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Roman Candle Accident: Comet Characteristics

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*[**Authors' note**: This article includes a number of notes with ancillary information. This information is not essential to the primary purpose of this article, and frequently interrupting one's reading of the main text to read the notes may be a distraction. Accordingly, the reader might wish to initially ignore the notes, and then if additional information is desired, read any notes of interest.]*

This article is the second in a series addressing the nature, cause and course of a most horrific accident caused by a large-bore Roman candle.[1] These articles are offered in the hope that through a sharing of what was learned in this case, similar accidents might be avoided in the future.

Upon initially learning of the nature of this horrific accident, it was thought that the powerful explosion most likely had resulted from the use of flash powder or salutes in substantial quantity (size or number). It simply was not believed that Roman candles firing simple white-tailed comets[a,b] could possibly produce such an incredibly powerful explosion, even from Roman candles with a bore diameter of 2 inches (50 mm).[c] However, as a result of the initial investigation, it seemed likely that the Roman candles were indeed responsible. Subsequently, during the course of extensive testing of Roman candles from the same shipment as were involved in the accident, it became clear that these Roman candles did indeed malfunction explosively. Testing also demonstrated that these Roman candles, when confined in steel support tubes,[d] did have the ability to fragment the steel tubes and disperse those fragments at high velocity. (A summary of the testing is planned as additional articles in this series.)

What is so unusual about the Bray Park incident is that the pressure that developed inside the Roman candle tube rose to incredibly high values and rose to those levels at an incredibly high rate. For this general type of Roman candle, neither the pressures reached nor the rate at which they were produced would have been predicted. This is especially important because had only one of the two unexpected factors happened during the malfunction, the accident would not have occurred. Had the pressures risen rapidly but to a less catastrophic level, the steel pipe (if not the Roman candle tube, which itself was quite strong) would have successfully contained the pressure until the gases were safely vented up the mostly open bore of the Roman candle and through the gap between the candle and steel support tube. Had the pressures attempted to rise to catastrophic levels, but at a lower rate, then the gases would have had ample time to vent and the pressure would never have been able to reach a high level. In this case, what happened is that the pyrotechnic composition, in the form of the comets, acted very much more like a powerful explosive than merely a solidly compacted pyrotechnic composition. This article is a discussion of the unique set of characteristics of the comet stars thought to have allowed the production of such powerful explosions.

Characteristics of the Bray Park Roman Candle Comets

What seems to have happened in this case, to cause the rapid and catastrophic rise of pressure inside the Roman candle, is that its comets were produced in such a manner as to have an apparently unprecedented combination of three properties that acted in concert to provide their

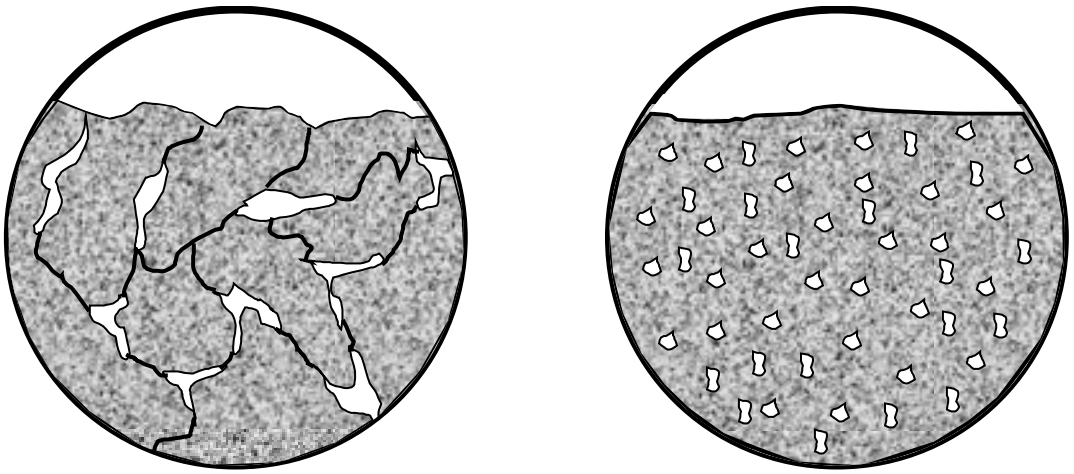

Figure 1. An illustration of the internal structure of the Bray Park white-tailed comets (left) and the normally expected structure (right).

unique explosive behavior. Had only two of these three properties been present in the comets, the accident would not have occurred as it did. Further, each of these properties ranged from being unusual to being extraordinarily unusual (if not unprecedented).

The first property of the comet that contributed to the cause of the accident is the manufacturer's use of a substantially higher-energy and more-reactive comet composition than is commonly used. For example, traditionally white-tailed comet effects were produced using relatively large particles of aluminum to produce sparks, plus charcoal and/or sulfur as the low-energy fuel, and potassium or barium nitrate as a low-energy oxidizer.[e] More recently granules of titanium are often used to replace the aluminum particles for spark production, with the bulk of the chemical composition continuing to be similar to Black Powder (gunpowder).[e] However, the Bray Park comets included the use of fine-grained magnalium[f,g] as a highly reactive metal fuel, plus the comets used potassium perchlorate as a more energetic oxidizer.[e] Normally, by itself, the use of a reactive and high-energy formulation would not cause a problem. However, in the presence of the other two unusual comet properties, the additional energy that was produced by this formulation and the additional speed with which the energy could be produced acted to both substantially increase the likelihood of an explosion occurring and to substantially increase the power of that explosion.[h]

The second property of the comets that contributed to the cause of the accident is that there needed to be some way for fire to sufficiently and nearly instantaneously penetrate throughout the interior of the comets. Normally such fire penetration is precluded because comets are made of tightly compacted and bound pyrotechnic composition. Thus, while there will always be some degree of porosity (tiny voids remaining within the composition), those voids are not sufficiently well connected to allow substantial intrusion of fire into the comet when it burns. What is so unusual with some of the Roman candle comets in this case is that they were permeable to a significant extent (i.e., their internal void spaces were not that tiny and they were sufficiently well connected such as to provide "fire-paths" into and through the comets' interior).[i] Figure 1 is an attempt at illustrating the difference between typical comets and those involved in the Bray Park accident. With the presence of many fire-paths into and through the comet, the time taken for the comet to burn can be reduced from several seconds down to a fraction of a second. That is to say its energy is released much more quickly and the potential for producing a powerful explosion is significantly increased.

The third property of the comets that contributed to the cause of the accident is that they were exceptionally strong structurally. Usually a Roman candle comet will be moistened with water and compacted to form a solid and reasonably hard pellet, bound together using something like dextrin. While this forms a solid mass when dried, if one were to scratch it, even with one's fingernail working sideways, one would soon make a shallow groove in the comet. One of the surprising properties of the Roman candle comets involved in the Bray Park accident was that they were incredibly hard and structurally strong. The comets were much more like rock or concrete than a normally bound and compacted pyrotechnic composition. The structural strength of the Roman candle comet is important because one thing that is needed, to cause a solidly compacted pyrotechnic composition to produce an explosion when it is burned, is that the burning pyrotechnic composition be strongly confined.[j]

The near total confinement of a burning pyrotechnic has two important effects. First, such confinement allows the pressure produced to rise significantly above atmospheric pressure. This rise in pressure, acts to significantly accelerate the speed of burning,[7] which acts to further increase the rate of pressure build-up. Thus the overall effect of such confinement of a burning pyrotechnic composition is to significantly reduce the time taken for its chemical energy to be released. The second effect of near total confinement is that when the pressure produced eventually exceeds the burst strength of the confinement, there will be an explosion as the confinement fails. However, in the case of the Bray Park comets, because of their structural strength, they provided their own strong confinement and can powerfully explode without the need for any external confinement.[k]

Discussion

Normally a Roman candle comet of the size of the Bray Park Roman candles, approximately 0.8 inch (20 mm) thick and 1.8 inches (45 mm) in diameter, takes several seconds to burn and release its chemical energy. However, in the case of the Bray Park Roman candle comets (with all three of the characteristics described above), instead of the energy being released slowly over an interval of several seconds, most of the energy manifested itself on a time scale probably less than (and possibly on a time scale substantially less than) a few milliseconds. The importance of this is that, while the total energy produced by normally-functioning and Bray Park comets is essentially the same, the power developed by such a malfunctioning comet is at least a 1000 times greater (and possibly much greater). As a result, in the case of the malfunctioning Bray Park Roman candles, even though the bore of the Roman candle tube was essentially unblocked, when one comet explodes, not much of the explosive pressure is able to be relieved by gases escaping up the essentially open bore of the Roman candle tube. Accordingly, the result of the explosion of a single comet within a Bray Park Roman candle can be the near simultaneous consumption (explosion) of all the other comets in the Roman candle. This combined explosive output is then sufficient to fragment the Roman candle tube and its supporting steel tube.

The unique and unexpected explosive performance of the Bray Park Roman candle comets was demonstrated in testing during field trials. This testing also provided partial confirmation that the cause of the malfunctioning Bray Park comets resulted from the combination of the three factors: their high energy composition, significant permeability and great structural strength. (The next article in this series will present a summary of the field trials.)

Conclusion

This article presented information on those characteristics of the Bray Park Roman candle comets thought to be most important in providing them with the ability to produce incredibly powerful explosions, even when completely unconfined. In the next article in this series, a summary of the testing undertaken by the Queensland Department of Natural Resources and Mines will be summarized. This testing clearly demonstrated the capability of Roman candles, in conjunction with their steel support tubes, to have produced the accident.

Ancillary Notes

a) The subject 2-inch (50-mm) Roman candles were imported into Australia early in 2000. Some 1.5-inch (38-mm) Roman candles, with identical labeling (considering their slightly smaller size) and of apparently identical construction, were imported into the US. (Photos of the labeling were included in the previous article.[1])

b) Many of the suspect Roman candles had been X-rayed, which revealed that the comets were solid with no internal structure (e.g., they were not crossettes). In addition, this was further confirmed when comets were extracted from the Roman candles, physically examined and broken apart to inspect their interiors.

c) Because the authors had not heard of another similar Roman candle malfunction, particularly with regard to having produced such a powerful explosion, inquires were made of more than ten researchers (mostly from government laboratories) from four countries with joint expertise in both pyrotechnics and fireworks. Those researchers were singularly of the view that they would not have predicted that a malfunctioning Roman candle was the cause of the accident at Bray Park. More specifically, prior to learning something about the testing of the comets in this case, these researchers each considered the malfunctioning of a Roman candle such as occurred at Bray Park to be virtually impossible, with no known previous occurrence.

d) The steel support tubes had an inside diameter of 3.00 inches (76 mm), a wall thickness of 0.14 inch (3.6 mm) and extended 19.7 inches (500 mm) up the length of the Roman candles. The Roman candles were 31.5 inches (800 mm) long and had an outside diameter of 2.48 inches (63 mm). Thus there was a relatively close fit of the Roman candle in the support tube, with the difference between the outside diameter of the candle and the inside diameter of the steel tube of 0.28 inch (7.1 mm).

e) Two examples of traditional (Black Powder and aluminum) white comet formulation are presented as 1 and 2 in Table 1. Two more recent formulations (Black Powder and titanium) are presented as 3 and 4. The high energy formulation used in the Bray Park white-tailed comets is also shown. (For convenience in preparing the table, the particle size and shape of the ingredients have not been specified for any of the formulations.)

Table 1. Example Formulations for White Comets.

	White Comet Formulations				
	Traditional		Recent		Bray
Ingredient	1	2	3	4	Park
Potassium nitrate	40	45	64	18	
Charcoal	20		13		
Sulfur	10	10	9	4	
Antimony sulfide	5				
Black (gun) Powder		5		50	
Aluminum	18	40		3	
Titanium			9	18	
Boric acid				1	
Dextrin	7	+5	5	6	
Potassium perchlorate					50
Magnalium[f,g]					35
Acaroid-type resin					11
Unidentified					4
Reference	2	3	4	5	6

f) The magnalium used in the Bray Park white-tailed comets was quite fine grained, with the median particle size averaging approximately 40 microns (a little finer than 325 mesh). Also the particle size distribution of the magnalium was quite varied, even within the comets of a single Roman candle. For example in one Roman candle in which four of the comets were analyzed, the median particle size differed by as much as a factor of two, ranging from 26 to 53 microns. Further in the case of the magnalium with the 26 micron median particle size (which was approximately 600 mesh), 15 percent of that magnalium was less than 12 microns (1200 mesh).

g) The alloy ratio of this magnalium (Mg:Al) was approximately 25:75.[6]

h) Power is defined as the time rate of energy production. Thus the speed at which a chemical reaction takes place (i.e., the rate of energy production) is important in determining the power of an explosion. Even if the Bray Park comets had produced no more energy than commonly used formulations, but they produced that energy more quickly, the power output would be greater.

i) During the course of the Department of Mines investigation, some of the Bray Park Roman candles were broken apart for the purpose of examining their interiors. Those examinations revealed the presence of internal channels when viewed under a low-power microscope.

j) Perhaps a good example of the need for confinement in this case is a pipe bomb, where one might take large masses (chunks) of a compacted pyrotechnic composition, put them in a pipe, seal the pipe, and ignite the contents inside the tightly closed pipe to produce a powerful explosion. However, if one of the end caps of this pipe bomb were left off, such that the pipe is open on one end, when its contents are ignited they will simply burn and vent the combustion gases out the open end of the pipe without exploding.

k) By way of emphasizing the incredible magnitude of some of the explosions that occurred, note that nothing near this same level of explosivity would have been produced had the tests been conducted using the same amount (approximately 60 g) of a firework flash powder similarly burned in the open on a flat surface.

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5) B. Sturman, "The Knox Pyroballets, 1988", *Pyrotechnica*, No. 13, 1990, p 36.

6) G. Downs, *Investigation Report – Bray Park Fireworks Tragedy – 20 May 2000*, v.1, Attachment 1.2 "Data sheet – 2" 8 shot white-tail Roman candle".

7) K. L. and B. J. Kosanke, " Control of Pyrotechnic Burn Rate", *Proceedings of the 2nd 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.

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Pyrotechnic Burn Rate Measurements: Interstitial Flame Spread Rate Testing

K. L. and B. J. Kosanke

*[**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.]*

Background

There are two general types of burning, sometimes described as *parallel burning* and *propagative burning*.[a] In the previous article in this series,[2] a method for determining parallel burn rate was discussed (*strand testing*), and a simplified method of testing under ambient conditions was suggested. In the current article, a method for determining one type of propagative burn rate (*interstitial flame spread rate*[b]) is discussed.

Knowledge of interstitial flame spread rates can be quite important in producing consistent pyrotechnic actions. For example, even though modern artillery uses smokeless powder as their primary propellant, it is common for these propellants to be ignited using an initial, centrally located, charge of Black Powder. This is because the proper functioning of the smokeless propellant in artillery rounds requires its rapid and controlled ignition under conditions of low initial pressure.[3,4] Black Powder accomplishes this rapid and controlled flame spread at near atmospheric pressure.[c,d] Similarly, the rapidity of flame spread at low pressure plays an important role in Black Powder's ability to successfully propel aerial shells high into the air, whereas smokeless powder and Pyrodex® are ineffective.

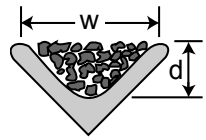
The methods used to determine the interstitial flame spread rate of powders range from quite simple to very complex. The procedure can be as simple as measuring the time to burn a trail of powder (e.g., burning 16 grams [6.6 oz] of Black Powder laid in a straight line on a flat surface and timing the burning with the aid of a video camera[7]). On the other hand, the hardware and procedure can become much more involved when performance is measured in the actual assemblies in which the powder is to be used. This can involve the use of multiple light and pressure sensors, special ignition methods, and a machined powder container mounted in a pressure vessel.[3]

One problem with interstitial flame spread testing is that many factors, other than the intrinsic nature of the pyrotechnic composition, can substantially affect flame spread rate. Probably foremost among these are what might be described as geometric effects. These include such things as the test powder's average grain size and the range of grain sizes present.[e] For example, if the same exact same pyrotechnic composition is used to produce two slightly different size granules, the flame spread rates of those granulations will differ. A more important geometric effect is the configuration of the powder during the test.[f] For example, even in the simplest configuration, such as a trail of powder burned in the open, the depth and width of the powder that is laid down will significantly affect the flame spread rate. However, despite the potential for uncertainties in making flame spread measurements, because of the simplicity of the method, this can be quite useful for comparing the performance of pyrotechnic powders.

Simplified Method

The simplified method suggested in this article is only slightly different than the "burn a trail" method described above. The primary difference is the use of a pre-made form (tray) that shapes and holds the powder trail. A convenient form is common steel angle iron. The use of this is illustrated in Figure 1, first shown in cross-

section, where the powder has been laid into the "V" groove formed by the angle iron. The approximate dimensions of the powder trail formed using a "small" tray made from 1/2 × 1/2 × 1/8-inch (13 × 13 × 3-mm) angle iron and a "large" tray made from 3/4 × 3/4 × 1/8-inch (19 × 19 × 3-mm) angle iron are shown in the accompanying table in Figure 1. Having two sizes of the apparatus can be useful; the smaller is perhaps better suited for fine-grained powders or if the amount of powder is limited. The amount of powder held by the smaller tray is approximately 40 grams (1.5 oz) whereas the larger tray requires approximately 130 grams (4.5 oz). The complete apparatus as seen from the side (at a reduced scale) is also shown in Figure 1. Here, a four-foot [1.2 m] length of material was used; however, end stops were inserted to provide a powder trail length of 39.4 inches (1 meter). When testing slower burning powders, or to save on the amount of powder consumed, the end stops can be moved closer together. Two common U-bolts are used to hold the end stops in place and provide support legs that keep the angle iron oriented upright. A small hole (not shown in the drawing) has been drilled into one end stop. This holds the electric match used to ignite the powder being tested. This hole is slightly below what will be the top of the powder in the V-channel of the apparatus.[g]



Size	Dimensions (in.)			
	w		d	
	in.	mm	in.	mm
Small	0.51	13	0.23	5.8
Large	0.85	22	0.38	9.7

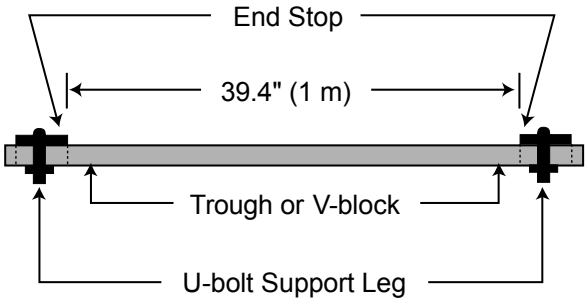


Figure 1. Illustration of a simple interstitial flame spread test apparatus.

To use the apparatus, first an electric match is inserted through the hole in the end stop such that its head (tip) protrudes approximately 1/8 inch [3 mm] into what will be the powder trail. Then the powder to be tested is added to the V-channel such that it completely fills the space of the channel without extending significantly above the top of the channel. (A small paper card can be useful for forming and smoothing the top of the powder trail.) To initiate the test, the electric match is fired.

For slow burning powders, it may be possible to measure the time for the fire to advance to the end of the unit simply using a stopwatch. However, to make a permanent record of the test and to much more accurately time the burning, a simple home video camcorder can be used. When this is done, the tape can be played back counting the number of 1/30 second frames (or 1/60 second fields, available from some VCR's). In the testing done by the authors, the light sensitivity of the video camera must generally be reduced such that the light from the burning powder does not overwhelm the camera. The first video frame (field) that documents a slight reduction of the light produced upon the flame front reaching the approximate end of the powder trail is taken as the indication that the end of the powder trail has been reached.[h,i] Typically, at least, three measurements are made for each powder type, and an average burn time is calculated. To demonstrate the use of the simple flame spread measurement method, a series of Black Powder samples were tested. The results are listed in Table 1.

Table 1. Results of Flame Spread Rate Measurements of Black Powder Samples.

Powder Description	Tray Size[a]	Burn Time (video fields, 1/60 s) 1	2	3	Average Burn Time (s)	Flame Spread Rate (in./s)	(m/s)
Goex™ – 3FA	Small	68	74	76	1.21	32.6	.83
	Large	60	59	54	0.96	41.0	1.04
Goex™ – 2Fg	Small	58	53	59	0.94	41.9	1.06
	Large	39	40	42	0.68	57.9	1.47
Goex™ – 4Fg	Small	63	57	55	0.97	40.6	1.03
	Large	45	41	43	0.72	54.7	1.39
Wano™ 4Fg	Small	58	58	59	0.97	40.6	1.03
Chinese Military 2Fg	Large	52	63	54	0.94	41.9	1.06
Elephant™ 2Fg	Large	42	41	46	0.67	58.8	1.49
Hobbyist 4FA[b]	Small	51	53	(c)	0.87	45.3	1.15
Pyrodex™ RS 2Fg[d]	Large	300	262	266	4.60	8.6	.22
Clean Shot™ 2Fg[d]	Large	138	127	128	2.18	18.1	.46
Black Canyon Powder™	Large	86	86	82	1.41	27.9	.71
Bullseye™ Pistol (Red)	Small	1106	920	1138	16.94	2.3	.06

a) The small tray was made of 1/2 inch (13 mm) angle iron 1/8 inch (3 mm) thick and 39.4 inches (1 meter) long. The large tray was made of 3/4 inch (19 mm) angle iron 1/8 inch (3 mm) thick and 39.4 inches (1 meter) long.

b) This powder was handmade, unglazed, of moderately low density, and made with handmade charcoal.

c) There was only enough of this powder to allow two flame spread rate tests using the small tray.

d) These powders were marked by their manufacturers as being equivalent to 2Fg Black Powder; however, their actual grain sizes were somewhat larger.

Some useful inferences and conclusions can be drawn from even the limited amount of test data presented in Table 1.

- The three Goex powders were tested using both the small and large tray, and they serve to demonstrate the effect that even relatively small differences in the powder's configuration have on the interstitial flame spread rate. Note that the flame spread rate using the larger tray is 20 to 35 percent higher than when using the small tray.
- The average particle size of the three types of Goex powder are approximately 14, 22 and 60 mesh for the 3FA, 2Fg and 4Fg powders, respectively. Note in Table 1 that the 4Fg (finest mesh) powder did not have the greatest interstitial flame spread rate. This would seem to be an indication that, for these three powders in the configuration used in these tests, the 2Fg powder has the optimum effective fire path cross-sectional diameter.[e]
- For the powder samples and configurations tested: the Wano brand powder (4Fg in the small tray) appears to be approximately equivalent to the Goex powder in terms of interstitial flame spread rate (approximately 40.6 and 40.6 inches/second (1.03 m/s) average burn rates, respectively). Similarly the Elephant brand powder (2Fg in the large tray) was approximately equivalent to the Goex powder (approximately 58.8 and 57.9 inches/second (1.49 and 1.47 m/s) average burn rates, respectively), whereas the Chinese military powder (2Fg in the large tray) had a distinctively lower flame spread rate than did the Goex powder (approximately 41.9 and 57.9 inches/second [1.06 and 1.47 m/s] average burn rates, respectively). Although 4FA powder from Goex was not tested, based on the granulations that were tested, it would seem likely that the flame spread rate in the unglazed and somewhat dusty hobbyist 4FA powder produced what would have been a higher flame

spread rate than the commercial powder of the same granulation.

- In strong contrast to the interstitial flame spread rates of Black Powder under the conditions of these tests, the flame spread rates of the Black Powder substitutes and the smokeless powder were significantly to dramatically lower. This performance difference serves as an indication as to why these powders generally are poor substitutes for of Black Powder in propelling fireworks aerial shells from their loose fitting mortars.

Conclusion

When it is sufficient to perform interstitial flame spread rate testing at atmospheric pressure under mostly unconfined conditions, the simplified method described in this article can be employed. Certainly the precision afforded in these measurements is sufficient for screening tests, and in some cases such testing might be employed as part of a quality control program.

Acknowledgments

The authors wish to acknowledge T. Cardell, M. Wilson and L. Weinman for providing background information. Also L. Weinman for commenting on an earlier draft of this article, and W. Meyerriecks for performing the thermodynamic modeling calculations mentioned in note "d".

Notes

a) In parallel burning, the burn front proceeds inward, into the solid mass of pyrotechnic composition, burning layer after layer as it proceeds, with each layer approximately parallel to the burning surface. The primary mechanism of energy feedback from the reacting (burning) layer to the pre-reacting (about to burn) layer is thermal conduction. This is in contrast to propagative burning of granular powders, where fire races down *fire paths* between individual grains of pyrotechnic composition, driven by the pressure of the gases being produced in the burning process. The primary mechanism of energy feedback, from burning grains to about-to-burn grains, is the convection of hot gas. (For more information about these two types of pyrotechnic burning see reference 1.)

l) In this article, these tests have been called "interstitial" flame spread rates, to emphasize that it is the collective rate of flame spread along the numerous fire paths between a large number of individual grains of powder. In the jargon of the trade, these and similar tests are sometimes referred to as *V-block tests*.

m) It is the combination of both rapid and controlled flame spread in Black Powder that is needed in the ignition of smokeless propellant in artillery. Clearly many pyrotechnic materials have the characteristic of rapid flame spread (e.g., flash powder). However, while under some conditions the flame spread in flash powder may be nearly as low as granulated Black Powder, under only slightly different conditions the flame spread in the same flash powder may be quite explosive. Thus the flame spread rate in flash powders is often unpredictable (i.e., it is not easily controlled or regulated).

n) In addition to Black Powder's rapid interstitial flame spread, another important characteristic is that it burns to produce a relatively high percentage of non-gaseous combustion products. Based on thermodynamic modeling using the CEQ code, the flame of burning Black Powder produces approximately 30% non-gaseous (liquid) reaction products.[5] As the flame cools, approximately another 25% of the reaction products condense (for a total of 55%).[6] Then as cooling continues these molten products may proceed to solidify. These non-gaseous, condensing and solidifying reaction products are much better than permanent combustion gases at carrying and transferring the heat energy needed to cause the ignition of other materials. Accordingly, it is the combination of Black Powder's rapid and controlled interstitial flame spread at near atmospheric pressure and its high proportion of non-permanent gaseous reaction products that make it so effective in the ignition of the smokeless powder in artillery rounds.

o) Average grain size and the range of grain sizes in the powder being tested act to determine the average or typical space between the individual powder grains. This is important because the spaces between the grains constitute the fire paths through the powder, and the effective cross-sectional diameter of the fire paths determines their effectiveness in producing high interstitial flame spread rates.[8] This is illustrated in Figure 2, in which burn rate is presented as a function of fire path diameter for a hypothetical pyrotechnic composition. In that figure, when there are no effective fire paths (i.e., the fire path diameter is zero) such as for a very tightly compacted pyrotechnic composition, the rate of burning is just that of the inward burning into the composition (R_I). This corresponds to parallel burning and is the burn rate that is measured in the surface inhibited strand testing as discussed in the previous article.[2] As the fire path diameter increases from zero, the burn rate increases until a maximum value is reached (R_M) corresponding to the most effective fire path diameter (D_M) for that composition under the conditions of the tests (temperature, pressure, etc.). Thereafter, as the fire path diameter continues to increase, the burn rate falls until it eventually reaches the burn rate approximating what would be measured across the surface (R_S) of a large compacted mass of composition.

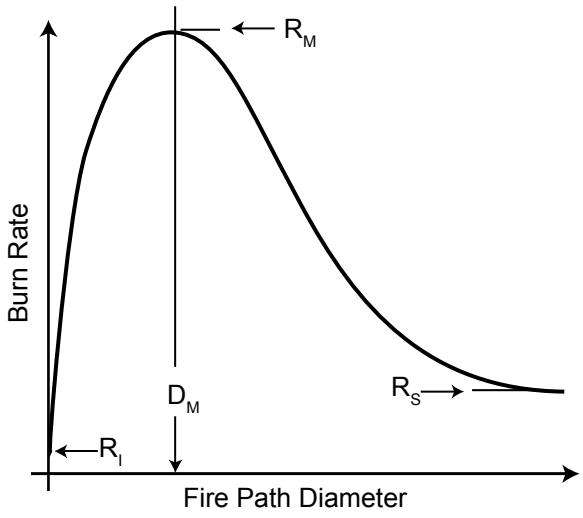


Figure 2. Illustration of the relationship between burn rate and fire path diameter for a hypothetical pyrotechnic composition.[8]

p) One important way in which the configuration of the powder during an interstitial flame spread measurement affects the burn rate is by limiting the ease with which the combustion gases can escape from the burning powder to the atmosphere. This is because any escaping gas will be lost for the purpose of traveling along fire paths to ignite additional powder. As an example of this effect, consider a demonstration in which one trail of powder is burned on a smooth flat surface, whereas a second trail of the same powder is burned after being loaded into an open-ended tube. When this is done for commercial Black Powder, it will be found that the same powder burns roughly 20 times faster in the open-ended tube than it does as a powder trail. This much greater rate of interstitial flame spread can easily be enough to produce an explosion of the open-ended tube.

q) On occasion the firing of the electric match may blow the powder away from it, without igniting the powder. This is not a significant problem as the match can simply be replaced and the test completed. However, on rare occasion (because of the force of the electric match ignition) some of the ignited powder can be seen to be propelled a few inches down the length of the apparatus. This is more problematic and is the reason that: generally at least three tests are repeated for the same powder, the length of the powder trail in the apparatus is fairly long, and the results are only considered to be approximate. If it is necessary to eliminate this occasional source of small error, one could simply use a hot wire igniter rather than a vigorously functioning electric match.

r) Shortly after ignition of the powder, as the flame front advances along the powder trail, the amount of powder burning at any instant is approximately constant, and thus the light output is also approximately constant. When the flame front reaches the end of the powder trail, no additional powder is ignited. Thus, the amount of powder burning starts

to decrease and the amount of light produced also decreases. Accordingly, the first indication of light reduction as the flame front approaches the end stop, serves as a reliable indicator that the flame has reached the end stop.

s) Using a video camcorder to measure the rate of interstitial flame spread along the apparatus is the method most often described in the literature.[3,4] Nonetheless, other methods, such as fuse wires, could be employed. However, this requires the use of timing electronics. More importantly, for fast burning powders, producing relatively low flame temperatures, the uncertainty introduced because of variations in the time taken for these wires to fuse is on the same order as the uncertainty in using the video method.

