Report of Aerial Shell Burst Height Measurements", *Pyrotechnics Guild International Bulletin*, No. 68, 1990; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)*. Journal of Pyrotechnics, Inc., 1995.

6) *Code for Fireworks Display*, National Fire Protection Association, NFPA-1123, 2000.

7) K. L. and B. J. Kosanke, "Aerial Shell Burst Height as a Function of Mortar Length", *American Fireworks News*, No. 253, 2002; also appears in this collection of articles.

An earlier version appeared in *Fireworks Business*, No. 217, 2002.

Electric Matches: Effective Thermal Output

K. L. and B. J. Kosanke

Introduction

A study of electric match sensitiveness and performance has recently been completed, and a summary of the results is being presented as a series of short articles. This is the ninth article in the series[1] and presents the results of tests to determine the effective thermal output for the same collection of 10 electric match types as in the previous articles.

Effective Thermal Output Test

The ignition of one pyrotechnic composition by another (an electric match in this case) is accomplished by the transfer of energy. This transfer is generally accomplished by some combination of thermally incendive sparks (incandescent solid or liquid particles), high temperature gases, and radiant thermal energy. These three ignition stimuli are listed in decreasing order of their effectiveness for the ignition of typical pyrotechnic compositions. Accordingly, the effectiveness of ignition transfer depends on the relative proportion of these three sources of ignition energy, which in turn depends on the chemical nature of the donor pyrotechnic composition, which is likely to be different for some of the various electric matches being tested.

The effectiveness of ignition transfer also depends on the nature of the material to be ignited. Accordingly, the best measure of an electric match's ability to cause the ignition of pyrotechnic materials would be to conduct a series of ignition tests on various pyrotechnic compositions, under various conditions and in each configuration determining the percentage of times ignition was accomplished. However, for the ten electric matches being evaluated in this study, this could easily run into the many thousands of individual test firings. Clearly such an extensive series of tests was not possible for this brief screening study, and a more general method had to be utilized. This article reports on the first of a short series of tests intended to provide information on the electric matches' ability to produce ignition.

The tests reported in this article are described as "effective thermal output" tests. This is in opposition to "total thermal output" tests, such as would be accomplished by sealing an electric match inside a tiny vessel, causing the ignition of the electric match and measuring the total energy produced, as reflected by the increase in temperature of the vessel. Because of the hierarchy of effectiveness of the three ignition stimuli mentioned above, it was thought that such a total thermal output measurement could produce misleading results. Accordingly, a slightly different approach was taken, as illustrated in Figure 1. In this case, the vessel was not sealed, such that any permanent gases produced by the firing of the electric match would escape without transferring much of their thermal and radiant energy to the walls of the vessel. On the contrary, a fair amount of any temporarily vaporized reaction products (temporary gases) are likely to condense on the walls of the tube, thereby transferring much of their thermal energy. Similarly, much of the thermal energy from incendive sparks is expected to be transferred to the brass tube.

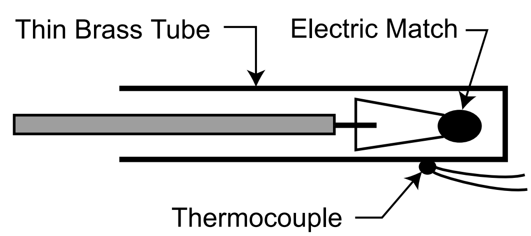


Figure 1. Illustration of the "effective thermal output" test configuration.

During the period of each test firing, the temperature of the thin brass tube was monitored using a thin gauge thermocouple attached to the outer surface of the tube. A typical temperature profile (temperature as a function of time) is shown in Figure 2, demonstrating the rapid rise and relatively slow fall of the temperature. This made it quite easy to accurately record the maximum temperature rise observed during each test firing. In each test, the initial and maximum temperatures were recorded, and the difference (increase) in temperature was calculated. Pairs of test firings were performed for each type electric match, and the average temperature increase calculated. These results are reported in Table 1. Prior to testing each pair of electric matches, a new (clean) brass tube was installed.

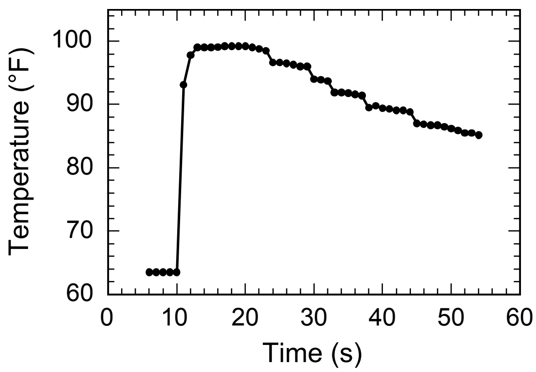


Figure 2. A graph of temperature as a function of time for an effective thermal output test.

If it can be assumed that the temperature rise, as determined in these tests, correlates with the electric matches' ability to produce ignitions of typical pyrotechnic materials, the Daveyfire A/N 28 F electric match is superior, producing a temperature rise of nearly 80 °C. Next are the Luna Tech Flash and Martinez Specialties E-Max electric matches, both producing an approximately 50 °C rise. The remaining seven electric match types then produce temperature increases ranging from approximately 20 to 35 °C.

Reported in the last column of Table 1 is the normalized temperature rise (i.e., the temperature rise in °C divided by the approximate mass of pyrotechnic composition used on that type electric match). While this information is of little practical significance, it was included to satisfy the potential curiosity of a few readers wishing more information on the relative efficiency of the different pyrotechnic compositions used by the various manufacturers.

Table 1. Results of Electric Match Effective Thermal Output Testing.

Supplier	Product Designation	Δ Temp.[a] °F	Δ Temp.[a] °C	Mass mg[b]	Norm. ΔT[c]
Aero Pyro		51	28	80	0.4
Daveyfire	A/N 28 B	35	20	40	0.5
	A/N 28 BR	53	29	80	0.4
	A/N 28 F	142	79	80	1.
Luna Tech	BGZD	56	31	10	3.
	Flash	96	53	20	3.
	OXRAL	41	23	40	0.5
Martinez Spec.	E-Max	85	47	20	2.
	E-Max Mini	39	21	6	4.
	Titan	62	34	20	2.

a) This is the average increase in temperature of the brass tube as a result of firing each of two electric matches inside the brass tube, reported to the nearest degree.

b) This is the approximate mass of pyrotechnic composition in mg used on each type of electric match, reported to only one significant figure, as reported previously, *Fireworks Business*, No. 206, 2001.

c) This is the normalized temperature increase (i.e., the temperature increase in °C divided by the mass of composition in mg) reported to only one significant figure.

Acknowledgments

The authors gratefully acknowledge that the four electric match suppliers provided samples of their products, at no cost, for testing. Further, the American Pyrotechnic Association provided a grant to help cover some of the costs of this study. Finally, the authors appreciate the technical comments provided by L. Weinman on an earlier draft of this article. Note that while many of the company and product names are apparently registered trademarks, they have not been specifically identified as such in this article.

References

1) K. L. and B. J. Kosanke, A series of eight articles appearing in *Fireworks Business*, Nos. 198, 199, 200, 201, 202, and 203, in 2000; Nos. 206, and 207 in 2001; also appearing in this collection of articles.

An earlier version appeared in *Fireworks Business*, No. 218, 2002.

Factors Affecting the Precision of Choreographed Displays

K. L. and B. J. Kosanke

For maximum effectiveness of tightly choreographed fireworks displays, it is important that shell bursts occur very near their intended times. For the purpose of this article, it is assumed that electrical firing employing a computer or other means of accurately applying the firing current to electric matches is being used. In addition, it is assumed that the choreographer has accurate information about the firing and burst characteristics of the shells being used, and that no errors are made in the design of the choreography or in the loading of the display. In that case, there are two primary sources of variation that combine to affect the overall precision of the shell burst times. First is the preciseness of the shell firings from their mortars; second is the preciseness of the time fuse burning. (In the context of this article, "preciseness" is intended to indicate consistency or reproducibility of events.)

The display company has some control over the firing precision of shells. The effectiveness of the commonly used methods of electric match installation was briefly studied and reported in a previous article[1] and is summarized again below. The three common points of attachment for electric matches are illustrated in Figure 1 and the degree of firing precision accomplished using each of them is presented in the first three rows of Table 1. (For more information on test conditions and methods, see reference 1.) As expected, the best firing precision (lowest standard deviation) is achieved with an electric match installed directly in the shell's lift charge. However, using an electric match attachment in the shell leader just above the shell, provides a level of firing precision that is equivalent to that achieved with the electric match in the lift charge, within the practical limits of human perception.[2]

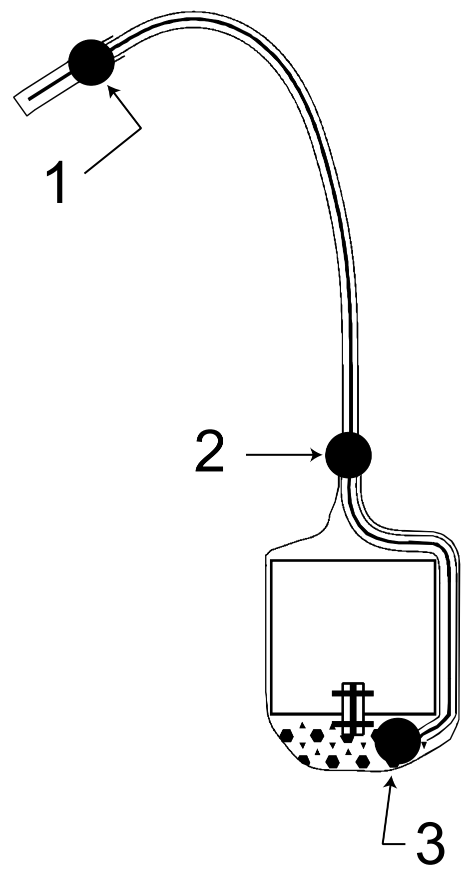


Figure 1. Illustration of the three common points of attachment of electric matches to aerial shells.

Table 1. Firing and Burst Time Results.

Test Conditions	Event Time[(a)] (s)	Std. Dev.[(b)] (s)
Attachment Point 1[(c)]	0.26	0.15
Attachment Point 2[(d)]	0.11	0.025
Attachment Point 3	0.04	0.005
Time Fuse Burning[(e)]	3.32	0.31

a) Event time for the various electric match attachment points is the average elapsed time between applying current to the electric matches and the shells exiting from the mortars. Event time for the time fuse burning is the average elapsed time between the shells leaving the mortar and their bursting.

b) The one-sigma standard deviations of the average event times were determined using the $n - 1$ method. This is an indication of the precision (reproducibility) of the timing of the event. Approximately 70% of the events occur within plus or minus one standard deviation of the average.

c) All using 24-inch long shell leaders with high quality quick match from a single manufacturer.

d) All using 6-inch long shell leaders with high quality quick match from a single manufacturer.

e) All shells were 3-inch Thunderbird Color Peony-White taken from the same case of shells.

Other than purchasing high quality shells, a display company generally has little control over the burst precision provided by an aerial shell's time fuse. To gain an estimate of the precision for shells of typical quality, a series of 29 three-inch Thunderbird aerial shells were test fired while being video taped. The shells were Color Peony-White (TBA-106), all taken from the same case of shells. The shells each had a pair of fairly high quality time fuses. Following the test firings, the video tape was studied frame by frame, to determine the time interval between each shell's firing from its mortar and its bursting. The results are presented as the bottom row in Table 1. (Based on a limited number of other testing over the years, it is thought that the burst time uncertainty reported in Table 1 is fairly typical.)

Fairly clearly the greatest source of imprecision in a tightly choreographed display is the uncertainty associated with the burning of the time fuse(s). It is possible that the use of well-made spolettes would reduce the uncertainty somewhat but probably not by very much. Accordingly, when very precise timing of shell bursts is needed, people have turned to the use of tiny electronic timers[3,4] to replace the shells' time fuses. While these electronic units are definitely not inexpensive, when precise timing of bursts is required to accomplish an effect, there would seem to be no alternative at this time.

References

1) K. L. and B. J. Kosanke, "Firing Precision for Choreographed Displays", *Fireworks Business*, No. 194, 2000; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

2) L. Weinman and K. L. Kosanke, "Tests of the Perception of Simultaneity of Fireworks Bursts", an unpublished study.

3) T. Craven "Air Launch Fireworks System at the Walt Disney Company", *Proceedings of the 2nd International Symposium on Fireworks*, 1994, p 74.

4) P. McKinley, "An Electronic Pyrotechnic Igniter Offering Precise Timing and Increased Safety", *Proceedings of the 4th International Symposium on Fireworks*, 1998, p 257.

An earlier version appeared in *Journal of Pyrotechnics*, No. 15, 2002.

Studies of Electric Match Sensitiveness

K. L. and B. J. Kosanke
PyroLabs, Inc., Whitewater, CO 81527 USA

ABSTRACT

The sensitiveness of a collection of ten electric match types, from four suppliers, was determined under conditions intended to reflect their actual use to ignite fireworks displays. The measurements included determinations of impact, electrostatic discharge (ESD), friction, and thermal sensitiveness. The ESD tests considered discharges both through the bridgewire and from the bridgewire through the composition to ground. When safety shrouds were provided by the manufacturer, additional impact and ESD (through the composition) testing was performed with the safety shrouds left in place on the electric match tips. (Note that users often remove the protective shrouds for convenience during use.) To simulate conditions during use, additional impact and friction testing was performed with Black Powder prime composition in the presence of match tips.

It was found that there was a wide range of electric match sensitiveness, that the presence of the shrouds provided significant decreases in sensitiveness, and that the presence of Black Powder prime did not significantly affect sensitiveness.

Keywords: electric match, impact sensitiveness, friction sensitiveness, thermal sensitiveness, electrostatic discharge sensitiveness, ESD, sensitiveness testing

Introduction

Although more expensive and time consuming to set up, when compared to traditional reloaded and manually ignited fireworks displays, electrically fired displays have become increasingly common. For the most part, this is because they offer the potential for greater artistry, through the use of intricate display choreography often synchronized to music. Electrically fired displays also offer the potential for greater display crew safety by requiring a smaller number of crew members when firing the display and by separating them from the mortars and the occasional malfunctioning aerial shell. Unfortunately, too often the full potential for increased crew safety has not been achieved, with the crew sometimes trading accidents caused by aerial shell malfunctions for those caused by the accidental ignition of electric matches during transportation to, set-up and disassembly of the display.

A study of electric match sensitiveness was completed for ten different match types from four suppliers, and brief summaries of the results have been reported in a series of short articles in *Fireworks Business*.[1] The present article was written to allow full presentation of the data and a number of photographs, as well as to allow a more complete comparison of the results. Table 1 lists the various suppliers and electric match types. Table 1 also presents the abbreviated designations of the electric matches used in many of the data tables throughout this article.

Table 1. List of Suppliers and Types of Electric matches Tested.

Supplier	Product Designation	Abbreviation Used
Aero Pyro[2]	none	AP
Daveyfire[3]	A/N 28 B	DF-B
	A/N 28 BR	DF-BR
	A/N 28 F	DF-F
Luna Tech[4]	BGZD	LT-B
	Flash	LT-F
	OXRAL	LT-O
Martinez Specialties[5]	E-Max	MS-EM
	E-Max Mini	MS-EMM
	Titan	MS-T

More than 1500 individual tests and measurements were performed during this study. However, it is important to acknowledge that, because of the large number of different combinations of electric match types and test configurations used, this sensitiveness testing must only be considered a screening study. For the most part, this is because only a limited number of individual tests were performed during each sensitiveness determination for each electric match type. Also note that the standard sensitiveness tests were often modified in an attempt to better characterize the electric matches in the environment typical of their use in fireworks displays. Accordingly, the statistical precision achieved is only sufficient to approximately characterize and rank the sensitiveness of the various electric matches, and then only under the specific conditions of this testing. For electric matches producing similar results, had additional numbers of matches been tested or had the conditions been somewhat different, it is possible that slightly different results would have been produced.

As a consequence of these only being considered screening tests, discussion of the results is often couched in terms indicating a significant lack of certitude. For example, terms such as "it is likely", "it would seem", "it is thought", etc. are frequently used.

The electric matches for these tests were supplied in late 1999. Accordingly, it is possible that current production electric matches from these same suppliers have been modified in some way, which may have caused them to have sensitiveness results different than those reported herein.

Background

Figure 1 is an illustration of a typical electric match. It most commonly consists of an electrically insulating substrate with copper foil cladding, somewhat similar to that used for printed electrical circuits. The size of the electric match tip is often approximately 0.4-inch long by 0.1-inch wide by 0.03-inch thick (10 × 2.5 × 1 mm), exclusive of the pyrotechnic composition. Copper leg wires, used to attach the electric match to the firing control system, are soldered to the copper cladding. Completing the electric circuit within the electric match tip is a thin, high-resistance bridgewire (nichrome) soldered across the end of the substrate. The tip of the electric match is dipped into one or more heat sensitive pyrotechnic compositions, typically depositing a total of about 40 mg of material. Then a protective lacquer coating covers the pyrotechnic composition. For the most commonly used electric matches, when an electric current of approximately 0.5 ampere is passed through the electric match, the relatively high-resistance bridgewire heats sufficiently to cause the ignition of the pyrotechnic composition. This produces a small burst of flame that is used to cause the ignition of a firework. (There are significant differences in the construction and performance of the ten electric match types studied. A proper presentation and discussion of this is well beyond the scope of the present article. However, some information on the construction and performance characteristics of these electric matches can be found in other articles.[6])

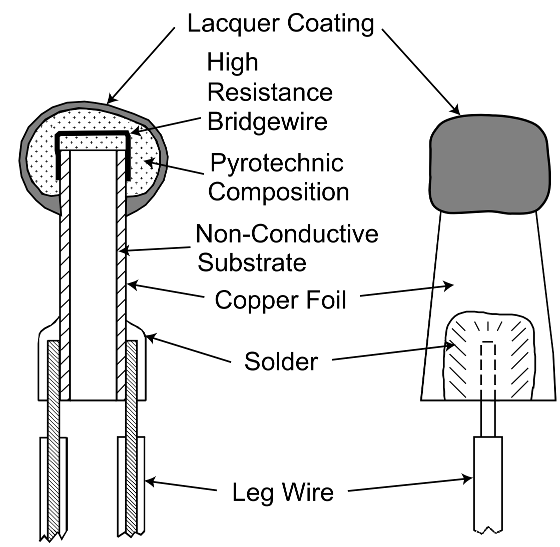


Figure 1. Illustration of a typical electric match in cross-section (left) and viewed externally after rotating 90° (right).

Figure 2 is a series of photographs of some of the types of electric matches tested in this study. Two views of each electric match are shown (rotated 90° from each other), as well as one view with a cut-away safety shroud when that was provided by the manufacturer. Some electric match types were not included in Figure 2 because they are similar in appearance to those shown. The Aero Pyro electric matches and Daveyfire A/N 28 B electric matches are similar to the Daveyfire A/N 28 BR electric match shown. However, the Daveyfire A/N 28 B electric match has somewhat less pyrotechnic composition than the A/N 28 BR, and the Aero Pyro electric matches were not supplied with safety shrouds. The Luna Tech BGZD electric match appears identical to their Flash electric match except for a different color coating. The Martinez Specialties E-Max electric match is virtually identical in appearance to their Titan electric match.

Pyrotechnic compositions are said to be metastable, meaning that they are reasonably stable under normal conditions, but when supplied with sufficient activation energy, they react to release their store of chemical energy,[7] typically in the form of a flame. For an electric match, the activation energy is intended to be the thermal energy produced by an electric current passing through the high-resistance bridgewire. However, the activation energy can come from other unintended sources, such as mechanical energy from impact or friction, or the electrical energy from an electrostatic spark, etc. When there is an unintended ignition of an electric match, too often this is the initiating cause of a significant accident, sometimes with the most serious consequences.

In general, hazards are managed by reducing the probability of the accident occurring, reducing the consequences of the accident should it occur, or preferably by reducing both the probability and consequences.[8] In the case of electric matches, the probability of having an accidental ignition is reduced by taking measures to limit the unintentional delivery of energy to the pyrotechnic composition. This can be accomplished using measures as simple as educating workers to take care not to forcefully crush the electric match or not to allow the forceful rubbing of the electric match against an abrasive surface. In addition, for electric matches used in situations where accidental crushing or rubbing might be expected, some manufacturers provide soft plastic safety shrouds to help protect the electric match tips. Clearly, the firing crew should be instructed to leave the safety shrouds in place and not to remove them during use (as is often done for convenience).

As is generally true for pyrotechnics, the consequences of having an accidental ignition of an electric match can be reduced by limiting the amount of fireworks in the immediate work area. Work should be performed in a manner such that, in the event of an accidental ignition, only one

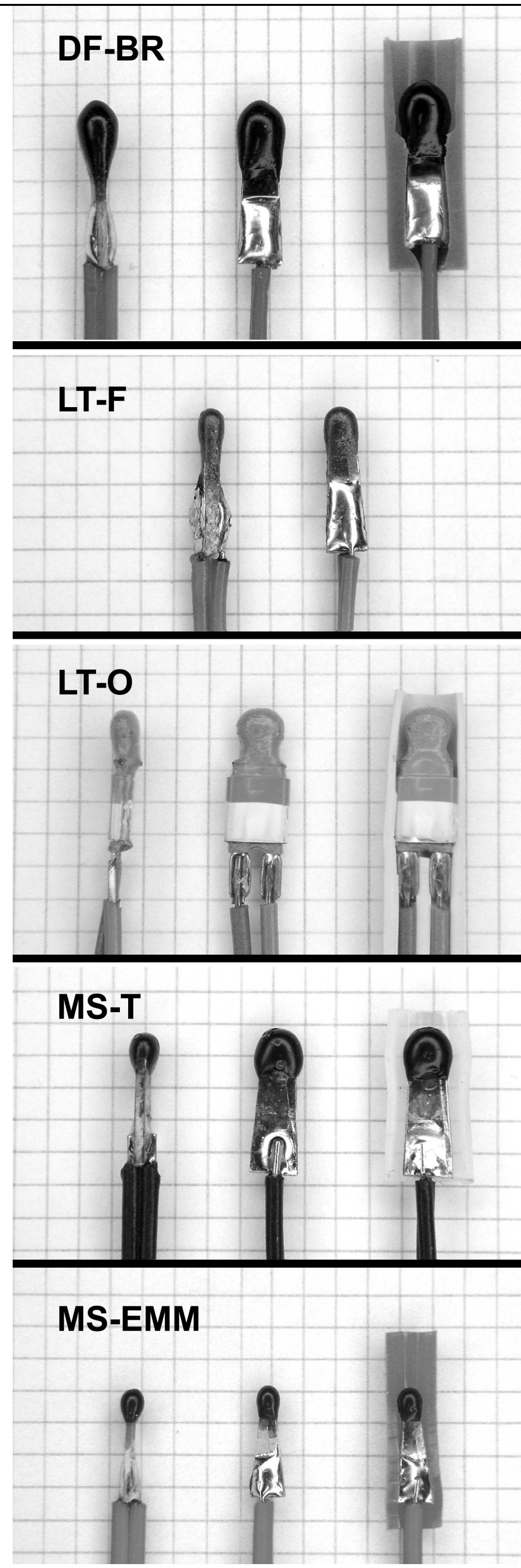


Figure 2. Photographs of some of the electric matches studied. (Each background square is 0.10 in., 2.5 mm.)

item will ignite and that it is unlikely that anyone will be seriously injured by that single ignition. For example, consider the case where an aerial shell has been loaded into its mortar before inserting an electric match into its shell leader and wiring the electric match into the firing circuit. In the event of an accidental ignition of that shell, it is likely that only the one shell would ignite and that it should fire relatively harmlessly into the air. (Of course, that assumes care was taken to not have any body parts over the mortar while working.)

In this study of electric match sensitiveness, it was found that the various electric matches demonstrate a wide range of sensitivity to accidental ignition. However, it is important to note that none were found to be so sensitive as to preclude their safe use, provided appropriate levels of care are taken. Further, it is a general principle of pyrotechnics that materials that are less prone to accidental ignition also tend to be more difficult to ignite intentionally. Thus, it should not automatically be assumed that the least sensitive electric match is the best choice for every application.

Impact Sensitiveness

Normal Configuration

The impact sensitiveness apparatus was of a standard drop-hammer (fall-hammer) design; however, because of the relatively high sensitiveness of electric matches, lighter than normal drop hammers were used. In these tests, a one-half kilogram drop hammer was used with the more sensitive electric matches and a one-kilogram drop hammer was used with the less sensitive electric matches. An additional modification was made in an attempt to better simulate the use environment of the electric matches. Typically, impact sensitiveness testing is performed by placing a sample between two steel anvils that are then forced together by the impact of the drop hammer. However, in this case, the match tips were inserted inside a fold of 0.010-in. (0.25-mm) thick paper card stock (see Figure 3) and the drop hammer was allowed to fall directly on the assembly. Also, because the solder connections on some of the electric match tips were thick enough to have absorbed some of the impact energy, the solder connections of the electric matches were cut off and only the very end of the match tips, with the pyrotechnic composition, were used in the tests. The electric match tips were oriented such that their wide dimension was parallel to the impact surfaces. For these tests, any shrouds supplied with the electric matches had been removed.

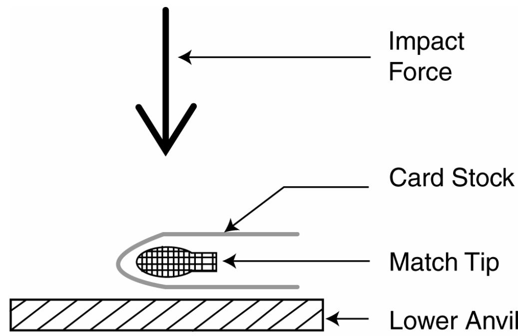


Figure 3. Illustration of the "normal" impact test sample configuration.

For each electric match type, approximately 20 were impact tested using the standard stair-step (Bruceton) method.[9] The results from testing using the *normal* configuration, as shown in Figure 3, are indicated in the "Test" column of Table 2 as "N-1/2" or "N-1", depending on whether the 1/2- or 1-kg drop hammer was used. The individual test results are reported as a pair of numbers, indicating the number of ignitions and non-ignitions, respectively, for each drop height used. The sensitiveness results are the Bruceton calculated heights that caused ignitions 50% of the time and are reported to the nearest inch. When the one-kilogram drop hammer had been used, the reported results were doubled (i.e., normalized to the corresponding half-kilogram drop hammer heights). (There is some concern that such drop-hammer normalization may not be completely correct. However, it was done to allow an easy comparison of results using the two different mass drop hammers.)

Based on these limited results, it would seem that the Aero Pyro, Daveyfire A/N 28 B and A/N 28 BR, Luna Tech BGZD, and Martinez Specialties E-Max Mini electric matches were all approximately equally sensitive, falling in the most sensitive group (50% sensitiveness height of seven to ten inches or 180 to 250 mm). A little less sensitive were the Luna Tech OXRAL and Mar-

Table 2. Results of Impact Sensitiveness Testing.

E-match Type	Test[a]	Drop Height (in.)[b]											Impact Sens.[c]	BP Sens.[d]
		6	9	12	15	18	21	24	30	36	42	48		
AP	N-1/2	0/4	4/6	7/0									10	4/6
DF-B	N-1/2	0/6	7/3	4/0									8	4/6
	S-1			0/1		1/6		6/3	3/1	1/0			S 44	
DF-BR	N-1/2	0/2	2/6	7/1	2/0								10	2/8
	S-1					0/4		7/4	4/0				S 46	
DF-F	N-1								0/1	1/1	0/2	1/5	>96[e]	7/3
LT-B	N-1/2	0/3	4/4	7/0	1/0								9	8/2
LT-F	N-1											0/6	>96[e]	0/5
LT-O	N-1/2			0/2	1/3	3/3	3/0						18	5/5
	S-1					0/1		0/6	4/5	3/1	1/0		S 62	
MS-EM	N-1/2		0/3	2/4	5/3	3/0							14	3/7
	S-1					0/1		1/5	6/3	4/1	1/0		S 60	
MS-EMM	N-1/2	0/9	9/0										7	4/6
	S-1					0/3		3/6	5/1	1/0			S 60	
MS-T	N-1										0/4	5/5	≈ 96	0/5

a) In column 2, "N" indicates the use of the set-up as shown in Figure 3. "S" indicates testing with the safety shroud in place. "1/2" indicates use of a 1/2-kg drop hammer and "1" indicates use of the 1-kg drop hammer.

b) For conversion of drop height to SI units, 1 in. = 25.4 mm. Reported are the number of ignitions and non-ignitions that occurred at this height. For example, "6/2" would indicate there were 6 ignition and 2 non-ignition events recorded at this particular drop height.

c) This is the height, reported to the nearest inch, that was calculated using the Bruceton method[9] to produce ignitions 50% of the time (i.e., it is the 50% impact sensitiveness). Those entries prefaced by an "S" indicate the result is for an electric match with its safety shroud in place.

d) This is an indication of the effect of the presence of Black Powder prime. It is the number of ignitions and non-ignitions that occurred in the presence of Black Powder, in tests performed at the 50% drop height found previously during testing without Black Powder present.

e) The practical impact height limit for the instrument being used was 48 inches (1.2 m). For a 1-kg hammer mass, this approximately corresponds to an equivalent 96 in. (2.4 m) had a ½-kg mass hammer been used. The sensitiveness of these electric matches fell below the limit of the instrument using a 1-kg drop hammer.

tinez Specialties E-Max electric matches (50% height of 14 to 18 in. or 360 to 460 mm). The Daveyfire A/N 28 F, Luna Tech Flash, and Martinez Specialty Titan electric matches were all much less sensitive (50% height of ≥96 inches or 2.4 m). (Note that the practical impact height limit for the instrument being used was 48 inches (1.2 m). For a 1-kg mass hammer, this approximately corresponds to an equivalent 96 in. (2.4 m) for a ½-kg mass hammer.)

As a point of comparison, rough Black Powder harvested from some Horse Brand black match was recently tested and found to have a 50% impact sensitiveness height (using steel anvils) that was roughly comparable to that of the least sensitive electric matches (Daveyfire A/N 28 F, Luna Tech Flash, and Martinez Specialty Titan). In this configuration, without safety shrouds, all of the other electric match types are five to ten times more sensitive to accidental ignition from impact. Accordingly, such electric matches must be treated with much care and respect.

One additional point should probably be raised regarding these impact sensitiveness results. In performing the testing on completed electric match tips, it appears there may be an effect due to the physical size of the mass of composition. Note that the sensitiveness of the Martinez Specialties E-Max Mini electric match is significantly greater than that for the E-Max electric match. It is possible that this is an effect of a difference in the size of the two electric match tips (see again

Figure 2) with the impact force being more concentrated on the smaller electric match tip. It is possible that a similar effect is seen for the Daveyfire A/N 28 B and A/N 28 BR electric matches, where results suggest that the larger A/N 28 BR electric match is a little less sensitive.

Effect of Black Powder

It has been speculated that some electric match compositions may be more sensitive to accidental ignition when in the presence of Black Powder, perhaps because of the sulfur contained therein. This is of particular concern because generally electric matches are in contact with Black Powder when being used to ignite fireworks. Accordingly, the electric matches in this study were subjected to impact sensitiveness testing in the presence of Black Powder. The normal test configuration was modified slightly, as illustrated in Figure 4. In these tests the inside surface of the piece of card stock around the electric match was heavily painted with a slurry of Black Powder (bound with 5% dextrin) and allowed to dry thoroughly before testing. However, to conserve on the number of individual tests performed, a full set of Bruceton impact tests was not performed. Instead, for each electric match type, a series of just ten individual impacts were used, each time using the 50% impact sensitiveness height found previously in the testing without Black Powder. If the presence of Black Powder had no effect on impact sensitiveness, the number of ignitions should be roughly five out of the ten tests. The results of this testing are presented as a pair of numbers in the final column of Table 2, indicating the number of ignitions and non-ignitions, respectively.

Within the precision limits of this testing, for a finding of three to seven ignitions, it must be concluded that any effect due to the presence of Black Powder is probably relatively small. Based on the testing, most of the electric match types are in this category. However, it is fairly likely that a finding of eight or more ignitions indicates added sensitiveness as a result of the presence of the Black Powder. The only electric match falling in this group was the Luna Tech BGZD electric match. Because these electric matches were already found to be fairly sensitive to impact—even without the presence of Black Powder, it might seem that this is a matter of particular concern. However, it must be recognized that

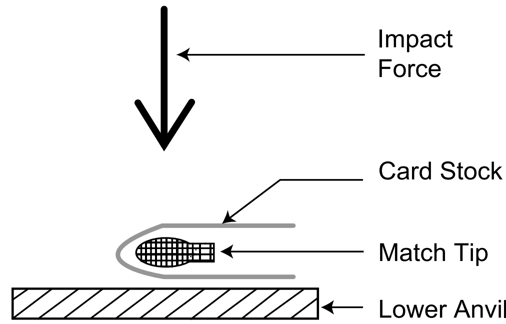


Figure 4. Illustration of the impact test sample configuration, with Black Powder prime present.

the Luna Tech BGZD electric matches are intended for use in stage effects where it is significantly less likely to be subjected to impact, than if they were being used in fireworks displays. Further, it is even less likely that they will be subject to a significant impact in the presence of Black Powder.

The Daveyfire A/N 28 F and Luna Tech Flash electric matches had been found to have 50% impact sensitiveness heights *without* the presence of Black Powder that exceeded 96 in. (2.4 m) (as corrected for using a 1/2-kg drop hammer). These electric matches were retested using the same impact (1-kg drop hammer at 48 in. or 1.2 m) with Black Powder present. For the Daveyfire A/N 28 F electric matches in the presence of Black Powder, there were now seven ignitions in ten tests, whereas without Black Powder there had been only one ignition in six tests. Accordingly, it would seem that there is an added sensitiveness due to the presence of Black Powder. However, since these electric matches are among the very least impact sensitive electric matches, it is thought not to be of significant concern. For the Luna Tech Flash electric matches, there were zero in six tests at 96 in. (2.4 m) without Black powder and zero of five ignitions in the presence of Black Powder. (In both cases the testing was terminated early because more definitive results seemed unlikely.) Accordingly, it is not possible to speculate on the possibility of their being more impact sensitive in the presence of Black Powder; however, they were the least impact sensitive of all the electric matches tested.

In one case, the impact results suggest that there might have been a reduction in the sensitiveness observed. It seems likely that this is an artifact of the test method. It is suspected that the presence of Black Powder may have provided more material over which the force of the impact was distributed. For that reason it might have been expected that reduced sensitiveness would be found. (This is similar to the size effect discussed above for the E-Max and E-Max Mini matches.)

Effect of Safety Shroud

Some electric match suppliers, in particular those whose customers are likely to use the electric matches to ignite fireworks, supply safety shrouds for their electric matches. (Safety shrouds are a soft plastic covering for an electric match.) These are either preinstalled or available for customer installation. (See Figure 5 for an illustration of a typical electric match and shroud configuration.) Suppliers of electric matches for use in proximate audience pyrotechnics typically do not supply shrouds, or they offer them as an optional feature. In the proximate audience use environment, it is often necessary to install electric matches through small holes in hardware (e.g., into flash pots and concussion mortars) or into small preload devices. Such installation often precludes the use of shrouds and tends to obviate the benefits of safety shrouds because of their use in a more physically protected environment.

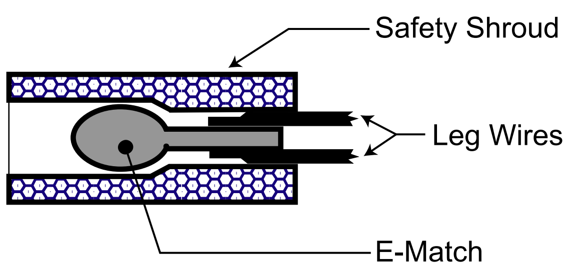


Figure 5. Illustration of a typical electric match with its molded safety shroud in place (not to scale).

While the safety shroud acts to direct the combustion products of the electric match ignition out its open end, it is generally thought that the primary purpose of the shroud is to protect the electric match and thus reduce its sensitiveness to accidental ignition. Accordingly, the electric matches in this study that were supplied with safety shrouds were also subjected to impact sensitiveness testing with their shrouds in place.

The safety shrouds found on the Daveyfire and the Luna Tech OXRAL electric matches are specially molded, similar to that shown in Figure 5. The soft plastic appears to be polyethylene, and although removable, the matches were supplied with the shrouds already in place. The shrouds for the Martinez Specialties electric matches were short lengths of soft plastic or rubber tubing (apparently a type of silicone or Tygon® tubing) and needed to be installed on the electric matches by the user when desired. Because of the electric match's somewhat arrowhead shape, this was fairly easy to accomplish and the safety shrouds tended to stay in place reasonably well.

The shrouded electric match impact sensitiveness testing was conducted using much the same method as used in the testing without the presence of safety shrouds. However, those electric match types not supplied with shrouds were not retested. One modification to the test configuration was that the electric matches were held in place on a piece of card stock (0.010 in.) using a small piece of cellophane tape. (See Figure 6.) This was to help hold the shrouded electric matches in the same orientation as in the testing without shrouds. In the shrouded electric match tests, there were generally approximately 20 separate test impacts for each electric match type, again using the stair-step (Bruceton) method.[9] The results of the testing are also presented in Table 2, with the data designated as "S-1", where "S" indicated that the electric matches had their shrouds in place, and the "1" indicated that the

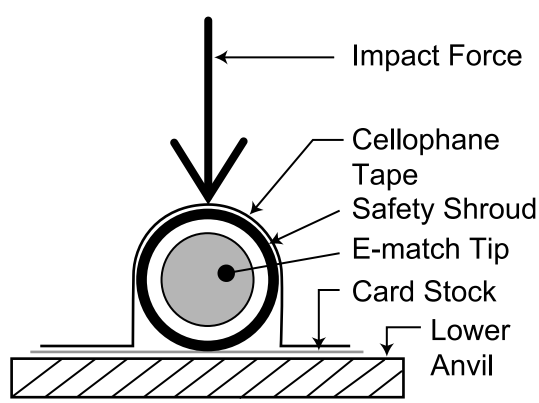


Figure 6. End-on, cross-sectional illustration of the configuration used for shrouded electric match impact testing.

1-kg drop hammer was used.

For those electric match types for which previous impact tests without a shroud produced a 50% impact sensitiveness height of at least 96 inches (equivalent for the ½-kg drop hammer) no testing was performed with safety shrouds in place. This is because it was thought that the impact sensitiveness of these matches was already so low as not to present a significant potential impact hazard during normal use. As expected, for the five electric match types that were tested, it was found that the presence of the shroud provided a substantial decrease in impact sensitiveness. The decrease ranged from a factor of three to eight and averaged a factor of a little more than five. That is to say, with the shrouds in place approximately five times greater impact energies were required to produce an ignition. Obviously, the presence of the safety shrouds on those electric matches that were fairly sensitive to impact stimulus affords a substantial safety benefit, and display crews should be instructed to leave the safety shrouds in place.

Electrostatic Discharge (ESD) Sensitiveness

In these tests, ESD sensitiveness was determined for two configurations. In the first series of tests, the electric discharge current was passed through the electric match bridgewire in much the same fashion as the intended firing current. This is illustrated in the upper drawing of Figure 7. In the second series of tests, the discharge current passed from the bridgewire through the pyrotechnic composition to ground, as illustrated in the lower drawing of Figure 7.

The high voltage discharge current used in this testing was provided by an instrument whose basic circuit diagram is shown in Figure 8. Each of the three main circuit components (R_c, R_s, and C) are removable so that their values can be selected as appropriate for the specific testing being performed. For these electric match tests, the charging resistor (R_c) was always 3.3 megohms, the series resistor (R_s) was always 100 ohms, and the charge storage capacitor (C) was varied between 0.001 and 0.25 microfarads depending on the ESD sensitiveness of the particular type of electric match being tested. In each case, to assure the full charging of the storage capacitor,

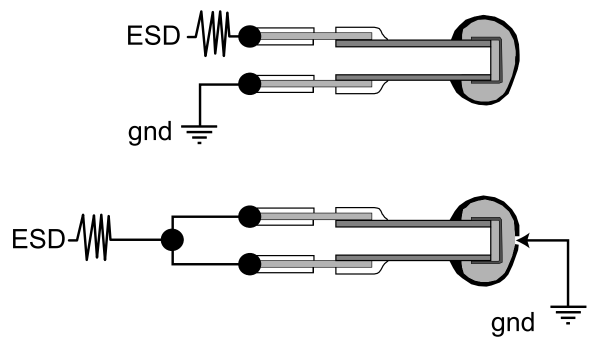


Figure 7. Illustration of the two basic ESD test configurations used in this study.

the instrument was operated such that the charging time was at least 10 RC time constants. The maximum high voltage available from the power supply used in these tests was 6 kilovolts. In the first test configuration (ESD passing through the bridgewire), solid electrical connections were made directly to the individual electric match leg wires. For each electric match type, approximately 20 individual discharge tests were performed, using the standard stair-step (Bruceton) method.[9]

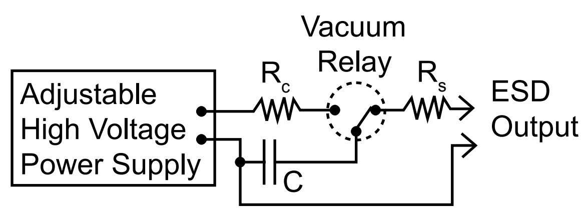


Figure 8. Circuit diagram for the ESD test apparatus used in this study.

While it is more typical to perform ESD sensitiveness testing using a higher voltage (up to 25 kV) than was used in these tests, it is thought that the lower voltages were a somewhat more realistic limit to the charge potential that might be developed on persons working at a fireworks display site in typical summer humidity. Another modification from more typical ESD testing conditions was the use of a series resistance of only 100 ohms as opposed the commonly used value of 500 ohms,[10] (or even 5000 ohms as used in some military ESD testing[11]). For human induced discharges, the series resistor is intended to be a substitute for the contact resistance of the person delivering the ESD to an electric match. The choice of this lower resistance value was somewhat arbitrary; however, measurements involving a heavily sweating person confirmed that body resistances of no more than approximately 100 ohms are common.