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Aerial Shell Augmentation Effects

K. L. and B. J. Kosanke

This article provides information about a method of augmenting an aerial shell's aesthetic performance that is simple, high profit and widely appreciated by display sponsors. This method was first discussed many years ago by the authors as part of an article on electrically fired displays.[1] In that article, these effects were described as *parasitic firework effects*. They were described in that way because the "parasitic" firework effects (small shells, mine stars and other small components) derived their lift energy from other "host" aerial shells. In the present article, because it is more descriptive, these same effects will be called augmentation effects.

To draw lift energy most effectively from their host shells, the augmentation effects must be loaded on top of the host shell. Based on empirical observations, when the total weight of the augmentation effects is modest in comparison with the weight of the host shell, the altitude reached by the host shell is not noticeably reduced, and the augmentation devices reach ample height. Table 1 presents typical weights of spherical host shells and the augmentation firework effects used with them. The weight of augmentation effects range from as much as approximately 1/2 the weight of the host for a 3-inch (75-mm) shell, down to approximately 1/10 the weight of the host for a 12-inch (300-mm) shell. In part these varying relative weights correspond to the effective carrying capacity of the host shell. [Because of the relatively low ratio of shell mass to projected area, 3-inch (75-mm) shells require disproportionately larger lift charges to reach proper altitude than is required for larger shells. Accordingly, for the shell sizes listed, 3-inch (75-mm) host shells have the greatest relative carrying capacity for augmentation effects.]

Carrying capacity not withstanding, the varying relative weights for augmentation effects are the result of aesthetic considerations. When a 3-inch (75-mm) shell is properly augmented, those effects usually weigh about three ounces (85 g). For an 8-inch (200-mm) shell near optimum results can be achieved with about 16 ounces (450 g) of augmentation effects. To maximize the artistic effect, augmentation effects must be properly timed and sized with respect to the host shell. In general, the lowest altitude and smallest effects should occur first, followed by higher and larger effects leading to the break of the host shell, which should be impressively greater than the augmentation effects that preceded it. To illustrate this, consider one possible 4-inch (100-mm) *shell set* (host shell plus augmentation effects). On firing, the shell set first produces a blue-willow mine effect extending about 150 feet (50 m) in the air; this is followed shortly by a

Table 1. Augmentation Effect Weights for Spherical Host Shells.

Host Shell (Spherical)				Point Rating	Augmentation Effect	
Size		Approx.Weight			Typical Total Weight	
(in.)	(mm)	(lbs)	(kg)		(oz)	(g)
3	75	0.3	0.1	1	3	85
4	100	0.8	0.4	2	5	142
5	125	1.5	0.7	3	8	227
6	150	2.5	1.1	4	10	284
8	200	5.5	2.5	8	16	454
10	250	11.	5.0	11	22	625
12	300	18.	8.2	14	28	795

flurry of four small purple (festival ball sized) breaks at about 250 feet (85 m), followed by the break of the 4-inch (100-mm) bright red chrysanthemum shell at about 500 feet (150 m). The synergistic effect of the combination of individual effects produces a result that is far more aesthetically pleasing than might be expected (particularly when the modest added cost for the augmentation effects is considered). Figure 1 is an attempt to illustrate how this 4-inch (100-mm) shell set might appear in comparison with the 4-inch (100-mm) shell alone.

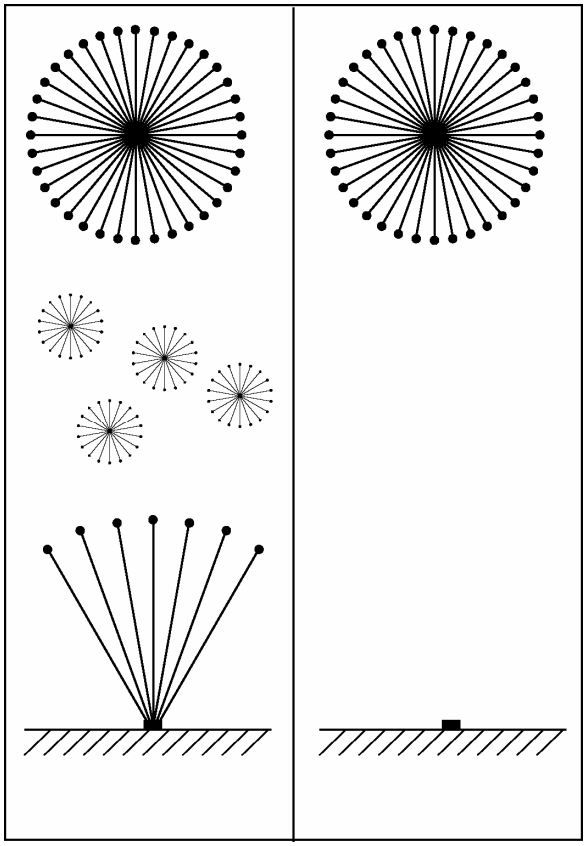

Figure 1. Illustration comparing augmented vs normal aerial shell bursts.

There are three main reasons to consider the use of augmentation effects. The first and most important reason was given above, aesthetics. Though often seriously under-utilized in displays, mines and ascending effects are attractive in their own right. They also offer variety, and they fill an otherwise unused portion of the sky. Another aesthetic payoff comes in the length of time the combined effects last; the use of a shell set such as the one described above produces a display that lasts at least twice as long as would be produced by the host shell alone. However, the most important aesthetic reason for using augmentation effects is that their use seems to significantly increase the perceived beauty of the host shell. This may be the result of helping to focus the audience's attention and build their sense of anticipation of the burst of the host shell, which then appears more beautiful than it would if seen as a single unheralded event. (Note that augmentation effects are most effective for displays using reasonably high quality star shells that are fired slowly enough for their beauty to be appreciated.)

The second reason to consider using augmentation firework effects is increased profit. Because the augmentation effects add so much to the favorable impression of the audience and yet cost relatively little, it is acceptable to increase the gross profit on their use. When the authors still performed displays, their gross profit for augmentation firework effects was approximately double that for the host shells. Yet the feedback from sponsors was universally favorable. (It's a great day when you can increase your profit and still have delighted sponsors wanting to shake your hand for the great job you did.)

The third reason for considering the use of augmentation effects is that their use allows a significant reduction in the variety of shells that must be kept in inventory. Consider the following three shell sets: (1) blue and willow mine followed by silver glitter augmentation shells followed by large red peony; (2) purple and gold glitter mine followed by green meteor shells followed by large red peony; and (3) green and silver comet mine followed by short-delay small artillery shells followed by large red peony. In each case the host shell was a red peony; however, even if these shell sets were fired one after the other, they would be perceived by the audience as presenting substantial variety. By using different combinations of only five types of mine stars (taken two types at a time), five types of augmentation shells and five types of host shells, it is possible to assemble 500 different shell sets. Obviously not all of the 500 shell sets will be artistically effective, but very many will. Thus the use of augmentation effects allows a significant reduction in the number of different

types of shells needed in inventory. (This is especially useful for small scale operations.)

Augmentation effects should be prepared in advance by loading the mine stars and small shells or other small components into plastic bags and sealing them. A few of the possible assemblages of augmentation effects are suggested in Table 2. Large quantities of these pre-bagged items can be stored until needed during final loading before a show. Also given in the table is a point rating for each of the different assemblages. These can be used as an easy way of determining which and how many of each of the assemblages can be loaded on top of any given size host shell. (Note that Table 1 included a point rating for typical host shells.) Any number and combination of assemblages can be used as augmentation effects providing their cumulative point total does not exceed the point rating given for the host shell. For example, a 5-inch (125-mm) host shell has a point rating of three, thus (in addition to mine stars) six festival balls, or two festival balls plus one 2½-inch (65-mm) shell, or one 3-inch (75-mm) shell are all acceptable as augmentation effects.

Table 2. Some Possible Augmentation Effects.

Points	Description[(a)]
1	2 Festival Balls plus 1 oz (28 g) of mine stars
1	4 packs (approximately 70) Firecrackers or Jumping Jacks plus 1 oz (28 g) of mine stars
2	1 – 2½" (65-mm) Shell (may include 1 oz (28 g) of mine stars)
2	3–1" × l½" (25 × 38 mm) Flash Salutes
3	1 – 2½" (65-mm) Shell plus 3 oz (85 g) of mine stars
3	1 – 3" (75-mm) Shell (may include 1 oz (28 g) of mine stars)
3	1 – 2" x 2" (50 × 50 mm) Crossette Comet
3	6 oz (170 g) of 1" x 1" (25 × 25 mm) Comets
4	1 – 3" (75-mm) Shell plus 3 oz (85 g) of mine stars

Note — all items are heavily primed.

It is important that augmentation effects be well primed to insure their ignition by the escaping lift gases from the host shell. (See reference 2 for more information about primes and priming.) Probably the most reliable priming method is one that concludes with pressing the prime-coated item into granulated commercial Black Powder while the prime is still wet. This provides many angular points on the primed surface insuring easy ignition. Small shells are usually primed by dipping the whole area of their fuse into a prime mix (usually handmade meal powder in nitrocellulose lacquer), then momentarily pressing the primed area into 3 or 4 Fg commercial Black Powder. Packs of firecrackers or jumping jacks can be primed by running a bead of prime from a catsup-like squeeze bottle down the spine of each pack, then pressing the primed area into the Black Powder. Small individual components (such as small bees) are usually primed by dipping batches of several hundred at a time into the prime mix, then gently tumbling the items in handmade meal powder. Mine stars need only be primed as they would be for use in star shells. Priming is important in all cases**,** but especially when augmentation effects are loaded on top of canister shells, where it may be less likely than with spherical shells that each of the items will be well exposed to the burning lift gases. When augmentation items without a mine effect are used with canister shells, it is desirable to add a small charge of Black Powder to the plastic bag containing the augmentation effects. This will help to insure proper ignition of the effects by more completely filling the bag with fire when the host shell is launched.

Augmentation effects are loaded into mortars by simply dropping the filled plastic bags into the mortar after the host shell has been loaded. It is inappropriate and unnecessary to remove the augmentation effects from their bags. (Inappropriate because loose components or stars might jam between the host shell and the mortar wall; unnecessary because the plastic bag will melt away almost instantly from the flame escaping around the host shell when it is fired.)[3]

One word of caution: there is always the possibility that sparks from the firing of one shell will fall into other mortars and unintentionally ignite augmentation effects in those mortars. However, this is easily prevented by the use of

individually applied protective covers placed over each mortar. Plastic sheeting and heavy aluminum foil is generally sufficient, but polyethylene pipe covers (such as those manufactured by Cap Plugs™) are probably superior. Further, it is thought that augmentation effects are only suited for electrically fired displays or preloaded manually fired displays. The use of augmentation effects in displays where mortar reloading is occurring is highly inappropriate for reasons of crew safety.

In the original version of this article, which included a discussion of augmentation (parasitic) effects, a series of reasons were given as to why there is essentially no reduction in the burst height of the host shells. However, at that time no measurements had been made to confirm and quantify that empirical observation. Recently, while studying the effect of varying mortar diameter and length on the height achieved by 3-inch (75-mm) aerial shells, some measurements were made of the degree to which the burst height of the shells was reduced when they were used as hosts for augmentation effects. In that work, it was found that under the conditions of the testing:

- 4600 feet (1400 m) above sea level
- 20-inch (500-mm) long mortars with an internal diameter of 2.93 inches (74.4 mm)
- The standard test shell was a 3-inch (75-mm) Thunderbird Color Peony-White, TAB-106, with an average diameter of 2.72 inches (69 mm) and an average mass of 4.8 ounces (36 g)

When fired alone, the aerial shell burst at an average height of 530 feet (162 m). (Further details of the test methods can be found in two articles reporting on those studies.[4,5]) When the augmentation effects with a weight totaling 3 ounces (85 g) were added on top of the test shells, the burst height of the host shell was reduced to an average of 505 feet (154 m). This corresponds to a reduction of only approximately 5 percent in burst height, which can be safely tolerated for properly performing aerial shells. While measurements were not made using larger shells, it is thought that the reduction of burst height would be proportionately no more than that found in this study. (This is because augmentation effect weights represent a smaller proportion of the weight of the larger caliber shell.)

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Feasibility Study on the Use of Nanoscale Thermites for Lead-Free Electric Matches

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ABSTRACT

Electric matches are used in the pyrotechnic industry to electrically initiate devices remotely and with precise timing. Unfortunately, most current commercial electric matches contain lead compounds, which when burned produce lead reaction products that may cause environmental pollution and contamination of firing areas. These lead compounds, namely lead thiocyanate, lead nitroresorcinate and lead tetroxide, are used in electric match pyrotechnic formulations because a small diameter resistive bridgewire can reliably initiate them. A possible alternative to lead-containing compounds is nanoscale thermite materials, otherwise known as Metastable Intermolecular Composite (MIC) materials. These super-thermite materials can be formulated to be sensitive to thermal stimuli, such as resistive heating. In the effort to produce a lead-free electric match, a feasibility study was performed using nanoscale aluminum and molybdenum trioxide mixtures in electric match formulations.

Keywords: nanoscale, thermite, lead-free, electric match, metastable intermolecular composite, performance test, sensitiveness test

Introduction

The pyrotechnic industry favors electrical ignition of fireworks and stage special effects over manual ignition when such displays are choreographed to music, when more precise timing is required for an artistic effect, or when ignition must be done remotely. In addition, very large firework shows are better and more safely managed with a central computerized firing station than by teams of personnel in the midst of the display area manually igniting devices. Unfortunately, electric matches are remarkably sensitive to electrical stimuli when compared to initiators sometimes used by other industries (e.g., aerospace, defense and petroleum), such as exploding bridgewires (EBW) or an exploding foil initiator (EFI or slapper). A current as small as 350 milliamps can reliably fire some electric matches, whereas an EBW requires a special capacitive discharge circuit to provide approximately 200 amperes of current and 2 joules of energy for proper functioning. The EFI has even higher power requirements. Although it is generally recognized by the pyrotechnic industry that electric matches are prone to accidental ignition, it is this same industry's demand for simple, relatively inexpensive initiators that has largely determined the performance characteristics of today's electric matches. This, along with the need for inexpensive firing sets and wiring, has played a predominant factor in their development. The need stems from the large number of individual ignitions that are required for a display. For example, a single pyrotechnic show may require hundreds, if not thousands, of electric matches and miles of wire.

For electric matches to fire at such low electrical energies, a thermally sensitive initiating composition is required. The typical means of initiation is a hot Nichrome wire having a diameter no greater than approximately 1 mil (25 microns). Of the compositions that are commonly used, many contain lead compounds in the form of lead thiocyanate, lead nitroresorcinate or lead tetroxide. These lead compounds—when formulated in appropriate ratios and with other constituents—produce the desirable thermally sensitive compositions. But, as expected,

these match compositions produce lead reaction products that may cause environmental pollution and contamination of firing areas, which is an undesirable feature. This paper reports on the performance and sensitivity test results of using nanoscale thermite, namely the aluminum and molybdenum trioxide pair, as a substitute for lead-based compositions in electric matches. Nanoscale reactants, which are also known as Metastable Intermolecular Composite—or MIC materials (pronounced "Mick"), were first developed by Los Alamos National Laboratory approximately 8 years ago.[1] Only in recent years, however, has research investigating the utility of MIC been expanded into the fields of explosives, thermobarics, lead-free primers, reactive projectiles, rocket propellants and electric matches.[2]

Match Head Design

While the construction and composition of commercially available electric matches are varied, a common form is diagrammed in Figure 1. The bridgewire, usually a fine filament of Nichrome, is strung and soldered across the edge of a copper-foil-clad substrate somewhat similar to circuit board material. The size of the substrate is approximately 0.4 inch long by 0.1 inch wide and 0.03 inch thick (10 × 2.5 × 1 mm). A bead of pyrotechnic material is formed over the bridgewire by dipping the end of the substrate into a slurry of a pyrotechnic composition. Although not shown in the diagram, a commercial match often contains two distinct layers of composition. The composition most sensitive to initiation by the bridgewire is applied first (generally referred to as the primary coating or layer). This is followed by a secondary coating of a different pyrotechnic mixture. The secondary composition, which is ignited by the primary, produces the desired thermal output (e.g., flame, sparks, molten slag or droplets) that initiates the pyrotechnic device, such as a Black Powder charge. To supply power to the bridgewire, electrical leads (approximately 24 gauge) are soldered at the base of the electric match substrate. The substrate containing the bridgewire and pyrotechnic bead is usually called the *match-head* (or *fuse-head* in other countries).

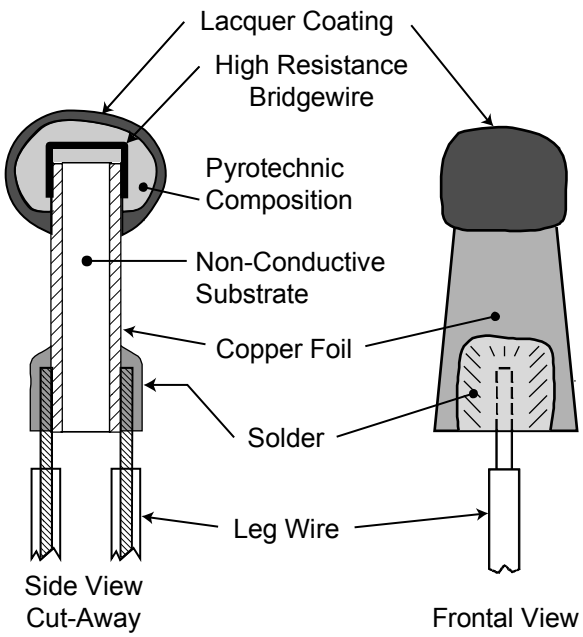

Figure 1. General diagram of an electric match.

The outer lacquer coating (see Figure 1) protects the match head from physical damage during handling and, if the composition is water sensitive, seals the match head from moisture. In addition, a non-conductive coating such as lacquer can act as an electrical insulator to prevent accidental ignition by electrostatic discharge (ESD). In one possible accident scenario, the current induced by static electricity can travel from a point external to the electric match tip, through the outer match coating and pyrotechnic composition, then to the electrical leads via the bridgewire. In this process, if the ESD energy is sufficient, the electric match composition is ignited. In an earlier study, the outer coating of a number of commercially available matches was examined.[3] It was found that matches with imperfections or holes in the outer coating are much more susceptible to this type of accidental ESD ignition.

The typical bridgewire resistance in commercially available electric matches is between 1 and 2 ohms (Ω).[4] Matches with higher resistances function better but are more difficult to manufacture, while those with lower resistances (less than 1 ohm) require more current to fire and are therefore less desirable to the industry. To illustrate the importance of the bridgewire's resistance to overall performance of an electric

match, Figure 2 shows an electric match in a typical firing configuration. The electric match, presumably imbedded within a pyrotechnic device, such as a fireworks aerial shell lift charge or star mine, is connected to a fire set by two annealed copper leads of 100 feet (30.5 m) length. For the purpose of this example, the 100 feet distance was arbitrarily chosen as a safe distance between the operator of the fire set and the display site. As the fire set powers the electric match, not all of the energy provided by the fire set is deposited into the bridgewire. The wire leads have electrical resistance that dissipates part of the energy. This is especially problematic when the resistance is substantial in comparison with that of the igniter (i.e., when the leads are long or the wire is of small diameter).

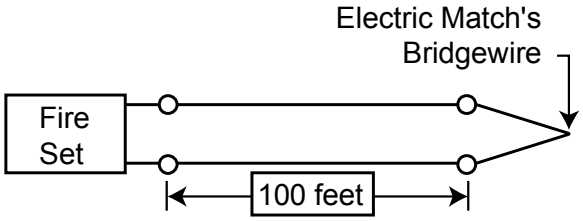

Figure 2. A typical setup for firing an electric match in a pyrotechnic display. A distance of 100 feet between the fire set and the electric match provides a safe operating distance between the fire set and the display site.

To better illustrate how the wire leads can affect the proper functioning of an electric match, Table 1 lists the resistance and diameter of three example wire gauges that might be used by an operator. (One should note from the table that the resistance of a copper wire increases with decreasing wire thickness, since electrical conductivity is proportional to the cross-sectional area of the wire.) The percentage of electrical energy deposited by the fire set onto the bridgewire (denoted as $\%E_{bw}$) is expressed in the most simple terms by the following equation, where R_{bw} is the resistance of the bridgewire in ohms, and R_w is the resistance of 200 feet of copper wire leads.

$$\%E_{bw} = \frac{R_{bw}}{R_{bw} + R_w} \times 100$$

Table 1. Measured Properties of Annealed Copper Wire of Three Gauges.

Gauge	Wire Thickness (mils)	Resistance for 100 ft wire at 20 °C (Ω)
18	40	0.64
20	32	1.02
24	20	2.57

Note 100 ft = 30.5 m, and 1 mil = 25 microns.

Figure 3 shows the change of $\%E_{bw}$ as the resistance of the bridgewire, R_{bw}, is varied from 0.1 to 3 ohms for the three different wire gauges. It can be seen that the energy deposited at the bridgewire significantly decreases for a bridgewire resistance less than 1 ohm, especially when thin wires—with relatively high resistances—are used. For this reason, commercially available electric matches intended for pyrotechnic displays generally have a bridgewire resistance of 1 ohm or more. To approximate the industry standards, the electric match chosen for this study had a resistance of about 1 ohm.

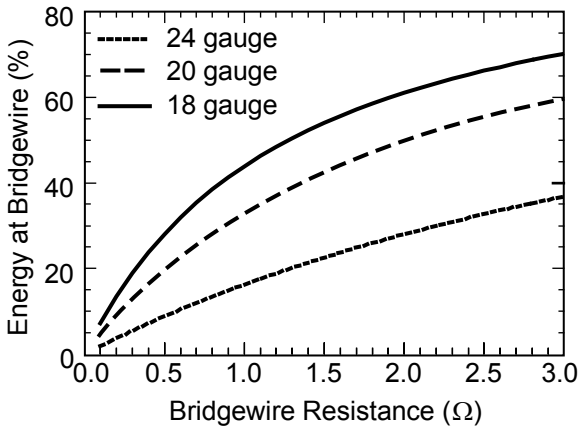

Figure 3. Percent energy at the bridgewire ($\%E_{bw}$) as a function of the bridgewire's resistance and the gauge of wire leads used. The upper curve represents two 100 feet wire leads with 18 gauge thickness; the middle curve represents that for 20 gauge; and the bottom curve is that for 24 gauge.

Materials Used

Nanoscale Thermite

Interest in nanostructures has grown since it has been demonstrated that the reactivity of MIC materials is much greater than those composed of micron-sized grains. For example, aluminum and molybdenum trioxide mixtures with an average particle size ranging from 20 to 50 nm react more than 1000 times faster than mixtures using conventional micron-sized or larger particles. The reason for such reactivity has been attributed to the large reduction in the diffusion barrier between reactants.[1] One process for manufacturing nanoaluminum involves vaporization of the metal from a resistively-heated ceramic boat followed by rapid condensation of the vapor in an inert atmosphere (argon or helium). Particle size and distribution can be controlled using various techniques.[5] Because pure aluminum of such small particle size is pyrophoric, the surface of the aluminum is passivated by controlled addition of oxygen (to form an oxide coating on the metal surface) soon after the aluminum has condensed. The oxidant of the thermite pair, molybdenum trioxide, is also produced in a similar fashion, except the addition of passivating oxygen is not needed.

Technanogy, Inc.[6] provided the three sizes of nanoaluminum that were used in this study, specifically 40, 121 and 132 nm powders (T40, T121 and T132, respectively). These sizes represent the approximate mean of their particle distributions. Only one type of nanoscale molybdenum trioxide was used as the oxidant with the above aluminums; this material was purchased from Climax Corporation.[7] Figures 4 and 5 are scanning electron micrographs (SEM) of the 40 nm aluminum and the Climax molybdenum trioxide powders, respectively. Unlike the nanoaluminums, the molybdenum trioxide has a more varied morphology and distribution of particle size, consisting of thin sheets and rounded particles. From small-angle scattering analysis, the sheet thickness was measured to be approximately 15 nm.[8]

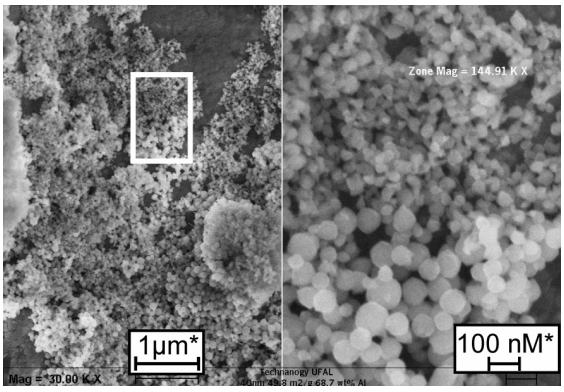

Figure 4. SEM of 40-nm Technanogy aluminum.

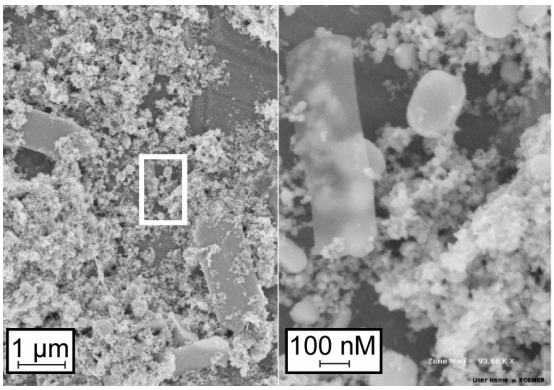

Figure 5. SEM of Climax molybdenum trioxide.

The aluminum and molybdenum trioxide thermite mixtures used for the test matches were composed of approximately 40 to 45 percent aluminum (by weight) with the remainder being molybdenum trioxide. The exact amount of aluminum used in the thermite mixtures depended on the thickness of the oxide coating for a given aluminum sample. The procedure for quantifying free aluminum was by thermogravimetric analysis (TGA), where the aluminum sample mass was monitored with increasing temperature in the presence of oxygen. Oxidation of the aluminum causes the sample mass to increase until all of the aluminum has reacted. Knowing that the increase in mass is attributed to the conversion of free aluminum to aluminum oxide, the amount of free aluminum can therefore be calculated.

Simple mechanical mixing of the thermite mixture does not produce a homogeneous mixture of nanosized reactants; rather coarse ag-

glomerates of each reactant are formed. To break up the agglomerates, hexane is added to the dry mixture and the resulting slurry was sonicated for about 30 seconds. The hexane was then evaporated and the resulting granulated powder sieved through a 45 mesh screen to break up the mass of powder. Because the resulting powder is ESD sensitive, small amounts (about 0.5 gram) are mixed and handled to minimize the hazards of an accidental initiation. Scanning electron micrographs (see Figure 6 for one example) have verified that the sonication procedure produces a highly intimate mixture of fuel (aluminum) and oxidant (molybdenum trioxide).

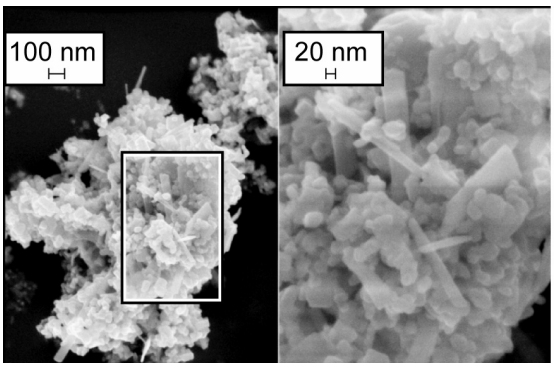

Figure 6. SEM of a 40 nm aluminum and molybdenum trioxide mixture.

Three different batches of electric match composition were prepared during the course of this study and are designated as Batch Nos. 1, 2, and 3. The differences between the batches are the types and amounts of MIC powders used in the primary formulations, which are given in greater detail below. (In general, the reactivity of the MIC powders increases with smaller particle size distribution.)

Blank electric matches (i.e., without pyrotechnic material dipped on the bridgewire) for this study were obtained from two sources. Batch No. 1 test matches used blank match heads purchased from Firefox Enterprises, Inc.[9] Unfortunately, these match heads had a bridgewire resistance of less than 0.1 ohms, and while they were deemed not suitable for firing current tests, they were suitable for most of the sensitiveness tests. To have match heads with a higher resistance and a narrower range of resistance values, other blank match heads were obtained from Martinez Specialties, Inc.[10] These blanks had a distribution of resistance values of approximately 0.9 ± 0.1 ohm. This resistance is somewhat low as compared to other commercially available matches[4] but is within the acceptable range. With these blanks, Batch Nos. 2 and 3 of electric matches were prepared for additional performance testing.

The first manufacturing step was to prepare the slurries for each layer in the match. The first layer, the primary, consisted of 91% MIC and 9% nitrocellulose (13.5% nitrogen content), which was dissolved with ethyl acetate containing 0.3% FC 430 surfactant from 3M, Inc. Depending on the viscosity of the slurry, the primary layer was built up on the bridgewire by dipping the match head three or four times. The secondary composition was composed of 56.1% potassium perchlorate (sieved through 120 mesh screen), 27.0% 12μ German black aluminum, 8.6% nitrocellulose, 8.1% sponge titanium (–80 to +100 mesh), 0.2% super-fine iron oxide[11] as a catalyst for decomposition of the potassium perchlorate, and enough ethyl acetate solvent to form a thin slurry. Approximately 6 to 8 dips into the secondary composition were needed to build up the match head to the desired size. The outer protective coating was produced by dipping the match head in a vinyl solution.[12] For Batch No. 1 test matches, only a single dip in the vinyl solution was performed; for Batch Nos. 2 and 3, four dips were performed. Between each of these 3 layers (primary, secondary and vinyl coating), the match heads were dipped once in 10% nitrocellulose lacquer to serve as a barrier between each layer.

As previously mentioned, the amount and type of MIC in the primary formulations were different for the three batches. For Batch No. 1, the aluminum portion of the thermite mixture was composed of 60% T121 and 40% T132. For Batch No. 2, only type T132 aluminum was used. Batch No. 3 matches were made somewhat differently from Batch No. 2, whereby the blank match head was dipped once in a thermite formulation composed with T40 aluminum only. Thereafter, the primary layer was built up with two to three successive dips into a thermite slurry composed with T132 aluminum. This was done to see if less electrical current would be required to fire a nanoscale thermite composed

with 40-nm aluminum rather than that containing the 132-nm aluminum. Previously, matches were made using a primary composition that contained only the T40 aluminum. However, when these matches were fired, it was found that their reactivity was too great. These matches exploded or ignited violently and had difficulty in fully igniting the secondary composition. Therefore, to reduce the quantity of the most reactive T40 aluminum in the primary layer, the T40 thermite was limited to a single dip on the bridgewire. Then the less reactive T132 thermite was used to complete the build up of the primary layer. Again, as stated previously, only one type of molybdenum trioxide, obtained from Climax, was used as the oxidant pair in all of the above thermite mixtures.

Results and Discussion

A reasonably thorough study of electric match sensitiveness has been published for ten different match types from four commercial suppliers in a series of short articles in *Fireworks Business* as well as in this journal.[3,13] Since testing of the prototype MIC matches was performed under similar conditions using the same equipment, some comparisons can be made between data of the MIC test matches and the data reported for the commercial matches. However, because of the voluminous amount of data that has been presented in these published works, the authors do not wish to reprint the data, but rather compare the results in qualitative terms. Furthermore, since these MIC matches are the first prototypes (i.e., not finalized designs for commercial production) and future iterations with improved performances are expected, strict interpretation of the test results may be considered superfluous. (Readers wishing for more information on the setup and conduct of the testing than is given below should consult reference 3.)

Impact Sensitiveness

The impact sensitiveness test apparatus is of a standard drop hammer design, except that a lighter than normal drop hammer (1 kg) was used. To better simulate the typical use environment of an electric match in a fireworks display (e.g., electric match inside the paper tube of a piece of quick match), the test match was inserted inside the fold of a 0.01-inch (0.25-mm) thick card stock, and the hammer was allowed to fall onto the assembly. For these tests, the match heads had their wire leads removed, as it was believed that the thickness of the solder connection and wire could absorb some of the impact energy. Earlier testing had shown that a protective shroud on electric matches provided a substantial decrease in their impact sensitiveness. However, at this time, the impact sensitiveness of these test matches covered with a shroud was not investigated. The impact result, typically reported in inches of hammer drop height, was determined for the test match heads following the standard stair-step (Bruceton) method for 20 samples from Batch No. 1.[14] A value of 56 cm (22 inches) was obtained for the test matches using the 1 kg drop hammer. This was significantly better than all of the commonly used commercial matches.[3] Only the low-sensitiveness matches had better performance (the Davey-fire *AN 26 F*, the Luna Tech *Flash* and the Martinez Specialties *Titan*).

The match head samples were also subjected to impact testing in the presence of Black Powder. In these tests, the inside surface of the card stock was heavily painted with a slurry of Black Powder (bound with 5% dextrin) and thoroughly dried. Using the previously obtained impact height of 56 cm, ten matches were consecutively struck at that height. A result of five ignitions out of ten suggests that the presence of Black Powder does not appear to increase their sensitivity to impact.

Friction Sensitiveness

Because a standard friction apparatus is more suitable for powdered samples, a modified test apparatus was used for friction testing the match heads. In these tests, the test match was used as the striker, held at a 45^{o} angle to a moving abrasive surface (#100 grit sand paper). Each test consisted of a set of three trials of three matches at the lowest force setting (a 1.5 N force holding the match head to the abrasive surface). If the matches failed to ignite, a greater force (3.0 N) was used for another set of three trials. Again, if there was no ignition, a still greater force of 6 N was applied on a final set of three matches. Test matches from Batch No. 1 demonstrated no ignition, even at the maximum force setting of 6 N.

This is better than all of the commonly used commercial electric matches and as good as any of the low sensitiveness matches that were tested.[3]

Thermal Sensitiveness

Two thermal test methods were employed for characterizing the match samples. In the first test, described as a *Ramp Ignition Temperature* test, electric match heads were placed inside individual small wells drilled into an aluminum block, which was heated at a rate of 5 °C per minute—beginning at room temperature. The test was concluded when all of the test matches ignited or a temperature of 300 °C was reached. With Batch No. 1 test matches, it was found that no matches ignited below 300 °C, which was as good as any of the electric matches tested previously, including the commercially produced low sensitiveness matches.[3]

Because some electric match compositions can slowly decompose without producing an ignition event while the temperature is ramped up, a second test method, described as a *Time to Ignition* test, was employed using the same heating block. However, the block was heated to a specific temperature and held constant. Then a single match was inserted into a well. If the match ignited within approximately 5 seconds, the temperature of the block was taken as an indication of its thermal sensitiveness. For those matches not igniting at this temperature, the block's temperature was increased by ten degrees and the test repeated. Similarly, if the match ignited in less than 5 seconds, the block's temperature was reduced 10 degrees and the test repeated. For the test matches, the time to ignition at the highest temperature attainable of 300 °C was 28 seconds. Again, this result was as good as any of the electric matches previously tested, including the commercially available low sensitiveness matches.[3]

ESD Sensitiveness

Two tests were performed on the prototype matches to characterize their ESD sensitiveness. In the first test, sensitiveness to electrostatic discharge through the bridgewire was determined by passing discrete amounts of discharge energy through the bridgewire in much the same fashion as the intended firing current (see top configuration, Figure 7). Using an energy storing power supply, the electric match is subjected to electrical discharge energy at a low setting and a positive or negative ignition is noted. The discharge energy is increased incrementally until an ignition is achieved. Much like the impact testing, the discharge energies are raised or lowered following the standard stair-step (Bruceton) method for a series of approximately 20 match tests. The resulting stair-step value provides an ESD energy value that should initiate approximately half of the matches. This test was performed on Batch Nos. 2 and 3 test matches. For Batch No. 2 matches, the ESD energy value was measured at 230 mJ, which is significantly better than all of the commonly used commercially produced electric matches and on a par with the low sensitiveness matches. For Batch No. 3 matches, which contained the more reactive T40 aluminum, the ESD result dropped to 120 mJ, which is comparable to the least sensitive of the commonly used matches.[3]

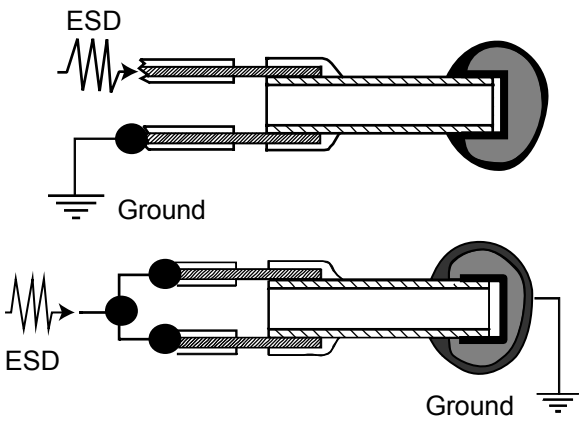

Figure 7. Illustration of the two basic ESD test configurations used in this study.

In the second series of tests, the discharge current is typically passed from the bridgewire through the pyrotechnic composition to ground, as illustrated in Figure 7 (bottom configuration). However, the test results can at times be difficult to interpret because they are highly dependent on the nature of the outer coating. All commercial matches have a protective coating that covers the pyrotechnic composition. This coating strengthens the match head, limits physical dam-

age during normal handling, and, if the composition is water sensitive, offers protection of the match head from moisture. However, an important characteristic of a non-conductive coating is that it can act as an electrical insulator to prevent accidental ignition by an electrostatic discharge through the composition. Unfortunately, imperfections in the coating seem to occur frequently, whether such imperfections are created at the time of manufacture or as a result of abrasion or crushing during rough handling. The effect is that such imperfections can greatly increase the sensitiveness of the match to electrostatic discharge through the composition.[3] Thus, before the test matches were subjected to this electrostatic discharge test, the integrity of the coatings was inspected.

An instrument designed to make high resistance measurements was used to evaluate the resistance from the coating to the bridgewire. In this analysis, the leg wires of the electric match are tied to one terminal of the instrument and a test probe is connected to the other terminal. The test probe applies up to 200 volts (but with limited current) to help induce a dielectric breakdown at the match surface as the probe is moved over the match tip to find points of low resistance. A good protective coating with no defects was generally found to provide more than 500 megohms (MΩ) of resistance. Some matches, specifically those with surface defects, register much lower surface resistance values. For Batch No. 1 test matches, which were coated with only one dip in vinyl lacquer, the surface resistance values varied greatly, measuring from less than 1 MΩ to approximately 200 MΩ. The consequence of the poor coating was demonstrated by subjecting these same matches to 18 mJ of electrostatic discharge energy through the coating; out of 10 matches tested, 9 ignited. Compared to some of the commercially produced matches, the Batch No. 1 matches faired poorly.[3] Gaining insight from these test results, Batch Nos. 2 and 3 matches were coated with four dips of vinyl instead of one, with the hope of covering any imperfections, such as tiny bubbles or cracks. The surface resistance values of 10 test matches from Batch No. 2 yielded only one match with 400 MΩ resistance, with the remainder registering 500 MΩ. For Batch No. 3, all were greater than 500 MΩ, which was the limit of the testing device. Undoubtedly the additional coats improved the surface resistance values. Out of 10 Batch No. 2 matches that were subjected to 18 mJ of electrostatic energy, 3 ignited; for Batch No. 3, only 1 match out of 10 ignited. For Batch No. 3, an additional 10 matches were subjected to 180 mJ of electrical discharge energy, and again only one ignited. While these results are positive, they do demonstrate that the matches are not entirely free of surface defects. An inspection using light microscopy indeed revealed the occasional presence of tiny bubbles in the vinyl coating.

Because it cannot be assumed that the electric match coatings will be in sufficiently good condition to completely protect the matches from discharges through the composition, the second type of ESD test was performed on matches that had intentional coating damage inflicted upon them. In this way, the test would be a measure of the ESD sensitiveness of the electric match composition only and not the degree of protection afforded by the coating. In this test, a portion of the outer coating of the electric match was removed using emery paper before they were subjected to the electrostatic discharges. Similar to the first test described above, the matches are exposed to increasing increments of discharge energy until initiation is observed. Using the Bruceton method, the discharge energy is raised or lowered for a series of 20 matches. From these results, an approximate 50% ignition energy value is obtained (i.e., the energy that would initiate 50% of the matches tested). Only Batch No. 1 matches were tested, which yielded an ESD value of 0.7 mJ, which is very low, but not quite as bad as the worst of the commonly used matches.[3] This is not surprising to the authors, as the aluminum–molybdenum trioxide MIC thermite has been previously demonstrated to be ultra-sensitive to spark initiation.[15] Attempts to reduce the spark sensitivity of MICs by using fluorocarbon coatings have produced positive results, but how such coatings may affect other performance and sensitivity parameters have yet to be investigated.

Firing Current Tests

The preferred electric match is one where its sensitiveness to friction, impact and other stimuli are low, while leaving the match with a recommended firing current that is less than 1 am-

pere. This value is not arbitrary, but rather a performance criterion that has been shaped by the electrical firing equipment in use by the pyrotechnic industry. However, the recommended firing current of commercially available matches falls into two groups.[4] One group, which consists of the electric matches most sensitive to accidental ignition by all causes, has a range of recommended firing currents between 0.5 and 1.0 ampere. The second group, with recommended firing currents of 2.0 to 3.5 amperes, is much less sensitive to accidental ignition. That is to say, the least sensitive matches are also the most difficult to ignite intentionally. What would be ideal, and what was hoped for with the MIC electric matches, is that they would combine general low sensitiveness to accidental ignition and yet have a firing current below 1 ampere (i.e., similar to those in the most sensitive group). Table 2 lists the no-fire, all-fire and recommended firing currents for Batch Nos. 2 and 3. These values are only estimates, since the number of electric matches made and tested was not sufficient to develop very accurate firing current values. The two values listed as recommended firing current are for firing individual matches (1.5 times the approximate all-fire current) and matches in series (2 times the approximate all-fire current). Because the matches of Batch No. 1 had relatively heavy gauge (large diameter) bridgewire, with resistance values around 0.1 ohms, they were deemed not suitable for current testing. For the prototype MIC electric matches, it appears that the firing current needed for ignition lies somewhere between those recommended for the sensitive and insensitive groups of commercially produced electric matches. It appears that less current was needed for Batch No. 3 matches (all-fire current of 0.70 ampere), which contained the most reactive T40 nanoaluminum. Batch No. 2 matches, having a primary composition composed entirely of the lesser reactive 132-nm aluminum, required a slightly higher current (all-fire current of 0.90 ampere).

A potential problem was discovered during the performance of the current-firing tests. It appears that the matches occasionally become non-ignitable when moderate currents, somewhat less than the no-fire current, are first passed through the bridgewire.[16] Thereafter, increasing the current only causes the bridgewire to fuse without initiating the composition. This occurred most often with those matches containing the less reactive 132-nm aluminum. It is speculated that the hot bridgewire, while not sufficiently hot to initiate the composition, is hot enough to decompose some of the material around the bridgewire, which creates a gap around it, thus thermally decoupling the wire from the remaining composition. This problem could be attributed to the decomposition of the nitrocellulose binder in the primary formulation. Future work may investigate the effect of binders on the reactivities of MIC thermites. It should be noted that some of the most commonly used electric matches also have a similar *fuse but no fire* problem when they are subjected to gradually increasing firing current.

Additional Discussion

There is concern that matches that contain nanoaluminum may not have good long-term storage, since moisture and atmospheric oxygen can oxidize the aluminum and render the composition useless. Such aluminum has extremely high-surface area and special care must be afforded to its storage, especially in humid environments. However, two simple and severe tests demonstrated that the vinyl coating used on the prototype matches appears to serve as an excellent barrier to moisture. In one test, five test matches were submerged in a container of water for 1 week before they were removed and test fired. All of the matches ignited properly. In the

Table 2. Estimates of the Likely No-Fire, All-Fire and Recommended Firing Currents for Batch Nos. 2 and 3 Prototype Electric Matches.

Batch No.	Resistance (Ω)		Current (Ampere)		
	Average	Range	No-Fire	All-Fire	Recommended
2	0.9	0.8–1.0	0.45	0.90	1.4 / 1.8
3	0.9	0.8–1.0	0.35	0.70	1.1 / 1.4

second test, two matches were exposed to steam by suspending them over boiling water for 14 hours. Again, the matches fired readily despite the vinyl coating taking on a cloudy and wrinkled appearance.

While a secondary formulation with good ignitability characteristics (aluminum and potassium perchlorate mixture) was employed for these prototype electric matches, more difficult-to-ignite (and generally less sensitive) secondary formulations could be used instead. In one example, matches were prepared with a T132 aluminum and molybdenum trioxide primary composition, followed by a secondary composition of aluminum powder alone. In both compositions about 10 percent of nitrocellulose was used as a binder. This aluminum had a broad particle distribution that centered at 200 nm but contained particles of up to 1 micron in diameter. Igniting this match produced an entirely unique effect; a half dozen sparks were thrown to a distance of 6 feet and burned white hot for approximately 2 seconds. It is thought that the aluminum burned slowly because it was dispersed as large fragments whose burn rate was limited by the availability of atmospheric oxygen. It would seem that such matches, with pure aluminum as the secondary component, would be less sensitive to accidental ignition from stimuli such as friction and impact.

Insofar as the aluminum–molybdenum trioxide MIC thermite appears to have functioned well in our feasibility study, there is no doubt that some improvements could be made. Only one thermite pair was investigated for this study, but scores of other thermites exist, as well as intermetallic reactions. It may very well be that an altogether different primary composition can be employed with better results. Fischer and Grubelich[17] produced an extensive compilation of these reactions along with their respective energy output. In addition to thermites and intermetallic reactions, simple oxidant–fuel combinations could be used. Recently, potassium perchlorate has been produced as nanoscale particles with the hope of having enhanced reactivity.[18] Such materials and their use in electric matches in primary compositions have yet to be investigated.

Conclusion

The utility of a nanoscale aluminum–molybdenum trioxide thermite as an initiating composition for electric matches was examined. These nanoscale reactants, otherwise known as Metastable Intermolecular Composite (MIC) materials, were demonstrated to be sufficiently sensitive for electric match use. The estimated recommended firing current for the MIC matches lies approximately between those of the least and most sensitive matches that are commercially available. Best results for minimum firing currents were achieved for matches with the most reactive aluminum (i.e., 40-nm particle distribution). In addition, the sensitiveness of these test matches was measured and compared to commercial electric matches. The prototype matches faired very well in impact, friction and thermal stability tests, equal or better than the most commonly used matches. The same matches were on a par with the most commonly used commercial matches in electrostatic discharge tests, both through the bridgewire and through the composition. Improvements in the manufacture of the protective outer coating should alleviate much of the electrostatic discharge sensitivity. In addition, a myriad of yet uninvestigated nanoscale thermites, reactants, or intermetallic pairs may prove more useful as electric match compositions.

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Characterization of Pyrotechnic Reaction Residue Particles by SEM / EDS

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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). In recent years, this same methodology is beginning to find use in detecting and characterizing pyrotechnic reaction residue particles (PRRP) whether produced by explosion or burning. This is accomplished by collecting particulate samples from a surface in the immediate area of the pyrotechnic reaction. Suspect PRRP are identified by their morphology (typically 1 to 20 micron spheroidal particles) using a SEM and then analyzed for the elements they contain using X-ray EDS. This can help to identify the general type of pyrotechnic composition involved. Further, more extensive laboratory comparisons can be made using various known pyrotechnic formulations.

Keywords: pyrotechnic reaction residue particle, PRRP, gunshot residue, GSR, scanning electron microscopy, SEM, energy dispersive spectroscopy, EDS, morphology, X-ray elemental analysis

Introduction

The combined use of scanning electron microscopy (SEM) and X-ray energy dispersive spectroscopy (EDS) for use in the detection of 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 locate particles with the correct morphology and X-ray EDS to determine the elemental constituents of those particles. The sought after GSR particles typically have a morphology that is nearly spherical in shape, range in the size from approximately 0.5 to 5 microns, and principally originate from the primer composition. Accordingly, 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.[2,3]

Pyrotechnic materials are mixtures of chemical elements and compounds that are capable of undergoing self contained and self sustained exothermic reactions, for the production of heat, light, gas, smoke or sound.[4] Black (gun) Powder, fireworks compositions, safety match composition, and solid rocket propellants are all examples of pyrotechnic materials. In the process of burning or exploding, pyrotechnic materials produce residues, much of which have physical characteristics similar to GSR and can be detected and analyzed using much the same methodology. The requirement for both the correct morphology and the correct elemental composition within an individual GSR particle provides high specificity, and this same high degree of specificity also applies to the identification of pyrotechnic reaction residue particles (PRRP). However, there are three important differences. First, the chemical elements present in PRRP are mostly different and often more varied than those most commonly found in GSR. Second, many of the elements that are present in pyrotechnic residues are also found in other (non-pyrotechnic) materials. Third, the quantity of PRRP produced during an event is generally

several orders of magnitude greater than that for GSR.

Although using the combination of SEM / EDS is well established from decades of use in GSR analysis, and although the same methodology applies to the detection and analysis of PRRP, relatively little information regarding its use for PRRP analysis has appeared in the literature. Most of the articles are recent and in the context of PRRP that may be found to meet the criteria of GSR.[5–9] The primary exceptions known to the authors are: an article produced at the Forensic Explosives Laboratory in the United Kingdom;[10] three earlier introductory articles by the authors of this article, written for researchers with varying degrees of knowledge of pyrotechnics, GSR analysis and SEM / EDS techniques;[11–13] and a compilation of data on the PRRP produced by consumer fireworks.[14] The scarcity of published information about PRRP analysis is unfortunate, because for those occasional cases potentially involving pyrotechnic residues, this can be an especially useful investigative tool about which too few forensic analysts are aware.

SEM / EDS Equipment Used

Most of what is described in the remainder of this article is independent of the type of instrument used. However, it may be useful to describe the instrument most often used by the authors. The SEM is a manually operated AMRAY 1000, recently remanufactured by E. Fjeld Co.[15] For this work, the instrument is most often used with an accelerating potential of 20 kV and operated in the secondary electron mode. The instrument provides software driven digital imaging. The X-ray spectrometer is energy dispersive, using a Kevex Si(Li) detector[16] (with a beryllium window) in conjunction with an American Nuclear System[17] model MCA 4000 multichannel analyzer using their Quantum-X software (version 03.80.20). Most typically, samples are collected on conductive carbon dots and are not carbon or sputter coated. (However, to improve the image quality of some of the micrographs in this article, some specimens were lightly sputter coated with gold.) Finally, it should be noted that additional and more detailed information on the techniques used by the authors in PRRP collection and analysis will be included in a subsequent article.

In the spectra reproduced for this article, the vertical scales were normalized such that the largest X-ray peak in each spectrum has the same, full-scale height. 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. Similarly, the portion of the spectrum below approximately 0.5 keV was not included. This was done to more clearly display the spectral regions of interest for this article.

Pyrotechnic Reaction Residue Particles (PRRP)

Morphology

In essentially every case, pyrotechnic reactions produce sufficient thermal energy to produce molten reaction products. Further, in the vast majority of cases, some combination of permanent gases and temporarily vaporized reaction products are also generated. Assuming the pyrotechnic reaction is somewhat vigorous, the permanent and temporary gases act to disperse the molten and condensing reaction products as relatively small particles. The size of these residue particles can vary from more than a millimeter down to considerably less than one micron, with those in the range from about 1 to 20 microns most often chosen for analysis. 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 mostly relatively small particles (smoke), whereas relatively mild burning tends to produce a wider particle-size distribution, including many much larger particles. Surface tension causes those PRRP that were molten while airborne to become spherical (or at least spheroidal) in shape. The collection of electron micrographs in Figure 1 demonstrates the appearance of some PRRP. In this case, the particles are in the range of approximately 5 to 20 microns in diameter.

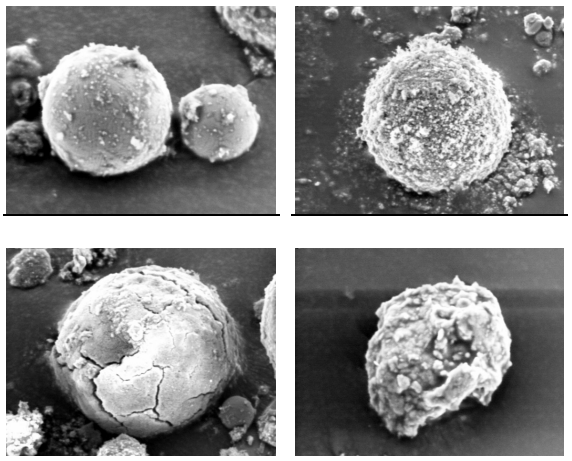

Figure 1. A range of typical 5 to 20 micron spheroidal pyrotechnic reaction residue particles (PRRP).

In examining GSR, it is apparently somewhat common to find multiple particles having agglomerated into grape-like clusters.[18] In the authors' experience, except for agglomerations of the type seen in Figure 1 (tiny particles collecting on the surface of larger ones, and poorly formed composites as the lower right image), such orderly agglomerations have not been observed for PRRP.

Although the fraction of PRRP to non-PRRP is much higher than is found when doing GSR work, often it is still quite low. Accordingly, as with GSR, it is appropriate to use morphology as an aid in selecting particles for further analysis. (This subject is discussed in somewhat greater detail in reference 11.) Although not specifically discussed in this article, note that PRRP can fail to be deposited and can be lost or transferred for many of the same reasons and in much the same way as with GSR particles.

Before leaving the subject of PRRP morphology, it is important to mention that, while in essentially every instance some spherical particles will be produced during pyrotechnic reactions, it is possible that much of the pyrotechnic residue produced will collect as a once molten slag. This is particularly true for slow burning compositions, compositions that do not form gaseous reaction products, and especially when those reactions occur within an unexploded container of some sort. (To help emphasize that not all pyrotechnic reaction residues will be in the form of particles, this article has adopted the formalism of referring to them as pyrotechnic reaction residue *particles* (PRRP) a sub-category of the total pyrotechnic reaction residues produced. In cases where pyrotechnic reaction slag is present, collecting and analyzing that slag using conventional chemistry may provide the best information about the nature of the unreacted pyrotechnic composition. However, even in such cases, the collection and analysis of PRRP can aid in identifying items and persons present in the immediate area at the time of the incident. Further, while beyond the scope of this article, a careful analysis of the distribution of such PRRP may allow one to determine details of the nature and course of an incident that are not available using other means.[19]

X-ray Signatures

Table 1 is a list of chemical elements somewhat commonly found in pyrotechnic compositions. Included in the table is an attempt to estimate the relative overall frequency of each chemical element's presence in civilian and/or military compositions. 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. Note that while lead, barium and antimony compounds are used in pyrotechnics, their use is not particularly common and only very rarely, if ever, are all three present in the same pyrotechnic composition.[5,9] Further, even when some combination of lead, barium and antimony are present in PRRP, typically much lower atomic number elements predominate in those PRRP. Accordingly, unlike when working with GSR particles, one cannot rely on there being significant backscatter electron brightness contrasts of PRRP to facilitate locating them. For this reason (and the relatively low sensitiveness to backscattered electrons of the instrument used by the authors) most commonly the instrument is operated in the secondary electron mode.

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

Element[a]	F/P[b]	Element[a]	F/P[b]
Sodium	1	Manganese	3
Magnesium	1	Iron	2
Aluminum	1	Copper	1
Silicon	2	Zinc	3
Phosphorous	3	Strontium	1
Sulfur	1	Zirconium	2
Chlorine	1	Antimony	2
Potassium	1	Barium	1
Calcium	3	Lead	2
Titanium	2	Bismuth	3
Chromium	3		

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

b) F/P means the "frequency of presence" of this element in pyrotechnic compositions. Rankings are based on the authors' experience and a large collection of pyrotechnic reference texts. The 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.

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 expressed in the solid residues to the same degree that they were in the unreacted composition. For example, permanent gases produced in the reaction will be lost. To the contrary, in a few cases, minor components may become concentrated in PRRP, because of their separation from other components as a result of the pyrotechnic reaction.[20]

In Figure 2, the three upper X-ray spectra (1 to 3) are from individual particles in an unreacted firework flash powder with the formulation: 60% potassium perchlorate, 30% magnesium-aluminum alloy 50:50 (commonly called magnalium), and 10% sulfur. Spectrum 4 is from a *gross* sample of the unreacted flash powder, collected such that the X-rays originate from a large collection of individual particles. This is intended to produce a spectrum that is somewhat representative of the average composition of the unreacted flash powder. (Through the use of the term "gross" rather then "bulk" it is hoped to avoid implying a high level of accuracy in the element ratios of the sample.) X-ray spectrum 5 is typical of those produced by PRRP in the range of 5 to 20 microns resulting from this flash powder composition. In spectra 4 and 5, note the

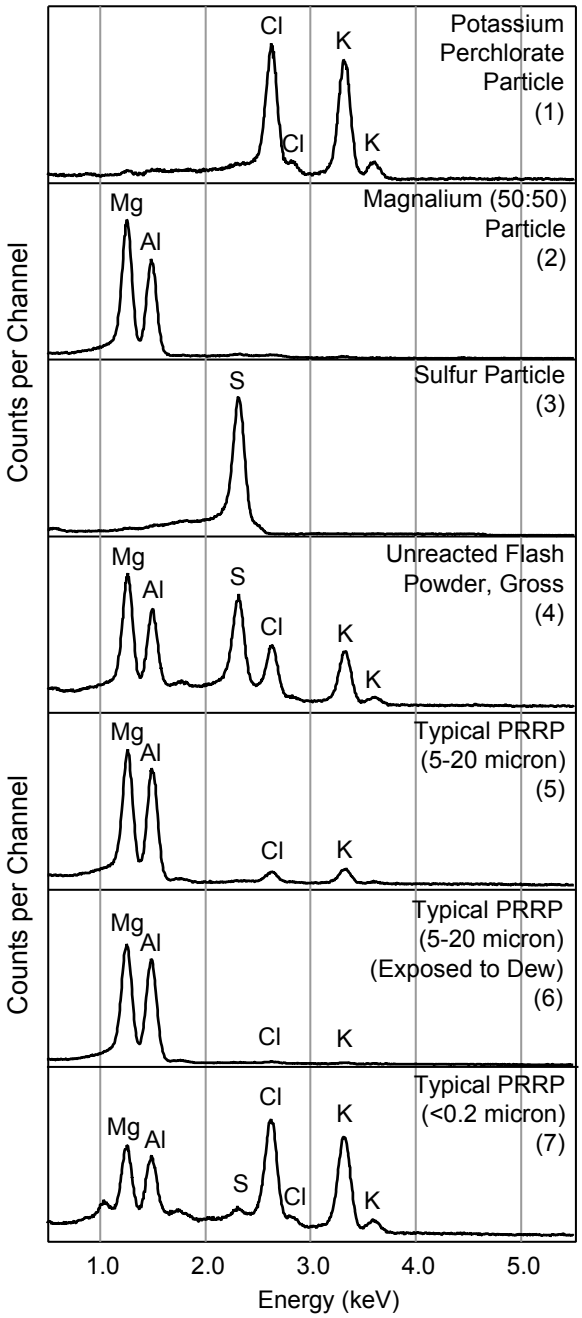

Figure 2. X-ray spectra associated with a pyrotechnic flash powder.

difference in the sulfur peaks; while quite prominent in the unreacted gross spectrum (4), it is missing from the typical PRRP spectrum (5). Almost certainly, this is the result of the sulfur reacting to form sulfur dioxide gas, which does not condense to become part of the PRRP. (It should not be assumed that there will always be similar reductions in the presence of sulfur peaks for other pyrotechnic compositions. In some cases, sulfur reacts to form sulfates and sulfides that remain in the residues. A prime example of where sulfur persists to some extent in PRRP is in the case of Black Powder.)