The choice of series resistance for these tests is an important parameter, in that it determines the partitioning of energy between that delivered to the series resistance and that delivered to the item under ESD test. Ignoring impedances other than resistance, the ESD energy being provided divides proportionally between the two resistances (in this case, between the series resistor and the electric match). Accordingly, with a 2-ohm test item and a 100-ohm series resistor, approximately 2% of the ESD energy is delivered to the test item. However, had a 500-ohm series resistor been chosen, only 0.4% (or 1/250) of the ESD energy would have been delivered to the test item. In addition to the 100-ohm body resistance being more likely, it was felt that using a 500-ohm series resistor in these tests might have given the reader a false sense of security regarding the ESD sensitiveness of electric matches under conditions typical of their use at fireworks displays.

Through-the-Bridgewire Test Configuration

The ESD sensitiveness test conditions and results for the *through-the-bridgewire* test configuration are presented in Table 3 with the designation of "TBW" in the column labeled "Test". The value of the charging capacitor for this test configuration ranged from 0.01 to 0.25 microfarad (μF) depending on the approximate sensitiveness of the electric matches and is given in the column labeled "Cap." The lowest ESD voltage used for each type of electric match and the voltage increment between the steps used for that electric match are given in the next two columns of Table 3, labeled "Min." and "Step", respectively. The next series of columns present the data from the individual test firings, where each pair of numbers is the number of ignitions and non-ignitions, respectively. The first of this series of columns, labeled "0", has the data obtained using the minimum test voltage. The succeeding columns, labeled "1" through "6", have the data obtained using stepwise increasing voltages. The final column of Table 3, labeled "Sens.", presents the sensitiveness results given as the discharge energies that produced ignitions in approximately 50% of the tests. (Note that some degree of caution is necessary in interpreting these results, because the test conditions used in these tests were significantly different from those often reported in the literature. Accordingly, the values reported in Table 3 must not be compared with values reported elsewhere, unless an adjustment is made to account for those significant differences in test conditions.)

Regarding ignitions produced by an ESD through the bridgewire, the electric matches can be roughly divided into four groups. Based on these limited results, it would seem that the Daveyfire A/N 28 B and BR, and the Martinez Specialties E-Max and E-Max Mini fall in the most sensitive group (70 to 80 mJ). A little less sensitive are the Aero Pyro, Luna Tech BGZD and OXRAL electric matches (100 to 120 mJ). Significantly less sensitive are the Daveyfire A/N 28 F and Martinez Specialties Titan electric matches (240 to 260 mJ). Substantially less sensitive still are the Luna Tech Flash electric matches (1900 mJ).

As a point of comparison, consider that the approximate maximum ESD energy that can be developed on a typical person (200 pF and 25 kV)[12] is on the order of 60 mJ. However, note that there are conditions under which a person can act as a conduit passing much greater ESD energy, from other objects that may be capable of storing considerably larger charges than a human body stores.

Electric match Tip Protective Coating Evaluation

The electric matches examined in this study all have a protective coating over their pyrotechnic composition. This coating provides a level of protection from physical damage during handling and use, as well as possible damage from exposure to moisture. The coatings also provide a significant degree of electrical insulation, which generally limits the ability to cause an ESD from the bridgewire through the composition (and its coating). However, imperfections are occasionally observed in the electric match coatings, such that discharges through the composition can potentially occur. These imperfections can occur as a normal consequence of manufacturing methods or as a result of the electric match tip being

Table 3. Electrostatic Discharge Sensitiveness Test Results.

Electric match Type	Test[a]	Cap. (μF)[b]	Min. (V)[c]	Step (V)[d]	Individual ESD Test Data[e]							Sens. (mJ)[f,g]
					0	1	2	3	4	5	6	
AP	TBW	0.01	4000	250	0/1	0/3	2/6	7/0				120
	TC	0.001	500	250	0/1	1/1	1/3	4/4	5/1	1/1	1/0	0.7
DF-B	TBW	0.01	3500	250	0/7	8/2	3/0					70
	TC	0.001	500	250	0/3	2/4	4/3	3/2	1/1			0.5
DF-BR	TBW	0.01	3500	250	0/5	5/3	3/1	1/1	1/0			70
	TC	0.001	1000	250	0/5	4/4	4/2	2/0				0.8
DF-F	TBW	0.1	2000	250	0/7	7/2	3/0					240
	TC	0.001	1750	250	0/1	1/1	1/3	4/1	3/4	5/1	1/0	3
LT-B	TBW	0.01	4000	250	0/1	0/6	6/4	4/0				100
	TC	0.01	500	500	0/2	2/2	2/6	5/4	4/2	2/1	1/0	20
LT-F[h]	TBW	0.25	3500	250	0/1	0/9	9/9	8/3	4/0			2300
	TC	0.01	500	250	0/2	2/3	5/3	3/1	1/2	2/1	1/0	6
	TBW	0.25	3000	300	0/5	6/5	6/0	1/0				1400
	TC	0.01	400	400	0/7	7/4	5/7	7/4	4/3	4/0		8
LT-O	TBW	0.01	4500	250	0/4	3/4	3/3	3/0				120
	TC	0.001	1500	250	0/4	3/3	3/2	2/1	1/1	1/0		2
MS-EM	TBW	0.01	3500	250	0/3	3/6	7/0					70
	TC	0.001	1250	250	0/2	2/2	3/4	5/0				2
MS-EMM	TBW	0.01	3750	250	0/4	4/4	5/1	2/0				80
	TC	0.001	1750	250	0/2	2/5	4/3	3/0				2
MS-T	TBW	0.1	2000	250	0/2	1/8	9/0					260
	TC	0.25	1000	1000	0/4	4/2	2/2	2/5	4/3	2/0		1000

a) Two test configurations were used. TBW indicates the *through-the-bridgewire* configuration, and TC indicated *through-the-composition* configuration, the upper and lower configurations shown in Figure 7, respectively.

b) This is the value of the storage capacitor (in micro farads–μF) labeled "C" in Figure 8.

c) This is the minimum voltage used during the testing of this type of electric match using the configuration listed.

d) This is the step size used (i.e., the voltage difference between the various stimulus levels).

e) These are the number of ignitions and non-ignitions that occurred at this ESD test voltage. For example, "6/2" would indicate there were 6 ignitions and 2 non-ignitions at this particular voltage. The voltage is equal to the minimum voltage (c) plus the product of the step size (d) and the number of steps.

f) This is the ESD energy that produced an ignition approximately 50% of the time. Because of the limited precision of these results, the energy values for through-the-bridgewire test configuration (TBW) are reported to the nearest 10 mJ, or two significant figures, whichever is less precise.

g) Because of the additional uncertainty associated with the removal of the protective coating, the energy values for through-the-composition test configuration (TC) are reported to only one significant figure.

h) Because of some concern regarding whether the initially collected data was generally representative of these electric matches, some additional trials were conducted using a second production lot of the Luna Tech Flash matches.

physically damaged (from crushing or abrasion) during handling and use. A close examination of electric match tips from each of the suppliers, revealed occasional visible imperfections (apparent voids or holes) in their coatings. Figure 9 is a collection of electron micrographs of such imperfections observed for each of the various sup-

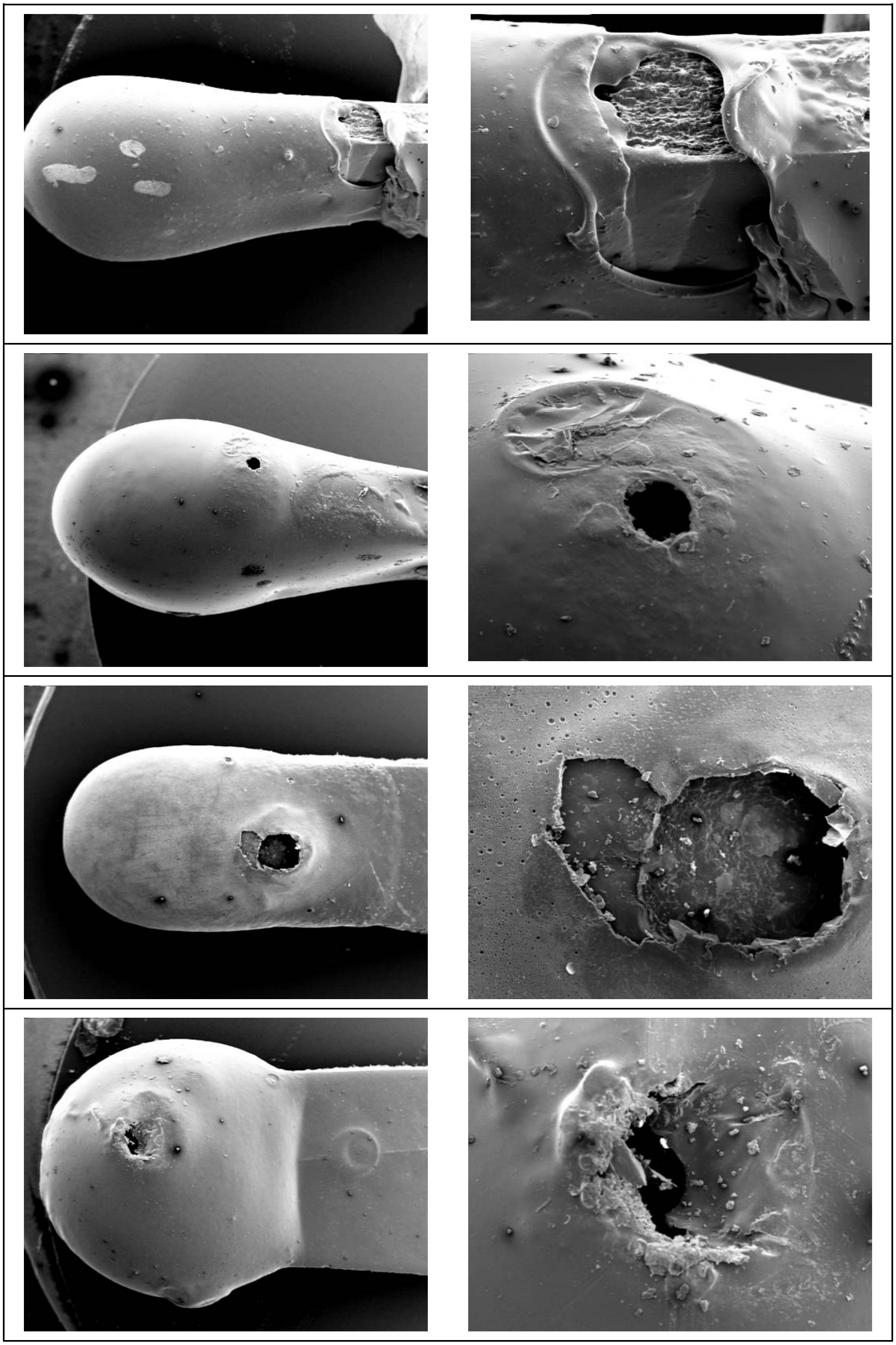


Figure 9. A collection of electron micrographs of imperfections found in some of the electric match tips from the various suppliers, with the image on the right being a close-up view of the imperfection.

pliers' electric matches. (It should be mentioned that only one example of a coating imperfection was found for the Aero Pyro matches, shown in Figure 9. Further, because those matches are apparently coated twice, and the imperfection was only in one of the coating layers, thus even in that one case there was ample ESD protection.)

To evaluate the nature of the electric match coating imperfections, a megohm meter, specifically designed to make high resistance measurements, was used to measure coating-to-bridgewire resistances. In stark contrast to typical resistance measuring instruments, this instrument applies a test voltage up to 200 volts (but with very limited current). The intention is that these higher voltages would induce dielectric breakdowns in imperfect electric match tip coatings similar to those produced during an ESD event. One terminal of the instrument was connected to the electric match leg wires, and a test probe—with a small rounded tip—was connected to the other terminal of the instrument. The probe was moved over the electric match tip looking for points with relatively low resistance. (Only those areas of the match tip where pyrotechnic composition was present were investigated.) In most instances, the coatings on the electric matches were found to provide a resistance of more than the maximum instrument reading, 500 megohms (MΩ); however, a fair number of electric match tips had one or more points on their coating where relatively low resistance values were found. The point on the electric match tip found to have the lowest resistance value was noted for each of a collection of ten electric matches of each of the ten types. Table 4 has those individual resistance values, plus both the minimum point resistance observed for any electric match tip in each group of ten tips of the same type and the average of the minimum resistance values for each set of ten electric matches. (For comparison, note that the resistance of unglazed Black Powder grains (20 mesh) was found to be in excess of 500 MΩ, and the resistance of glazed Black Powder grains was found to be less than 1 MΩ.) Because of a fairly large uncertainty in the resistance measurements, all values in Table 4 are reported to only one significant figure. (Further, given the nature of dielectric

Table 4. Minimum Electric Match Tip Coating Resistance Measurements.[(a)]

Electric match	Lowest Resistance of Each Electric match Tip (MΩ)[(b)]										Lowest Resistance (MΩ)	
Type	1	2	3	4	5	6	7	8	9	10	Of Any[(c)]	Average[(d)]
AP	500	500	500	500	500	500	500	500	500	500	>500	>500
DF-B	70	50	500	500	500	500	10	20	500	500	10	300
DF-BR	40	500	500	50	500	500	500	500	500	500	40	400
DF-F	500	500	1	20	500	500	500	500	500	500	1	400
LT-B	<1	3	4	2	3	<1	1	4	2	2	<1	2
LT-F	<1	<1	<1	2	<1	1	<1	3	2	<1	<1	<1
LT-O	20	40	30	60	20	30	60	40	40	<1	<1	30
MS-EM	500	500	500	500	500	500	500	500	500	500	>500	>500
MS-EMM	500	50	300	300	500	500	100	100	500	500	50	300
MS-T	60	<1	2	20	1	3	500	3	<1	<1	<1	60

a) Because of a fairly large uncertainty in the resistance measurements, all values are reported to only one significant figure.

b) This is the lowest single point resistance, in megohms (MΩ), found on each of ten individual electric matches of this type. The reporting of a value of 500 means that at no point on the surface of the electric match tip was the resistance found to be less than 500 MΩ.

c) This is the lowest single point resistance value found on any of the ten individual electric match tips.

d) This is the average of the lowest single point resistances for the collection of ten electric matches. When the lowest resistance value for an individual electric match was >500 MΩ, a value of 500 MΩ was used. When the lowest resistance value was <1 MΩ, a value of 0 was used.

breakdown, the resistance values are expected to depend on the measurement voltage.)

Through-the-Composition Test Configuration

A limited number of *through-the-composition* ESD sensitiveness tests were conducted. This was accomplished by connecting the positive terminal of the ESD test apparatus to the shunted pair of leg wires of an electric match, connecting the negative terminal of the ESD tester to a steel post, causing the electric match tip to be held in loose contact with the metal post, and applying the ESD energy. As might have been expected, the stair-step (Bruceton) method of testing produced highly variable results. When the electric match tip was well coated, there were no ignitions even with high discharge energy. When there was a significant imperfection(s) in the electric match tip coating, there were ignitions even at low discharge energies. To that extent, the testing served as more of an indicator of when there was a significant coating imperfection as opposed to being purely an indication of the ESD sensitiveness of the electric match composition.

Accordingly, the test was modified from the normal stair-step method. Instead, a collection of ten electric match tips of each type were a tested using a relatively high voltage but storing only a relatively low energy (6 kV with a charging capacitor of 0.001 μF to store energy of 18 mJ). In most cases, when the test produced no ignition of the electric match composition, the ESD spark passed harmlessly over the coated surface of the match. Whenever the first discharge produced no ignition, the same electric match was subjected to two more discharges of the same energy. (On several occasions, an ignition did occur on the second or third discharge. When this happened, it was considered the same as if it had occurred with the first discharge. This was done even though the previous ESD events could have acted to damage the coating to some extent.)

The results of this testing are presented in Table 5 in the column titled "18 mJ", as the number of ignitions in ten trials. Of the ten tests of electric matches of each type, when less than two of them ignited using the 18 mJ stored ESD energy, the test was repeated using a higher discharge energy. In this case, another set of ten electric matches was subjected to ESD energies of 180 mJ (6 kV using an 0.01 μF capacitor). The results of these tests are also reported in Table 5, in the column titled "180 mJ", as the number of ignitions out of ten trials. (Note that in those cases where the manufacturer had provided electric matches with safety shrouds, those shrouds were removed prior to testing.) (It must be expected, under the conditions of these tests, that only a fraction of the energy stored in capacitor C in Figure 8 was successfully delivered to the ESD event.)

Based on the observation of electric match coating imperfections, low coating resistances and the electric match ESD test results reported in Table 5, it seems obvious that coating imperfections afford the ability for ESD events to pass from the bridgewire through the pyrotechnic composition of the match tip. Further, it must be expected that at least on some occasions, damage to electric match tips during use might be sufficient to introduce discharge paths through the composition of electric matches with initially perfect coatings. (Shrouded electric match tips must be significantly less prone to being damaged during use, but in extreme cases, even they could be damaged.) Accordingly, since the ESD protection offered by the electric match coatings can be, or can become compromised, it was decided to perform additional tests to determine the ESD sensitiveness of the exposed electric match compositions themselves.

For these tests, a small portion of the protective coating on the tip of each test electric match was intentionally removed with emery paper before testing. This was done in an attempt to simulate a significant imperfection in the electric match coating or the damage that might occur during prolonged or rough handling and use. In this test series, one terminal of the ESD apparatus was connected to the shunted pair of electric match leg wires, the other terminal of the ESD tester was connected to a metal post, the match tip was held in loose contact with the metal post, and the ESD energy applied. For each electric match type, approximately 20 individual discharge tests were performed, using the standard stair-step method.[9] The data and results of these *through-the-composition* electric match sensitiveness tests are also presented in Table 3, where the test configuration is indicated as "TC". The sensitiveness is reported as the discharge energy

Table 5. Additional Through-the-Composition ESD Test Results.

Electric match Type	Number of Ignitions in 10 trials(a)				
	Without Shroud(b)		With Shroud – 18 mJ(c)		
	18 mJ	180 mJ	g/BP(d)	u/BP(e)	Air(f)
AP	0	2	—	—	—
DF-B	4	(g)	4	1	1
DF-BR	2	(g)	3	0	0
DF-F	6	(g)	3	0	0
LT-B	1	4	—	—	—
LT-F	0	5	—	—	—
LT-O	10	(g)	10	9	10
MS-EM	2	(g)	2	0	1
MS-EMM	7	(g)	7	0	0
MS-T	0	2	0	0	0

a) These tests were performed at 6 kV. To store an ESD energy of 18 mJ, a 0.001 µF charging capacitor was used. To store an ESD energy of 180 mJ, a 0.01 µF capacitor was used.

b) For those electric matches supplied with safety shrouds, they were removed for these tests.

c) These tests were only performed for the electric matches with safety shrouds, and they used the lower stored ESD energies of 18 mJ. The "—" symbol is meant to indicate those electric matches not supplied with safety shrouds, which were not tested.

d) The "g/BP" column is the number of ignitions that occurred when the end of the safety shroud was filled with *glazed Black Powder*.

e) The "u/BP" column is the number of ignitions that occurred when the end of the shroud was filled with *unglazed Black Powder*.

f) The "Air" column is the number of ignitions that occurred when nothing filled the end of the shroud.

g) These electric match types were not tested at the higher ESD energy because there were at least two ignitions at the lower energy.

that produced an ignition in approximately 50% of the tests. (Note that in those cases where the manufacturer had provided electric matches with safety shrouds, those shrouds were removed prior to testing.)

Regarding ignitions produced by an ESD from the bridgewire through the pyrotechnic composition when the coating is imperfect or damaged (and without safety shrouds), the electric matches can be roughly divided into four groups. Based on these limited results, it would seem that the Aero Pyro and Daveyfire A/N 28 B and BR electric match compositions fall in the most sensitive group (0.5 to 0.8 mJ 50% ignition energy). Somewhat less sensitive (2 to 6 mJ 50% ignition energy) are the Daveyfire A/N 28 F, Luna Tech Flash and OXRAL, and Martinez Specialties E-Max and E-Max Mini electric match compositions. Still less sensitive (20 mJ 50% ignition energy) are the Luna Tech BGZD electric matches. Surprisingly, less sensitive yet (1000 mJ 50% ignition energy) are the Martinez Specialties Titan electric matches.

As a point of comparison, consider that these through-the-composition (TC) ESD ignitions were produced using roughly 100 times less energy than those occurring through the bridgewire. Accordingly, through-the-composition discharges represent a much greater risk of accidental ESD ignition. Further, shunting the electric matches has no effect in reducing this hazard. Finally, note that most of these 50% ESD ignition energies are a small fraction of the approximate maximum ESD energy (approximately 60 mJ) that can be developed on a typical person (200 pF and 25 kV).[12]

Effect of Safety Shroud and Black Powder

The appearance and design of the safety shrouds, for those electric matches supplied with them, were illustrated above in Figures 2 and 5. The ESD sensitiveness testing with shrouds in place was conducted using much the same method as the through-the-composition testing without shrouds. However, only those electric match types supplied with safety shrouds were tested. The electric matches were used as supplied (i.e., without altering the protective coating over the pyrotechnic composition). One point of electric contact was the shunted leg wires of the electric match, and the other point of electric contact was a flat piece of metal placed across the end of the shroud. In each test, a stored energy of only 18 mJ was used (6 kV stored in 0.001-μF capacitor and discharged through a 100-ohm series resistance).