The reduction of the potassium and chlorine peaks between spectra 4 and 5 is a little more complicated to explain, but it demonstrates some of the thinking needed to properly interpret PRRP results. In this case, the reduction is the result of differences in the physical properties of the condensing reaction products. A somewhat simplified chemical equation for the pyrotechnic reaction of this flash powder is

$$KClO_4 + Mg/Al + S + O_2(air) \rightarrow KCl + MgO + Al_2O_3 + SO_2$$

Table 2 lists the melting and boiling points of the products of this reaction. Based on thermochemical modeling calculations, all of these reaction products will initially be vaporized at the completion of the reaction.[21] As the vapor cloud expands after the explosion, it quickly cools and the metal oxides condense, then solidify. Because of potassium chloride's lower boiling point, the metal oxides solidify before any of the potassium chloride can condense. As a result, the potassium chloride associated with the metal oxide particles is found to have only been deposited on the surface of the metal oxide PRRP. This is readily confirmed by exposing the particles to moisture, which dissolves the highly soluble potassium chloride from the surfaces, to leave the insoluble metal oxide cores. The ease and extent to which moisture acts to remove potassium chloride can be seen by examining spectra 5 and 6 in Figure 2. The difference between these spectra is that the particle in spectrum 6 has been exposed to moderate dew, which was sufficient to wash essentially all of the potassium chloride from the PRRP.

Table 2. Flash Powder Reaction Products [22,23]

Reaction Product	Temperature (°C)	
	Melting	Boiling
KCl	771	1478[a]
MgO[b]	2832	3260
Al_2O_3[b]	2054	3528
SO_2	–73	–10
K_2SO_4[c]	1069	1689

a) Note that while KCl has a reported melting point, its vaporization is nonetheless characterized in some reference texts as subliming rather than boiling.[22]

b) For simplicity, MgO and Al_2O_3 are listed as the reaction products; however, analysis by X-ray diffraction indicates that some of the crystallized reaction product is actually $MgAl_2O_4$, which has a melting point of 2135°C.[22]

c) K_2SO_4 is a potential reaction product that might be formed and collect with KCl in the smaller PRRP and may account for the weak sulfur peak in spectrum 7.

Another result of the potassium chloride condensing relatively late in the cooling process explains the reduction of potassium and chlorine peaks in spectrum 5 as compared with spectrum 4 in Figure 2. It is reasoned that, because the larger PRRP tend to remain hot longer, the potassium chloride is predominantly found to be associated with the smallest particles. This can readily be seen in a comparison of spectra 5 and 7 in Figure 2, where spectrum 7 is typical of particles that are less than 0.2 microns in diameter. The small sulfur peak seen in spectrum 7 is thought to be contributed by the conductive carbon dot used to secure the sample. The less than 0.2 micron particles are sufficiently tiny so as to allow the electron beam to stimulate X-ray emissions from the underlying carbon dot (which has previously been found to produce a weak sulfur peak). However, it must be acknowledged that it is possible that a small fraction of sulfur in the pyrotechnic reaction was oxidized to potassium sulfate, and because of its comparatively low boiling point, it also became concentrated in the smaller PRRP.

In addition to the variability that can exist in the chemistry of PRRP as a function of their size, there are other sources of systematic and random variability. In some cases, there seems

to be relatively small systematic differences in the chemistry (relative quantity of different reaction products) as a function of distance from the pyrotechnic reaction. These changes generally are on the order of 10 to 20 percent and are thought to reflect such things as the reduction in temperature within the cloud of condensing reaction products that must occur as the distance from the initial reaction site increases. However, these systematic variations are made more difficult to observe because of rather large random variations in PRRP chemistry due to the lack of complete chemical equilibrium in the reactions occurring in the expanding cloud of reaction products. For example, for the flash powder example discussed above, the one sigma coefficient of variation in the ratio of magnesium to aluminum peaks is approximately 20 percent. (Recall that the magnesium and aluminum is present in the pyrotechnic composition as an alloy and not as individual magnesium and aluminum particles. Accordingly, it might have been expected that their ratio in PRRP would be nearly constant.) While not an area that has been well studied, it seems apparent that the processes at work in the condensing cloud of pyrotechnic residues are such that a large degree of variability from one PRRP to the next must be expected. However, to the contrary, the distribution of elements across the surface of individual PRRP seems to be quite uniform. (Unfortunately, a more complete discussion of these phenomena is beyond the scope of the present article.)

Particle Identification

It is not intended that the information included in this section be all inclusive, especially in regard to non-PRRP. There is a vast amount of that information available from many different sources (a few of which are referenced below). Only enough material has been included to make this introductory article reasonably complete.

Pyrotechnic Reaction Residue Particles (PRRP)

Sometimes the presence of pyrotechnic residue is so abundant that it is clearly visible as whitish, grayish or blackish material on the surface of items exposed during the incident. In that case, samples taken from those locations will contain a high proportion of PRRP. This combined with the relatively small number of non-PRRP that fit the morphology criteria for residues, often allows the tentative identification of residue particles based primarily on morphology and statistical considerations alone. For example, consider the case of examining a sample collected from such a PRRP rich item. Of the first 50 suspect particles selected (because they meet the PRRP morphology requirements), suppose that 45 of these have elemental signatures consistent with being of pyrotechnic origin and from the same source. In this case, based on probability alone, it is quite likely that the 45 particles are from the pyrotechnic event being investigated. (One's level of confidence increases if the X-ray elemental signature for those 45 particles is not found to be associated with any background source.)

More commonly, the exposure to pyrotechnic residues is more limited, either in the duration of exposure, by the distance from the event, or both. In addition, there are all of the potential difficulties associated with the recovery of GSR. Further, 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 upon sampling. In these cases, gross statistical considerations and general pyrotechnic knowledge will not be sufficient to produce results with a high confidence level. In such cases, and to generally increase one's confidence in the identification of suspect particles, background samples need to be taken and analyzed, and other possible sources for the suspect PRRP need to be considered. These background samples can come from at least three different sources. They 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. (How far away is sufficient, will depend on things such a the size and explosivity of the event.) Background samples can be taken of the soil (dirt) in the local area that is thought to be reasonably free of the pyrotechnic residues of interest. Finally, if necessary, background samples can also be taken from the primary items being sampled for PRRP. Although not ideal, in that case, an examination of angular particles

that clearly appear to be non-pyrotechnic in origin can be useful in establishing the elemental signatures of non-PRRP. Any (all) of these various background samples are useful in comparing with the suspect PRRP.

Accordingly PRRP can be identified through the combination of spherical morphology, particle size, and an elemental signature that is both consistent with being of pyrotechnic origin and substantially absent in background samples. Typically, it will not be possible to establish the identity and origin of each particle analyzed and these must be characterized as being "indeterminate". However, in most cases the sheer number of PRRP produced is so great (generally at least a thousand times more than for GSR) that there is no need to positively characterize each suspect particle. Further, there is no need for the search for PRRP to be exhaustive. Rather a statistical approach can be taken, in which analysis continues only until the degree of certitude reaches the level needed.

Geologic Particles

For the most part, those non-PRRP of geologic origin, such as comprising the inorganic components of soil, can be eliminated from consideration based on their distinct non-spheroidal morphology. In addition, those few geologic particles that appear roughly spheroidal can almost always be eliminated based on their X-ray signatures. However, to someone without a geochemistry and pyrotechnic chemistry background, this might not be readily apparent, especially after considering that, of the ten most abundant crustal elements,[24] all eight of those with atomic numbers from sodium and above also appear in the list of elements potentially present in pyrotechnic compositions.

A great aid in discriminating between geologic and PRRP is knowledge of the likely elemental signatures for both types of particles. For example, for many common EDS systems, the most abundant geologic element that can be detected is silicon, and the most common minerals are one or another form of quartz (silicon dioxide) and various silicates.[25a] Accordingly, it is not uncommon to find particles that produce essentially only or primarily silicon X-rays. Further, it is known in pyrotechnic compositions that: 1) silicon is not one of the more common elements found; 2) silicon is primarily used in military formulations and in safety matches (as powdered glass); 3) silicon tends to be only used in the igniter portion of a device, which is generally only a small portion of the total amount of pyrotechnic composition; and 4) silicon is essentially always used in combination with other readily detectable elements that are present in substantial quantities. Thus, when a particle is examined and found to exhibit only or primarily silicon X-rays, even when it has a morphology roughly consistent with PRRP, one can be virtually certain that it is of non-pyrotechnic origin, especially if particles producing similar X-ray spectra have also been found in background samples. (Note that silicates, as clay, in the form of plugs for tubes are commonly used in some fireworks.) An argument similar to that made for particles producing primarily silicon X-rays can be made for particles exhibiting primarily calcium X-rays, which may be one or another geologic form of calcium carbonate and other minerals.[25b]

Geologic particles producing combinations of X-rays are a little more problematic, but most can also be identified with a high degree of confidence. For example, feldspar refers to a group of minerals making up about 60% of the Earth's crust.[25c] Most commonly feldspars 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 PRRP. Although a little too simplistic to make it a general rule, most common geologic particles will have silicon or calcium as the most prevalent X-ray peak, whereas pyrotechnic material will generally have relatively little, if any, of these present. (For more complete information on the forensic analysis of soils using SEM / EDS, see reference 26.)

Organic Particles

Like particles of geologic origin, those that are organic in nature (whether biologic or man-made), generally do not have morphologies mistakable for PRRP. Also, similar to geologic particles, organic particles have X-ray characteristics that aid greatly in their identification. Foremost among these characteristics is their low rate of production of X-rays with energies greater

than approximately 0.6 keV. This is a result of organic particles being mostly comprised of elements with atomic numbers no higher than oxygen. Thus, while these particles still produce a Bremsstrahlung continuum, it is common for biologic particles to produce no more than about 1/3 the number of X-rays above 0.6 keV that inorganic (geologic particles and PRRP) produce.

While the use of approximate MCA dead time 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 constant conditions, there are a number of factors that can give rise to low dead-times. For example, for the very smallest particles (those significantly less than the interrogation depth of the electron beam) the count rate 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; however, effects such as these are expected and manageable. For the instrument and configuration used in this article when the dead time is less than approximately five 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 (sodium).

Another useful indicator of organic particles is that the spectrum will generally not contain any peaks of major intensity in comparison with the background (Bremsstrahlung) continuum. Usually a visual inspection of the spectrum is sufficient to reveal this; however, if desired, a quantitative measure of the peak-to-background ratio for the most prominent peak(s) in the spectrum can be produced. For the instrument and its configuration used in this article, purely organic material generally produces peak-to-background ratios less than 2. As with MCA dead times, peak-to-background ratios are not a completely reliable indicator of prevalent atomic number. When there is a mixture of several moderate to high atomic number (Z) materials in the particle, such that there are many prominent peaks in the spectrum, peak-to-background ratios are reduced. Further, sometimes particles are mixtures of organic material with other material having higher atomic number (Z) components. For example, white paper has calcium carbonate added to make it whiter and more opaque, and other organic material may similarly have inorganic material imbedded within or adhering to its surface.

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 to limit problems such as flaring or excessive contrast. Further, because the difference in Z between organic and geologic or PRRP is not very great, the image intensity contrast may not be sufficient to allow their differentiation.

Other Inorganic Particles

While the majority of other inorganic particles are clearly identifiable on the basis of their morphology, a few are not and deserve mentioning. Spheroidal particle morphologies are the norm for tiny bits of most any material that was molten while airborne. One example of this phenomenon is the particles formed during metal fabrication such as grinding (including "chop sawing") and arc or gas welding or cutting. Other examples are common fly ash and even components of an unreacted pyrotechnic composition, wherein certain milled and atomized materials are included that are spheroidal and in the same size range as PRRP. (See references 11, and 27 to 29 for more information on other sources of spheroidal non-PRRP.)

Case Example

This example comes from a case wherein an individual was burned when a pyrotechnic device (a consumer firework) was alleged to have exploded sending pieces of burning composition in his direction. Figure 3 is an electron micrograph of a small portion of one sample taken from the inside surface of the individual's clothing in the general area where the burn injury 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 4 is a collection of

the X-ray spectra, two from laboratory work plus those collected from the six particles (items) identified in Figure 3.

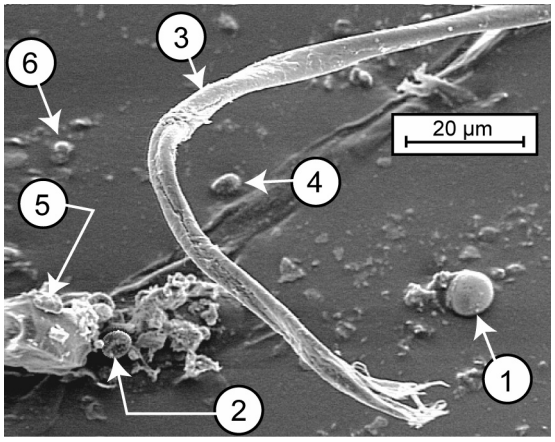

Figure 3. An electron micrograph identifying a series of particles (items) analyzed during an accident investigation. (See Table 3.)

The uppermost X-ray spectrum is the gross spectrum of one of the four different unreacted compositions taken from the type of firework suspected to have been responsible for the injury. Below that is a spectrum typical of a PRRP produced by burning this same pyrotechnic composition under laboratory conditions.

Table 3 presents the results from the analysis of the six particles identified in Figure 3 and illustrates a typical methodology used in performing an analysis of PRRP. However, the categories and classifications will often need to be adjusted for specific investigations and generally will not be formalized by the use of a table to classify the individual particles. 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 man-made) often have this appearance, while PRRP 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*.

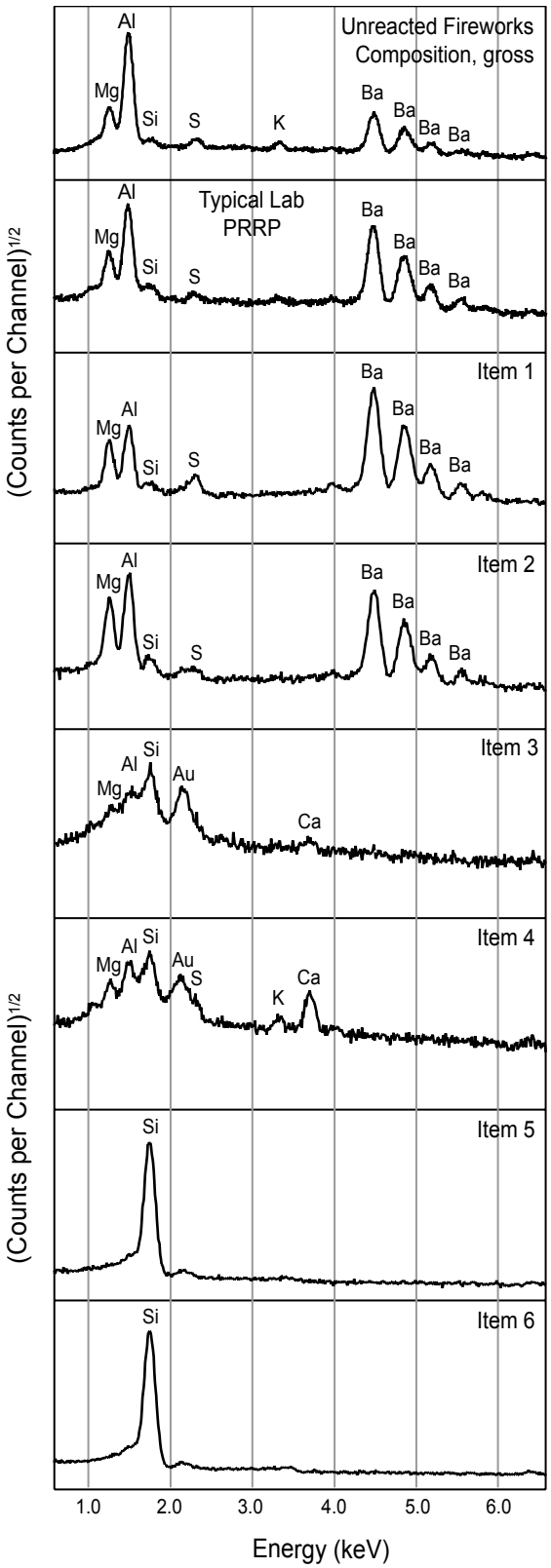

Figure 4. X-ray spectra from laboratory samples and the six particles identified in Figure 3.

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

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-PRRP
5	Non-Spheroidal	12	13.	Geologic	Geologic
6	Spheroidal	14	16.	Geologic	Geologic

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 being PRRP, which had been confirmed through the production of effectively identical (matching) PRRP in the laboratory using one of the suspect pyrotechnic compositions. Further, many more particles with the same morphology and elemental signature were found distributed on clothing in the general area where the injury occurred, specifically on both the inside and outside surfaces of remnants of the individuals outer and underclothing. Finally, no similar particles were found on background areas of clothing remote from the area of the injury. Accordingly, particles one and two are identified as PRRP.

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. The same gold X-rays were produced by all of the particles being analyzed; however, when the particle being examined produces 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 often 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-PRRP*.

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 PRRP, 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 period of 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 PRRP. As a practical matter, during an analysis it would be unusual to bother to document the nature of a high percentage of non-PRRP. Typically, only enough of these particles would be analyzed and documented such as to reasonably represent the range of different non-PRRP found. Instead, most of the time would be devoted to finding and analyzing PRRP. 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 identify and analyze PRRP in the course of investigating incidents involving pyrotechnic materials can provide information with a degree of sensitivity and specificity that is unavailable with other commonly used techniques. That is not to say these analyses are necessarily easy and without potential pitfalls. The degree of confidence in the results will vary greatly depending on things such as the elemental and physical nature of the particles, their abundance and distribution within the area of the incident, their degree of rarity in background samples, and the extent to which there are possible alternative sources or explanations.

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 incidents involving pyrotechnics. Obviously one reason for its infrequent use is that many investigations would benefit relatively little from the type of information that could be developed. However, even for those incidents where PRRP analysis would be of significant benefit, often that analysis is not performed. After speaking with several investigators, the authors have concluded the likely reason for its under use is simply that many investigators 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 forensic community.

In further support of the goal of disseminating information regarding PRRP identification and analysis, one additional article has recently been published and at least two more are planned. The already published article[19] further demonstrates the nature and utility of the information produced by considering a series of investigations of actual and staged incidents. The planned articles will present much more information about the mechanics of specimen production, collection, and their subsequent analyses, and an investigation of some of the complexities of the chemistry of pyrotechnic reactions and PRRP.

Acknowledgments

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WARNING: Serious Product Malfunction

K. L. Kosanke

In 2003 a fireworks display company experienced two serious malfunctions of a product. The items were 5-inch White Tiger Tail shells under the brand name of Flower Basket (See Figure 1). These shells are spherical in shape and at the time were thought to be solid masses of comet composition, without a shell or other component inside the comet composition. The items were received in January of 2003. Forty of the comets were fired in a display. Two of these comets exploded with great violence within their HDPE mortars as they were being fired, destroying both the mortars and the wooden racks holding the mortars. (While there were no injuries in this instance, given the apparent power of the explosions, that certainly was a possibility.)

A complicating factor was that the 5-inch Tiger Tail comet shells are thought not to have been manufactured by Flower Basket, but rather by an unidentified subcontractor. Accordingly, there is some possibility that similar malfunctioning comets may have been distributed under other brand names as well.

The cause of the problem with these tiger tail comets had not been determined at the time this article was originally published, but it was being investigated.[1] (Pending further testing, the display company experiencing the malfunctions withdrew all of this product from inventory.)

Because of the great violence of these malfunctions, there was concern that the cause of the problem may be similar to that which lead to a fatality and traumatic amputations in an accident involving 2-inch white comets in Roman candles in Australia (previously reported in *Fireworks Business*[2,3]). In that case the 2-inch comet Roman candles were found to explode powerfully enough to shatter heavy steel support tubes.

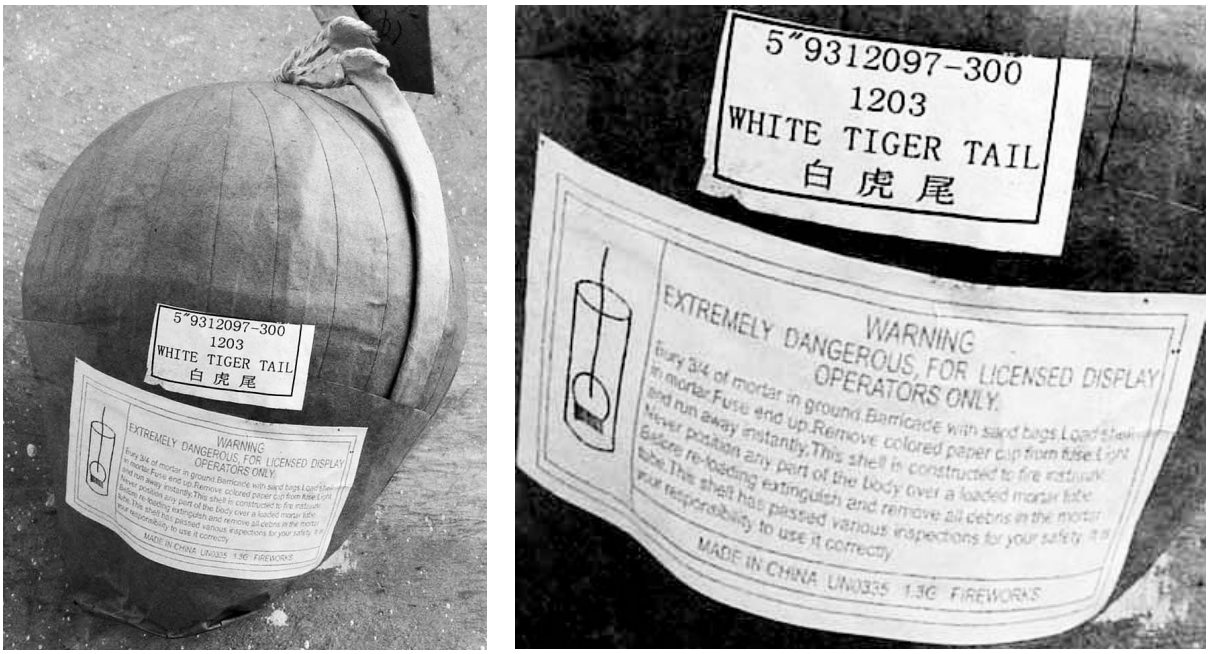

Figure 1. Photos of a 5-inch Tiger Tail comet and a close-up of its product label.

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Flowerpots and Muzzle Breaks

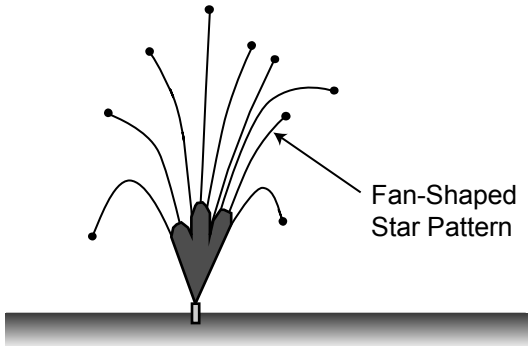
K. L. and B. J. Kosanke

Introduction

Flowerpot and *muzzle break* are descriptive terms for two types of star shell malfunctions. There can be serious safety consequences from these malfunctions, especially for manually fired displays. Some commonly held beliefs as to the cause of these malfunctions are challenged by the available data. This article summarizes some of that data and then draws inferences from that data.

A common definition for a flowerpot is:

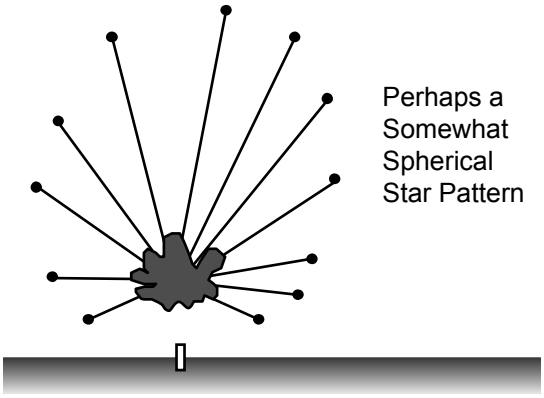
A type of aerial display shell malfunction where the shell bursts with relatively low power within a mortar. It produces an upward spray of ignited stars and other effects, as illustrated below.[1]



The odds of a star shell experiencing a flowerpot depend on many factors, but for typical shells and conditions it is probably in the range of 1 flowerpot in 200 to 500 shell firings.[2] It would seem that the likelihood of a shell experiencing a flowerpot is mostly independent of shell size. For the most part, since the power of the explosion is relatively low and the mortar often remains intact. Flowerpots represent a relatively minor hazard. A hazard that does result is from the potential for burning debris to fall to the ground in the area of the mortars, thus presenting a possibility for the unintentional ignition of other fireworks. This is a minor concern for an electrically fired display with no personnel present and where the fireworks are already loaded into mortars ready for firing. However, when personnel are present, such as for a manually fired display, especially when stores of firework shells are being reloaded, burning debris raining down is a serious safety concern. When a flowerpot occurs for a salute or large caliber star shell, there is the potential for the firing mortar to burst. In that case, the potential hazard from mortar and mortar rack fragments will be much greater.

A common definition for a muzzle break is:

A malfunctioning aerial shell which bursts just as it leaves the mortar, scattering high velocity burning stars and other material in all directions near ground level. It appears somewhat like the following illustration.[1]



The odds of a star shell experiencing a muzzle break also depend on many factors, but for typical shells and conditions it is probably in the range of 1 muzzle break per 500 to 2000 shell firings.[2] In addition, it seems that muzzle breaks are significantly more common for large

shells as compared with small shells. The hazards posed by muzzle breaks are in two areas. First are hazards arising from the blast force of the exploding aerial shell. For salutes and large shells the blast force can be sufficient to cause injury to persons in the immediate area. The blast force can also be sufficient to reposition nearby mortars, such that shells fired subsequently from those mortars could proceed in dangerous directions. Second are hazards arising from the generally wider spread of burning stars than from a flowerpot. While this poses somewhat similar problems as the burning fallout from flowerpots, the hazard is more extreme with a muzzle break. The burning components from a muzzle break will be traveling much faster in a horizontal direction, thus not allowing sufficient time to react to the threat. Another consequence of the high speed of the burning stars is that their horizontal range will be much greater.

Before a manufacturer can effectively take steps to reduce the occurrence of star shell malfunctions, it would be helpful to accurately understand the nature and cause of those malfunctions. While some may think they know the causes of flowerpots and muzzle breaks, for the most part this seems to be based on conjecture and intuition, rather than solid evidence.

Regarding flowerpots, it is often suggested that the cause is a fire leak into the shell through a small crack or tiny hole in the shell's casing. Another common explanation for flowerpots is that it is a result of *setback*, where a common definition for setback is:

The inertial response to the extreme acceleration of aerial display shells upon firing.[1]

The peak acceleration of a star shell will be approximately 1000 times the acceleration due to gravity.[3] In response to this acceleration, the contents of the shell will forcefully compress into the lower portions of the shell casing. It is possible that this forceful motion of internal pyrotechnic materials may on occasion produce sufficient frictional force to cause the ignition of the shell's contents, leading to the premature explosion of the star shell. Regarding muzzle breaks, it is often suggested that the cause is unusually fast burning (defective) time fuse. However, no published data confirms that these presumed causes for flowerpots and muzzle breaks are correct. In fact, the little published data on the subject seems to contradict these presumed causes. This article will examine the available data and suggest alternate theories more consistent with the data.