To test for a variety of possible use conditions, three test configurations were used. In one series of tests, the safety shroud was filled with fine-grained glazed Black Powder (20 mesh). In a second series of tests, the shroud was filled with fine-grained unglazed Black Powder. (Recall that the resistance of glazed Black Powder grains was less than 1 MΩ, and the resistance of unglazed Black Powder grains was found to be in excess of 500 MΩ.) In the third series of tests, the shroud was left empty. In each configuration, a total of ten electric matches were tested. The results of the testing are presented in the last three columns of Table 5.

When filling the safety shroud with glazed Black Powder, note that the presence of the safety shroud apparently provided no decrease in ESD sensitiveness; compare column 4 (“g/BP”) with column 2 (“18 mJ” “without shrouds”) of Table 5. It would seem the reason is that glazed Black Powder is fairly conductive because of its graphite coating, thus allowing the discharges to gain access to the electric match tips and any imperfections in their coating. In contrast, note in column 5 (“u/BP”) that when unglazed Black Powder was used to fill the shroud, there was nearly a total elimination of ignitions (for all but Luna Tech’s OXRAL electric matches). Given that the typical grain resistance of unglazed Black Powder exceeds 500 MΩ, such a reduction in the number of ignitions was expected. Finally, in column 6 (“Air”) the test with empty (air-filled) shrouds produced virtually the same results found for the tests using unglazed Black Powder.

In the test results for safety shrouds filled with unglazed Black Powder and for empty shrouds, the Luna Tech OXRAL electric matches standout as a notable exception to the reduction in the number of ESD ignitions produced. The apparent reason for this is the limited distance between the end of the electric match tip and the end of the shroud. Typically, this distance is only approximately 0.03 inch (0.75 mm) for the OXRAL electric matches and, under the conditions of these tests, the distance was short enough to allow a discharge to take place even without partially conductive material filling the shroud. (See again Figure 2.) In contrast, the typical distance for the Daveyfire electric match types was approximately five times greater (approximately 0.15 inch or 3.8 mm) and sufficiently great to usually prevent a 6 kV ESD from taking place. In the case of the Martinez Specialty matches, which use short lengths of tubing as safety shrouds to be installed by the user, it is possible to install the shroud with a range of distances between the end of the electric match tip and end of the shroud. For these tests, the electric match tips were installed so that the widest end of the electric match tip (its leg wire end) was pushed just slightly inside the length of tubing supplied.

Additional ESD Discussion

It is perhaps worth reiterating that an ample and well-applied protective coating can offer a high degree of ESD protection. Note that the Aero Pyro electric matches apparently have a two-layered protective coating. Accordingly, while their composition is among the most ESD sensitive, these electric matches tied for producing the least number of intact electric match tip ignitions (zero in ten tests). They equaled the performance of the Martinez Specialty Titan electric matches, which use a composition with approximately a thousand times less ESD sensitiveness. (See again Tables 3 and 5.)

At the time of this writing, it was unclear why two of the Titan electric matches ignited with only 180 mJ of energy in the intact electric match tip ESD tests when the 50% ignition energy was found to be more than five times higher. Laib[13] has suggested that this might be caused by a particularly high percentage of conductive metal particles in the composition. If so, when the coating is intact, the spreading of the discharge energy across numerous potential conductive paths is inhibited by the presence of surface dielectric. In that case the discharge is relatively confined to fewer discharge paths in the vicinity where dielectric breakdown through the coating occurs. When the coating is damaged, more surface conductors are available along with more numerous paths through the material, thus reducing the average ohmic heating available per path, leading to higher required ignition energies.

In interpreting the ESD sensitiveness data presented here, some degree of caution is necessary. The reason is that the conditions for these tests were substantially modified from those commonly used. (This was done in an attempt more nearly to duplicate the typical conditions during electric match use in the field.) Accordingly, the results reported in this article should not be directly compared with other data reported in the general pyrotechnic literature, unless adjusting for the different test conditions being used.

Probably the most important conclusion to be drawn from this study is that, while there is a very wide range of sensitiveness to ESD ignition, under some conditions all of the electric match types could be ignited by an accidental discharge. (If not as a result of an ESD from a person through an electric match with a perfect coating, consider the possibilities of damaged electric match tips or something like a nearby stroke of lightning.) Further, in almost all cases the ESD energy capable of initiating an electric match by a discharge through the composition is very much less than that required for a discharge through the bridgewire. (Note that shunting the electric match leg wires provides no protection against such through-the-composition discharges.) Finally, some of these 50% ignition energies are so small that they are less than a typical person can feel.[12]

Friction Sensitiveness

Normal Configuration

The standard method of friction sensitiveness testing is illustrated in Figure 10. This method works well for loose powders; however, in this case, friction sensitiveness for the intact electric match tips was being sought. Unfortunately, during testing it was found that the standard method was mostly unsatisfactory for intact electric match tips. Often the electric match tips just slid loosely along the surface in front of the striker without ever being caught forcefully between the striker and the abrasive surface. Accordingly, the test setup was modified to use the electric match tip itself as the striker. The tip was supported from behind and held at an approximate 45° angle to a moving abrasive surface, #100 grit sand paper (see Figure 11). To configure the test to be somewhat consistent with anecdotal accounts of accidents, it was thought that the force holding the electric match tips against the abrasive surface should be fairly low and the rate of movement along the surface should be fairly high. The combination of a force of 0.33, 0.67 or 1.35 pounds (1.5, 3.0 or 6.0 N) at a rate of movement of 10 feet per second (3 m/s) was found to be reasonably effective for the range of electric match friction sensitiveness of the various electric match types. It must be acknowledged that the test conditions were quite severe (with the electric matches being quickly sanded into non-existence) and that some ignitions could have been produced as a result of frictional heating of non-pyrotechnic elements in the electric matches as they abraded away.

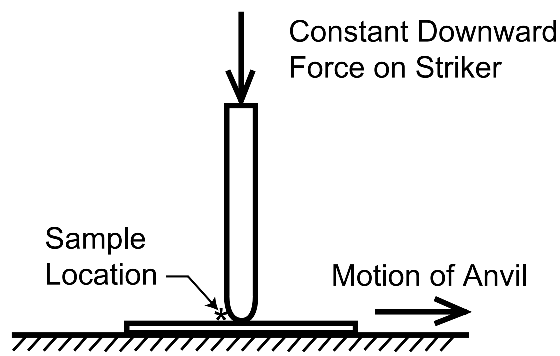


Figure 10. Simplified illustration of a typical friction test apparatus.

Each test consisted of a set of three trials of the same electric match type and same downward force. For those electric match types failing to ignite at least once during the three trials with the applied force, the next greater force was used for another set of three electric matches. For different electric match types found to ignite with the same applied force, their times-to-ignition were used to discriminate between them in terms of sensitiveness. Ignition times were determined by video taping each test, then playing back the tape and counting the number of individual (1/60 second) video fields elapsing before ignition

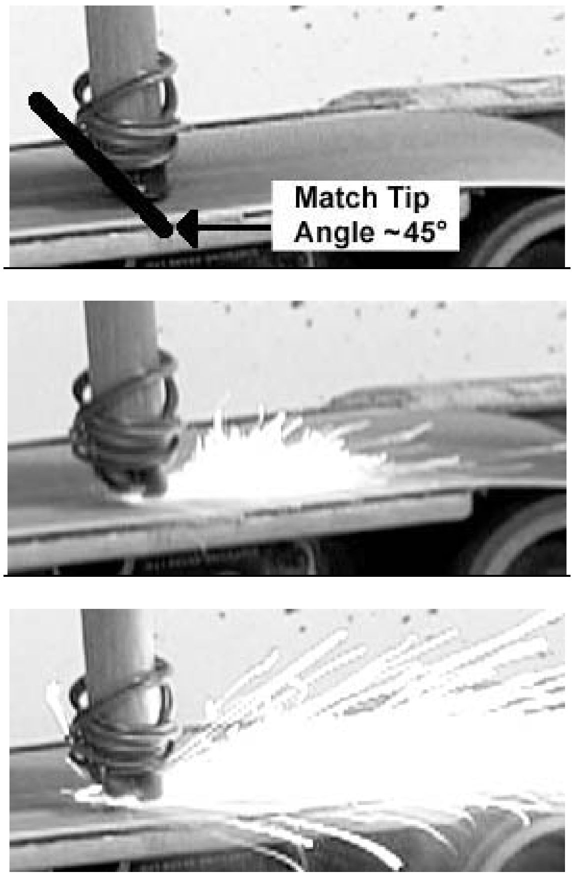


Figure 11. Photographs of the friction test setup as modified for electric matches. There is a time lapse of 1/60th second between images.

occurred. The raw data from this friction sensitiveness testing and the results are presented in Table 6, with the ignition times in the set of columns labeled “w/o BP”, indicating the testing was performed *without Black Powder* being present. (Note that the testing was performed on bare electric matches without the safety shroud present.)

Friction sensitiveness of the electric matches was found to fall into three groups. In the most sensitive group were the Aero Pyro, Daveyfire A/N 28 B and A/N 28 BR, and the Martinez Specialty E-Max and E-Max Mini; all these electric matches ignited with an applied force of 1.5 N (0.33 lbf). Less sensitive were the Luna Tech BGZD and OXRAL electric matches, which required an applied force of 3.0 N (0.67 lbf) for ignition. Substantially less sensitive still (failing to ignite even with an applied force of 6.0 N (1.35 lbf) were the Daveyfire A/N 28 F, Luna Tech Flash, and Martinez Specialty Titan electric matches.

Configuration with Black Powder and Safety Shrouds

There are a number of anecdotal reports of accidental ignitions occurring when electric matches were being forcefully removed from aerial shell leaders where the electric match was in contact with the Black Powder coating on the black match fuse. Accordingly, it was thought to be appropriate to attempt to determine whether added friction sensitiveness resulted from the presence of Black Powder. In this case, each test electric match was coated with a slurry of Black Powder (fine meal powder bound with 5% dextrin) and allowed to dry thoroughly. (Note that the testing was performed on bare electric matches without the safety shroud present.) In this series of tests, the same downward force was used as was found to be the minimum capable of producing ignitions without the presence of Back Powder. Using this force, the average time to ignition for a series of three Black Powder coated electric matches was determined. If the presence of Black Powder had little or no effect on friction sensitiveness, it would be expected that the average time to ignition would be roughly the same as found when testing without Black Powder. The raw data and results of this testing are presented in Table 6, with the ignition times in the set of columns labeled “w/ BP”, indicating the testing was performed with Black Powder being present. Note that the average times to ignition are all essentially unchanged (i.e., for these test conditions, apparently no increased friction sensitiveness resulted for any electric match in the presence of Black Powder).

Additional friction sensitiveness testing was not performed with safety shrouds present on the electric matches. This is because, during normal use or even abuse, so long as the shrouds survived and stayed in place, it could not be imagined that an ignition would be produced due to friction.

Table 6. Results of Friction Sensitiveness Testing.

E-match Type	Force (N)[(a)]	Time to Ignition w/o BP (s)				Time to Ignition w/ BP (s)			
		1	2	3	Average[(b)]	1	2	3	Average[(c)]
AP	1.5	0.37	0.25	0.23	0.28	0.23	0.38	0.25	0.29
DF-B	1.5	0.17	0.20	0.22	0.20	0.25	0.20	0.15	0.20
DF-BR	1.5	0.13	0.25	0.12	0.17	0.15	0.10	0.17	0.14
DF-F	6.0	n/i	n/i	n/i	n/i	n/i	n/i	n/i	n/i
LT-B	3.0	0.20	0.33	0.12	0.22	0.07	0.37	0.56	0.33
LT-F	6.0	n/i	n/i	n/i	n/i	n/i	n/i	n/i	n/i
LT-O	3.0	0.80	0.58	0.32	0.57	n/i	0.38	n/i	0.6[(d)]
MS-EM	1.5	0.12	0.12	0.10	0.11	0.13	0.28	0.13	0.18
MS-EMM	1.5	0.20	0.22	n/i	0.3[(d)]	n/i	0.12	n/i	0.2[(d)]
MS-T	6.0	n/i	n/i	n/i	n/i	n/i	n/i	n/i	n/i

a) This is the minimum applied force that produced at least one ignition during testing.

b) This is the average time-to-ignition for a set of three electric matches without the presence of Black Powder. "n/i" means no ignition(s) occurred.

c) This is the average time-to-ignition for a set of three electric matches in the presence of Black Powder. "n/i" means no ignition(s) occurred.

d) There were one or two non-ignition(s) observed. The average time to ignition was calculated using twice the longest time-to-ignition as the time for each electric match failing to ignite during the test. This value is reported to only one significant figure.

Thermal Sensitiveness

The initial attempt at determining thermal sensitiveness of the complete electric match tips was to insert the various matches into a series of six small wells, 0.25-inch (6-mm) diameter and 0.5-inch (12-mm) deep, drilled into a block of aluminum that was heated electrically. See Figure 12 for an illustration of the thermal test apparatus. The temperature of the block was monitored using a thermocouple inserted into one of the six wells. The power to the electric heating element was adjusted to provide approximately a 5 °C per minute rate of temperature rise in the wells. In preparation for the test, five electric matches of the same type (after cutting off their leg wires) were loaded into the available wells. Then, starting at room temperature, the block was heated, and the test continued until all of the test electric matches ignited or until a temperature of 300 °C was reached. Although the temperature of each ignition was noted, the lowest temperature at which any of five test electric matches ignited was considered an indication of their thermal ignition sensitiveness and is reported as "Ramp" ignition temperature in Table 7.

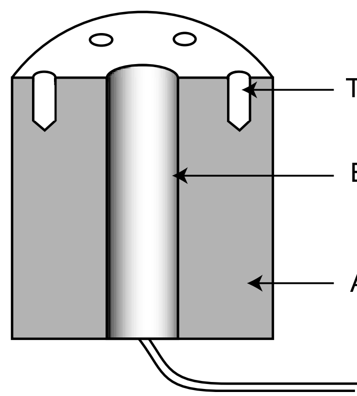


Figure 12. Illustration of the thermal sensitiveness test apparatus.

Even though the rate of temperature rise in the initial testing was fairly rapid (approximately 5 °C per minute), it was found that most of the electric matches being tested decomposed during the heating period without actually igniting. Accordingly, a second series of tests was performed. In these tests, the thermal block was pre-heated to a specific temperature. Then a single electric match tip (with leg wires removed) was placed into a well. The time taken for that electric

Table 7. Results of Thermal Sensitiveness Testing.

Electric match Type	Ramp Ignition Temperature (°C)[(a)]					Time to Ignition (s) at the Indicated Temperature (°C)							5-Sec Temp. (°C)[(b)]
	1	2	3	4	5	180	200	220	240	260	280	300	
AP	170	178	192	208	232	19	12	6	2				225
DF-B	165	>	>	>	>	22	12	5					220
DF-BR	245	>	>	>	>	16	10	4					215
DF-F	>	>	>	>	>	>60		>60		>60		>60	>300
LT-B	217	>	>	>	>	>60		>60		9	6	5	300
LT-F	>	>	>	>	>	>60		>60		>60		>60	>300
LT-O	204	205	206	207	209	32		14		5			260
MS-EM	164	>	>	>	>	18		19		10	7	6	≈300
MS-EMM	159	161	162	162	>	29		11		7	5		280
MS-T	>	>	>	>	>	>60		>60		>60		43	>300

a) These are the ramp ignition temperatures for each of five electric match tips tested. Values are listed in order of increasing temperature. The ">" indicates that no ignition occurred below 300 °C.

b) The 5-second ignition temperatures were determined graphically and are reported to the nearest 5 °C.

match to ignite was noted; if the time exceeded 60 seconds, the test was terminated for that temperature. If the electric match did not ignite within 5 seconds, the temperature of the block was increased 20 °C, and the test was repeated using a new electric match tip. The data from this second series of thermal tests are reported in Table 7 as "Time to Ignition" at the temperatures specified. These times-to-ignition were plotted graphically to estimate the 5-second ignition temperature, which was reported in the final column of Table 7 to the nearest 5 °C.

The temperatures found to produce electric match ignitions in these tests are all sufficiently high as to seriously discount the possibility that accidental ignitions caused by thermal sources are likely to be encountered during use on a fireworks display site. Accordingly, it was not thought to be appropriate to rank the different electric match types based on their thermal sensitiveness.

It may be of interest to note that the American Pyrotechnic Association is party to an exemption (DOT-E 11685) allowing the shipment of previously approved fireworks combined with previously approved electric matches. However, one requirement of that exemption is that the electric matches "be certified by the manufacturer to be thermally stable at 150 °C for 24 hours". While a test for this was not conducted, it may be worth noting that, in the ramp temperature tests, several of the electric match types ignited at only slightly higher temperatures.

Additional thermal sensitiveness testing in the presence of Black Powder was not performed. This is because the exterior of the electric matches has a protective coating, and there is no opportunity for the electric match composition to have direct contact with the Black Powder. Accordingly, it is believed that the possibility of the presence of Black Powder having a significant effect on the thermal sensitiveness of electric matches is rather remote. For much the same reason, there was no thermal sensitiveness testing of electric matches with their safety shrouds in place.

Conclusion

Although a large number of individual tests were performed, it is important to recall that this sensitiveness testing was limited in scope and that it must only be considered a screening study. Further, many of the standard tests were modified somewhat in an attempt to better characterize the electric matches in an environment similar to their use for fireworks displays. Accordingly, the statistical precision achieved is only sufficient to approximately characterize and rank the sensitiveness of the various electric matches, and then only under the specific conditions of this testing. For electric matches producing similar results, had additional electric matches been tested or had the conditions been somewhat different, it is possible that slightly different results would have been found.

One further caution is that the electric matches tested were supplied in late 1999. Accordingly, there is no guarantee that current production electric matches have the same sensitiveness characteristics as observed in the tests reported herein.

While a large range in sensitiveness was observed for the different electric matches under various conditions, none was found to be so extremely sensitive as to preclude their safe use providing appropriate care and safety measures are taken during their use. Probably the single most appropriate safety measure is to educate fireworks display crews of the potential for accidental ignition of electric matches, and the measures to take to minimize both the probability and the consequences of an accidental ignition. One obviously appropriate safety measure is to leave the safety shrouds in place on electric matches to be used in any situation where they could be subject to physical abuse.

In selecting a supplier of electric matches, it is generally thought to be appropriate to use the least potentially dangerous materials that will successfully and reliably (and economically) perform the needed task. Unfortunately, this study has only reported on the sensitiveness and not on the performance of those electric matches studied. In an attempt to provide some of the additional information needed for users to make the best choice in their selection of electric matches, a second study is under way to characterize the performance of the same ten types of electric matches. As the individual testing is being completed, those results are being reported.[6]

Acknowledgments

The authors appreciate the many useful technical comments provided by L. Weinman during the testing. The authors also appreciate the comments of G. Laib and L. Weinman on a draft of the present article.

The authors gratefully acknowledge that the four electric match suppliers provided samples of their products, at no cost, for testing. Further, the American Pyrotechnic Association provided a grant to help cover some of the costs of this study. Note that while many of the company and product names are apparently registered trademarks, they have not been specifically identified as such in this article.

References

1) K. L. and B. J. Kosanke, A series of articles on “Electric Matches:” “General Safety Considerations and Impact Sensitiveness”, *Fireworks Business*, No. 198, 2000; “Sensitiveness to Electrostatic Discharges Through the Bridgewire”, *Fireworks Business*, No. 199, 2000; “Sensitiveness to Electrostatic Discharges Through the Composition”, *Fireworks Business*, No. 200, 2000; “Sensitiveness to Friction and Temperature”, *Fireworks Business*, No. 201, 2000; “Black Powder’s Effect on Sensitiveness”, *Fireworks Business*, No. 202, 2000; “Effect of Shrouds on Sensitiveness”, *Fireworks Business*, No. 203, 2000.

2) Aero Pyro, Inc., PO Box 12853, Reno, NV, 89510, USA. (Has since ceased business.)

3) Daveyfire, Inc., 2121 N. California Blvd, Suite 290, Walnut Creak, CA, 94596, USA.

4) Luna Tech, Inc., 148 Moon Dr., Owens Cross Roads, AL, 35763, USA.

5) Martinez Specialties, Inc., 205 Bossard Rd., Groton, NY, 13073, USA.

6) K. L. and B. J. Kosanke, A series of articles on Electric Matches: “Physical Parameters”, *Fireworks Business*, 206; “Ramp Firing Current”, *Fireworks Business*, 207; “Effective Thermal Output”, *Fireworks Business*, 217; also in this collection of articles.

7) K. L. and B. J. Kosanke, “Introduction to the Physics and Chemistry of Low Explosives, Parts 1 to 3”, *Pyrotechnics Guild International Bulletin*, Nos. 68 to 70, 1990; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)*, Journal of Pyrotechnics, 1995.

8) K. L. and B. J. Kosanke, and C. Jennings-White, “Basics of Hazard Management”, *Fireworks Business*, No. 129, 1994; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996.

9) W. J. Dixon and F. J. Massey, *Introduction to Statistical Analysis*, Chapter 19 “Sensitivity Experiments”, McGraw-Hill, 1957.

10) S. L. Hingorani, “Electrostatic Discharge Testing of Electroexplosive Devices”, *Proceedings of the Pyrotechnics and Explosives Section Meeting*, American Defense Preparedness Association, 1990.

11) US Military Standard, MIL-STD 331C.

12) K. Bell and A. S. Pinkerton, “The Fatal Spark”, *IEE Review*, Feb., 1992 pp 51–53.

13) G. Laib, private communication, 2002.

An earlier version appeared in *American Fireworks News*, No. 248, 2002.

Sodium / Potassium Ratio and Hygroscopicity of Civil War Era Black Powder

K. L. and B. J. Kosanke

Several years ago a sample of Black Powder, which had previously been recovered from US Civil War era cannon balls (ca. 1865), was made available for analysis. This made possible a brief comparative study of the Civil War era sample and one representing currently produced Black Powder. That study found the performance of the Civil War era powder sample to be roughly comparable to current production Black Powder.[1] Following that initial study, a very brief study was conducted regarding the purity of the potassium nitrate used in the Civil War era powder sample. Specifically, the molar percentage of sodium to potassium was determined, and those results were compared with the results from two more recently produced powders. This was of interest because it was speculated that the potassium nitrate in the Civil War era Black Powder might have been of lower purity with regard to the amount of sodium present (potentially as sodium nitrate). If that were the case, it might contribute to the susceptibility of the powder to absorb moisture, potentially leading to its degraded performance under battle field conditions.

The samples for analysis were prepared by the prolonged agitation of small portions of Black Powder in hot (near boiling) water, followed by filtration and washing of the residue with additional amounts of hot water. (Note that this method may have also extracted some components of the ash in the charcoal. However this is thought to be of relatively little consequence.) The resulting aqueous solutions were then analyzed spectroscopically to determine the ratio of sodium to potassium, using their emissions at approximately 589 and 768 nm, respectively. (For analysis, the samples were aspirated into a gas flame to produce the emissions, which were then analyzed using an Ocean Optics CHEM2000 spectrometer.) For calibration, a 0.1 molar standard solution with a sodium to potassium mole ratio of 5.0% was used. Table 1 presents the results of the analyses.

Before discussing these results, a note of caution is appropriate. Only one sample of the Civil War era and Dupont powders were available for analysis, where it would have been preferable to have analyzed multiple representative samples of each powder type. Further, while it is not thought to have produced any interference, it would have been preferred that the standard solution contained somewhat less sodium. Nonetheless, for the samples analyzed, it seems clear that the relative amount of sodium in Black Powder has increased substantially over the years. The Dupont powder (ca. 1950) was found to have approximately 4 times the amount of sodium found in the Civil War era powder sample; and the Goex powder was found to have approximately 12 times the amount of sodium. Accordingly, the supposition that the sample of Civil War era Black Powder might have been made using potassium nitrate with a higher concentration of sodium than current production powder

Table 1. Sodium to Potassium Ratios for Solutions Prepared from Black Powder Samples.

Source	Approximate Date of Mfg.	Peak Ratio (Na / K)	Mole Percent (Na to K)	Relative Amount
Calibration Std.	—	0.189	5.0	—
Civil War	1865	0.0056	0.15	≡ 1.0
Dupont	1950	0.024	0.63	4.2
Goex	1995	0.067	1.80	12.

was definitely not found to be correct. Somewhat surprisingly, the more modern powders contain substantially more sodium.

The relatively high sodium to potassium ratio found in the solutions prepared from the Black Powder samples does not necessarily correspond to a high susceptibility to problems with moisture absorption. Accordingly, it was decided to proceed with determination of the moisture absorbing tendency (hygroscopicity) of the three different era powder samples. This was accomplished by first reducing the size of the powder grains with a mortar and pestle to approximately 100 mesh. This was done to eliminate any differences from the powder samples being of different granulations. However, it also reduced the length of time taken for the powder samples to reach their equilibrium moisture contents, after being placed in various constant humidity environments (hygrostats). Following particle size reduction, the samples (each a little over 3 grams) were dried for 4 hours at a temperature of 110 °C. (Note that this temperature was more extreme than the conditions for drying used in moisture determination according to the current military specification.[2] The reason for using the higher temperature was simply to be assured of the complete dryness of the samples before testing.)

The constant humidity chamber used in this study was a large glass desiccator with the desiccant removed and a tray containing one of a series of saturated aqueous solutions installed in its place. Depending on the nature of the saturated solution (and the temperature in the lab, 17 °C) various constant humidity levels were produced.[3,4] Using saturated solutions of lithium chloride, potassium carbonate, ammonium nitrate, sodium chloride, strontium nitrate, and barium chloride, relative humidity levels of 11, 43, 67, 76, 88 and 92 percent were produced in the test chamber. In each case the time of exposure was approximately two days, which is about twice as long as it took for the samples to come to equilibrium. (In each case, this was confirmed by continuing exposures until no further moisture was acquired by the samples). All three samples were placed in the humidity chamber at the same time, and their exposure was begun using the solution producing the lowest relative humidity level. Following exposure at one humidity level, the samples were removed, covered and weighed. Then the tray of saturated solution was replaced with the one producing the next higher relative humidity level. (As a point of reference, note that the humidity level sufficient to cause moisture to collect on pure potassium nitrate, at the temperature of the lab, is 95%, a little higher than the maximum relative humidity used in these measurements.)

Table 2 lists the percentage weight gain for each of the three samples for each relative humidity exposure level, and these values are presented graphically in Figure 1. As suspected, the current production Black Powder (Goex), with the greatest sodium content, experienced the greatest weight gain upon exposure to humidity (i.e., it was the most hygroscopic). However, based on its lower sodium content in comparison to the Dupont powder, it had been anticipated that the Civil War era powder would be the least hygroscopic. Instead it was found that the Civil War era and Dupont powders both gained about the same amount of weight (moisture), with the Dupont powder gaining slightly less.

Table 2. Percentage Weight Gain for Samples of Black Powder as a Function of Relative Humidity Exposure.

Relative Humidity (%)	Weight Gain (%) Civil War	Dupont	Goex
11	0.36	0.22	0.46
43	0.84	0.75	1.01
67	1.13	1.03	1.41
75	1.25	1.15	1.68
88	1.46	1.31	2.66
92	2.00	1.78	3.73

Since the results of the hygroscopicity measurements for the Civil War era and Dupont Black Powders were somewhat unexpected, perhaps it worth speculating as to the reason. It is thought that the results (percentage weight gains) are correct for two reasons: 1) for each of the humidity exposures, the Dupont powder always gained less than the Civil War era powder, and 2) the initial weights were confirmed by redrying the powder samples after the highest humidity exposure. This leaves the sodium to potassium ratio measurements potentially suspect. While it would have been appropriate to redo

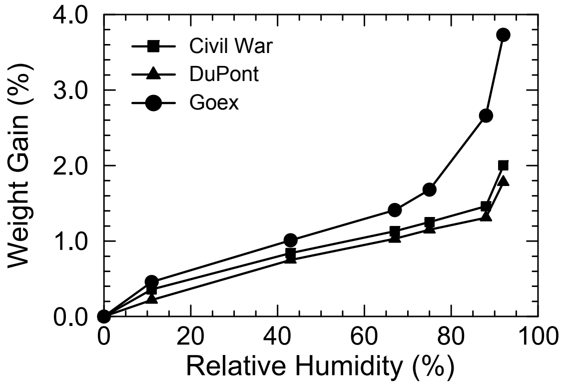


Figure 1. Percent mass gained as a result of exposure to various relative humidity levels.

these determinations, that was not done for four reasons: 1) the necessary instrument was in the process of being reconfigured and would not be available for some time, 2) interest in this project relative to other ongoing projects had diminished substantially, 3) it is possible that the sodium to potassium results are fully correct (see below), and 4) the answer to the question initially being raised was already in hand (see below).

First consider the possibility that the sodium to potassium ratios were indeed correct. It would seem possible that the relatively higher sodium content of the Dupont powder (compared with the Civil War powder) was in a form that was successfully extracted after the prolonged agitation in hot (near boiling) water, but which was mostly non-hygroscopic, even at the highest relative humidity exposure used in these tests. One example of how that might occur, could be that much of the sodium in the Dupont powder was bound in some non-hygroscopic form, possibly associated with the charcoal in the powder.

Next consider the initial supposition, regarding whether battle field humidity was likely to have been especially detrimental to the performance of the Black Powder being used during the Civil War. Based on the weight gain measurements of the sample tested, this would clearly seem not to have been the case, since the current production powder was found to be the most hygroscopic. The fact that the Dupont powder apparently was slightly less hygroscopic than the Civil War era powder tested is interesting but not particularly relevant to the question initially posed.

Acknowledgements

The authors are grateful to F. Ryan for previously supplying the sample of Civil War era Black Powder used in this study and to L. Weinman for commenting on a draft of this article.

References

1) K. L. & B. J. Kosanke and F. Ryan, “Performance Study of Civil War Vintage Black Powder”, *Journal of Pyrotechnics*, No. 9, 1999; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

2) *Military Specification: Powder, Black*, MIL-P-223B, 1962.

3) *Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions*, American Society for Testing and Materials, E-104-85, 1991.

4) *CRC Handbook of Chemistry and Physics*, CRC Press, 1995, p **15**-25.

An earlier version appeared in *Fireworks Business*, No. 226, 2002.

DOT Exemption for Display Fireworks with Electric Matches Attached

K. L. and B. J. Kosanke

Background

Several years ago the US Department of Transportation granted an exemption[1] that, under certain conditions, "*authorizes the transportation in commerce of Division 1.3 and 1.4 display fireworks with igniters (electric matches) attached to either the fuse or the lift charge.*" Because of concern regarding one of the specific provisions of that exemption, a brief study was undertaken. This short article discusses that concern and reports on the results of the study. (A restatement of the full set of conditions that must be met is beyond the scope of this article, see reference 1.)

The specific provision that gives rise to concern is the requirement that the electric match attached to the firework must have its safety shroud in place if the electric match is in the lift charge, but the safety shroud is not required if it is securely attached to the shell leader fuse (see Reference 1, paragraphs 8f and g). The concern is that, assuming one of the two electric match locations should not require the presence of the safety shroud, it seems that the requirement for when the safety shroud is to be in place is reversed.

It would seem that the safety shroud is most needed when the electric match is attached to shell leader fuse. This is the case where the electric match is most exposed to the potential for impact that could produce an accidental ignition. This is illustrated in Figure 1. The upper left sketch attempts to illustrate the potential problem of two shell casings (or one shell casing and another rigid object) coming together in such a manner as to pinch a portion of one shell's leader fuse between them. In this case, see the lower left sketch, the full impact force is delivered to the fuse. Were there to have been an electric match inserted into the fuse at the point of impact, there is potential for the impact to cause the electric match to be crushed and to ignite as a result of the impact. (The amount of impact energy needed to cause the ignition of the most common electric matches in use today is uncomfortably low.[2])

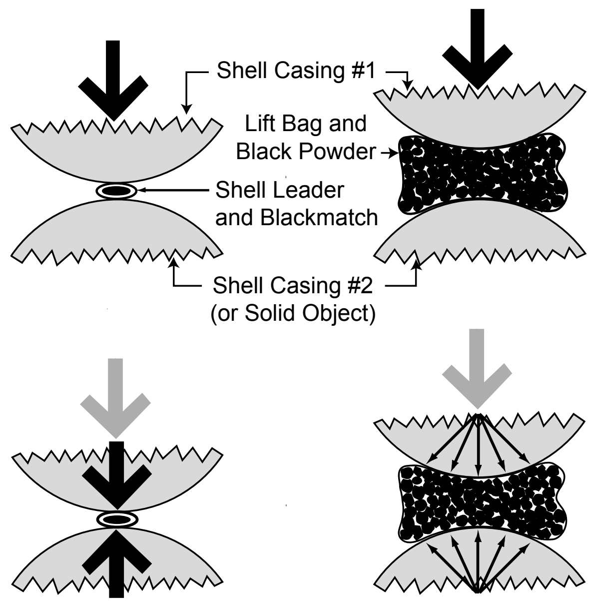


Figure 1. Sketches illustrating two possible impact scenarios occurring between two aerial shells: left, an impact with a shell leader at the point of contact; right, an impact with a bag of lift powder at the point of impact.

In contrast, consider the case where the impact occurs such as to catch the bag of lift powder between the colliding shells. The upper right sketch of Figure 1 attempts to illustrate this situation. In this case, because of the very nature of the granulated lift powder, the impact force comes to be distributed fairly evenly across a much larger area, see the lower right sketch. Accordingly, were there to have been an electric match inserted into the lift charge at the point of impact, there is substantially reduced potential for its being crushed and igniting as a result of the impact.

Testing

While the reduction in impact force for the lift bag case seems obvious, because of the important safety implications, it was thought to be worth confirming by testing. Two series of tests were undertaken. In the first tests, the relative impact forces for the two cases illustrated in Figure 1 were measured. For these tests an impact sensitiveness tester, with a 0.5 kg (1.1 lbf) drop hammer, was used to provide the impact force. To simulate the approximate rigidity of aerial shell casings, the end of both the drop hammer and the impact surface of the calibrated piezoelectric force gauge were covered with a 3-mm (1/8-in.) thick Kraft paper disk. For the case where the aerial shells impact against shell leaders, a short section of quick match was placed between the drop hammer and force gauge. The data from the impacts were recorded and stored using a digital oscilloscope. The result of an impact from a height of 300-mm (1-ft) is documented in the upper graph of Figure 2, where it is the much taller of the two peaks.

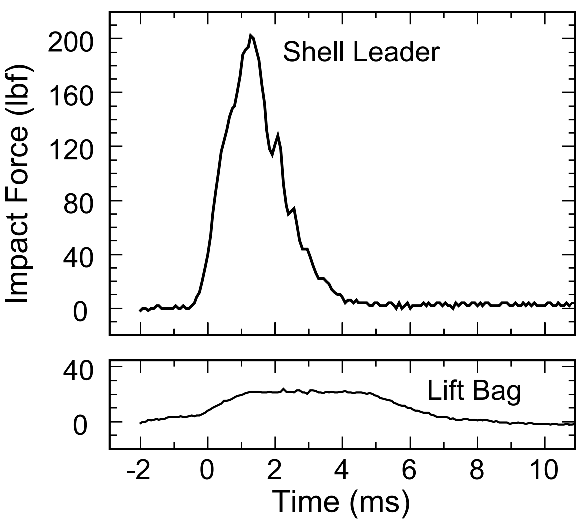


Figure 2. A graph of data demonstrating the substantial difference in the impact forces delivered to an electric match size object in collisions between two aerial shells with a shell leader and with a bag of lift powder at the point of contact.

Aerial shell impacts against bags of lift powder were simulated using much the same method; however, small plastic bags filled with silica sand were used as a substitute for Black Powder. (This was done to limit the amount of fire that would be produced in the laboratory in the case of an ignition.) The recorded impact force from a test is shown in Figure 2 as the curve with the much lower peak force. The ratio of peak impact forces developed for the two cases examined is approximately 10 to 1. This confirms the prediction of much greater impact force against electric matches in shell leaders caught between aerial shells as compared with impacts against electric matches in lift bags, where the force is distributed over a much greater area.

As a final test, a series of impacts were made to occur when actual electric matches were used to determine the relative ease of their accidental ignition in the two scenarios being investigated. The electric matches used in these tests were the Daveyfire A/N 28 B matches with their safety shrouds removed. For these tests the same impact sensitiveness tester was used; however, this time it was fitted with a 5 kg (11 lbf) drop hammer. As in the earlier tests, the approximate rigidity of aerial shell casings was simulated by covering both the end of drop hammer and the lower impact surface with a 3-mm (1/8-in.) thick Kraft paper disk. A short section of quick match shell leader with an electric match attached was placed between the drop hammer and the lower impact surface at the point of impact. After some initial experimentation to discover the approximate sensitiveness of the electric matches in this configuration, four tests were performed using an impact height of 0.45-m (18-in.). Each time it was found that the electric match (and shell leader) ignited from the impact.

In the lift bag test configuration, silica sand was again used as a substitute for Black Powder. (This was done to limit the amount of fire that would be produced in the laboratory in the case of an ignition.) In deciding on the appropriateness of the use of silica sand, it was considered that: 1) the sand grains are both stronger and more abrasive than Black Powder; and 2) for the electric matches being used, an earlier study found that they did not exhibit greater sensitiveness in the presence of Black Powder. Accordingly, the electric matches should be at least as likely to ignite in these tests in the presence of silica sand as they would had Black Powder been used. Four tests were performed using the 5-kg (11-lbf) drop hammer, the most massive available, and an impact height of 1.5 m (60 in.), the maximum convenient height for the impact tester. It was found that no ignition of the electric match occurred in any test. Accordingly, the un-shrouded electric match in the shell leader configuration was found to be at least 3.3 times as sensitive to accidental ignition from impact as compared to the un-shrouded electric match in the lift bag configuration.

Discussion

The DOT exemption of shipping display fireworks, with electric matches attached, requires that the safety shroud be in place when the electric match is in the lift charge, but not when the electric match is in a shell leader fuse. It seemed that the requirement for when safety shrouds were required to be in place was reversed from what it should have been considering accidental ignition from impact. This was readily confirmed even with the very limited amount of testing performed, in which the sensitiveness due to impact was at least 3 times greater (and perhaps 10 times greater) for un-shrouded electric matches in the shell leader fuse as compared with electric matches inserted into the lift charge.

Certainly, there are possibilities for accidental ignition during transportation other than impact. However, the authors can think of no case where there is greater need for the presence of the shroud when the electric match is in the lift charge as compared to the shell leader. For this reason, and because safety shrouds do provide substantial reductions in both impact and friction sensitiveness,[2] it is strongly recommended that shippers of display fireworks with electric matches installed in shell leader fuses, only do so with the safety shrouds left in place.

Acknowledgment

The authors are grateful to L. Weinman for reviewing an earlier version of this article.

References

1) US Department of Transportation, DOT–E 11685.
2) K. L. and B. J. Kosanke, "Studies of Electric Match Sensitiveness", *Journal of Pyrotechnics*, No. 15, 2002; also appearing in this collection of articles.

An earlier version appeared in *Fireworks Business*, No 224, 2002.

A Rule for Improving Manufacturing Safety Involving the Use of Energetic Materials

K. L. Kosanke and L. Weinman

Over the years there has been an almost continuous series of accidents involving people using energetic materials, too many of which involve fireworks, their manufacture or their preparation for use. There are important lessons that can be learned from these accidents; unfortunately most of these come too late for the people suffering those accidents. Even more unfortunately, many of the same factors have combined to produce similar accidents again and again.

The "rule" was developed as part of the safety training of personnel of a major (non-fireworks) pyrotechnic manufacturing company.[1] Before discussing the rule, perhaps it is appropriate to review a few points from hazard management in general.[2] Hazard management is generally thought to consist of three activities: Recognition, Evaluation, and Control. In simplest terms, recognition is just making a list of hazards; those things that could go wrong that have some potential for injury or financial loss. In evaluating the list of hazards, they are ranked (prioritized) according to the magnitude of the risk associated with each hazard. In doing this, there are two central considerations: what is the likelihood (probability) of having an accident, and what are the consequences (severity) in the event of an accident. Control consists of those actions taken to mitigate the hazards on the prioritized list, generally starting with those representing the greatest risk. Risk is reduced whenever actions are taken to reduce the probability of having an accident, or when actions are taken to reduce the severity of the consequences. Certainly the greatest reduction of risk occurs when both the probability and consequences of an accident are minimized. In considering those actions that might be used to reduce (control) risk, it is often useful to have a somewhat formalized process to help guide ones thinking. This process is often referred to as following or applying a risk control hierarchy. The remainder of this article is a discussion of one possible risk control hierarchy for working with energetic materials.

The rule is simple, each time before using energetic materials, especially if there is any change in the conditions of use, ask yourself the set of questions given below and act accordingly. These questions sound simple, perhaps almost to the point of seeming so trivially simple as to be ridiculous. However, before you dismiss them out of hand, please spend a moment considering them more fully. The questions are:

1) *Do you really need to use it?*
2) *How little of it can you use?*
3) *Can it be somewhere else?*
4) *Do you really have to do what you are doing to it?*
5) *Can you use "personal protection equipment"?*

In considering these questions, do not automatically dismiss any of them with "that's how it has always been done" attitude. It is true that one may conclude that the way it has always been done is the best. However, in the authors' experience, very often there are safer ways to operate that involve no more work or expense. Further, it is surprising how many times it will be discovered that there are safer ways to operate that are actually easier or involve less expense. The key part of the exercise is to spend some time honestly considering alternatives and to keep an open mind while doing so. Although one might argue a little about the order of the questions, generally start at the top and work down. In the remainder of this article, each of the questions will be discussed briefly.

1) Do you really need to use it? This is really asking, are there safer alternatives you should be considering? In some cases this may even include the use of non-explosive materials or methods. However, generally it is intended to assess the possibility of using less sensitive materials. Most typically, the greatest hazards associated with working with energetic materials are associated with their accidental ignition (or initiation). Obviously the likelihood of accidental ignition is reduced when less sensitive materials are used. Among approximately equally sensitive materials, consideration should also include considering alternatives that have fewer undesirable health or environmental effects in either their unreacted or reacted form. Also the consequences of an accident are reduced when less violent or less energetic materials can be substituted. Further, one should consider other hazardous features of a process, such as the use of flammable versus non-flammable solvents or adhesives.