Test Data

Several years ago, in an attempt to learn more about the cause of muzzle breaks, a series of tests were conducted.[4] Subsequently, some relevant data was collected during the course of two other brief studies conducted for other purposes.[5,6] Recently some additional data was produced for use in the present study.[7,8] While the overall results of these studies are used in this article, a detailed presentation of those results and the methods used to produce them will not be repeated here.

A total of 35 measurements were made of the time taken for a range of typical spherical star shells to explode after being ignited internally using an electric match. The average values of these *burst delay times* ranged from approximately 30 milliseconds (ms) for 2.25-inch shells to 110 ms for 10-inch shells. (Note that, for all of the testing reported here, the conditions were such that the electric match fired in less than 1 ms.)

A total of 61 measurements were made of the time taken for a range of typical spherical star shells to exit their mortar after firing an electric match to ignite their lift charges. The average *mortar exit time* (the time interval between the electric match firing and the when the shell exited the mortar) was approximately 40 ms. It was observed that there was relatively little if any dependence of mortar exit time on shell size (in the range from 2.25 to 8 inches) fired from mortars of typical construction.

When interpreting the mortar exit time data, it is important to recognize that, for a significant portion of the time while the lift powder is burning and before the shell exits the mortar, there is no detectable increase in pressure inside the mortar, see Figure 1. (This is the time required for fire to spread throughout the mass of lift powder and then to have sufficiently vigorous burning of the lift charge to produce more combustion gas than can easily escape through the gap between the shell casing and mortar wall.)

This is important in the context of this article, where consideration is being given to fire leaks through small cracks or tiny holes into the interior of a star shell as it is being fired. Until there is a significant difference between the pressure in the mortar and that inside the shell, there is no driving force to cause the entrance of the burning lift gas through any small crack or tiny hole. Similarly for setback as a possible cause of flowerpots, until there is a significant rise in the pressure under a star shell, it will not begin to accelerate up the mortar, and there will be no inertial forces to potentially cause the ignition of the shell's internal contents. (For a more complete discussion of the timing of the sequence of events during typical star shell firings, see reference 6.)

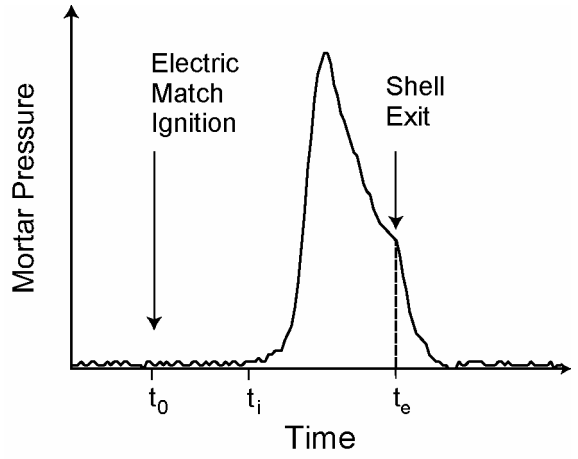


Figure 1. Mortar pressure versus time for the firing of a typical star shell, where the pressure impulse time equals the time difference between t_i and t_e.

A total of 39 measurements were made of *pressure impulse time* (the time interval between the first detectable rise in mortar pressure, t_i, and when the shell exited the mortar, t_e). In effect, only during the pressure impulse time is there a pressure differential that could force burning lift gas through any small crack or tiny hole in a shell's casing. It was found that the pressure impulse time averaged 20 ms, mostly independent of shell size.

Conclusion

After an amount of fire approximately equal that provided by an electric match has entered a star shell, the average time taken for the shell to explode (approximately 30 to 110 ms, depending on shell size) is always longer than the average time for the shell to exit the mortar once the lift pressure under the shell starts to rise (approximately 20 ms). The inescapable conclusion for such relatively small fire leaks and setback caused ignitions is that on average star shells will have left their mortars well before they have time to explode. However, there are rather large variabilities observed in individual burst delay and pressure impulse times. Thus, if a star shell's pressure impulse time is longer than average, while at the same time its burst delay time is shorter than average, it is possible that some small shells will still be inside the mortar when they explode (as flowerpots). However, larger shells, with their significantly longer burst delay times, will essentially always be well clear of the mortar before they can possibly explode from such small fire leaks or from setback. (This has been confirmed in recent studies, only some of which have been published at this time; see references 7 and 8.)

The overall results of this study are substantially inconsistent with the commonly cited causes of flowerpots. Fire leaks, approximating the fire produced by an electric match, are not expected to produce flowerpots, but rather to cause muzzle breaks. Thus one must conclude that flowerpots are rarely if ever caused by fire leaks through small cracks or tiny holes, or as a result of setback. Although not specifically investigated in the testing reported in this article, it seems certain that the time taken for a star shell to explode depends on the amount of fire leaking into it. To account for the observation that many more star shells flowerpot than muzzle break, most flowerpots must be the result of much more substantial fire leaks, up to and including the more-or-less complete failure of the shell's casing. (Note that the substantial failure of a shell's casing as a cause of many flowerpots is consistent with the empirical observation that the explosive power for many flowerpots is substantially less than would be expected for an intact shell exploding within the added confinement of a mortar. In fact, many flowerpots seem

to be not much more violent events than normal shell firings.)

In considering the cause of muzzle breaks, while the data reported here does not disprove the fast burning time fuse hypothesis, it is certain that small fire leaks and setback are also viable (and at least certainly more likely) explanations. Further, the conclusion that it is primarily larger shells that will be well clear of the mortar before they can explode as a result of small fire leaks is consistent with common experience regarding muzzle breaks.[2] This gives one added confidence that the cause of many (most) muzzle breaks is relatively small fire leaks.

Acknowledgment

The authors are grateful to L. Weinman and G. Hanson for reviewing and commenting on a draft of this article.

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An earlier version appeared in *Fireworks Business*, No. 233, 2003.

Report on the Initial Testing of Suspect Tiger Tail Comets

K. L. and B. J. Kosanke

It was previously reported that two out of forty 5-inch White Tiger Tail comet shells had explosively malfunctioned upon firing, destroying their mortars and the racks that contained them.[1] While traveling to conduct display safety training, it was arranged to visit the display company that experienced the problem with the comet shells. During that visit, the damaged mortars were inspected, photographed and sampled for pyrotechnic residues; the problem shells and some similar items were dissected, their components weighed and photographed; and fifty of the comet shells were test fired while being video taped. This article reports on that work.

The two mortars that had been damaged previously by the malfunctioning tiger tail comet shells are shown in Figure 1. The photos document that the explosions were powerful, most especially that which occurred in the second of the two mortars.

When the photograph of the suspect 5-inch White Tiger Tail comet shells was published,[1] one reader called to comment that there must have been a mistake, because the item was fairly obviously a pasted shell as opposed to being a normally constructed tiger tail comet. The astute reader was correct, at least to the extent that the construction of these so-called tiger tail comet shells was not normal. The construction of the item is illustrated in Figure 2. It was constructed somewhat similar to a star shell; however, there was a relatively small number of outer wraps over a normal pair of shell hemispheres, a hole was left where the time fuse would normally have been installed, a small amount of rice hull break powder was around the comet, and inside the shell was a relatively small cylindrical comet and the balance of the shell was filled with a large amount of cotton seeds as inert filler. As expected, based on the shell design and confirmed by the test firings, the shell explodes relatively weakly while still inside the mortar or shortly after leaving it. After the shell bursts, the comet proceeds upward, producing an ascending trail of sparks.

During daylight, a series of 50 of the 5-inch White Tiger Tail comet shells were test fired from HDPE mortars staked above ground. Most of the shells burst weakly while they appeared to still be inside the mortar (although apparently near the top) and produced no damage to the mortars. Some of the shells burst just after leaving the mortars, obviously without damaging the mortar. The exact number of shells bursting inside or outside the mortars could not be accurately determined. Because of the fire exiting the muzzle of the mortar, it was essentially impossible to determine whether they were just inside or

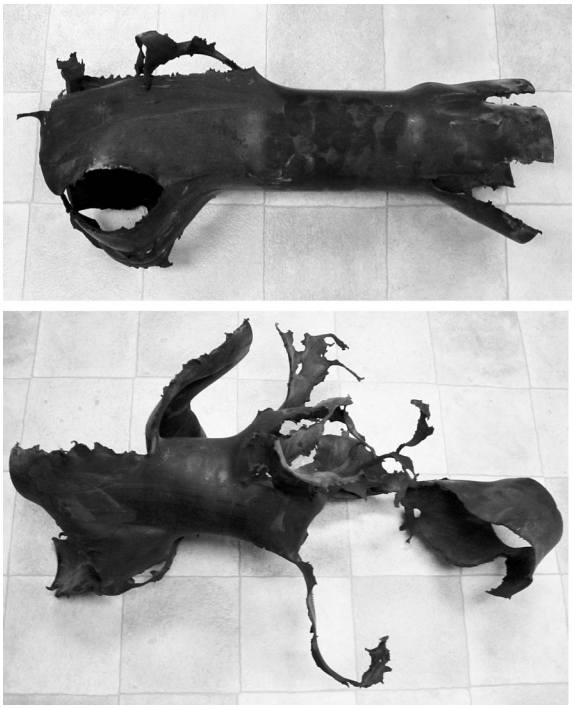

Figure 1. Photographs of the two mortars that had been damaged previously when 2 of 40 5-inch White Tiger Tail comet shells exploded within them upon firing.

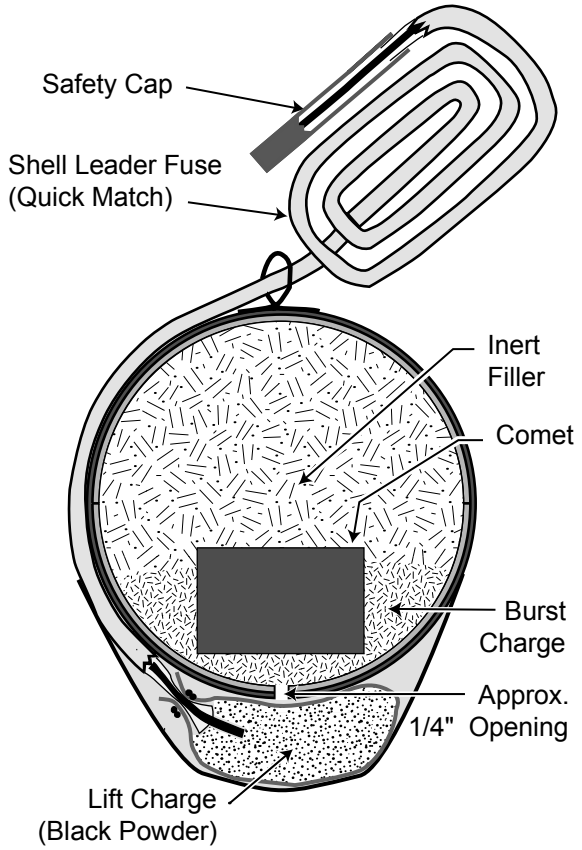

Figure 2. An illustration of the style of construction used for the "Tiger Tail" comet shells.

just outside the mortar. On three occasions, based on the sound produced, the comets themselves seemed to explode in the air above the mortars. On one of those occasions, the explosion was fairly powerful, but it did not seem to be powerful enough to have produced serious damage to a mortar. On a few occasions, based on observing the comet having fragmented into a number of pieces, it seemed that the comet may have exploded while still within the mortar, but so weakly as not to damage the mortar. (It was difficult to say whether those comets exploded weakly or if they simply broke apart because of insufficient structural strength of the comets.) The most important result of the test firings was that none of the 50 shells exploded sufficiently powerfully within their mortar when being fired to cause damage to the mortar.

Some additional work was performed in an attempt to determine the cause of the previous mortar explosions (see Figure 1). A preliminary analysis of the pyrotechnic reaction residue has been done and those initial results seem to be consistent with having been produced by the comet shells. However, at the time of writing this article, final conclusions needed to be deferred. (Further reporting on the mortar explosions was published.[2] The preliminary results in the current article were reported to help put concerns regarding the use of these suspect comet shells into better perspective.)

Normally (traditionally) tiger tails are made by forming a thick layer of comet composition on the outside of an aerial shell, which is then covered with a single loose wrap of paper. The purpose of this type construction is to produce a comet with a much greater burning surface (i.e., one producing a much more dense trail of sparks) than would be possible by simply attaching one or more comets to the outside of a shell. To that extent the so called "Tiger Tail" comets suspected of producing the powerful in-mortar explosions are not really tiger tail comets in the normal sense. To determine the manner of construction of some other tiger tail comets in stock at the

Table 1. Characteristics of Some "Tiger Tail" Comet Shells.

	Shell				Comet								
	Size		Mass			Diameter		Height		Mass		Surface Area	
Mfg. / Brand	(in.)	(mm)	(oz)	(g)	Shape	(in.)	(mm)	(in.)	(mm)	(oz)	(g)	($in.^2$)	(cm^2)
Flower	5	125	18	457	Cylindrical	1.8	45.7	1.2	30.5	2.8	79	12	77.4
Basket	4	100	9.8	249	Cylindrical	1.6	40.6	1.2	30.5	2.2	62	10	64.5
Formex	5	125	18	457	Cylindrical	2.4	61.0	1.5	38.1	6.5	184	27	174.2
Lidu	4	100	18	457	Spherical	3.6	91.4	n/a	n/a	18[(a)]	510[(a)]	39	251.6

a) Because of the lack of equipment, this comet could not be safely broken apart to determine how much of the total mass was comet and how much was from a core of some other material.

display company, those shells were also dissected. The results are summarized in the Table 1.

Of the four shells dissected, only the Lidu was constructed as normal for a tiger tail comet. Note that the surface area for the Lidu 4-inch comet is more than three times greater than that of the 5-inch Flower Basket comet shell. Given the shape and mass of the Lidu comet, it will also have a higher ballistic coefficient. Thus, all else being equal, the 4-inch Lidu comet would produce a much denser tail and would reach a greater altitude than the 5-inch Flower Basket comet.

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This article originally appeared in *Fireworks Business*, No. 234, 2003.

The Effect of Reflected Blast Waves in HDPE Mortars

K. L. Kosanke and L. T. Weinman

A recent article discussed a problem with some comet shells exploding as they were being fired, and thus seriously damaging the HDPE mortars being used.[1] Included in the article were photographs of the two mortars that had been damaged. In these photos, it was clear that, while both ends of the mortars received serious damage, the middle section of the mortars received less damage in one case and no damage in the other. This raised a question in the minds of some readers, how could a single explosion damage both ends of a mortar while leaving the middle of the mortar essentially undamaged? The purpose of this article is to address that question.

During the course of conducting initial studies of the overall suitability of HDPE pipe for use as fireworks mortars,[2-5] many explosions were caused to occur inside HDPE pipes. However, as it turned out, these explosions were all made to occur in the lower portion of the mortars and never near the top (muzzle) of the mortar. As a result, the damage was always observed to only occur in the lower portion of the test mortars. Accordingly, upon first observing a mortar damaged by a single explosion occurring near the open end, and with the resulting damage concentrated at both its ends, it was necessary to contemplate why this would happen.

When a powerful explosion occurs near the top of a mortar, the top of the HDPE mortar will be damaged by the blast as the blast wave radiates outward. However, the blast wave must also propagate down the bore of the mortar where it will be reflected upon meeting the mortar plug (at least so long as the plug remains in place). During the time that the incident and reflected blast waves overlap in the area just above the mortar plug, their pressures will add constructively to produce a greater blast pressure. Therefore, if the incident blast wave pressure is sufficient, when it adds to the pressure of the reflected blast wave, it is possible to explode the bottom of the mortar (as well as the top of the mortar) from a single explosion. This seemed simple enough, but did it really work that way in actuality? Accordingly, some testing was performed.

In the first series of tests, a starter pistol (firing blanks) was discharged into the muzzle of a 3-inch mortar, after having installed a quartz (piezoelectric) pressure sensor at various points near the bottom of the mortar. Figure 1 is a sketch of the bottom portion of the test mortar that includes the location of the lowest two positions for the pressure transducer. Pressure data was collected at four locations, 16.0, 8.0, 4.0 and 0.5 inches above the mortar plug. The data from the lowest three positions in the mortar are

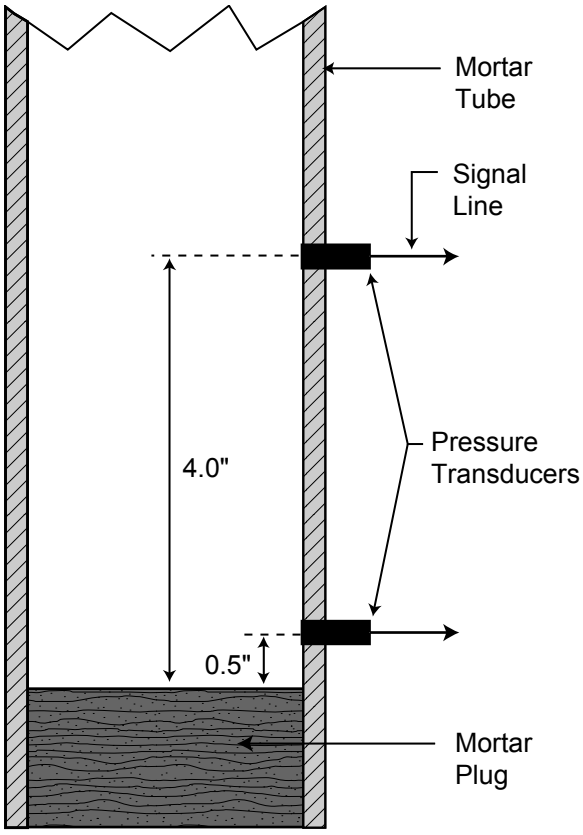

Figure 1. Sketch of the set-up for the first series of mortar tests. (Not to scale.)

shown in Figure 2. For each location, the data from four separate measurements were averaged and then smoothed for presentation, using a simple running average filter.

In the data taken at 8.0 inches above the mortar plug, the incident pressure wave is shown as black and the reflected pressure wave, with its somewhat reduced magnitude, is shown as lightly shaded. The incident and reflected waves are clearly resolved and are separated in time by approximately 1.14 ms (milliseconds). The pressure wave needed to travel a total of 16.0 inches (8 inches down to the plug and 8 inches back up to the transducer) or 1.33 feet, during the interval between the arrival times at the transducer. At the temperature in the lab, and the initial temperature of the air in the bore of the mortar, the speed of sound would have been approximately 1130 feet per second. This computes to a time interval between incident and reflected pressure waves of slightly less than 1.18 ms, or about 3 percent longer than was measured. That the pressure wave traveled slightly faster than the speed of sound is consistent with its being a weak blast wave. (This was confirmed by examining details of the shape of the pressure event as seen in the raw, non-smoothed, data.)

In the data taken at 4.0 inches above the mortar plug, the incident and reflected pressure waves are less separated in time, and have started to merge together. In the data taken at 0.5 inch above the mortar plug, the incident and reflected pressure waves are seen to have merged into one. It can be seen that the amplitude of the combined pressure wave is approximately equal to the sum of the incident and reflected waves seen in the data taken higher in the mortar. Thus it seemed clear that the theory was being borne out in practice, but how would an actual mortar react to a pressure pulse sufficiently strong to damage it?

In the next pair of tests, 2-inch HDPE mortars were subjected to explosive blasts. During the course of a fireworks display a powerful explosive blast inside a mortar might potentially originate from a premature functioning of a star shell or a salute. In these tests, the pressure events were produced using flash powder charges contained in thin-walled polyethylene bottles that were of only slightly smaller diameter than the inside diameter of the mortars. Each

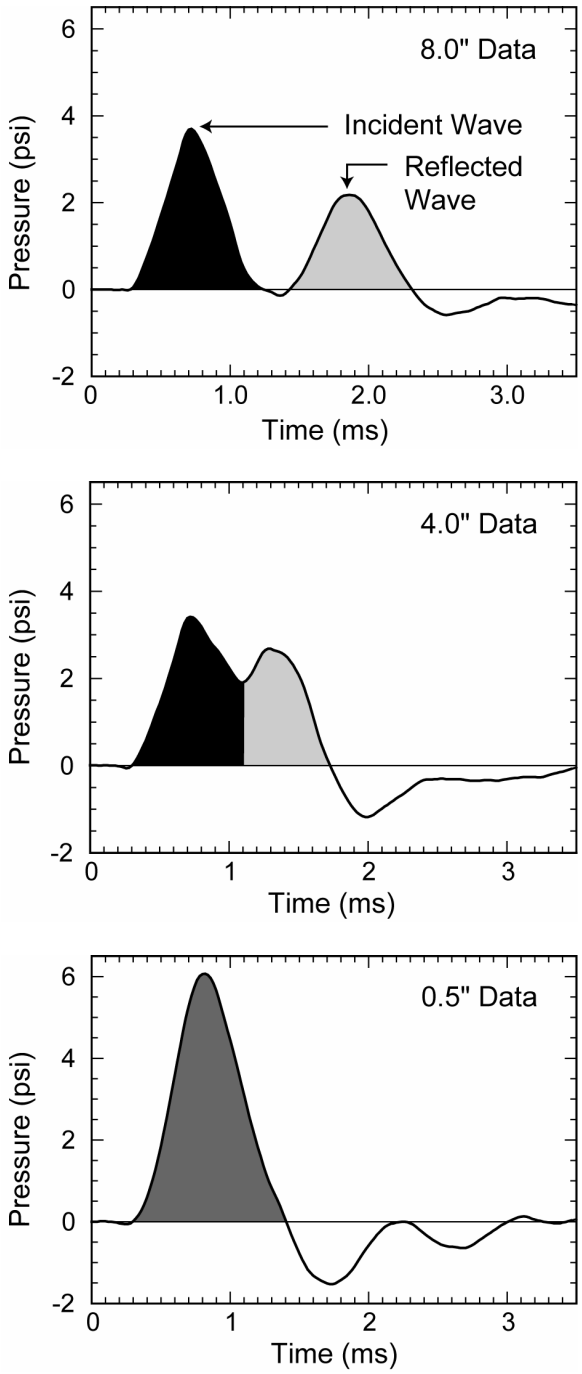

Figure 2. Internal mortar pressure data from the first series of tests.

test charge was suspended just inside the mortar near its muzzle. The results of the two tests are shown in Figure 3. In one test a charge mass of only 25 grams of flash powder was used (upper mortar in Figure 3), and in another test a charge of 50 grams was used (lower mortar in Figure 3). With the smaller flash powder charge most of the mortar is undamaged, except for its

two ends, which are damaged almost equally. In the photograph, the left end of the mortar is the muzzle of the mortar (nearest the explosive charge) and the right end is where the plug had been. With the larger explosive charge, the damage is more extreme but is still concentrated at the two ends of the mortar. Thus the reflected blast wave prediction was fully borne out in these tests.

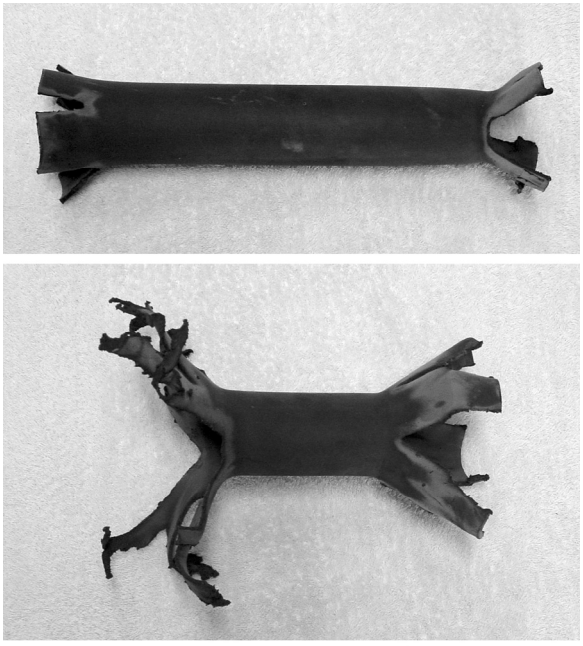

Figure 3. Photographs of the two mortars tested using small explosive charges.

Acknowledgment

The authors wish to acknowledge B. J. Kosanke for preparing the figures for this article and for her editorial comments.

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Electric Match Lead Spatters

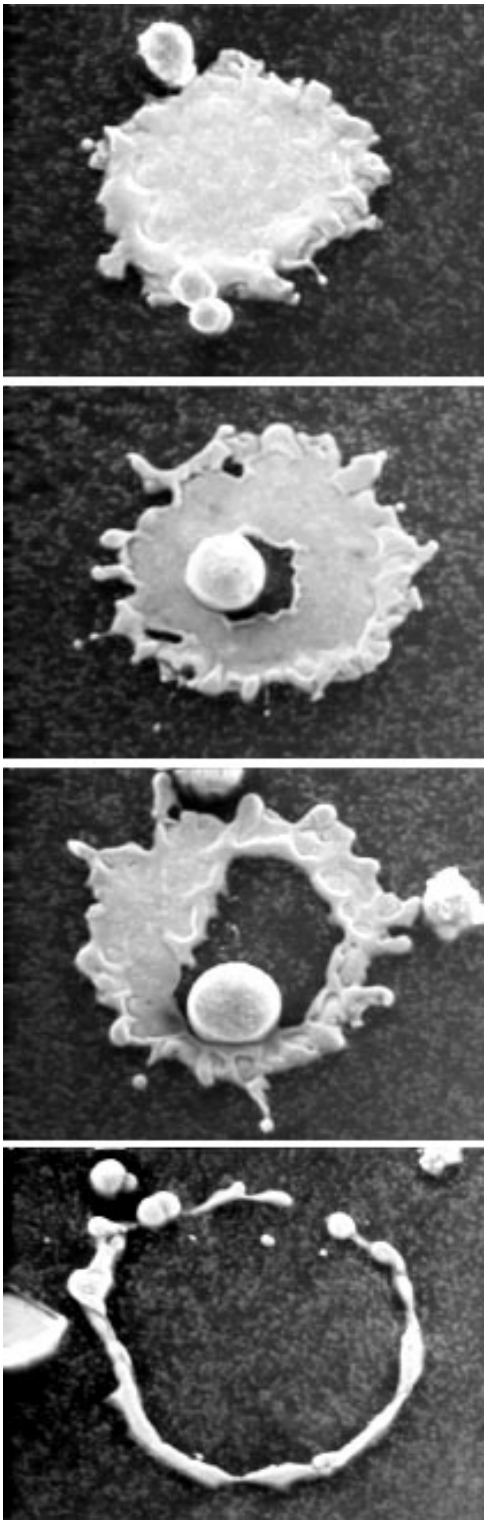
K. L. and B. J. Kosanke

A study of performance characteristics of some common electric matches had been conducted.[1] During the course of that study, a series of electron micrographs were made of the residues produced upon firing the electric matches. Those electric matches using lead mononitroresorcinate as a significant ingredient of their composition produced some interesting, albeit incredibly tiny, splatters of molten lead metal. In the thought that it might prove interesting to users of electric matches, four of these micrographs are shown in the accompanying figure.

Each of the splatters is approximately 50 micrometers (approximately 0.002 inch) in diameter. It is speculated that the primary factor for the different shapes of the splatters may be the velocity with which the particles of molten lead hit the collecting surface. It seems likely that the lowest velocity particles produce splatters without a central void spot, such as in the top micrograph of the figure.

It is thought that particles with a mid range of velocity produce a void spot that increases in diameter with increasing impact velocity, such as in the middle two micrographs. In addition, the impact of these mid velocity molten lead particles is generally associated with a tiny spherical ball of lead. This is suspected as being produced when some of the lead splashes up from the surface, with surface tension then forming the material into a spherical particle, which comes to rest again on the surface somewhere near the center of the splatter.

It is thought that the highest velocity particles may produce a ring of lead (very large void spot) as in the bottom micrograph. It was not established whether one or more spherical balls of lead was associated with these splatters that then came to rest some distance away.



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Color Values and Spectra of the Principal Emitters in Colored Flames

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ABSTRACT

The emission spectra of many of the more important emitters in pyrotechnic flames were collected. For this purpose solutions and suspensions of sodium, potassium, calcium, strontium, barium and copper salts were aspirated into a propane gas flame as the excitation source. Performing instrument corrections and using appropriate data reduction strategies allowed the isolation of the individual spectra. Among these are the monochlorides and monohydroxides of strontium, calcium, barium and copper. The CIE color coordinates of the principal emitters were calculated from the isolated spectra. In addition, a table of normalized band and line intensities was produced for each of the successfully isolated emitting species.

Keywords: flame spectra, flame color, color emitter, color coordinate, monochloride, monohydroxide, barium, calcium, copper, strontium

Introduction

The desire to produce improved flame color has been an enduring goal of pyrotechnists. However, over the last century, much of the effort in that quest has not been guided by accurate spectral information. Two pioneers in quantifying this work were T. Shimizu[1] and B. E. Douda.[2–4] Most recently, with the introduction of relatively inexpensive computer-based spectrometers,[5] hard-data—rather than subjective impressions—are being more widely used to guide developments. However, to date, the lack of relatively complete and reliable information on the spectra and CIE color coordinates of the individual colored flame emitters remains as an impediment.