2) How little of it can you use? In a sense this is really at least two questions. This is asking you to consider whether you can use less of the energetic material in manufacturing a specific device. However, it is also asking you to consider things such as, do you really need to have as much raw material and/or completed items in the immediate work area. Obviously both are important because the consequences (severity) of an accident upon the accidental ignition of energetic materials is reduced when the total amount of those materials involved is reduced.

3) Can it be somewhere else? For the most part, this is suggesting consideration be given to conducting the most hazardous operations remotely. However, this also includes less expensive things such as keeping raw materials covered and/or stored at a safer distance, not allowing finished items to accumulate in the work area, and keeping the area free of spilled composition and dusts. As in question 2, these are actions that will reduce the consequences of an accidental ignition.

4) Do you really have to do what you are doing to it? For the most part, this is another step in reducing the probability of an accident, this time by considering alternate processing methods. For example, this might include the alternative of pressing a composition as opposed to ramming it using mallet blows, considering the use of a phlegmatizer (adding a small amount of lubricant) to reduce sensitiveness to friction when compacting a composition, and using electrostatically conductive containers and grounded equipment during processing. As another example, one should consider using less hazardous mixing techniques, such as adding the chlorate oxidizer to a smoke composition in increments so as not to temporarily produce an especially hazardous mixture.

5) Can you use "personal protection equipment"? This is really ones last line of defense, and while the use of personal protection is certainly appropriate, it should not be seen as a substitute for other methods of reducing the severity of an accident. Personal protection equipment includes items such as small fire and explosion shields, face shields, safety glasses, leather aprons and gloves, hearing protectors, and breathing masks.

Hazard management is little more than the application of common sense and finding safer alternatives that are no more difficult or expensive often requires only a little thought. It is amazing how infrequently this is done, especially when one considers the high personal and business expense of accidents, and the consistency with which accidents seem to occur. Please take a little time to consider how your operations involving energetic materials might be performed more safely.

References

1) L. Weinman, Pyrotechnic Safety Training Seminar, ca. 1991.
2) K. L. Kosanke and C. Jenings-White, "Basics of Hazard Management", *Fireworks Business*, No.129, 1994; also in *Selected Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996.

An earlier version appeared in *American Fireworks News*, No. 283, 2002.

Aerial Shell Burst Height as a Function of Mortar Length

K. L. and B. J. Kosanke

[This article is augmented with a number of text notes, indicated using superscript letters. While it is hoped these provide useful information, they are not essential, and the reader may wish to ignore them unless further information is desired.]

From time to time over the years there has been discussion of the effect of mortar length on the burst height achieved by fireworks aerial shells. However, rarely has burst height versus mortar length data been presented,[1,2] even then the data has been of limited value. In one case, the results were predictions using a ballistics model where only the maximum possible height reached by aerial shells was presented, not the measured height at the time of their actual burst.[a] In the other case, only a one shell was fired for each mortar length, and the method of determining the height of the shell burst was rather imprecise. The study being reported in this article is more useful in that actual burst heights were reasonably accurately measured and there were several firings from each mortar length. Unfortunately, this study only examined the effect of mortar length on 3-inch (75-mm) spherical aerial shells. While it is expected that similar results would be found for other shell types and sizes, that cannot be assured.

The test shells used in this study were Thunderbird brand, Color Peony-White (TBA-106). For consistency, all the test shells were taken from the same case of shells. The shells had an average mass of 136 g, with an average diameter of 2.72 inches (69 mm), and an average of 37 g of lift charge (apparently 4FA granulation). The mortars used in this study were high density polyethylene (HDPE) with an inside diameter of 2.93 inches (74.4 mm)[b]. Ten different mortar lengths were used, ranging from a maximum of 60 inches (1.5 m) down to just 6 inches (150 mm) (in each case, the length was measured from above the mortar plug). There were three to five test firings for each mortar length examined, for a total of 42 test firings. Approximately 10 minutes were allowed to elapse between each use of a mortar to allow time for the mortar to cool before its next firing.

The burst height of these shells was determined by measuring the amount of time elapsing between the burst of the shell (as determined optically) and the arrival of the sound of the burst.[c,d] The individual burst heights and a trend line visually fit to those data points are shown in Figure 1.[e] Further, the average burst height for each mortar length is presented in Table 1. While the measured burst heights are probably greater than many might have expected, for a number of reasons it is believed they are correct for the conditions existing for these tests.[g] However, it is the trend in burst height that is of most general interest. Accordingly, presented in the last column of Table 1 are burst heights normalized to that achieved using a 20-inch (510-mm) mortar.[h]

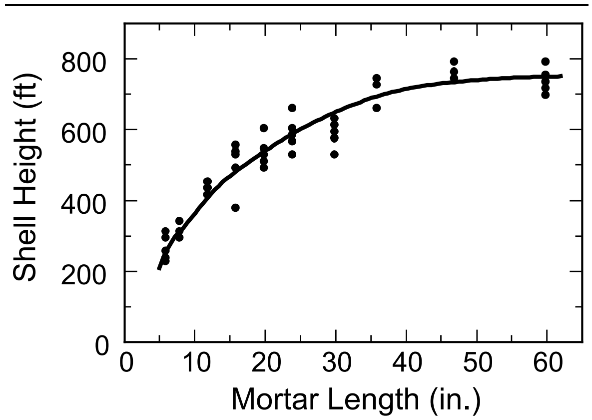


Figure 1. A graph of the burst height results as a function of mortar length for 3-inch spherical aerial shells.

Table 1. Average and Normalized 3-inch Shell Burst Height for Various Mortar Lengths.

Mortar Length (in.)	Number of Tests	Average Height (ft)[f]	Normalized Burst Height
60	5	740	1.39
47	3	760	1.36
36	3	710	1.29
30	5	590	1.20
24	5	590	1.09
20	5	530	≡1.00
16	5	495	0.90
12	3	430	0.76
8	3	310	0.58
6	5	260	0.48

To convert from inches to millimeters, multiply by 25.4.

To convert from feet to meters, multiply by 0.305.

It may be of interest to note that reducing the mortar length from 20 to 6 inches (510 to 150 mm) produced a reduction in the average aerial shell burst height by about 50 percent. This result was somewhat of a surprise, even though earlier calculations using the Shimizu's[1] ballistic model had suggested that the reduction would not be overwhelming. It was surprising because the top of the mortar was only about 2 inches (50 mm) above the top of the aerial shell. Even though model calculations had suggested that the aerial shell would still be propelled to a significant height, it was hard to believe, because it seemed to contradict "common sense".

Increasing the mortar length from 20 to 60 inches (0.51 to 1.5 m) was found to produce an increase in burst height by about 40 percent, with the strong suggestion that further increases in mortar length cannot be expected to produce much more of an increase in burst height. That the effectiveness of ever longer mortars decreased, essentially to the point of no longer producing greater burst height, was not a surprise. This is because ballistic modeling had predicted this and it seemed quite logical.

It is hoped that this brief article provided some interesting and useful information about the effect of mortar length on aerial shell burst height.

Notes

a) For common mortar lengths, aerial shells typically burst prior to reaching what would be their maximum height. There will be a somewhat greater difference between burst height and maximum possible height for longer than normal mortars. Also, for especially short mortars the opposite will be true, where the shells may burst on their way back down, after having reached their maximum height.

b) While the mortar diameter was smaller than desired, it was typical of many HDPE mortars made from commercially produced pipe. This pipe was SDR 17 (standard dimensional ratio), which is specified as having an internal diameter (ID) of 2.97 inches (74.5 mm).[3] However, manufacturers consistently produce pipe with a wall thickness greater than the minimum specification. Because the outside diameter of the pipe is tightly controlled, the thicker walls cause the ID to be less than specified. In this case, the pipe was supplied with an ID of only 2.93 inches (74.4 mm).

c) The air temperature was approximately 68 °F (17 °C) at the time of the measurements. This corresponds to a speed of sound of approximately 1126 feet (343 m) per second, which was the value used in calculating the burst height of the test aerial shells.

d) If desired, see references 4 and 5 for discussions of two slightly different methods using the delay in arrival of the sound of the explosion to determine the distance to the explosion.

e) The average deviation of the individual data points from the trend line is 37 feet (11 m).

f) As an expression of the statistical uncertainty in the measurements, average burst heights are only reported to the nearest 10 feet (3 m).

g) There are a number of reasons for believing the burst height results are correct: 1) the method for determining burst height is simple; 2) the data produced was internally consistent; 3) the testing was conducted in western Colorado at an altitude of 4600 feet (1400 m) above sea level, where the reduced air density results in lower drag forces, allowing aerial shells to reach greater heights than when fired at elevations nearer to sea level; 4) the relatively small internal mortar diameter causes the shells to exit the mortar at greater velocities and thus be propelled to greater heights; and 5) these results are reasonably consistent with previous measurements[6,7] performed at lower elevations and with nominal diameter mortars.

h) A 20-inch (510-mm) mortar length was chosen because it is thought that is the approximate length of the most commonly used mortars for 3-inch (75-mm) single break aerial shells.

References

1) K. L. and B. J. Kosanke, "Shimizu Aerial Shell Ballistics Predictions, Part I", *Pyrotechnics Guild International Bulletin*, Nos. 72 and 73 (1990); also in *Selected Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)*, Journal of Pyrotechnics, 1995.
2) R. Dixon, "Shell Altitude vs. Mortar Length", *Journal of Pyrotechnics*, No. 10, 1999.
3) Specifications published by Poly Pipe Industries, Inc., Gainesville, TX.
4) K. L. Kosanke, "Determination of Aerial Shell Burst Altitudes", *Pyrotechnics Guild International Bulletin*, No. 64, 1989; also in *Selected Publications of K. L. and B. J. Kosanke, Part 1 (1981 through 1989)*, Journal of Pyrotechnics, 1996.
5) K. L. and B. J. Kosanke, "Simple Measurements of Aerial Shell Performance", *American Fireworks News*, No. 181, 1996; also in *Selected Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999.
6) K. L. Kosanke, L. A. Schwertly, and B. J. Kosanke, "Report of Aerial Shell Burst Height Measurements", *Pyrotechnics Guild International Bulletin*, No. 68, 1990; also in *Selected Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1994)*, Journal of Pyrotechnics, 1996.
7) T. Shimizu, *Fireworks from a Physical Standpoint, Part III,* Pyrotechnica Publications, 1985; also in *Selected Publications of K. L. and B. J. Kosanke, Part 1 (1981 through 1989)*, Journal of Pyrotechnics, 1996.

An earlier version appeared in *Fireworks Business*, No. 225, 2002.

Aerial Shell Burst Delay Times

K. L. and B. J. Kosanke

If you have ever wondered how long the shell burst process takes after the time fuse burns through to the interior of the shell, this article may be of interest to you. Although rapid, the process is not instantaneous. A flame front must advance through the burst charge and an amount of combustion gas must be produced that is sufficient to pressurize the shell casing beyond its burst strength. Some time ago, as part of a study of the possible cause of muzzle breaking aerial shells, we needed to determine approximately how long this process takes.[1] That burst delay time data is summarized below.

Burst delay times were measured for spherical aerial shells ranging in size from 3 to 10 inches. The shells were ignited using an electric match inserted into the shell. This was accomplished by making a small hole, only slightly larger than the electric match, by remotely pressing a pointed tool through the shell casing a little above or below the equator of the shell. The tip of the electric match was inserted about 0.6 inch into the shell. (This is approximately the same distance as would be typical of the inside end of the time fuse in a shell without a flash tube to the center of the shell.) The hole was closed using three layers of strapping tape encircling the shell in different directions. As a sensor to indicate the bursting of the shell, two loops of wire encircling the shell were used. The loops crossed the poles of the shell at approximately a 90° angle. These wires were held in position on the shell using small dabs of hot-melt glue along its length. To make the measurement, the test shell was suspended above the ground, and then electrically attached to the timing and firing apparatus. The electric match was energized with sufficient current to cause its ignition in less than one millisecond. The contents of the shell were thus ignited, causing the shell to burst (explode). As the casing expands and fragments, the loops of wire break. Burst delay times were determined using an electronic timer to measure the time between application of current to the electric match and when the wire loops break.

For the burst delay times to be representative of typical shells, the shells used in these measurements came from seven different manufacturers. These manufacturers were: Yung Feng (Y), Horse (H), Temple of Heaven (T), Onda (O), Red Lantern (R), Sunny International (S), and Flying Dragon (F). In the data presented in Table 1, the manufacturer is identified using the code letter listed for each manufacturer. Burst delay times are also presented in Table 1. It would have been preferred to have tested a larger number of shells and to have used a wide and consistent set of manufacturers for each shell size. However, this was not possible because of economic constraints.

While most of the burst delay times for each shell size are fairly well grouped, there are occasional values that are significantly longer than the rest of the group. The most extreme example is the delay time for the Horse brand 8-inch shell, which was 329 ms as compared with 52 and 96 ms for the other two shells tested. Similarly, the 122 ms for the 3-inch Temple of Heaven shell and the 104 ms for the 4-inch Red Lantern shell, are significantly longer than the burst delay times for the other shells in those size groups. It is felt that these longer delay times were real. This is because, in each of these three cases, the time interval, between pressing the button to energize the electric match and when the shell explosion occurred, was noticeably longer than for the other shells. The cases of longer than normal burst delay times may represent some type of anomalous ignition of the shells' contents, in which the fire transfer from the match was substantially less effective than in the other cases. This notion is supported by the fact that in two other cases, although the electric match fired normally inside the shell, the contents were not ignited and the shells failed to explode. In both cases, a second attempt (after another electric match was installed) produced a

Table 1. Aerial Shell Burst Delay Times.

Shell Size (mm)	Shell Size (in.)	Burst Delay Time (ms) / Manufacturer	Average Time (ms)	Fitted Time (ms)
75	3	30/S, 32/S, 36/Y, 41/S, 48/T, 76/H, 122/T	43[a]	41
100	4	21/S, 44/Y, 50/R, 51/H, 53/R, 78/T, 81/S, 104/R	54[b]	51
125	5	26/S, 40/S, 59/O, 62/R, 73/T	52	60
150	6	54/H, 55/S, 77/T, 82/F, 89/T	71	70
200	8	52/Y, 96/Y, 329/H	74[c]	89
250	10	134/O	134	108

(a) The burst delay time of 122 ms was not included in the average.

(b) The burst delay time of 104 ms was not included in the average.

(c) The burst delay time of 329 ms was not included in the average.

shell explosion with the delay time typical for shells of that size. In order to not bias the data by including the abnormally long burst delay times, they were excluded when calculating the average delay times reported for each size shell.

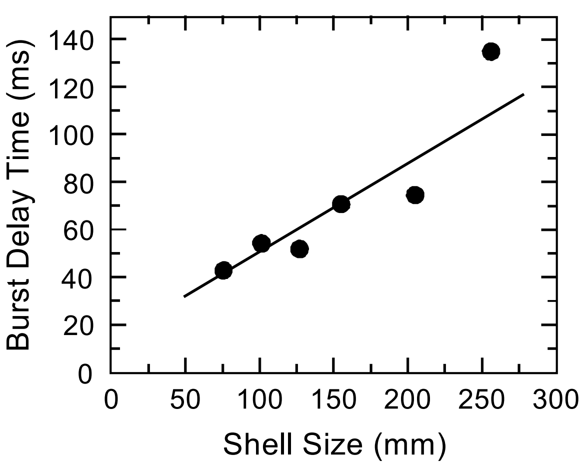


Figure 1. Average shell burst delay times as a function of shell size.

Average shell burst delay times, as a function of shell size, are presented as a graph in Figure 1. In calculating the linear least squares fit to the data, the average delay times were weighted according to the number of shells of each size that were included in the average. It is apparent that there is a significant increase in burst delay times for larger shells, with the least squares fitted burst delay times ranging from approximately 40 ms for 3-inch shells, to approximately 110 ms for 10-inch shells. That larger shells take longer to burst (explode) is reasonable, as a result of the need to produce more combustion gases to pressurize their larger volumes.

Reference

1) K. L. and B. J. Kosanke, "Hypothesis Explaining Muzzle Breaks", *Proceedings of the Second International Symposium on Fireworks* (1994). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 3 (1993and 1994)*, Journal of Pyrotechnics (1996).

An earlier version appeared in *Fireworks Business*, No. 225, 2002.

"Impossible" and Horrific Roman Candle Accident

K. L. and B. J. Kosanke
PyroLabs, Inc., Whitewater, CO 81527, USA
and
Geoff Downs and John Harradine
Department of Natural Resources and Mines, Queensland, Australia

*[**Authors note:** This article includes a number of notes with ancillary information. This information is not essential to the primary purpose of this article. Accordingly, it is suggested that the reader might wish to initially ignore the notes, and then subsequently, if additional information is desired, read any notes of interest.]*

Introduction

In May of 2000 in Queensland Australia, a most horrific accident[a] occurred involving large bore (2-in., 50-mm) Roman candles, which had generally and widely been thought to have been impossible. Because the set of conditions leading to this accident could occur again, and because requirements in the national fireworks standards (in both the US[2] and Australia[3]) should be modified somewhat to help mitigate the potential for future injuries, a series of articles derived from this accident and its investigation are being written.[b]

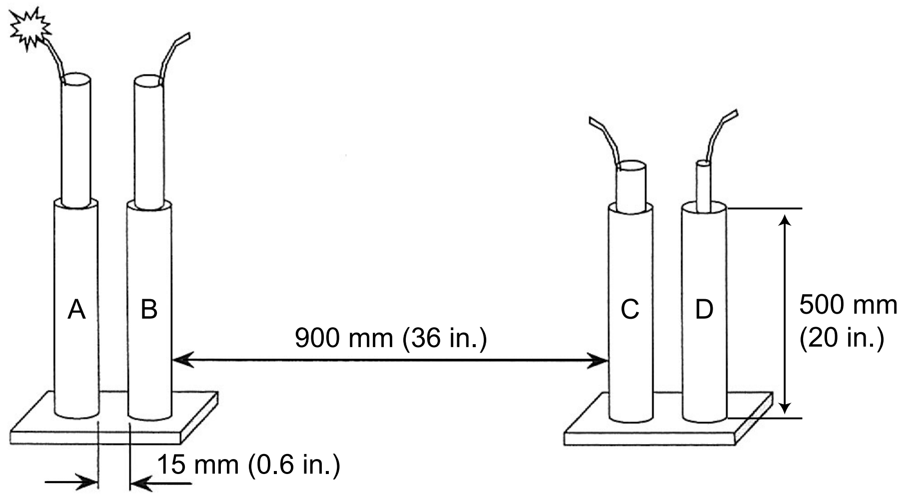
To facilitate their publication, the length of these articles will be limited such that only a portion of the overall subject will be addressed in each. This first article begins with a brief discussion of common Roman candle malfunctions. The bulk of the article presents the basic facts of the accident. Subsequent articles will present: a discussion of the Roman candle characteristics that caused the powerful explosion; partial summaries of the results of the many and in-depth scientific investigations undertaken to elucidate and confirm the cause and course of this accident;[c] recommendations of some changes to the safety procedures for the use of large bore Roman candles; and warnings regarding the manner of manufacture of large Roman candle stars.

Common Roman Candle Malfunctions

It is well known that Roman candle fireworks do malfunction on occasion. The most common malfunctions include: inconsistency in the timing between firing of the individual shots; having more than one star (or comet star) fire at virtually the same time, somewhat like a machine gun; and some shots remaining unfired. However, there are few if any safety ramifications with these types of malfunctions. By far the most common spectator accident with Roman candles is the result of their realignment (tipping over) due to their not being sufficiently secured, after which they proceed to fire projectiles into the crowd.

There are two basic ways in which unintended repositioning of Roman candles occur. Probably most common is when the recoil forces, produced when a star (or other projectile) fires from the Roman candle, exceeds the strength of its support system.[d] For example, this might happen when a Roman candle is secured to a frame above the ground using tape or wire that provides insufficient strength to successfully maintain its position during the course of its firing. Another common way for a Roman candle to become repositioned is when the tube of the Roman candle bursts, thus putting an additional strain on the support system, or otherwise defeating the support system in some way.[e] For example, this might happen when a collection of Roman candles have been bundled together using tape to form a Roman candle battery. In that case, if one Roman candle tube bursts, the resulting forces or fire may sever the tape allow the individual Roman candles to become reoriented.

In reference to other types of Roman candle accidents known to the authors. There was a case



Tube	Firework
A	2-inch 8-shot White Tail Roman Candle
B	2-inch 8-shot White Tail Roman Candle
C	2-inch 5-shot Gold Tail Roman Candle
D	1-inch 8-shot Cracker Tail Roman Candle

Figure 1. Configuration of Roman candle fireworks in twin-tube steel fireworks stands.

where it was alleged that the tube of the Roman candle was propelled into a spectator area (with the stars being propelled in the opposite direction). However, prior to the accident in question, the authors knew of no case where a portion of the support system of a Roman candle was so seriously and violently damaged (even when the tube of the Roman candle bursts) that a portion of the support system of a Roman candle was propelled into a spectator area.

The Bray Park Accident[1]

The accident (explosion) occurred when the fireworks display had been underway for approximately two minutes. Before the explosion occurred, the operator had manually ignited the fuse of one 2-inch, 8-shot white tail Roman candle in tube A (see Figure 1) and then proceeded to ignite a second 2-inch, 8-shot white tail Roman candle approximately 12 feet (3.6 m) away (not shown in Figure 1). The first comet of the 2-inch 8-shot white tail Roman candle in tube A functioned normally. Three seconds later a most powerful explosion occurred. The explosion was described by a witness as ‘extremely loud and intense and created a powerful shock wave’.

The twin-tube steel Roman candle fireworks stands involved in the explosion are shown in Figure 1. The three 2-inch, Roman candles in tubes A, B and C each exploded. These Roman candles were the two 2-inch, 8-shot white tail Roman candles in tubes A and B of the first steel fireworks stand and one 2-inch 5-shot gold tail Roman candle in tube C of the second steel fireworks stand 36 inches (900 mm) away. Each of these firework stands consisted of a heavy steel base plate with two steel tubes 20-inches (500-mm) long, 3.00-inches (75-mm) outside diameter with 0.14-inch (3.6-mm) wall thickness welded to the base plate. The Roman candles, with an outside diameter of 2.44 inches (62 mm), were a relatively close fit inside the steel tubes.

The blast pressure (shock) produced by the three exploding Roman candles was sufficient to fragment the three steel tubes in which they were standing. Some of these steel fragments caused a fatality and serious bodily injuries. Fragments of various sizes were found at various distances up to approximately 580 feet (175 m) from the blast center. Fragments were found in the fireworks display area, spectator-viewing locations, and the adjoining neighborhood. A total of 42 steel fragments were recovered.

After extensive research (including thermodynamic and explosion modeling, and numerous and varied field trials) the investigation concluded that:

- The Roman candles contained simple comet stars (i.e., they were solidly compressed pellets of pyrotechnic composition and were not crossettes).[f]
- In the operation of the 2-inch, 8-shot white tail Roman candle in tube A, the first comet had functioned normally.
- After a 3-second delay, when the second comet was expected to be expelled from the Roman candle, the powerful explosion occurred.
- This Roman candle (in tube A) exploded when the second comet in the tube exploded powerfully and very shortly after its ignition (i.e., while still in close proximity to its at-rest position in the Roman candle).
- The powerfully exploding comet caused all of the remaining comets and Black Powder in the Roman candle to explode en masse.
- The cause of the comet exploding was a unique collection of characteristics of the comet, which will be discussed in some detail in the next article in this series.
- The exploding Roman candle (in tube A) caused the metal tube surrounding the candle to expand and fragment, producing high-energy steel fragments.
- The velocity of the steel fragments from tube A are estimated to have been as high as 900 miles per hour (400 m/s).
- Tube A expanded and impinged or struck the adjacent steel tube (tube B) approximately 15 mm (0.6 in.) away, which also contained a Roman candle, and caused the steel tube to be dented inwards.
- The dent compressed the contents of the second 2-inch, 8-shot white tail Roman candle, which caused that Roman candle to also explode en masse and produce steel fragments similar in form and mass to the steel tube fragments from the first tube.
- The velocity of the steel fragments from tube B was estimated to be as high as 1100 miles per hour (500 m/s).
- Both steel tubes in the fireworks stand had totally fragmented leaving only the base plate remaining. This 0.5-inch (12-mm) thick steel base plate had been dished about 0.25-inch (6-mm) deep beneath tube A.
- A fragment or fragments from the first twin-tube steel fireworks stand struck a second twin-tube steel fireworks stand approximately 900 mm (36 in.) away, containing the 2-inch 5-shot gold tail Roman candle in tube C.
- The point of fragment impact was probably 8 inches (200 mm) from the top of tube C.
- The 2-inch 5-shot gold tail Roman candle also exploded en masse.
- The explosion caused the tube to partially rupture producing several small fragments and one large fragment, with a steel collar being a part of this large fragment.
- Tube D was damaged but was not fragmented.
- The fatality and serious injuries were the result of the steel fragments produced during the course of the near simultaneous explosions.

Caution / Warning

To date only one shipment of Roman candles to Australia is known to have had the combination of characteristics (defect) that produced the very powerful explosions described above. The manufacturer's name does not appear on these Roman candles; however, they have the product code KL301B on their label. Figure 2 is a photograph of the product and instruction labels from these Roman candles. Other shipments into Australia of this same type of Roman candle were found to have been manufactured using much the same materials and processes. They were found to have most of the characteristics leading to the production of such powerful explosions as occurred in the Bray Park accident. Also, apparently the same Roman candles have been found in the US. Thus it should be considered that the potential exists for additional catastrophic explosions of these or similar large bore Roman candles. Accordingly, if such items are used, it is appropriate to: 1) use methods and materials to secure these Roman candles that allow the ready escape of any explosive pressures that might be produced such that those materials will not become especially dangerous flying debris, 2) use added separation between any such Roman candles and other Roman candles or any other display item that might become repositioned or damaged as a result of such a powerful explosion, 3) take added precautions for the protection of any display crew working in the immediate area during a display, and 4) use added separation between the Roman candles and spectators.

Conclusion

In this article, only the basic facts of the accident have been presented, generally without explanation or any supporting test results. To the extent practical, that supporting information will be presented in subsequent articles. The next article in this series will present information about the unique combination of characteristics of the Roman candle comet stars that is thought to have allowed them to produce such horrendous explosive forces.

Ancillary Notes

a) The most serious spectator injuries were a fatality (child), severe brain damage with the loss of an eye (adult female), and the partial amputation of a foot (adult male). In addition a male crew member suffered the traumatic amputation of a leg.[1]

b) While the Queensland Department of Natural Resources and Mines did issue warnings and imposed other restrictions, confidentiality agreements associated with the accident investigation and a trial has here-to-fore restricted the authors' ability to freely discuss the details of this accident.

c) The investigation report is roughly 1500 pages in length and contains approximately 20 sub-reports from various private and government research organizations.

d) This type of Roman candle repositioning is often the result of the display operator underestimating the magnitude of the recoil forces produced upon the firing of Roman candle projectiles. For example, even a relatively small diameter display candle (1 in. or 25 mm) can produce peak recoil forces in excess of 100 lbf (450 N).[4] However, these peak forces only persist for a brief moment. On occasion, at least a part of the fault for Roman candles over powering their support lies with the manufacturer, because of things such as the overloading of a Roman

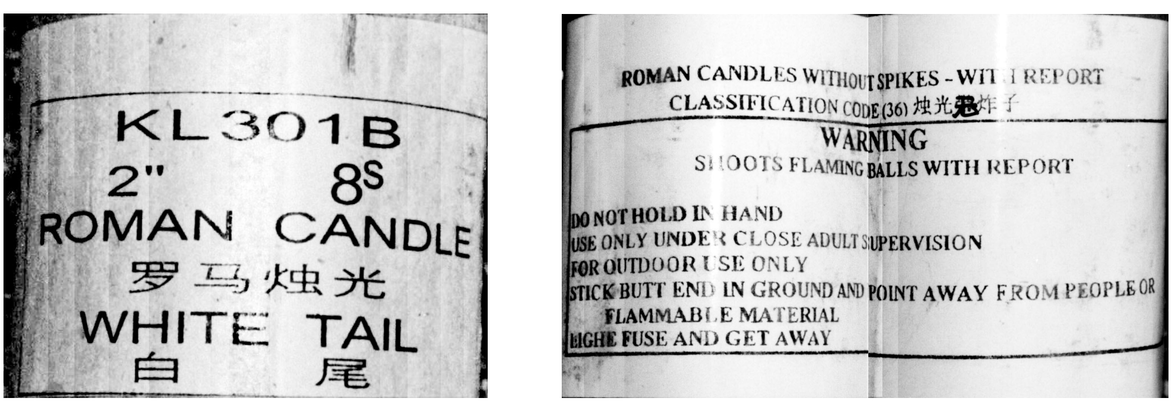


Figure 2. Photographs of Roman candle labels .Note: The left label, with the product number, is hot-pink in color, whereas the instruction label on the right is white.

candle shot, or when an ineffective seal between shots allows two or more projectiles to fire at the same time.

e) Such common Roman candle tube failures are typically the result of the tube being too weak to accommodate the additional pressure caused by things such as: the occasional overloading of one of the shots, the occasional near simultaneous firing of more than one shot, and the occasional jamming of a star in the tube as it attempts to exit the tube. Certainly Roman candle tube failures can be the result of an explosion occurring within them, such as when an explosive projectile (e.g., a salute) functions prior to being expelled.

f) A crossette is a special type of comet star, typically made with a large internal void that is filled with a flash powder. After a period of normal burning, the flash powder is ignited causing the comet star to explode into several smaller burning pieces.

References

1) *Investigation Report - Bray Park Fireworks Tragedy*, Queensland Government, Department of Natural Resources and Mines, 2001.

2) *Code for Fireworks Display*, National Fire Protection Association, NFPA-1123, 2000.

3) *Explosives – Storage Transport, and Use, Part 4: Pyrotechnics – Outdoor Displays*, Australian Standard, AS 2187.4 – 1998.

4) K. L. and B. J. Kosanke, "Recoil Forces Produced by Large-Bore Roman Candles", unpublished.

An earlier version appeared in *American Fireworks News*, No. 254, 2002.

Pyrotechnic Burn Rate Measurements: Strand Testing

K. L. and B. J. Kosanke

Background

Burn rate is one of the most fundamentally important properties of pyrotechnic materials. While burn rate may be measured as a mass burn rate (mass of pyrotechnic composition consumed per unit time, e.g., g/s), linear burn rate is most commonly used. Linear burn rate can be defined as the distance the burning surface of a pyrotechnic composition advances inwardly (perpendicular to the burning surface) per unit time, and typically would be reported as inches per second (or mm/s). Even for a specific pyrotechnic material with a defined composition (including prescribed particle size and shape) there are a number of factors that will effect its burn rate.[1] Generally the most important factors, ranked roughly in order of importance, are: ambient pressure, loading pressure (composition density), temperature, and burning surface area. Accordingly, for burn rate measurements to be most useful, they must take each of these additional factors into consideration.

During World War II, B. L. Crawford, et al. developed the *strand burner* (sometimes also called the Crawford Bomb) for making linear burn rate measurements of propellants under suitably controlled conditions.[2–4] The strand was a thin column of pyrotechnic, typically about 1/8 inch (3 mm) in diameter and about 7-inches (180-mm) long. Today the strand is often 1/4-inch (6-mm) thick and may be square in cross section. The test strand is held in the burn chamber of the strand burner, which is a pressure vessel that is maintained at constant gas pressure for the duration of the test. The temperature of the strand during the test is the same as that of the strand burner and is held reasonably constant by the flow of gas (usually nitrogen or argon) through the burn chamber. When temperatures other than ambient are needed, the strand burn chamber and gas supply can be heated or cooled to the desired temperature.

Prior to loading into the strand burner, a series of small diameter holes are drilled through the strand at precisely determined points along its length; thin, easily-fused wires are then threaded through the drilled holes. The number of fuse wires may be as few as two, but it is common to use more. Typically the wires are made of lead and are about 0.01 inch (0.25 mm) in diameter. The outer surface of the strand will usually have been coated (painted) with a suitable flame-resistant inhibitor, to cause the strand to only burn inwardly from one end, in a cigarette-like fashion, rather than along its outer surface. (See Figure 1.)

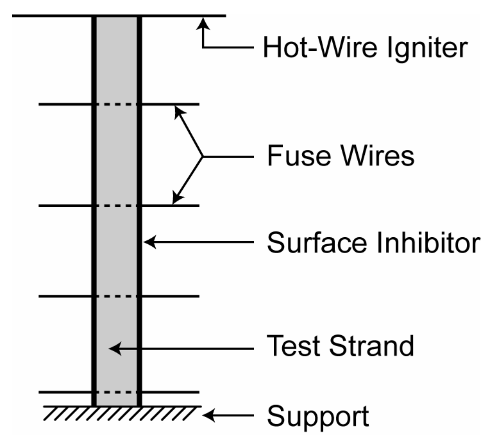


Figure 1. Illustration of a strand prepared for burn rate testing (not to scale).

After being placed in the burn chamber, the strand is ignited from one end using a hot-wire igniter. Then, as the strand burns, the heat fuses (melts) each wire as the burn front passes. The fusing of the first wire is used to provide the 'start' signal for the burn rate measurement, and then each successive wire fusing provides a 'stop' signal to indicate the progress of the burning. Knowing the time of the wire fusings and the spacing between the wires, the linear burn rate can be calculated.

Table 1. Sample Data from a Study of the Effect of Nano-Molybdenum as a Burn Rate Catalyst.[8]

Oxidizer →	Ammonium Perchlorate (80%)		Potassium Perchlorate (71%)		Potassium Chlorate (74%)		Potassium Nitrate (80%)	
Fuel →	Shellac (20%)		Sorbitol (29%)		Sorbitol (26%)		Charcoal (20%)	
	No Cat.(b)	Cat.(b,c)	No Cat.	Cat.(c)	No Cat.	Cat(c)	No Cat.	Cat(c)
Burn Time(a) (s)	8.63	6.73	20.10	16.60	5.27	2.67	6.33	5.20
	9.73	6.57	21.00	17.20	6.57	2.67	5.73	5.53
	8.17	7.43	20.63	16.47	6.00	2.50	6.50	5.50
	9.47	6.87	19.40	15.20	6.07	2.53	6.23	5.77
Ave. Burn Time (s)(d)	9.0	6.9	21.3	16.3	6.1	2.6	6.2	5.5
% Increase(e)	—	30%	—	30%	—	135%	—	15%

a) Time to burn 1.4 g of composition (including approximately 3 mg of oil to aid compaction) pressed at 4000 psi (30 MPa) in a paper tube with an internal diameter of 5/16 inch (8 mm) and a wall thickness of 3/32 inch (2.5 mm).

b) These test items had a 3/32-inch (2-mm) diameter by 1/8-inch (3-mm) long indentation formed in the ignition end of the test strand when being pressed. This was done to provide some erosive burning to help sustain the burning of the test items.

c) Four percent molybdenum trioxide (MoO_3) as nano-particles was used as the catalyst.

d) To better reflect the uncertainty in the results, average burn times are only reported to one decimal place.

e) This is the percent increase in burn rate for the composition with the catalyst present. To better reflect the uncertainty in the results, increases in burn rate are only reported to the nearest 5%.

The dependence of burn rate on local pressure is especially important for propellants, in particular, gun propellants where the pressures can range to especially high values. The pressure dependence of the burning of a propellant (or a pyrotechnic composition) can often be characterized using the Vieille burn rate equation,[1]

$$R = a\,P^{\,b}$$

where R is linear burn rate, P is pressure, and a and b are constants. For example, in one series of strand tests of the burning of Black Powder, when R and P have the respective units of cm/s and atmospheres, the constants a and b were found to have the values 1.72 and 0.164, respectively.[5] (While the Vieille equation generally applies over a reasonably wide range of pressures, often more than one set of constants is necessary to fit the data over the entire pressure range.[6])

Simplified Strand Test Method

When simple comparisons between similar compositions are desired, it is often possible to make a number of simplifications to the strand burner test. For example, a series of tests was recently conducted to investigate the potential for nano-particle size molybdenum trioxide[7] to function as a useful burn rate catalyst. In these tests, simple comparisons were made between the burn rate of pairs of compositions made with and without the presence of a small amount of the potential catalyst. Accordingly, in these initial tests it was not necessary to determine burn rate as a function of pressure and temperature, and testing could be performed at atmospheric pressure and room temperature. Accordingly, a complex strand burner apparatus was not needed.

In the catalyst tests, each oxidizer was prepared by simultaneously ball milling two samples of the oxidizer, the first sample with 4% of the molybdenum trioxide added and the second sample without the catalyst. In this way the nano-catalyst was well mixed with the oxidizer without otherwise treating the two oxidizer samples differently. Following this, the fuel was mixed with each oxidizer sample. Finally, to aid in compacting the compositions a tiny amount of a light oil was added (approximately 2 mg per gram of composition). This was accomplished by first dissolving the oil in acetone, then mixing the oil/acetone solution into the composition and continuing mixing until the acetone completely evaporated, leaving the trace of oil evenly distributed through the composition.

Once the test compositions were prepared, a series of eight test strands were prepared, four with and four without the catalyst added. Each test strand was made by pressing a series of small increments, totaling 1.4 g into a small paper tube, 5/16-inch (8-mm) ID by approximately 1-3/4-inches (44-mm) long. To further help produce a consistent composition density, the composition was compacted using a constant loading pressure of 4000 psi (30 MPa). The tubes provided a constant cross sectional area of composition and acted as the flame resistant surface inhibitor to cause the burning to proceed in a cigarette-like fashion. With consistent composition density and constant amounts of composition compressed into each tube, the length of each test strand was nearly the same [in this case approximately one inch (25-mm)]. Since each test strand was approximately the same length, it was only necessary to compare their burn times to determine whether and approximately how great a catalytic effect was produced.

In this case, burning of the test strands was initiated using a small torch flame applied to one end of the composition. Accurate burn times were measured using a video camera to make a record of each burn test, then playing back the tape one video field at a time, while counting the number of video frames (each 1/30 second) between the first sign of ignition and the first indication of fire from the other end of the tube (test strand). As a check on the results, for each composition, four separate burn tests were performed. See Table 1 for a sample of the catalyst data produced.

The test results exhibit a moderate amount of variability. This is thought to reflect somewhat of a lack of care in preparing the sample items, the relatively short length of the test strands, plus variations in ignition stimulus from the torch. For some purposes, such variation would not be acceptable; however, for simple screening tests as in this case, it is not a major concern. It seems clear that the nano-molybdenum trioxide does have the ability to act as a burn catalyst.

Conclusion

When it is sufficient to perform strand testing under ambient conditions, the greatly simplified method, as described for this initial study of the burn catalytic effect of nano-molybdenum trioxide, can be employed to produce reasonably useful screening data.

Acknowledgements

The authors wish to acknowledge D. Dillehay, D. Tanner and L. Weinman for commenting on an earlier version of this article. Also, the authors are grateful to L. Johnson for supplying a sample of nano-molybdenum trioxide for testing.

References

1) K. L. and B. J. Kosanke, "Control of Pyrotechnic Burn Rate", *Proceedings of the Second International Symposium on Fireworks* (1994); also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, Inc., 1996.

2) *Encyclopedia of Explosives*, US Army Picatinny Arsenal, 1966, pp S218–219, C335, and C555.

3) N. Kubota, *Propellants and Explosives*, Wiley-VCH, 2002, pp 235–236.

4) A. Bailey and S. G. Murray, *Explosives, Propellants and Pyrotechnics*, Maxwell Pergamon, 1989, p 83.

5) R. A. Sassé, *Strand Burn Rates of Black Powder to One Hundred Atmospheres*, Technical Report ARBRL-TR-02490, 1983.

6) L. Weinman, Personal Communication, 2002.

7) Supplied by Climax Molybdenum, Tucson, AZ, USA.

An earlier version appeared in *Fireworks Business*, No. 226, 2002.

Fireball Characteristics as Determined in a Test Simulating the Early Stage of a Fireworks Truck Loading Accident

K. L. and B. J. Kosanke

A few years ago there was an investigation and analysis of an accident thought to have been initiated by the ignition of a case of spherical aerial shells in the cargo area of a truck. It was thought that the case of shells had been dropped or thrown to the floor of the truck during the course of its loading. (Note that some of the facts of the matter may be in dispute.) As part of that investigation, it was thought that a simple test would aid in establishing the likely sequence of events during the early stages of the accident. Accordingly a test was performed to estimate the extent and rapidity with which the initial fireball would develop from the ignition of a case of spherical aerial shells. Because the information developed by the test is of general interest to persons working with display fireworks, this brief article has been written.

At the time of the accident, it was known what display was being loaded into the truck, including the total number and type of aerial shells, and the total number of cartons. However, it was not known what was in each carton or which of the individual cartons of aerial shells ignited first. Accordingly, the best that could be done was to assemble a test case of aerial shells containing the average number of each size shell (see Table 1) known to have been in the display.

Among the shells known to be present were a large number of Horse Brand shells, which had quick match shell leaders made using a combination of a long strand (or two) of Chinese style firecracker fuse along with black match. Unfortunately, the Chinese fuse powder contained a chlorate (presumably potassium chlorate) and the black match contained sulfur. It was thought that a likely explanation for the accidental ignition was the pinching of one of these shell leaders between two colliding shell casings as the carton impacted the floor of the truck. This somewhat violent pinching is suspected to have caused both a commingling of the chlorate and sulfur compositions, and the mechanical energy for their ignition. (The inherent dangers of chlorate and sulfur mixtures are quite well known.[1]) In an attempt to approximately simulate this manner of ignition, an electric match inserted into one of the shell leaders was activated to initiate the test. (Note that in the accident, it was reported that no electric matches were present.)

Table 1. Number and Size of Inert Shells Used, Including Estimates of the Amount of Lift Charge and the Length of Shell Leader.