Shimizu, in his textbook,[6] was probably the first to address the assignment of a series of the principal colored flame emitters to their position in the chromaticity diagram. Nevertheless he made essentially no attempt to determine the composite chromaticity values (color coordinates) for emitters having more than one narrow spectral line such as sodium. Instead he made a series of somewhat expressionistic intensity assignments for the respective lines, such as for potassium, and assignment of the bands of the monochlorides and monohalides of the alkaline earth metals and copper.

Several reference texts are available with tables of wavelengths and peak intensities for atomic and molecular visible-light emitters.[7–11] Unfortunately they are somewhat incomplete and even contradictory. The intended use of these tables seems to be primarily geared towards analytical chemistry—for identifying the probable emitting atom or molecule for a given line or band present in a spectrum. (An extensive table, compiled from some of these sources, and including the authors' current work, has been appended to this paper.) Further, very few of the reference texts include actual spectra for the various emitters, and when they do, instrumentation effects have not been removed. What is generally presented are the "raw readings" directly from the instrument, which often includes many different emitting species.

No reference text that the authors have seen has presented isolated spectra for the various individual colored flame emitters. Having such data would allow the investigator to more accurately determine the emitting species present in the spectra of test compositions, and thus be bet-

ter able to rapidly advance one's research goals. Also, having spectra, where instrumentation effects have been removed, allows for the computation of standard CIE chromaticity coordinates, which collectively quantify the gamut of all practical colors that may be obtained in fireworks and related pyrotechnics. The authors conducted a series of spectroscopic experiments, isolated the spectra, and produced chromaticity coordinates for some of the most abundant emitters in common pyrotechnic flames.

Visible Light Flame Spectrometer

The energy source used to produce the spectra was a gas burner of the type typically used in an atomic absorption spectrometer. This type burner was well suited to the needs of a flame spectrometer for this project. Its aspirator provided a ready mechanism to introduce solutions (and fine suspensions) into the flame. The burner produced a fairly narrow, but 4-inch (100-mm) long flame. This provided a long optical path for the spectrometer, thereby increasing its efficiency. The burner and a specially fabricated gas handling system facilitated the use of various and mixed gas sources. At the heart of the system was an Ocean Optics[5] CHEM2000 spectrometer installed into a slot in a computer. The spectrometer was connected to a chimney and ambient light shield using a large (400 micron) diameter optical fiber that terminated in an adjustable light-collecting lens. Figure 1 is an illustration of the overall flame spectrometer as configured for this project.

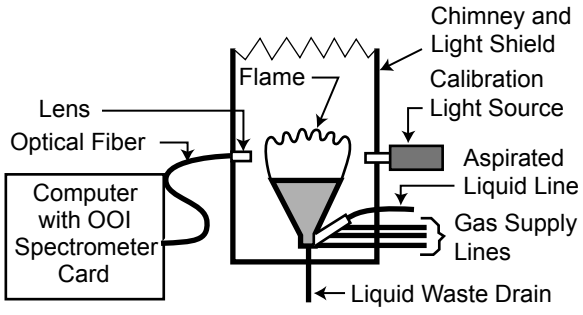


Figure 1. An illustration of the flame spectrometer as configured for this project.

Figure 2 is a diagram of the gas handling system for the spectrometer burner. In producing the spectra for this project, propane was the only fuel gas used. The supply of air (or air plus oxygen) to the flame was adjusted while aspirating pure water [or a mixture of carbon tetrachloride (CCl_4) and perchloroethylene (C_2Cl_4) for some of the measurements]. The relative proportion of oxidant supplied was only the amount sufficient to produce clean blue flame tips with a small distinct inner blue cone at the base of the flame. Figure 3 presents the spectrum of the flame and the classic C_2 (Swan) and CN band groups with perchloroethylene being aspirated into the flame. In each case, it is estimated that the temperature of the flame was approximately 1900 °C. This flame temperature is a little less than that of typical non-metal fueled pyrotechnic flames.[6] However, that is not thought to significantly alter the character of the isolated spectra reported in this article.

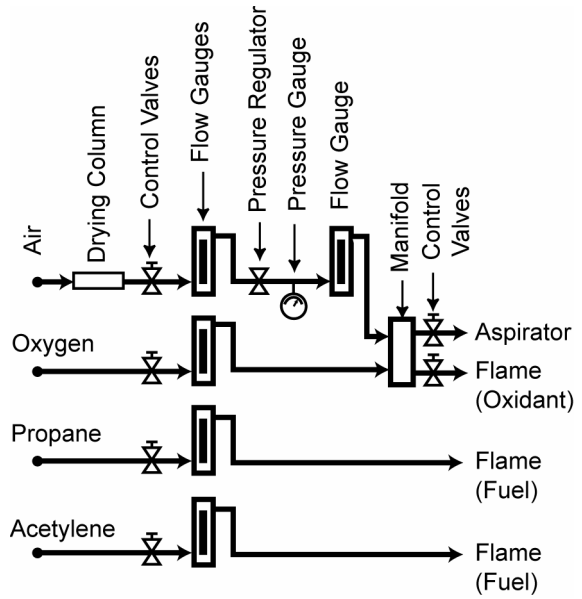


Figure 2. The diagram of the gas handling system for the spectrometer burner.

Instrument Calibration

The spectrometer was calibrated for wavelength by refining slightly the instrument calibration provided by the manufacturer. This was accomplished by fitting a simple linear equation to the actual and measured wavelengths for 15 sharp and clearly defined atomic peaks of the elements strontium, calcium, barium, potassium, sodium, mercury, and neon. This set of peaks

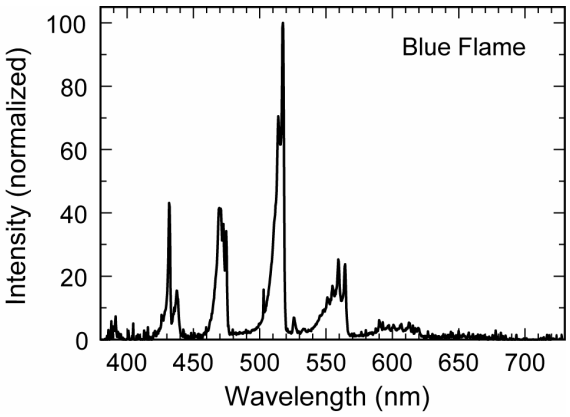


Figure 3. The spectrum of the blue flame with perchloroethylene aspirated into the flame.

ranged from 404.66 to 769.90 nm, which adequately covered the visible light range. (See Figure 4.) The goodness-of-fit parameter, r^2 (where unity is a perfect fit) was greater than 0.9999. The standard error was approximately 0.3 nm, which is less than the spectrometer's measured wavelength interval of approximately 0.4 nm. Note that the resolution of the spectrometer is 1.5 nm full width half maximum (FWHM).[5]

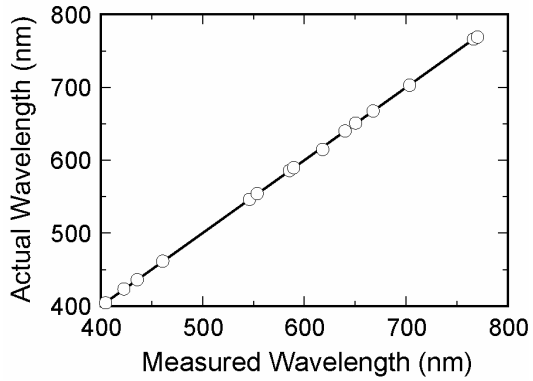


Figure 4. The wavelength calibration curve for the OOI spectrometer.

The optical path that a light ray follows into and through the spectrometer includes the collimating lens, optical fiber, a mirror, and a diffraction grating before it is dispersed onto a linear CCD (charge-coupled device) sensor that converts the light into an instrument-measurable electronic signal. Each of these components attenuates the incoming light by differing degrees at different wavelengths. The CHEM2000 spectrometer's diffraction grating exerts the greatest effect. It is designed with a blaze centered on approximately 555 nm[5]—the region of the spectrum where it is most efficient.

To calibrate for intensity, the spectrum of the supplied CHEM2000 tungsten-halogen bulb was taken, which is stated by the manufacturer to have a *color* temperature of 3100 K. A software application was developed to calculate the color temperature of tungsten at specified filament temperatures using Planck's Equation, and taking into account the temperature- and wavelength-dependent emissivity of tungsten. It was found that a *filament* temperature of 3035 K produced the closest match of chromaticity coordinates to those calculated for the stated *color* temperature of 3100 K. Both spectra—emissivity and measured—were normalized to unity at 555 nm, corresponding roughly with the blaze of the spectrometer. The corrected spectrum was then divided by the measured spectrum to obtain the required instrument intensity correction factors as a function of wavelength. Figure 5 presents the calibration curve that was required to remove the optical-path effects from the measured spectral data.

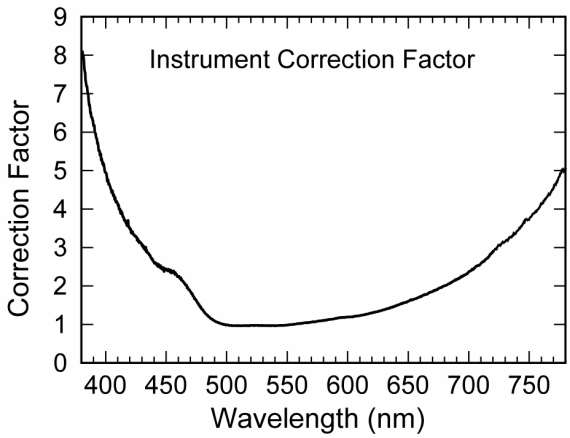


Figure 5. The intensity calibration curve for the OOI CHEM2000 spectrometer.

The CHEM2000 spectrometer is hardware programmable for sample integration time, ranging from as short as a few milliseconds to as long as two seconds per sample. The software acquisition mode used in this project is referred to as "Scope Mode"—a real-time function that is similar to watching an oscilloscope. The output

of this mode is raw spectrometer data, with intensities ranging from 0 to 4095. The CCD and 12-bit analog-to-digital converter both introduce noise into the measurements. It was found that integration times of less than approximately 250 ms resulted in a very good signal-to-noise ratio. For example, the spectrum of the blank (distilled water with no test emitter species present), integrated for 100 ms, accounted for an average intensity reading of 18 parts in 4096, or less than one-half of one percent of the full instrument range. Figure 6 shows the spectrum of a distilled water blank, where the peak at 589 nm is from a trace amount of sodium impurity. The spike at 502 nm is a single channel wide, and there is a lack of any identifiable source. It was concluded that it is probably a slightly noisy CCD detector well. The control software allows for samples to be repeatedly taken and averaged together, to effect additional noise reduction. This feature was utilized whenever the experimental setup permitted its usage.

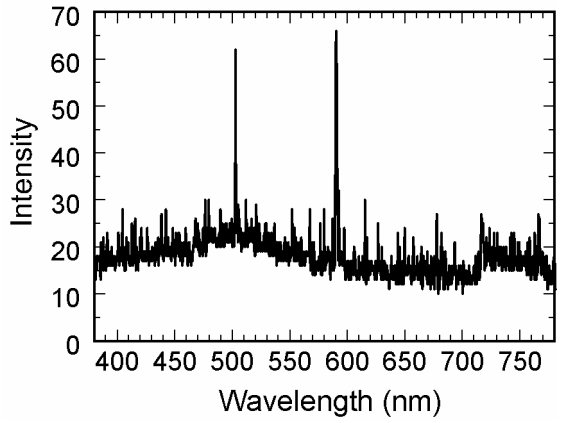


Figure 6. Spectrum produced using a blank sample (i.e., distilled water). (Intensity is in "scope units".)

Sample Preparation

The solutions for the production of the atomic spectra of sodium and potassium, and the molecular spectra of the monohydroxides of strontium, calcium, barium and copper were all prepared in the same way. These simply consisted of a set of fairly dilute aqueous solutions that were made using analytic reagent grade chemicals. The primary criteria used in selecting the chemicals were their availability in the chemical stocks of the laboratory and for their ability to produce the monohydroxide spectra, while avoiding halides or other species that might produce interferences. The nature of the aqueous solutions and their concentrations are reported in Table 1. These solutions were then aspirated into the propane-air flame of the spectrometer to produce the raw spectral data.

Table 1. Nature and Concentrations for Aqueous Solutions.

Chemical Name	Concentration (M)
Sodium hydroxide	0.10
Potassium nitrate	0.10
Strontium nitrate	0.20
Calcium nitrate	0.20
Barium hydroxide	0.10
Copper(II) nitrate	0.20

Samples for the production of the raw spectra for the monochlorides of strontium, calcium, barium and copper as the principal emitters were all made as suspensions. In each case, the appropriate metal chloride was thoroughly dried at 120 °C. While the sample was still hot, it was thoroughly crushed with a preheated mortar and pestle and transferred to a sealed flask for ball milling. The milling was accomplished using steel shot approximately 0.1 inch (2.5 mm) in diameter and using a sufficient amount of carbon tetrachloride (CCl_4) to cover the steel shot. The milling proceeded for 6 to 12 hours during which time the particle size was reduced to an average of approximately 1 micron (as determined using a scanning electron microscope). A magnet was used to remove any trace amount of iron that was worn from the steel shot during milling. To allow for successful aspiration of the suspensions into the spectrometer flame, they were diluted using perchloroethylene (C_2Cl_4) with a slight addition of the surfactant Neodol 23–5 (an alcohol ethoxylate, $C_{22}H_{46}O_6$). Further, during the time the suspensions were being aspirated into the flame, they were mechanically stirred. To produce a reasonably clean burning flame in the presence of the vaporized carbon tetrachloride and perchloroethylene, and to maintain a flame temperature estimated to be approximately 1900 °C, the propane-air supply was augmented by supplying additional oxygen.

Data Reduction

After all of the spectra were taken and saved to the computer, they were initially processed to remove instrumentation effects. The method used was the same for all of the gathered spectra, and proceeded in the following order:

- The slight wavelength correction was applied.
- The spectrum was visually inspected:
  - For spectra where there were extensive regions that had no apparent features—flat and near-zero intensity (instrumentation noise only), such as that for potassium and sodium—an average value was taken of the background regions. This average value was then subtracted from the spectrum.
  - For spectra where most of the visible range included features of interest, the removal of the background was more complicated. The intensity values were divided by the integration time of the particular sample, thus converting the intensity from "scope units" into "scope-second units". A blank with a similar integration time was processed in the same manner, and the resulting spectrum was then subtracted from the spectrum being processed.
- The spectrum was rescaled using the instrument intensity correction factor.
- Any negative intensity values were set to zero.

Having removed instrumentation effects, peak identification and isolation was then performed. While the method varied as to the emitter, it was essentially a peak-by-peak subtraction of the individual species emissions from the composite spectrum, until only the sought-for emitter spectrum remained.

The various reference texts with tabulated wavelengths and emitting species materially helped in the identification of the individual peaks from the various emitting species, as did the few spectrographs found in some of the reference texts. Alkemade and Herrmann's work[12] proved valuable in identifying features in the spectra for calcium, barium, and the Swan series of the flame's blue cone. Another text,[13] edited by Mavrodineanu, proved very valuable for identifying copper and copper chloride spectra. Mavrodineanu and Boiteux's work[14] was useful for calcium, strontium, and barium. The work of Li et al.[15] helped in isolating gaseous barium oxide.

For complex spectra with numerous overlapping peaks of different emitters, the PeakFit software application[16] was utilized for peak isolation. Asymmetric peaks were placed at the correct wavelengths that correspond to the tabulated locations of the respective lines and bands for each probable emitter identified in the spectra. The individual peaks were interactively and iteratively adjusted for amplitude and asymmetry until the original spectrum was very closely approximated. In a few cases, an individual peak required a minor shift in wavelength from the tabulated value—on the order of 0.5 to 1.5 nm—to afford the best possible fit. The resulting sets of individual peaks were exported from the peak fitting application to a spreadsheet. The spreadsheet was used to isolate the approximated individual emitters.

Figure 7 illustrates this process: a small region of the measured spectrum of aqueous barium hydroxide is shown. Portions of four fitted peaks [three BaO peaks (centered at 481, 485, and 497 nm) and BaOH centered at 488 nm] and a linear baseline are shown. Figure 8 presents the same portion of the spectrum, where the original spectrum has been plotted along with the fitted

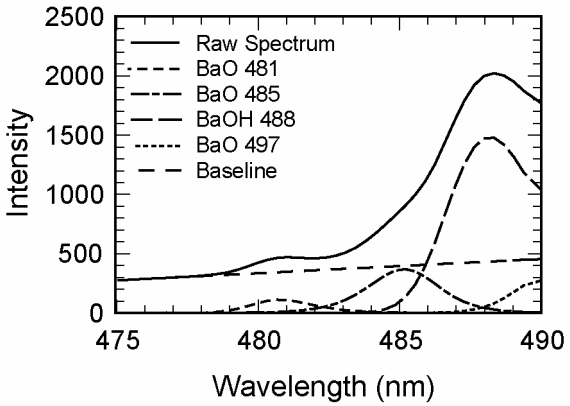


Figure 7. An example of the peak fitting method used to isolate the various contributions to a small portion of the raw barium monohydroxide spectrum.

spectrum (offset by 100 intensity units for clarity). The close approximation of the peak fitting to the original spectrum is evident. Centered about the zero-point of the intensity axis is the residual spectrum, which has been scaled-up by a factor of five to improve its visibility in the graph.

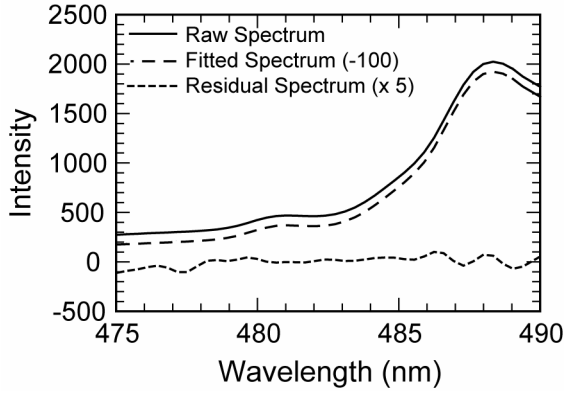


Figure 8. The result of peak isolation for the same spectral region shown in Figure 7. (Note that the fitted spectrum has been slightly offset from the raw spectrum, and the residual spectrum has been multiplied by 5.)

After the individual emitter spectra were isolated, a final "cleanup" was made to remove very minor amounts of unwanted, residual noise from the featureless regions of the graphs. This was followed by the calculation of 1931 CIE *xyz* chromaticity coordinates using the standard 2-degree, nanometer-increment, color matching functions.[17]

Each of the following spectra has been normalized such that the most intense peak equals 100 intensity units. Thus reported peak intensities can be compared within the same spectrum, but not between different spectra (emitter species).

The composite spectra and those of the various isolated components are presented and discussed below. (Table 2 later in this paper presents the normalized band and line intensities for the various emitting species.) Most of the spectra use a wavelength range of 380–730 nm, which represents the visible light range for most people. There are a few spectra that use the range 380–780 nm to allow inclusion of features in the near infrared. In the discussion of spectral features in the remainder of this text, wavelengths have been rounded to the nearest nanometer.

Sodium

The raw spectrum of the sodium hydroxide solution (NaOH in H_2O) had no measurable impurities. It is not shown, because it appeared fundamentally the same as the isolated spectrum of atomic sodium (Na), shown in Figure 9.

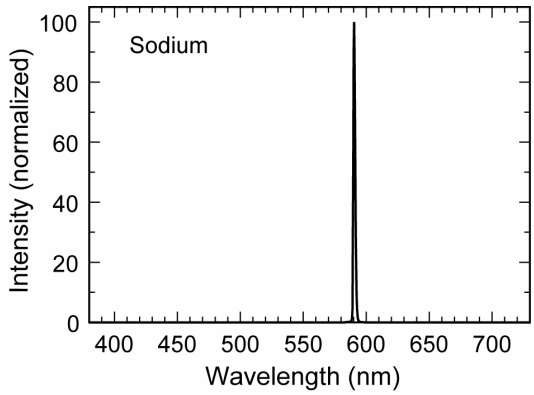


Figure 9. Spectrum of the isolated atomic sodium doublet peak.

Potassium

The spectrum of the potassium nitrate solution (KNO_3 in H_2O) included a small amount of sodium as an impurity, as is evidenced by the small peak at 589 nm in Figure 10a. (To make it easier to see, the region of the sodium impurity peak was multiplied by a factor of 10.) Also shown in this figure is the *very* small potassium peak at 404 nm, which has an intensity of 0.058. (To make it possible to see, the region of this peak has been multiplied by a factor of 100.) The sodium peak was removed to produce the pure atomic potassium (K) spectrum in Figure 10b. The peak at 767 nm is about 1700 times more intense than the one at 404 nm. This combination of peaks has a subtle but important effect on the perceived color of potassium flames, as described later. Note that these two graphs use a range of 380–780 nm.

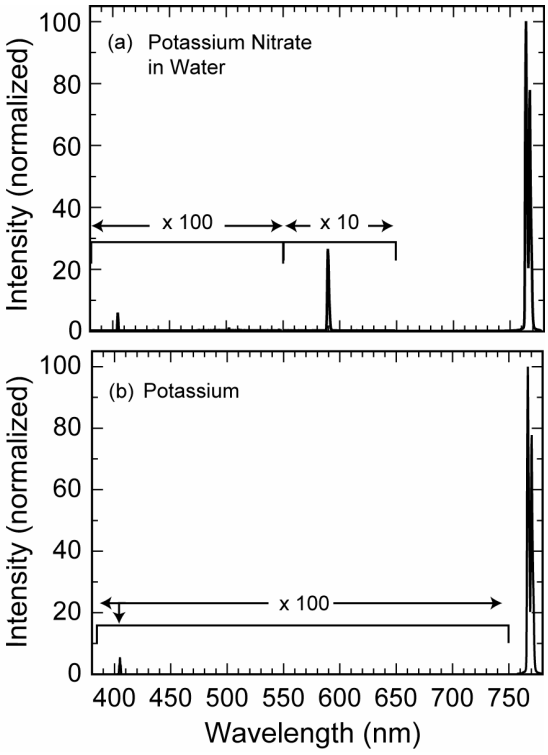
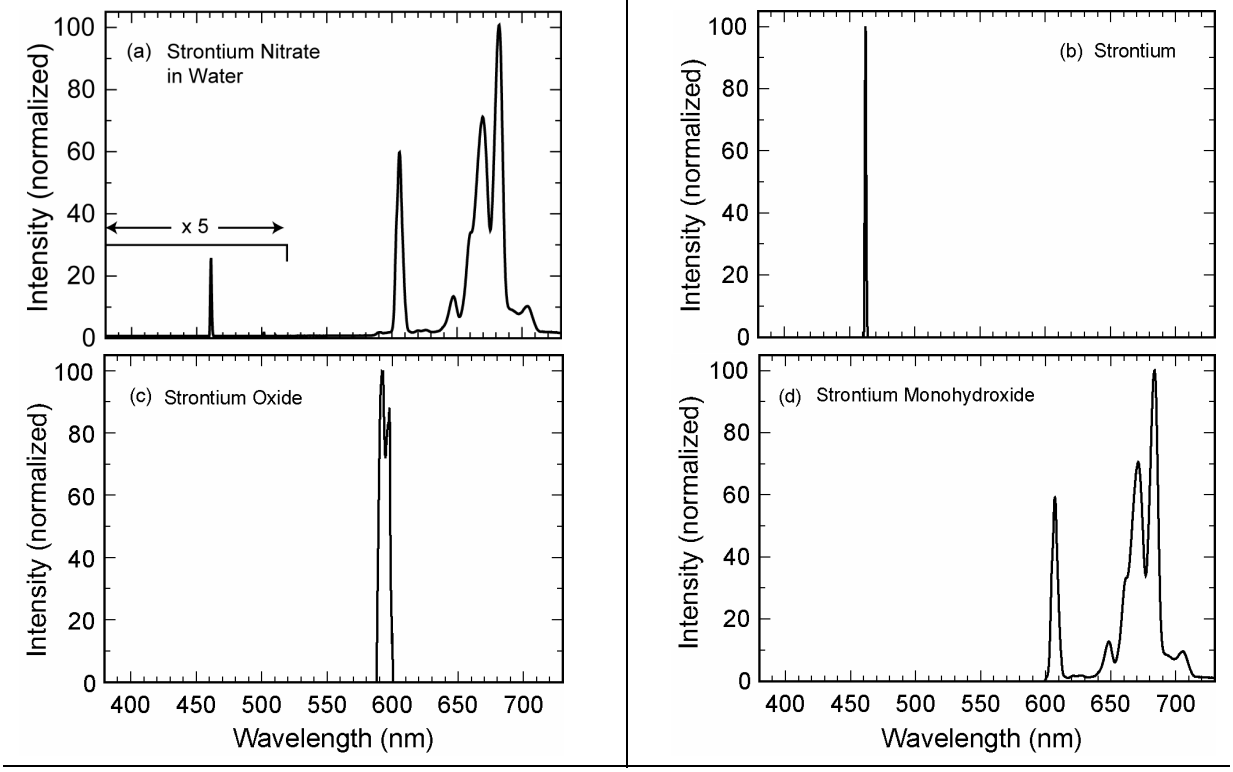


Figure 10. a) The spectrum of potassium nitrate dissolved in water. b) The isolated spectrum of atomic potassium.

Strontium

The spectrum for the strontium nitrate solution ($Sr(NO_3)$ in H_2O) is presented in Figure 11a. (Note: the region of the atomic strontium peak was multiplied by a factor of 5 to make it easier to see.) After subtracting the minor sodium peak, isolating the individual spectra was straightforward since very few of the observed peaks of atomic strontium (Sr), strontium oxide (SrO), and strontium monohydroxide (SrOH) overlap. The isolated atomic strontium (Sr) peak is shown in Figure 11b. The two main strontium oxide peaks at 595 and 597 nm are barely visible, and the weaker ones—reported to be less than 1/20 the amplitude of the two main peaks—are lost in the intense strontium monohydroxide peaks. For this reason, the graph for strontium oxide (Figure 11c) is necessarily incomplete, but it does provide a useful reference for the two most prominent peaks. The isolated strontium monohydroxide spectrum is presented in Figure 11d.

Figure 11 ***[below].*** *a) The spectrum of strontium nitrate dissolved in water. b) The isolated spectrum of atomic strontium. c) The spectrum of the two strontium oxide peaks that could be cleanly isolated. d) The isolated spectrum of strontium monohydroxide.*



The spectrum for the strontium chloride suspension ($SrCl_2$ in CCl_4) is presented in Figure 12a. Subtracted from this spectrum were rescaled atomic strontium, strontium oxide and strontium monohydroxide spectra, resulting in an isolated strontium monochloride (SrCl) spectrum as seen in Figure 12b. It is interesting to note that none of the references in the Table in the appendix mention the two low-intensity peaks centered at about 687 and 700 nm. The character of the peaks—their spacing and width—suggest that they are a continuation of the strontium monochloride spectrum and are included as such.

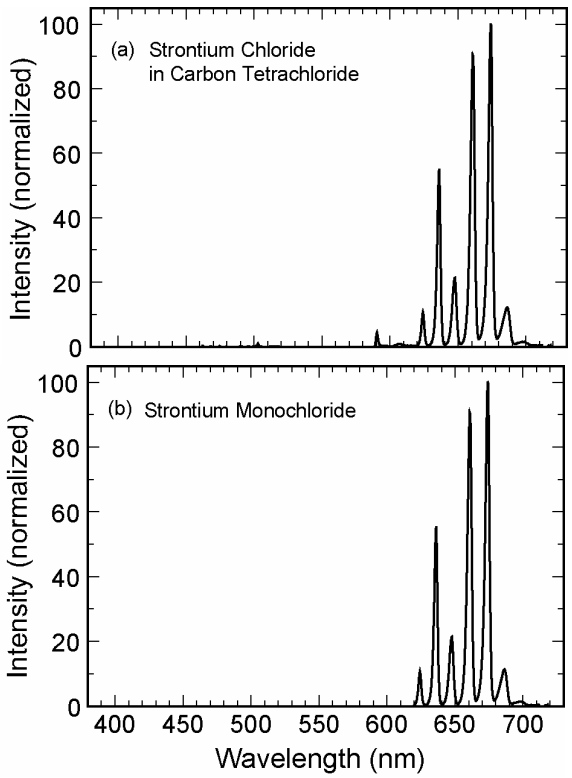


Figure 12. a) The spectrum of strontium chloride suspended in carbon tetrachloride. b) The isolated spectrum of strontium monochloride.

Calcium

The spectrum for the calcium nitrate solution ($Ca(NO_3)_2$ in H_2O) is presented in Figure 13a. The range for this figure extends from 380 to 780 nm so that the intense atomic potassium peaks, present as an impurity, may be clearly seen. After subtracting the potassium and sodium peaks, the isolation of the atomic calcium (Ca) peak (see Figure 13b) and the calcium monohydroxide (CaOH) peaks (see Figure 13c), were readily made. Unfortunately, calcium oxide (CaO) was not detected, and it cannot be reported in this work.

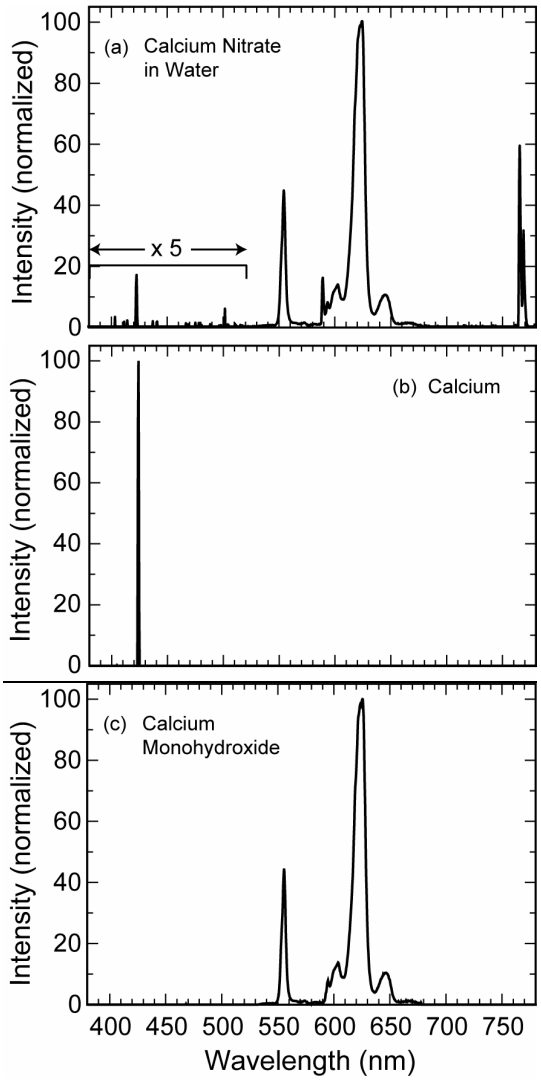


Figure 13. a) The spectrum of calcium nitrate dissolved in water. b) The isolated spectrum of atomic calcium. c) The isolated spectrum of calcium monohydroxide.

The spectrum for the calcium chloride suspension ($CaCl_2$ in C_2Cl_4) is presented in Figure 14a. Calcium monohydroxide was rescaled and subtracted from this spectrum, resulting in the isola-

tion of the calcium monochloride (CaCl) spectrum as seen in Figure 14b.

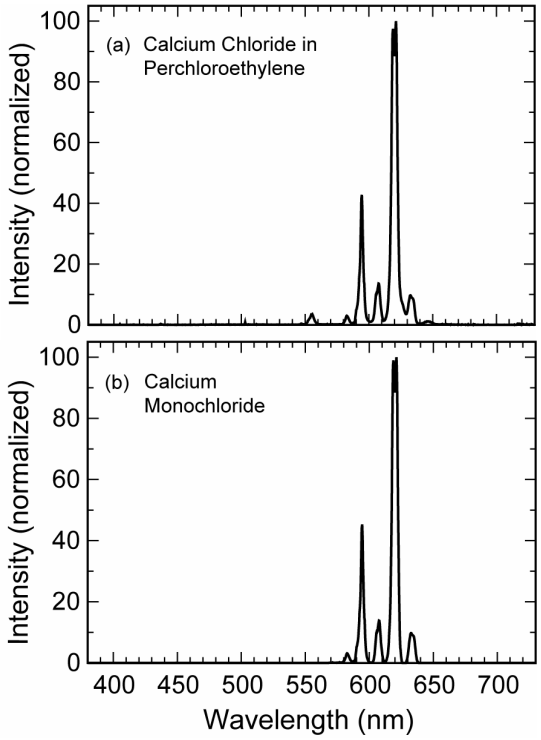


Figure 14. a) The spectrum of calcium chloride suspended in perchloroethylene. b) The isolated spectrum of calcium monochloride.

Barium

The spectrum for the barium hydroxide solution ($Ba(OH)_2$ in H_2O) is presented in Figure 15a. The range for this figure extends from 380 to 780 nm so that the prominent feature centered about 750 nm can be seen. Underlying this complex spectrum is a continuum that is produced by condensed-phase barium oxide (BaO).[6] The profile of this continuum (see Figure 15b) was approximated by fitting a curve to the local minima present in the raw spectrum. This continuum was then subtracted from the original spectrum, yielding an intermediate spectrum that represented the gas-phase emitters. Asymmetric peaks were then placed at the wavelengths corresponding to the tabulated locations for atomic barium (Ba), barium oxide (BaO), and barium monohydroxide (BaOH). The approximated barium monohydroxide peaks were thus isolated and are presented in Figure 15c. Likewise, the peak for atomic barium (Ba) was also isolated and appears in Figure 15d. Finally, the barium monohydroxide and atomic barium peaks were then subtracted from the intermediate spectrum, leaving gaseous barium oxide (see Figure 15e).

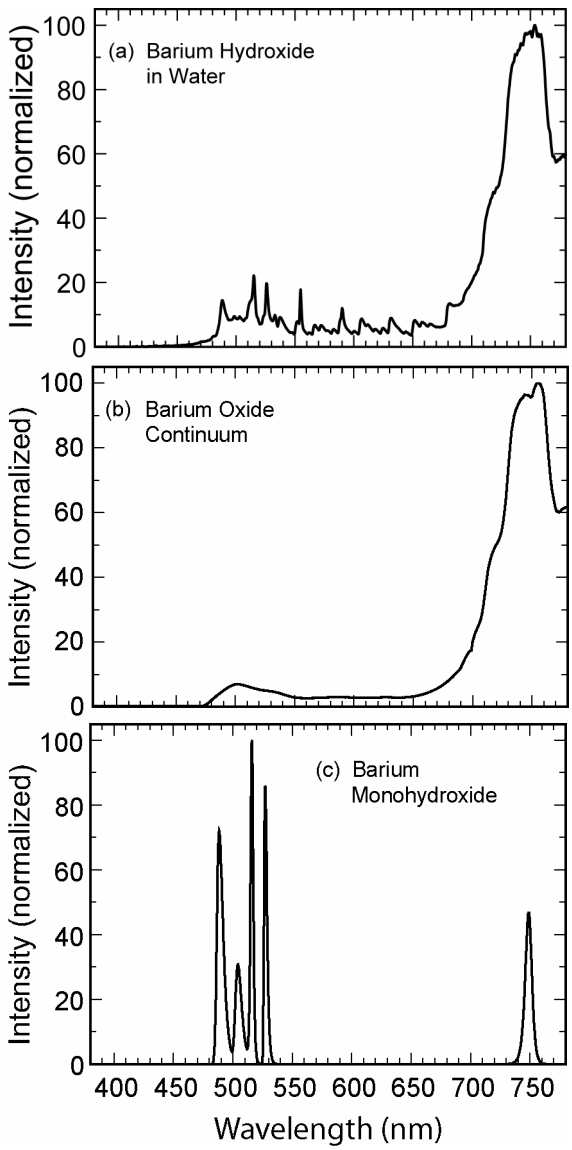


Figure 15. a) The spectrum of barium hydroxide dissolved in water. b) The spectrum of the condensed phase of barium oxide. c) The isolated spectrum of barium monohydroxide. [continued on next page]

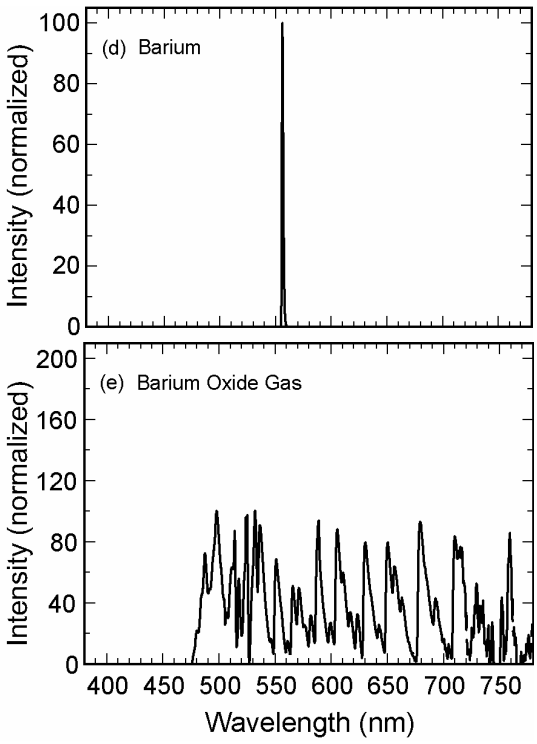


Figure 15. [continued] d) The isolated spectrum of atomic barium. e) The spectrum of vaporized barium oxide.

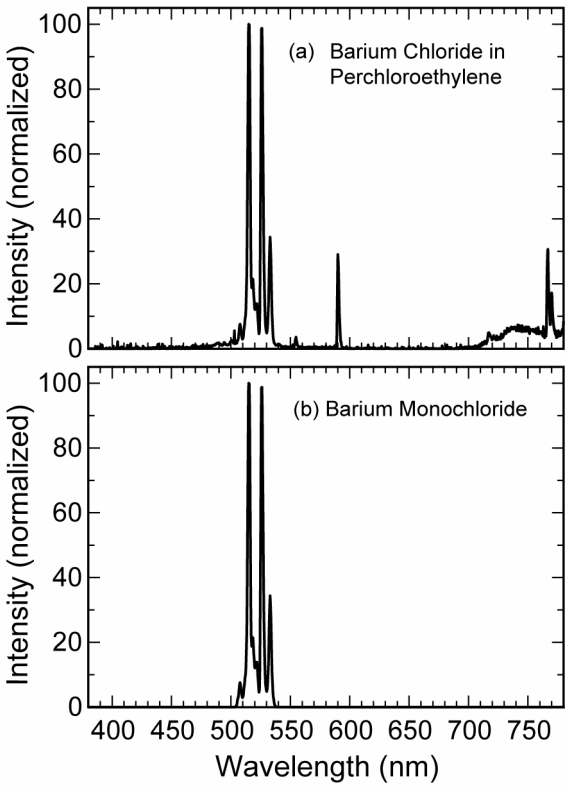


Figure 16. a) The spectrum of barium chloride suspended in perchloroethylene. b) The isolated spectrum of barium monochloride.

The spectrum for the barium chloride suspension ($BaCl_2$ in C_2Cl_4) is presented in Figure 16a. The range for this figure extends from 380 to 780 nm so that the peaks for atomic potassium impurities may be seen, as well as the low-intensity barium oxide continuum. Rescaled atomic sodium, potassium and barium, as well as barium oxide and barium monohydroxide spectra were subtracted, leaving an isolated barium monochloride (BaCl) spectrum, as seen in Figure 16b.

Copper

An attempt was made to acquire copper spectra by using copper nitrate dissolved in water, but the intensity of the peaks was so weak that it required an integration time of 2000 ms. This lead to excessive noise in the spectrum, making it impractical to resolve the individual and complex peaks for atomic copper (Cu), copper hydride (CuH), copper oxide (CuO), and copper monohydroxide (CuOH).

Copper(II) chloride in an aqueous solution ($CuCl_2$ in H_2O) was then tried, and this resulted in a reasonably intense and useful spectrum, as seen in Figure 17. Note that this figure is scaled from 380 to 780 nm, clearly showing the atomic potassium peaks, and also the atomic sodium peak at 589 nm that was so intense it was clipped by the spectrometer at the integration time used. This spectrum also includes low-intensity copper monochloride (CuCl) peaks, which further complicated peak identification and isolation. For this reason, a copper chloride suspension in perchloroethylene (discussed later) was processed first so that an isolated copper monochloride spectrum could be obtained, which was then rescaled and subtracted from the aqueous spectrum. This left an intermediate spectrum including peaks for atomic copper, copper oxide, copper monohydroxide, copper hydride, and impurities.

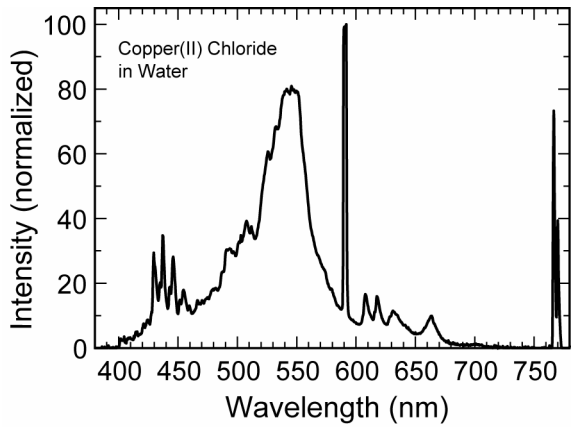


Figure 17. The spectrum of copper(II) chloride dissolved in water.

The copper monohydroxide peaks, located from approximately 490 to 540 nm, are the most prominent features seen in this figure. Copper hydride predominates towards the blue end of the spectrum, even riding up onto the shoulder of the first copper monohydroxide peak. Towards the red end of the spectrum copper oxide predominates, riding on the shoulder of the last copper monohydroxide peak. In a manner similar to that described above for barium hydroxide in water, the peaks for atomic sodium and potassium, copper hydride, copper monohydroxide, and copper oxide were manually placed and shaped using software, and then exported to a spreadsheet.

Interestingly, atomic copper peaks could not be positively identified despite there being a reported 18 peaks in the wavelength range from 380 to 750 nm. It is assumed that conditions were unfavorable for their formation in significant concentrations in the flame.

The atomic sodium and potassium peaks were subtracted from the intermediate spectrum. The individual copper monohydroxide peaks were summed, and this sum subtracted too, thereby eliminating the effect of the pronounced impact of the copper monohydroxide shoulders on copper hydride and copper oxide. The individual peaks for copper hydride and copper oxide were then isolated and cleaned up. Copper hydride and copper oxide are reported to overlap at 445, 446, and 464 nm, but none of these features could be positively discerned. Likewise, the reported (and low intensity) peaks of copper oxide at 583–584 nm could not be positively identified. Copper hydride and copper oxide spectra are presented in Figures 18a and b. The resulting clean copper hydride and copper oxide spectra were then subtracted from the intermediate spectrum, leaving the copper monohydroxide spectrum, which was then cleaned up and is presented in Figure 18c.

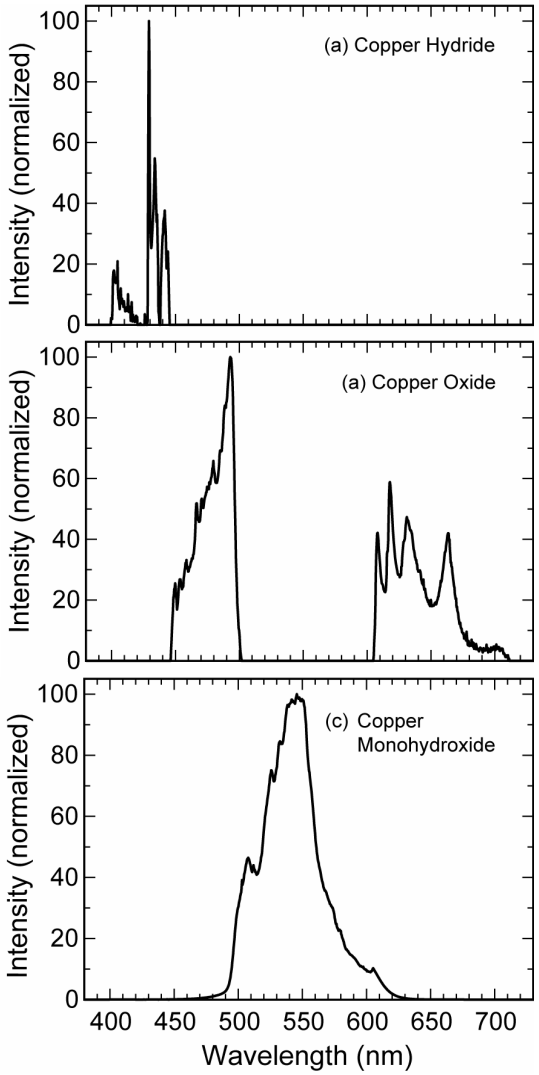


Figure 18. a) The isolated copper hydride spectrum. b) The isolated copper oxide spectrum. c) The isolated copper monohydroxide spectrum.

The spectrum for the copper chloride suspension ($CuCl_2$ in C_2Cl_4) is presented in Figure 19a. Virtually all of the features are associated with copper monochloride, which made isolation of the spectrum straightforward. This was rather fortunate in that it made the isolation of the other copper emitters present in an aqueous-based solution (discussed earlier) much easier. The isolated spectrum for copper monochloride is illustrated in Figure 19b.

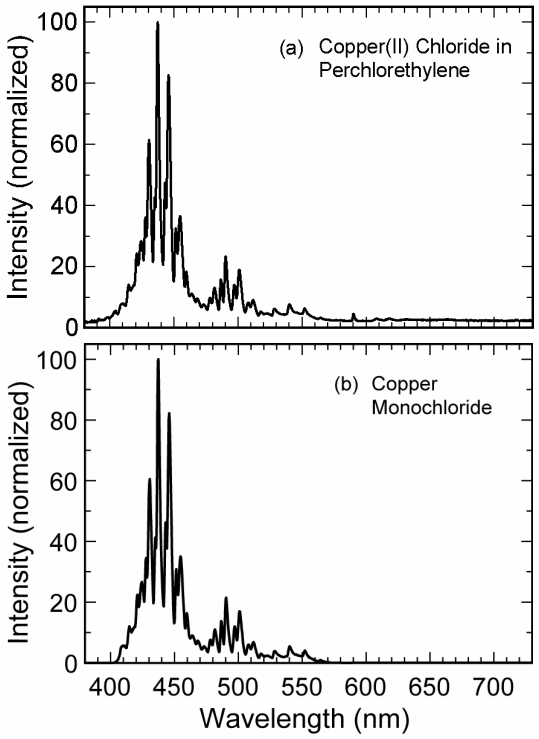


Figure 19. a) The spectrum of copper(II) chloride in perchloroethylene. b) The isolated spectrum of copper monochloride.

Results

The normalized (to 100 for the most intense peak) line and band intensities for the collection of principal colored flame emitters are presented in Table 2. (A presentation of some of the intensity data collected by others is included as a data table in the Appendix.) Table 3 presents the chromaticity coordinates for the principal emitters investigated in this study.

Table 2. Normalized Line and Band Intensities for the Principal Color Flame Emitters.

W. L.[a]	R. I.[b]	W. L.[a]	R. I.[b]
SrCl		**BaOH**	
624	11	488	72
636	55	502	30
648	21	513	100
661	90	524	86
674	100	745	47
687	11	**CuCl**	
700	1	412	6
SrOH		415	12
606	59	419	12
620	2	421	22
626	2	426	27
649	13	428	35
659	33	431	61
671	70	435	41
682	100	436	100
707	9	443	46
722	1	446	82
CaCl		449	31
581	3	452	35
593	45	460	16
605	11	465	9
608	14	469	7
619	99	476	5
621	100	479	7
633	9	482	11
635	8	485	13
CaOH		489	21
555	45	496	12
572	1	498	17
594	7	509	6
600	11	512	6
604	14	515	3
625	100	526	4
645	10	538	5
665	1	552	4
BaCl		**CuOH**	
507	8	505	46
514	100	512	44
517	21	524	75
521	14	533	84
524	99	546	100
532	34	605	10

a) W.L. = wavelength.

b) R.I. = relative intensity.

A normalized graph of the luminous sensitivity of the human visual system[17] is presented in Figure 20. The wavelength range corresponding to 1% or more of the maximum and extends from approximately 410 to 650 nm, with sensitivity approaching zero beyond this range. The intense potassium peaks at 767 nm (See Figure 10) are at what may be considered the edge of human visual perception and very near the infrared. However, due to its substantial intensity, the peaks at 767 nm produce a measurable shift in the perceived color of any flame that has potassium present in significant amounts. Chromaticity coordinates for the atomic potassium peaks at both 404 and 767 nm, for just the atomic potassium peak at 404 nm, and for just the pair of atomic potassium peaks at 767 nm have been included in Table 3 to demonstrate this effect. The influence of the near-infrared but intense 767 nm peaks is evident.

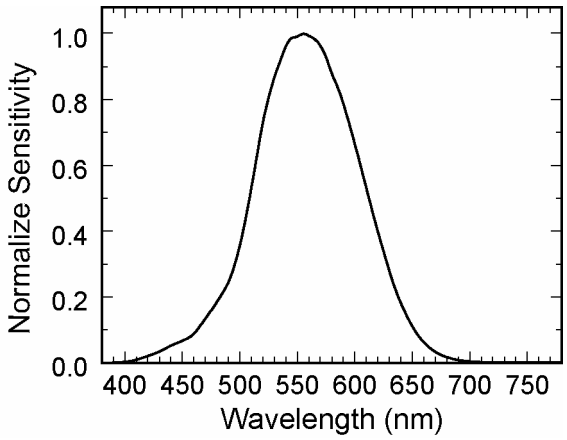


Figure 20. The luminous sensitivity of the human visual system, normalized to 1 at 555 nm.

The solutions produced for this work used reagent grade chemicals; even then the potassium peaks at 767 nm and the ubiquitous atomic

Table 3. Chromaticity Color Coordinates for the Color Emitters Characterized in this Study.

Emitter	CIE 1931 Color Coordinates		
	x	y	z
K (with both 404 & 767 nm peaks)	0.676	0.238	0.087
K (404 nm peak only)	0.173	0.005	0.822
K (767 nm peak only)	0.735	0.265	0.000
Na	0.576	0.423	0.001
Ba	0.344	0.653	0.003
BaO (Condensed)	0.380	0.520	0.101
BaO (Gas)	0.406	0.507	0.087
BaOH (approximated)	0.066	0.606	0.328
BaCl	0.094	0.811	0.094
Ca	0.171	0.006	0.824
CaO	NA	NA	NA
CaOH	0.630	0.369	0.001
CaCl	0.661	0.338	0.000
Sr	0.141	0.033	0.826
SrO (Incomplete)	0.593	0.406	0.001
SrOH	0.679	0.321	0.000
SrCl	0.720	0.280	0.000
Cu	NA	NA	NA
CuH	0.167	0.009	0.824
CuO	0.315	0.187	0.499
CuOH	0.290	0.666	0.044
CuCl	0.156	0.073	0.771
Blue Flame (with perchloroetylene)	0.218	0.395	0.387

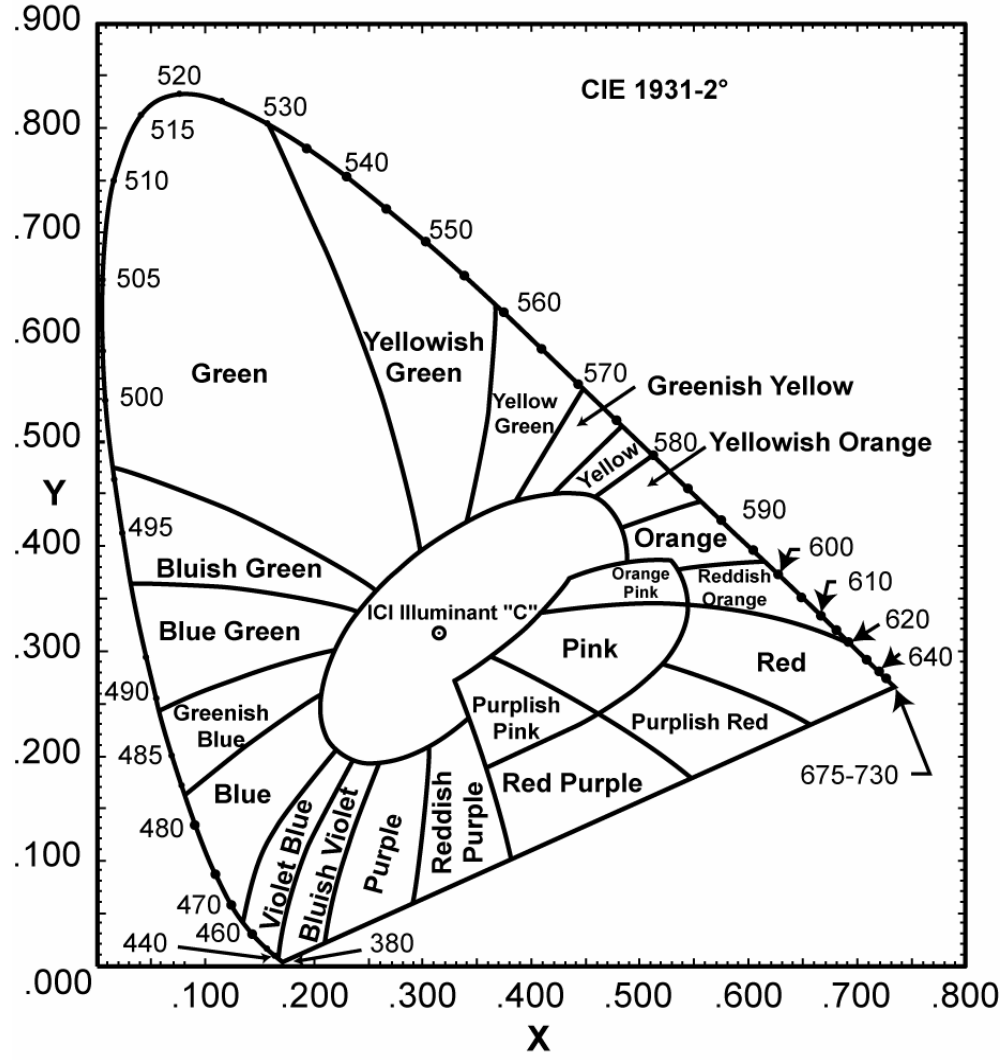


Figure 21. 1931 2° chromaticity diagram.

sodium peak at 589 nm were very often intense. One may conclude that commercial grades of chemicals used in pyrotechnic applications will likely have greater concentrations of impurities such as these, with correspondingly greater interferences and perceived color shifts.

As an aid in interpreting the color point data in Table 3, Figure 21 has been included. This is a black and white rendition of the CIE 1931 2° Chromaticity Diagram. The color points determined in this work are plotted in Figure 22 on simplified versions of the chromaticity diagram of Figure 21. There are two chromaticity diagrams: the first (Figure 22a) displays the location of the color points for the principal colored flame emitters, and the second (Figure 22b) displays the location of the other color emitters studied.

In Figure 22b, some clarification is needed regarding the identification of some of the color points. The color point for potassium (K) is that including both the 404 and 767 peaks. Only a portion of the strontium oxide spectrum could be isolated from the more intense emitters and thus has not been included in Figure 22b. There are two color points for barium oxide, one corresponding to its emissions when vaporized, designated with the subscript (g), and one for its emissions when condensed, designated with the subscript (cond.).

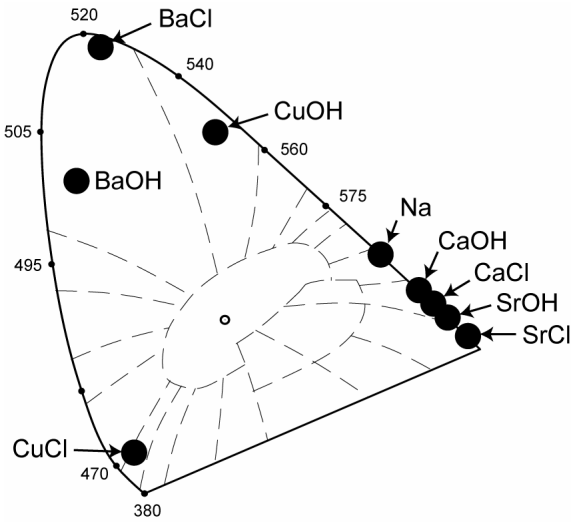


Figure 22a) chromaticity diagram showing the location of the color points for the principal colored flame emitters.

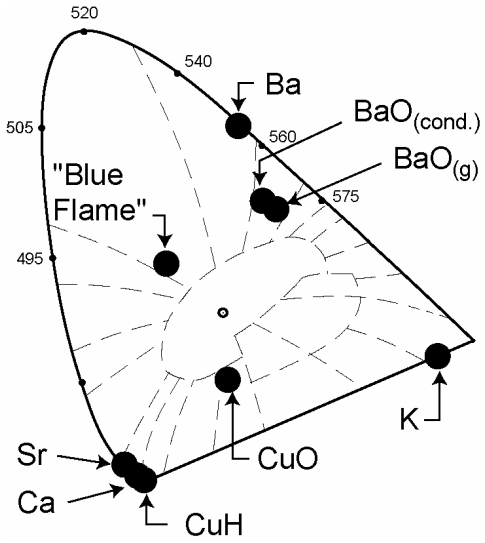


Figure 22b) chromaticity diagram showing the location of the other colored flame emitters studied.

Conclusions

With more complete and more detailed information regarding the spectral nature of the emitting species in pyrotechnic flames, work to improve flame color should be facilitated. For the most part, this project has been successful in producing that data (with another project anticipated to carry the work further). Upon considering the spectral data for the principal colored flame emitters, it does not appear that progress toward improved flame color will be easy.

Figure 23 summarizes the state of the art with respect to colored flame production, as well as identifying the probable limits of future improvements. The range of colors within the smallest of the quadrangles (shaded) represents the approximate limits of common high quality color formulations.[18,19] This covers a relatively small portion of the chromaticity diagram, and much of that consists of what would normally be described as shades of white. It is perhaps fortunate, that observers of fireworks displays do not have light sources producing bright and highly pure color available to them to compare with the colors of the fireworks, many of which would pale by comparison. The small size and central location of this color quadrangle for typical compositions probably also goes a long way toward explaining why photographs and video records of displays seem to reproduce the colors of the displays so poorly, unless the recorded colors are artificially enhanced.