Shell Size (in.)	No. of Shells	Lift Charge (oz)		Shell Leader (ft)	
		Per Shell	Comb.	Per Shell	Comb.
3	24	0.5	12	2.0	48
4	7	1.0	7	2.5	18
5	5	1.7	8	3.0	15
6	2	2.7	5	3.5	7
Totals	38	—	32	—	88

To convert approx. ounces to grams, multiply by 28.
To convert approx. feet to meters, divide by 3.3.

Following the ignition of the first carton of shells, there would have been a delay of approximately 3 to 5 seconds before the ignited time fuses would cause shells to explode. Further, because the collective burning of the shell leaders and lift charges in the ignited case would only have been very mildly explosive, it was thought that the ignition of the shells in the other cases would likely not have occurred until exposed to the fire for at least several seconds or, more likely, when the shells in the first case started exploding. Because of the likely delay of 3 to 5 seconds before the participation of additional pyrotechnic materials, the question attempting to be answered was: to what extent would the conflagration produced by just the shell leaders and lift charges in the first carton have tended to engulf persons working in the cargo area and impede them from exiting? Accordingly, the test shells were inert except for their leader fuses and lift charges. The shell leader lengths and lift charge amounts are also given in Table 1.

The ignition of the test case of shells and the progress of the ensuing conflagration was recorded using two video cameras, providing close-up and full views of the fire output. Figure 1 is a composite sequence of individual video fields recorded at times of 0.0, 0.2, 0.5, and 0.9 second after firing the electric match. Unfortunately, in a gray scale image such as in Figure 1, it is not possible to differentiate between the yellow/orange fire and the white smoke. Accordingly, for the purposes of this article, prior to converting the series of color images to gray scale, the approximate area of the fireball in each frame was outlined with a black line. In determining the extent of the fireball in each video image, it was the extent of the yellow/orange (fire) area that was used. Over the course of the images, the fireball is seen to drift to the left due to an approximate 4 mph (1.8 m/s) breeze in that direction. However, it is not thought that this significantly affected the results.

Using the full video record, the volume of the fireball was estimated after each 0.1 second time interval. First, an estimate of the projected area and length of the fireball was made. (The length of the fireball was determined as distance from the approximate center of its bottom to the approximate center of the highest extent of the fireball.) The projected area and length were determined through a comparison of the fireball with features in the background of known dimension, and considering the distances from the camera to the fireball and background. Then, assuming the shape of the fireball was approximately cylindrically symmetric about an axis running from the center of its base to its tip, calculations were performed to estimate its volume. Those volumes as a function of time are presented in Table 2 and as a graph in Figure 2. It was not known what the shape of the fireball volume curve should be expected to have. However, it was fit reasonably well by simply using two straight lines. (It is thought that a reasonable estimate for the uncertainty in the results being reported is 10 to 20 percent.)

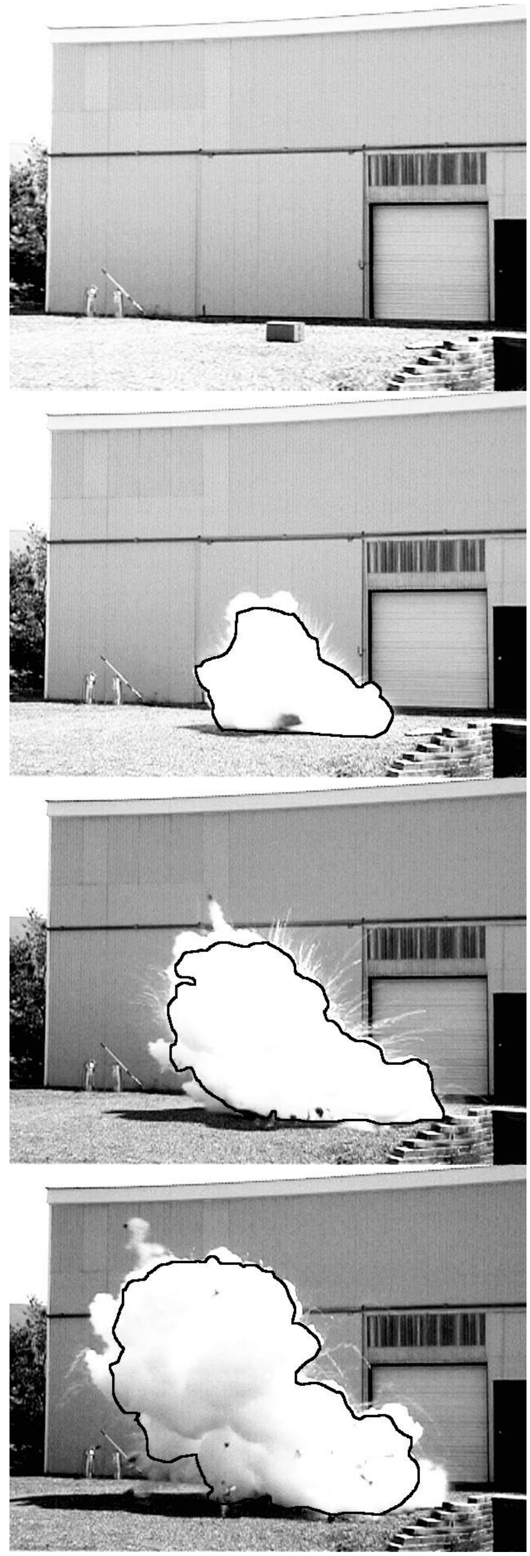


Figure 1. A collection of video fields recorded at times of 0.0, 0.2, 0.5, and 0.9 second after firing the electric match. The approximate extent of the fireball, as opposed to white smoke, has been outlined in each image.

Table 2. Estimates of the Volume of the Fireball Produced during the Course of the Test.

Time	Volume	
(s)	(ft^3)	(m^3)
0.1	50	1.4
0.2	250	7.1
0.3	380	10.8
0.4	480	13.6
0.5	560	15.9
0.6	750	21.3
0.7	780	22.1
0.8	970	27.5
0.9	1100	31.2
1.0	1100	31.2
1.1	940	26.6
1.2	790	22.4

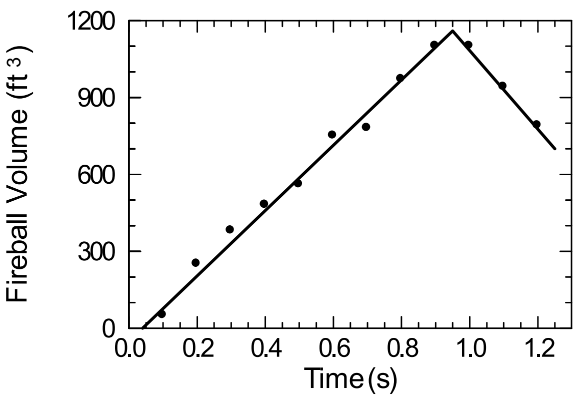


Figure 2. A graph of estimated fireball volume, as a function of time, fitted using two straight lines. (To convert from cubic feet to cubic meters, divide by 35.)

For the purpose of the accident investigation it was of interest to learn the extent to which the likely fireball, produced by the shell leaders and lift charges from this first case of aerial shells, would fill the open volume of the cargo area of the truck. In addition, it was of interest to discover whether there was any realistic probability that a person in the cargo area near the point of origin could exit prior to being engulfed within the fireball. This was of prime interest because it has been reported that for a person attired in normal clothing, such clothing will spontaneously ignite and the person will receive deep third degree burns, if engulfed by a pyrotechnically produced fireball.[2] Further, it is suggested ("assumed") that there is essentially no chance of a person's long term survival from having received such extensive burn injuries.[3]

If the height and width of the cargo area are each assumed to be 8 feet (2.4 m), based on the test results reported above, the approximate volume of the fireball is capable of completely filling a 17-foot (5.2-m) length of the cargo area. Further, this will occur in slightly less than 1 second, clearly much less than the time it would take for a person near the point of origin to exit the cargo area. (Indeed, in the accident under consideration, the two persons nearest the point of origin were fatally burned, and the two persons near the back of the truck escaped, although having sustained significant burn injuries.)

Before leaving this subject, it is of interest to compare the approximate results of this simple test using a case of simulated aerial shells, with the results for loose Black Powder reported in the literature (see Table 3). The results reported[4] for 1 kg (35 oz) of Black Powder are for a fireball with a diameter of 3.2 m (10.5 ft), a volume of approximately 17.6 m^3 (620 $feet^3$) and a duration of 1.0 second. In the current test, the fireball was produced by 32 ounces (0.91 kg) of Black Powder plus 88 feet (27 m) of quick match and black match, which contributed approximately 6 additional ounces (0.17 g) of powder. This produced

Table 3. A Comparison Between these Approximate Results and those Reported in the Literature.

Data Source	Powder Mass (oz)	Fireball Characteristics Diam. (ft)	Vol. (ft^3)	Duration (s)
Current Test	38[(a)]	12.7[(b)]	1100	1.6
Literature[4]	35	10.5	620	1.0

To convert approx. ounces to grams, divide by 28.

To convert approx. feet to meters, divide by 3.3.

To convert approx. cubic feet to cubic meters, divide by 35.

a) This includes both the Black Powder lift charge and an approximation of the powder content of the shell leaders.

b) The approximate diameter reported for this asymmetric fireball was calculated for a sphere based on its approximate volume of 1100 cubic feet.

a fireball with an approximate volume of 1100 ft^3 (31 m^3) with a total duration of approximately 1.6 seconds. While there was slightly more Black Powder in the current test, that certainly cannot account for all of the difference between the two sets of results.

In the present aerial shell test, it must be considered that there was also a significant amount of non-pyrotechnic, but readily combustible, material present. For example, there was the cotton string in the black match, the paper match pipe, the plastic bags containing the lift charge, the paper making up the lift bags, the tape, and the corrugated cardboard in the carton. Thus, while these combustible materials will take essentially no part in the pyrotechnic reactions, in response to the thermal output from the pyrotechnic reactions, they will decompose to produce an amount of highly combustible gas and particulate matter. Surely these gasses and particulates will then burn as air oxygen mixes into the periphery of the fireball. This added fuel will act to sustain the duration of the fireball and allow it to further expand before cooling. Note that the combustion products from a fireball continue to expand somewhat after the fireball is considered to have ended. It is the cooling of the fireball, from the loss of heat, that marks its end. Accordingly, burning the additional non-pyrotechnic fuel must be expected to both extend the duration of the fireball and thereby increase its volume beyond that of the fireball without the additional non-pyrotechnic fuel.

In addition to the non-pyrotechnic combustibles adding to the volume and duration of the fireball, another factor must also be considered for the case of a substantial fireball produced inside the cargo area of a truck. In that case, the fireball would be expected to further increase in both its size and duration. Inside the cargo area, the pyrotechnic combustion products will displace the air, thus limiting the mixing and cooling of the fireball by incorporating cool air into it. In addition, some of the radiated thermal energy will be reflected back into the fireball from the surfaces (walls, ceiling, etc.) inside the cargo area, again acting to extend the duration of the fireball.

Using the data reported in the literature and from this test—using a case of simulated aerial shells—it would be possible to comment on the personal survivability of a collection of accident scenarios involving various amounts of aerial shells and in various circumstances. While that information is certainly an important subject, it is beyond the scope of the current article.

Acknowledgement

The authors are grateful to R. K. Wharton and L. Weinman for commenting on an earlier draft of this article.

References

1) D. Chapman, et al., "Studies of the Thermal Stability and Sensitiveness of Sulfur/Chlorate Mixtures: Part 1, Introduction; Part 2, Stoichiometric Mixtures; Part 3, The Effects of Stoichiometry, Particle Size and Added Materials; and Part 4, Firework Compositions and Investigation of the Sulfur/Chlorate Initiation Reaction", *Journal of Pyrotechnics*, Nos. 6, 1997; 7, 1998; 11 and 12, 2000.

2) R. Merrifield, R. K. Wharton and S. A. Formby, "Potential Fire and Explosion Hazards of a Range of Loose Pyrotechnic Compositions", *US Department of Defense, Explosives Safety Board, 27th Explosives Safety Seminar*, 1996.

3) R. K. Wharton and R. Merrifield, "Thermal Hazards from Accidental Ignition of Pyrotechnic Compositions", *Journal of Pyrotechnics*, No. 6, 1997.

4) R. K. Wharton, J. A. Harding, A. J. Barratt and R. Merrifield, "Measurement of the Size, Duration and Output of Fireballs Produced by a Range of Pyrotechnics", *Proceedings of the 21st International Pyrotechnics Seminar,* 1995.

Pyrotechnic Literature Series No. 1

Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 1 (1981 through 1989)

Table of Contents — Part 1

Pyrotechnic Literature Series No. 2

Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)

Table of Contents — Part 2

Pyrotechnic Literature Series No. 3

Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)

Table of Contents — Part 3

Pyrotechnic Literature Series No. 7

Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 and 1997)

Table of Contents — Part 4

Pyrotechnic Literature Series No. 8

Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)

Selected Pyrotechnic Publications of Dr. Takeo Shimizu Part 1 (1985 to 1994) from the International Pyrotechnic Seminars

Table of Contents — Part 1

Selected Pyrotechnic Publications of Dr. Takeo Shimizu Part 2. Translated Articles

Table of Contents — Part 2

Selected Pyrotechnic Publications of Dr. Takeo Shimizu, Part 3 Studies on Fireworks Colored-Flame Compositions

Table of Contents — Part 3

Selected Pyrotechnic Publications of Dr. Takeo Shimizu, Part 3 The Design Criteria for Chrysanthemum Shells

Table of Contents — Part 4

Pyrotechnic Reference Series

Includes:

- ***Illustrated Dictionary of Pyrotechnics***
- ***Lecture Notes for Pyrotechnic Chemistry***
- ***Lecture Notes for Fireworks Display Practices***
- ***Pyrotechnic Chemistry***

Illustrated Dictionary of Pyrotechnics

Many areas of applied pyrotechnics, fireworks in particular, suffer from a lexicon that contains many specialized terms, is poorly documented, and about which there is much disagreement. For example, what you call *glitter*, others still call *flitter*, and vice-versa; your *separation distance* may be someone else's *setback*. As a result, effective communication is made more difficult than necessary. Having an extensive dictionary of terms will not instantly solve such communication problems, but it can help, especially over time. Unfortunately, until now such a dictionary has not been available.

The *Illustrated Dictionary of Pyrotechnics* [ISBN-1-889526-01-0] is 130 pages in length, 8½" by 11", and it has a durable binding. There are more than 1200 entries, 130 figures and illustrations, and 50 short tables. It includes scientific and craft terms from fireworks, explosives, rocketry and pyrotechnic special effects.

In addition to the principal authors, eight individuals with expertise from each of the technical areas addressed, reviewed and contributed to the development of the dictionary. Most entries go well beyond merely defining a term; many terms are explained using examples, data, and/or illustration. Accordingly, the dictionary should be both authoritative and easy to comprehend.

Lecture Notes for Pyrotechnic Chemistry

Lecture Notes for Pyrotechnic Chemistry [ISBN-1-889526-16-9], **revised and enlarged in early 2005**, contains the class notes for a three-day course on the Pyrotechnic Chemistry. The Course Notes assume only minimal levels of understanding of Chemistry and Pyrotechnics. Each 8½×11" page contains a pair of viewgraphs from the course lectures. The over 440 viewgraphs include many illustrations and tables. Each viewgraph of text is complete enough for the reader to be able to understand the subject being discussed. Following is the outline of topics:

- I Basic Chemical Principles
- II Pyrotechnic Chemistry, Ignition and Propagation
- III Pyrotechnic Primes and Priming
- IV Factors Affecting Burn Rate
- V Aspects of Pyrotechnic Burning
- VI Physical Basis for Colored Light Production
- VII Chemistry of Colored Flame
- VIII Chemistry of Sparks, Glitter and Strobe
- IX Pyrotechnic Smoke and Noise
- X Approaches to Formulation Development
- XI Pyrotechnic Sensitivity
- XII Pyrotechnic Hazard Management

Lecture Notes for Fireworks Display Practices

The *Lecture Notes for Fireworks Display Practices* [ISBN-1-889526-03-7] contains class notes from a week-long course on practical and safety aspects of performing fireworks displays. Each 8½×11" page contains a pair of viewgraphs from the course lectures. The 440 viewgraphs include many photographs and tables. Each viewgraph of text is complete enough for the reader to understand the subject being discussed. **Revised 02/05.**

I. **Elements of Hazard Management for Fireworks**

II. **Fireworks Construction, Operation, and Characteristics**

III. **Fireworks Display Safety**

IV. **Fireworks Transportation and Storage Requirements**

V. **Fireworks Display Design**

Pyrotechnic Chemistry

Pyrotechnic Chemistry [ISBN: 1-889526-15-0] is a hard cover book on the chemistry of pyrotechnics. The book was authored by a collection of 13 renowned pyrotechnic researchers from around the world. It contains over 400 pages in a large 8½ × 11" format.

This text is written at an introductory to intermediate level. As such it is intended for readers with limited prior knowledge of chemistry or limited knowledge regarding specific areas of applied pyrotechnics. One goal of this text is to provide an extensive list of references, thus directing readers to sources of additional information.

The Table of Contents is extensive, running to 9 pages with approximately 600 entries. Because of the extensive table of contents, this text has not been provided with an index. It is suggested that readers wishing to research a specific topic first consult the list of chapters to find the one most relevant to the topic of interest, and then consult the detailed table of contents to locate the page number(s) of the section(s) addressing that topic.

List of Book Chapters

1 Introduction to Pyrotechnic Chemistry
2 Chemical Components of Fireworks Compositions
3 An Introduction to Chemical Thermodynamics
4 Pyrotechnic Ignition and Propagation: A Review
5 Control of Pyrotechnic Burn Rate
6 Our Present Knowledge of the Chemistry of Black Powder
7 Pyrotechnic Primes and Priming
8 Pyrotechnic Delays and Thermal Sources
9 The Chemistry of Colored Flame
10 Illuminants and Illuminant Research
11 Propellant Chemistry
12 Principles of Solid Rocket Motor Design
13 Pyrotechnic Spark Generation
14 Glitter Chemistry
15 Strobe Chemistry
16 A Study of the Combustion Behaviour of Pyrotechnic Whistle Devices (Acoustic and Chemical Factors)
17 Sensitiveness of Pyrotechnic Compositions
18 Hazardous Chemical Combinations: A Discussion
19 Assessing the Risks — Suggestions for a Consistent Semi-Quantified Approach

Review of: Pyrotechnic Chemistry

Bernard E. Douda
Crane Division, Naval Surface Warfare Center

Pyrotechnic Chemistry is the fourth in the Pyrotechnic Reference Series produced by the publisher of the *Journal of Pyrotechnics*. It is composed of nineteen stand-alone presentations each authored by pyrotechnic experts in their specialty area.

There are chapters dealing with pyrotechnic materials, thermodynamics, ignition and propagation, burning rate control, black powder, primes and priming, delays and thermal sources, illuminants, solid rocket motor design, spark generation, whistle devices, and the chemistry of colored flames, propellants, glitter, and strobes. Safety aspects are addressed in chapters discussing composition sensitiveness, hazardous chemical compositions, and risk assessment.

One advantage of a compilation of this sort is that it makes it convenient for the reader to find information across a wide range of pyrotechnic topics. The extensive Table of Contents makes this possible. The book contains a large number of figures and tables to support the text material. There are many examples of application of the information to pyrotechnic practical situations. For the most part, this book addresses the topics thoroughly but perhaps in some cases not to the degree that one would find in a textbook.

The compilation format provided the opportunity for each of the authors to address their topic to a degree sufficient to relate all aspects of their topic to practical pyrotechnics. They accomplished this by providing the underlying theory, the relevant equations, illustrative figures, and tables of supporting data. The result of this is that some chapters are much larger than others.

Another important characteristic of this book is that it addresses many pyrotechnic safety issues in chapters dedicated to this purpose. Not only were the authors able to point out safety concerns with material incompatibilities throughout their individual topics but also they prepared three chapters dedicated to sensitivity of pyrotechnic compositions, hazardous chemical combinations, and risk assessment.

Each chapter includes a set of its own references. These will be valuable to those wishing to explore a subject further. The book is easy to read. The topics are presented in an informative and educational manner. This book not only addresses topics related to fireworks but also addresses topics relevant to military pyrotechnics. It complements other pyrotechnic reference books and will serve as a valuable addition to one's library.

Tables of Contents for Issue 1 through 21 [1995–2005]

Issue 1, Summer 1995

Issue 2, Winter 1995

Issue 3, Summer 1996

Issue 4, Winter 1996

Issue 5, Summer 1997

Issue 6, Winter 1997

Issue 7, Summer 1998

Issue 8, Winter 1998

Issue 9, Summer 1999

Issue 10, Winter 1999

Issue 11, Summer 2000

Issue 12, Winter 2000

Issue 13, Summer 2001

Issue 14, Winter 2001

Issue 15, Summer 2002

Issue 16, Winter 2002

Issue 17, Summer 2003

Issue 18, Winter 2003

Issue 19, Summer 2004

Issue 20, Winter 2004

Issue 21, Summer 2005

ORDER FROM:

Journal of Pyrotechnics, Inc.

1775 Blair Road

Whitewater, CO 81527, USA

Phone/FAX: +1-970-245-0692

e-mail: bonnie@jpyro.com

web: http://www.jpyro.com