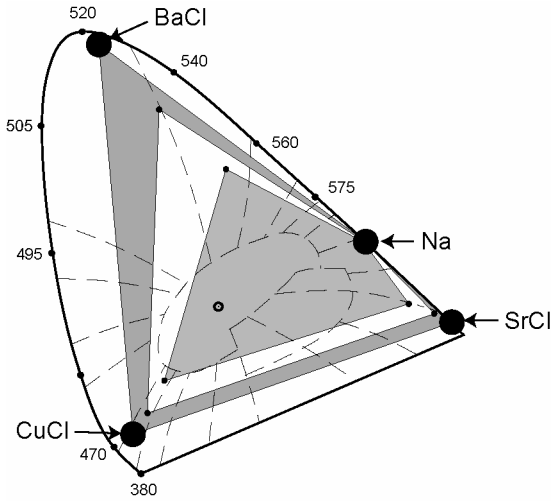


Figure 23. The state of the art for colored flame production. The smallest shaded quadrangle represents the limits of common high quality formulations. The mid-size un-shaded quadrangle demonstrates the very best color formulations reported to date. The largest shaded quadrangle is for the pure color species reported in this paper.

The next larger quadrangle (not shaded) demonstrates the approximate limits of the best color formulations reported to date.[18,20] These colors are quite impressive when viewed and are readily discernable as significantly better than even the best of the commonly produced colors. (Unfortunately, there are some limitations associated with the use of these formulations in terms of cost, non-color related performance, and convenience of manufacture.) Using any of the color mixing schemes to produce blended colors,[21–23] and even assuming the color formulations are perfectly compatible, one is constrained to produce colors no better than those inside this quadrangle.

Finally there is the outer quadrangle (shaded) formed by the color points of the most desirable color species (the monochlorides of strontium, barium and copper, plus atomic sodium). Unless other, even better color species can be found (and researchers have looked without significant success[2,24–27]), this is the ultimate limit of what is possible. In fact, given that flames generally consist of very many chemical species, of which many emit in the visible region, even reaching these limits will probably be impossible to achieve.

Acknowledgments

The authors gratefully acknowledge the work of all those who have added to the understanding of the chemistry of colored flame, most especially the pioneering work of T. Shimizu and B. Douda. The authors are also grateful to K. Hudson and especially to E.-C. Koch for their comments and suggestions on a draft of this paper.

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Appendix — Summary of the Reported Spectral Information for Colored Flame Emitters, Including the Results from this Study [See notes at end of Table.]

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
Ba								
552							6	
554	200	170		8.5			10	100
578							9	
602	4							
606	4							
611	12							
645	4							
648	4							
650	50							
653	25							
660	25							
706	4							
BaCl								
507	2				1			8
514	20				10			100
517	4				2			21
521					1			99
524	30				10			34
532	10				3			
BaO								
452	3							
454			vvW					
458	4		vvW					
462	7		vvW					
464	5		vvW					
466	3		vvW					
468	10		vvW		5			
472	5		vvW					
474	10		wM					
478			wM					
479	15							
483	10		wM					
485	50		wM		6			72
487			wM					
490			wM					
494			vvW					
497	30		vvW		3			100

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
BaO (cont.)								
501	10		vvW					
509	100		W		6			
514								87
521	70		vW		7			
526								97
533								100
535	90	80	vW	4	8	s		90
537			vW					
540			vvW					
542	5		vvW					
546	20							16
549	70	80	vvW	4	10	vs		
551	10		vvW					68
560	10							
564	40	80	vvW	4	9	vs		
566	5		vvW					
567	10		vvW					51
570	40	80		4	8	s		
571			vvW					
574								36
576	15		vvW					
577			vvW					
581	20		vvW		6	m		
582			vvW					
583			vvW					32
586	40		W	3.5	10	vs		
587		80						
588			W					
589	10		W					93
598	10		vvW		3	w		
604	50	70	W	3.5	9	vs		
608								88
610	20		W		5			
611	10		W					
612			W					59
616	10							
617			vvW		6			34
622			vW		6	m		

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
BaO (cont.)								
623	15							32
626								29
629	25		W		8	s		
632								79
636			vvW					
642	15		vW					26
649	25		wM		9	vs		
653								71
656	10		vW					57
663			vW					39
666								
670			vvW					
678	50		wM		8	s		
682								56
686	40		vW					33
693	60		vW					26
701			vW					10
710	80		vW		5			50
718			vW					46
725			vW					14
734			vW					32
744			vW					16
752			vW					26
755								
761			vW					41
BaOH								
487			wM					
488	120	100		5				72
497		80		4				
502	30	80		4				30
512			W					
513	140	150		7.5				100
524	80	80		4				86
745	45	50		2.5				47
Ca								
423	10k	250	vS	5				100
428	4							
430	15							
432	3							
444	10							
446	15							
459	8							

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
CaCl								
383	12							
388	13							
581	250							3
593	500							45
605					2			11
608					2			14
618					10			
619	500				5			99
621	500				10			100
622					5			
633					2			9
635					2			8
CaO								
385			vW					
386			vW					
387					2			
389			vvW					
392			vvW					
397					3			
408					5			
410					4			
413					3			
421					6			
422					5			
424					3			
435					5			
437					5			
438					6			
440					6			
443					3			
451					4			
452					3			
598					8			
600					8			
601					8			
604					3			
606					5			
607					7			
608					5			
609					6			
610					10			
618					6			
626					9			

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
CaO (cont.)								
628					4			
632					2			
634					4			
636					4			
731			vvW					
732			vvW					
733			vvW					
771			vW					
772			vW		6			
CaOH								
539			vW					
543	100		W					
546	100							
551	100							
552	200							
553	600							
554	1.2k	500			5			45
555	1k		vS	10	5			
556	400				2			
565	100							
570	100							
572	100	25		0.5				1
578			W					
581	100							
583			W					
594	100							7
597	200							
599	400							
600	400							11
601	600							
602	400	100						
603	400		[a]					
604			M	2				14
605	300							
607	200							
608	200							
609	200							
610	400							
612	200							
622		500		10				
623			vS					
625								100
644		70						

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
CaOH (cont.)								
645			M	1.4				10
665			W					1
683			vW					
698			vvW					
Cu [b]								
450					4			
455					7			
460					10			
461					8			
465					10			
471					5			
486					4			
487					4			
490					10			
492					8			
497					4			
498					8			
500					7			
511	50		vvW				4	
515							4	
522							5	
570	5							
578	10							
CuCl								
412					5			6
415								12
419	2				6	w		12
421	2				4	w		22
426	5				8	s		27
428	10				7	vs	9	35
433	10				10	vs		35
435	20				9	vs	10	41
436					5			100
441	7				6	s		
443	15				6	vs	9	46
446								82
449	4				4	m		31
452	5				1	m	5	35
460								16
465								9
469								7
476					5	vw	1	5
479					5	vw	2	7

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
CuCl (cont.)								
482								11
485					8	w	3	13
488	3				8	w	4	
489					6			21
495					4	vw	1	
496					5			12
498					4	vw	2	17
509								6
512								6
515					2	m	3	3
526					4	w	6	4
538					2			5
552								4
CuH								
401	5							18
407								12
413								10
416								7
428	30		vvW			vs		100
433	11					m		55
435	10							
436	9							
437	7							
438	9							
439	9							
440	9							
441	9							38
442	7							
443	8							
444	7							24
445	10							
446	11							
465	8							
CuO								
445					8			
446					7			
450								25
452					5			
453					5			27
458					6			33
464					6			
467								52
469					5			

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
CuO (cont.)								
470					5			
471					7			53
472					7			
477					6			57
480								66
483					4			
485					5			
486					5			69
488					5			83
492					5			100
583					2			
584					3			
605	10				9			
606	50				10			42
615	50				8			
616	50				9			59
628					1			
629					5			
632								47
638					2			
640					5			
643					3			
649					1			
CuOH								
493	60							
505	70	50		5				46
512								44
524	110	70	vvW	7				75
530	110		vvW					
512								84
537	120	100	vvW	10				
533								100
605								10
615-625			vvW					
	[c]	**K**						
404	500			0.03			5	0.06
405	250	30					4	
580	25							
694	40							
766	40k	10k		10			10	100
770	200k	10k		10			9	78

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
	[d]	**Na**						
568	40							
569	80							
589	800k	30k		10			10	100
590	400k			10			9	100
	[e]	**Sr**						
461	10k	500		1			10	100
483							5	
487							2	
496							3	
SrCl								
389	4							
392	4							
394	4							
396	4							
398	4							
401	4							
624							2	11
636	20						10	55
648							4	21
661	20						10	90
662							5	
674							5	100
675	10						5	
676							3	
687								11
700								1
SrO		[f]	[g]	[h]				
390			vvW					
392			vvW					
593								100
595		500	W	1				
597		500		1				88
608	25							
609	20							
610	10							
611	7							
750	5		vvW					
752	7		vvW					
754	10		vvW					
756	10							
787	20							
788	25							

WL	Intensity							
(nm)	A	B	C	D	E	F	G	H
SrOH								
604	3k							
605		5k		10			Str.	
606	7k					vs		59
608							10	
609							6	
610							4	
611							1	
620						vw		2
624	150							
626						vw		2
645		250		0.5				
646	700		M			m		
649								13
659	1.5k	500	W	1		w		13
666	5k	500		1				
671			vS			vs		70
672	4k							
680		250						
682	7k		vS	0.5		vs		100
704	500							
707			wM			m		9
722			W			w		1

Sources of Spectral Data in Table

A) R. Herrmann and C. T. J. Alkemade, *Chemical Analysis by Flame Photometry*, Translated by Paul T. Gilbert, Interscience Publishers, 1963. [Note: Does not include peaks with an intensity of one.]

B) *CRC Handbook of Chemistry and Physics*, 46th ed., Robert C. Weast, Ed., Chemical Rubber Co., 1965. [Note: Only air-hydrogen flame values using aqueous solutions reported.]

C) R. Mavrodineanu and H. Boiteux, *Flame Spectroscopy*, John Wiley & Sons, Inc., 1965 [Note: Only acetylene-air, outer cone values reported.]

D) M. L. Parsons and P. M. McElfresh, *Flame Spectroscopy: Atlas of Spectral Lines*, IFI/Plenum, 1971. [Note: Only air-hydrogen values reported.]

E) R. W. B. Pearse and A. G. Gaydon, *The Identification of Molecular Spectra*, 3rd ed., Chapman and Hall LTD, 1963. [Note: Variety of sources, flame types, furnaces, and arcs reported.] NOTE: Looking at the more recent (4th) edition from 1975, there are obviously some deviations between the transitions listed in this Table under **E**. At the time of writing, the authors did not have this edition available. In all probability – knowing the types of budgets that university libraries face – the older edition may be more readily found.

F) A. G. Gaydon, *The Spectroscopy of Flames* 2nd ed., Chapman and Hall, John Wiley & Sons, 1974.

G) B. E. Douda, *Theory of Colored Flame Production*, U.S. Naval Ammunition Depot, RDTN No. 71, 1964. [Note: Values from Gaydon are not reproduced for this column.]

H) This work.

Table Notes

Note: Some researchers used a non-numerical scale, such as *vvW* for Very Very Weak, *vs* for Very Strong, etc. No attempt was made to convert these to a numerical scale. In addition, there are discrepancies in wavelength assignments between the various sources. No attempt was made to reassign wavelengths.

a) 604–698 nm designated as "CaOH (?)" in the original text.

b) Designated as Cu_2, not Cu, in the original text.

c) Only values ≥ 25 are listed.

d) Only values ≥ 25 are listed.

e) Only values ≥ 25 are listed.

f) 595 and 597 nm are designated as possibly being Sr_2O_2 in the original text.

g) 595 nm is designated as Sr_2O_2 in the original text.

h) 595and 597 nm are designated as Sr_2O_2 in the original text.

An earlier version appeared in *Fireworks Business*, No. 237, 2003.

Further Report on the Testing of Suspect Tiger-Tail Comets

K. L. and B. J. Kosanke

In the hope of avoiding a serious accident, earlier issues of *Fireworks Business* carried a report of the powerfully explosive malfunctions of some tiger-tail comets,[1] and then a brief report of an examination and initial testing of a number of the suspect comets.[2] Since that time, samples from one of the suspect comet shells were provided for laboratory analysis. This article reports on the results of that analysis.

Based on a semi-quantitative chemical analysis of the comet composition, the approximate formulation of the problematic comets was as reported in Table 1:

Table 1. Approximate Composition of the Problematic Comets.

Ingredient	Percent
Potassium perchlorate	40
Aluminum (coarse)	30
Magnalium (fine)	25
Binder (unidentified)	5

The binder was water soluble but not otherwise identified, and it was assumed to be present in an amount equaling 5%. The aluminum had the appearance of being the type that is sometimes referred to as *blown* aluminum, which is an irregularly-shaped type of coarse atomized aluminum. The magnalium was granular and had the approximate ratio of 50:50 of magnesium to aluminum. (As determined from electron micrographs, the magnalium was seen to exhibit fracture characteristics consistent with being approximately 50:50 magnalium.) The approximate (rounded to the nearest 10%) mesh fractions of the two metal powders were as reported in Table 2:

Table 2. Approximate Mesh Fractions of the Comets' Metal Powders Reported in Table 1.

Mesh Range (US Standard)	Mass Percent	
	Aluminum	Magnalium
+ 60	65	10
60 – 100	25	10
100 – 200	10	30
200 – 400	0	20
– 400	0	20

Since 90% of the aluminum was coarser than 100 mesh, that suggests that the primary purpose of the aluminum is to produce the comet's spark trail. Also since 80% of the magnalium had a particle size smaller than 100 mesh, combined with the lack of another fuel, that suggests that the primary purpose of the magnalium is the primary fuel for the composition. Normally an atomized aluminum, with particles as large as was used in this case, would not be particularly effective as a source of white sparks. This is because of the difficulty in achieving ignition of such large size aluminum particles with the relatively low burning temperature of Black Powder-based compositions. This perhaps explains the reason for the manufacturer resorting to the use of the potassium perchlorate and small particle size magnalium as a high flame temperature composition.

Calculated from the size and mass of the comet, its bulk density was approximately 1.5 g/cm^3. Based on its apparent formulation, the maximum theoretical density of the comet composition is approximately 2.5 g/cm^3. This difference corresponds to a porosity of approximately 40%, whereas a porosity of roughly 20% is more typical for well-compacted pyrotechnic compositions. The particularly high porosity was confirmed through a microscopic examination, which suggested that gas permeability would also be high. Figure 1 contains two electron micrographs of the comet composition. The upper

micrograph demonstrates the extent to which there tends to be void spaces between individual particles in the comet, which themselves appear somewhat like a collection of boulders in a loose pile. The lower micrograph (taken at lower magnification) is similar in appearance but also documents the occurrence of larger more cavernous voids in the composition.

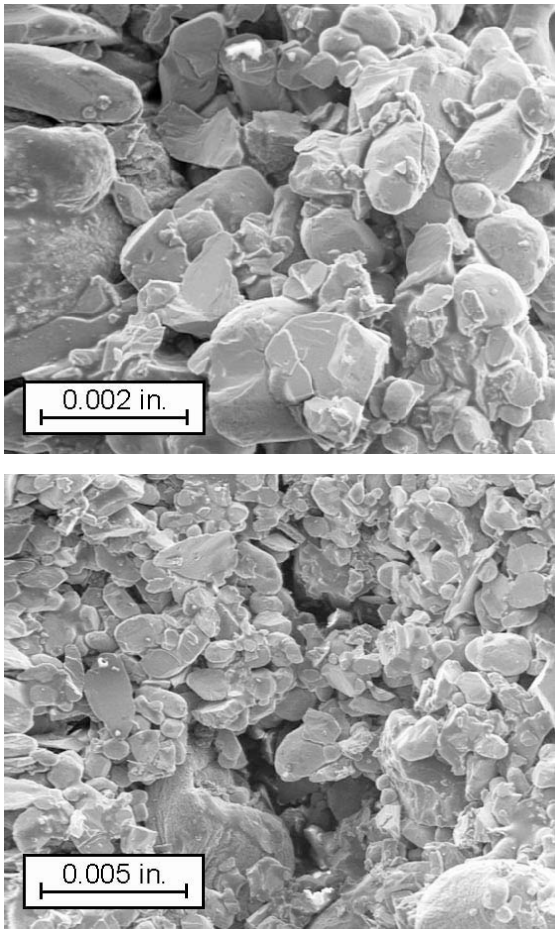

Figure 1. Electron micrographs of the problematic comets.

Although there are differences in construction between these malfunctioning comets and those producing the powerful explosions of comet Roman candles occurring previously in Australia,[3] they share characteristics that are thought to have been the cause of the malfunctions. Both types of comets combine a high energy oxidizer (potassium perchlorate) with small particle size magnalium (in effect constituting somewhat compacted and bound flash powder). Both types of comets have internal structures thought to produce a relatively high degree of gas permeability (fire paths that allow the rapid spread of combustion). The combination of these characteristics is thought to allow the near instantaneous release of large amounts of pyrotechnic energy, occasionally manifesting itself as a powerful explosion. What makes these malfunctions especially problematic is that they are occurring in items generally thought not to be capable of exploding at all.

References

1) K. L. Kosanke, "Warning: Serious Product Malfunction", *Fireworks Business*, No. 232, 2003; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 7 (2003 and 2004)*, Journal of Pyrotechnics, 2005.

2) K. L. Kosanke, "Report on the Initial Testing of Suspect Tiger Tail Comets", *Fireworks Business*, No. 233, 2003; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 7 (2003 and 2004)*, Journal of Pyrotechnics, 2005.

3) K. L. & B. J. Kosanke, G. Downs and J. Harradine, "Roman Candle Accident: Comet Characteristics", *Fireworks Business*, No. 228, 2003; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 7 (2003 and 2004)*, Journal of Pyrotechnics, 2005.

An earlier version appeared in *Fireworks Business*, No. 240, 2004.

Shogun Electric Match Connectors

K. L. and B. J. Kosanke

The most common point of attachment of an electric match to a fireworks aerial shell is via the shell leader, and most commonly the installation of the electric match is performed by a display company when preparing for a display. Because of the difficulty of performing that operation with the safety shroud left in place, too often the shrouds are removed prior to their installation. Unfortunately, while removing the safety shroud is allowed under a US-DOT exemption,[1] this greatly increases the likelihood of an accidental ignition.[2,3] Fortunately, now there is a simple and effective solution to the problem; the Shogun Electric Match Connector.[4]

The connector is a small piece of somewhat soft plastic that facilitates the attachment of electric matches to aerial shell leaders and is shown in cross section in Figure 1. Figures 2 and 3 are a drawing and photo of how the connectors are used. Once the connector has been installed, the electric match can then be quickly installed. This is accomplished by simply inserting the electric match into the connector and securing it in place using the leg wires around the built-in hooks for that purpose. As can be seen, the safety shroud of the electric match is left in place. In fact, the physical strength of the safety shroud is reinforced by the body of the connector, thus affording the sensitive electric match tip a substantially increased level of protection. Since the actual installation of the electric match itself can be accomplished so quickly, that operation can be delayed until rather late in the process of preparing for a display. Also, in the event that the electric match needs to be removed, that task can be accomplished both simply and safely.

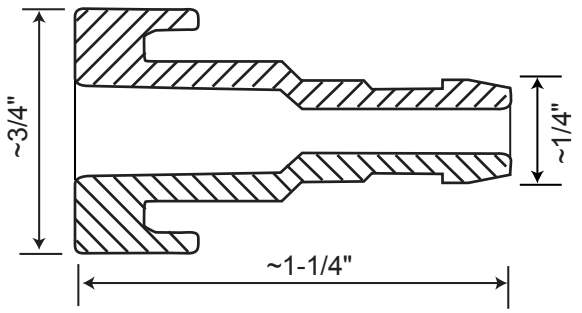

Figure 1. A cross-sectional drawing of the Shogun Electric Match Connector giving approximate overall dimensions.

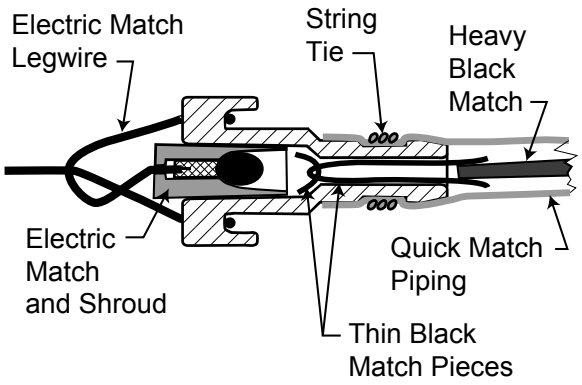

Figure 2. A cross-sectional drawing showing the operational configuration of the electric match connector.

While the connectors are apparently available for sale to display companies wishing to use them, reportedly[5] Shogun (USA) Pyrotechnics (offering Shogun, Vulcan and Haga brand display shells) started offering shells for the 2004 season with the connectors preinstalled. The aerial shells were to be supplied with the normal shell leader, thus allowing for their manual firing or chaining by a display company. In addition, the shells were to come with a short length of quick match fuse with the electric match connector already installed at the factory, thus facilitating electrical firing. As installed by the manufacturer of the aerial shells, the opening in the electric match end of the connector will have a small plastic plug inserted to close the opening (not shown in the above figures). To install the

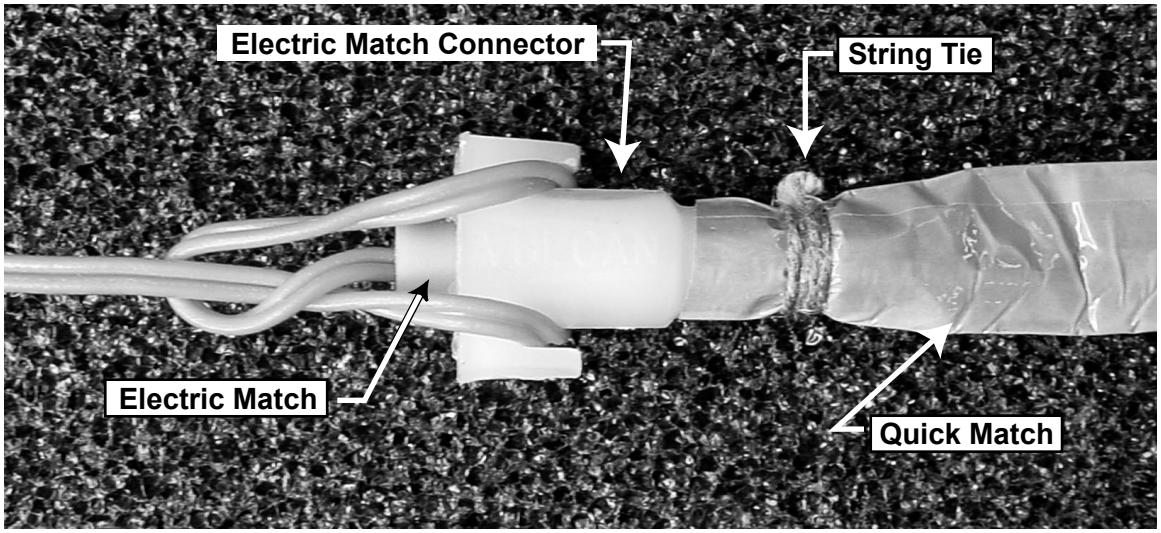

Figure 3. A photograph of the operational configuration of the electric match connector.

electric match, the user needs to first remove that protective plug.

Initially it had been anticipated that some sensitiveness testing would be performed using the electric match connectors. However, after examining the nature of the connectors and reviewing the test results of electric matches with their safety shrouds left in place,[2] further sensitiveness testing seemed pointless. Given the yielding nature of the plastic, the connector can only act to further reduce the already low impact sensitiveness of shrouded electric matches. Given the added protection afforded by the connector, it can only act to further reduce the already low friction sensitiveness of shrouded electric matches. Use of the connector will in no way affect the sensitiveness of the electric match to thermal ignition. However, because of the high temperatures needed to cause the ignition of electric matches, compared to temperatures at which humans can survive, this was not found to be a likely source of accidental ignition.

Use of the electric match connector will do nothing to affect the sensitiveness of electric matches to electrostatic discharges (ESDs) through the bridgewire, but this is already relatively low.[2] The type of ESD events that are most problematic for electric matches are those ESD events occurring from the bridgewire and passing through the electric match composition. This second type of ESD sensitiveness is only possible when there is a conductive path for the discharge leading away from the tip of the electric match. In earlier testing, it was found that black powder compositions were only capable of providing the necessary conduction path if the grains of powder were coated with graphite, such as is sometimes done with granulated lift powders. For the low electrical conductivity of black match, the only material potentially in contact with the electric match tip inside a connector, it was found that the static voltage level anticipated under the likely conditions of use was not sufficient to cause the ignition of an electric match due to a discharge from the bridgewire through the electric match composition.

The pieces of thin black match, shown inside the connector in Figure 2, should serve well to insure the rapid and reliable ignition of the short length shell leader attached to the shell's lift charge. Given the labor costs in China, the use of pieces of thin black match would seem to be a prudent expenditure. However, in the thought that some users of the connectors installed in the US might be tempted to forego the use of pieces of thin black match, some testing was undertaken. Figure 4 is a photograph of the jet of fire produced by the firing of a Daveyfire A/N 28 BR match installed into the end of a bare Shogun electric match connector, without the use of the thin strands of black match. The main body of the jet of fire extended approximately 5 inches (125 mm) from the end of the connector and sparks ranged to about 15 inches (380 mm). This

result suggests that coupling a connector directly to a reasonably good grade of quick match under reasonably good conditions should provide a reasonably high level of ignition reliability.

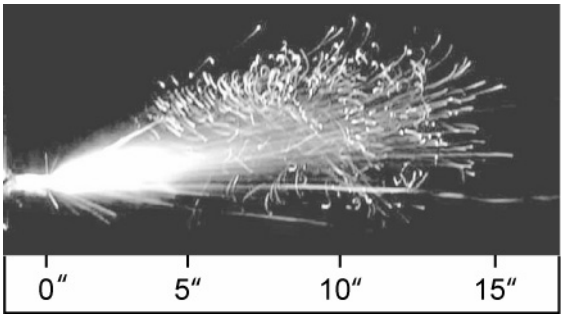

Figure 4. A photograph of the firing of a Daveyfire A/N 28 BR electric match from a bare electric match connector, without the use of the thin strands of black match.

The authors are grateful to John Werner for providing a number of the Shogun Electric Match connectors for evaluation and testing.

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 in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 6 (2001 and 2002)*, Journal of Pyrotechnics, 2005.

3) K. L. & B. J. Kosanke, "DOT Exemption for Display Fireworks with Electric Matches Attached," *Fireworks Business*, No. 221, 2002; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 6 (2001 and 2002)*, Journal of Pyrotechnics, 2005.

4) Shogun (USA) Pyrotechnics, Ltd., US Technical Correspondent, John Werner, 410-287-4849, jawerner@dol.net.

5) Personal communication, John Werner, Shogun (USA) Pyrotechnics, Ltd.

An earlier version appeared in *Fireworks Business*, No. 241, 2004.

The Effect of Intentionally Caused Fire Leaks into 2¼ -Inch Plastic Firework Aerial Shells

K. L. and B. J. Kosanke

A series of experiments are being conducted to more definitively establish the difference between the causes of so-called flowerpots[1] and muzzle breaks.[2] Testing was performed to document the effect of firing small firework aerial shells after having intentionally provided fire leaks into those shells. The idea for this testing originated from a conversation that occurred during a break between paper presentations at the First International Symposium on Fireworks. At that time, the authors were engaged in research to determine the cause and mechanism of some types of aerial shell malfunctions. This work focused on the time taken for various size aerial shells to explode after the ignition of their contents and the time for those same size shells to exit a mortar after ignition of their lift charges. Based on this work, the authors had concluded that relatively minor fire leaks (through small holes and cracks) would be expected to preferentially produce muzzle breaks rather than flowerpots and that flowerpots must be the result of more substantial fire leaks into the shells.[4] Part of the reason for the conversation was to solicit input regarding the authors' work from two persons highly knowledgeable in the manufacture of aerial shells.

That conversation produced two especially useful pieces of information. The first was that substantial fire leaks could be introduced into aerial shells as a result of a time fuse being pulled out of a shell by the fuse rubbing against the mortar wall as the shell attempted to rotate while still inside of the mortar.[5,6] The second piece of information was a report of some testing previously done on small diameter plastic aerial shells wherein holes were drilled into their plastic casings before being fired.[7] While details of that testing could not be recalled, it was reported that not until "incredibly large holes" were drilled into the shell casings, could they be caused to explode as a flowerpot while still inside the mortar. In the absence of such large holes, the shells proceeded upward some distance from the mortar before bursting as muzzle breaks. The testing being reported in this article is an attempt to reproduce and document this second piece of information.

Test Procedure

For these initial tests, 2 1/4-inch (57-mm) Holiday shells (kits of 6 shells and a mortar[8]) were chosen (see Figure 1). The Holiday shells had: plastic casings with an external diameter of

Figure 1. Photograph of a Holiday 2¼-inch (57-mm) shell.

2.01 inches (51.1 mm), a wall thickness of 0.07 inch (1.8 mm) in the area of the time fuse (where fire-leak holes were to be drilled), and an integrally molded lift cup. The shells had an average overall mass of approximately 2.5 ounces (70 g) (exclusive of lift powder), of which approximately 1.3 ounces (36 g) were small spherical stars primed with Black Powder, and there was little or no additional break powder. The mortars were paper, with an average internal diameter of 2.19 inches (55.6 mm) and a length of approximately 11 inches (279 mm) above the mortar plug.

To prepare the shells for firing, the bottom of their lift cup was removed; the lift powder was poured out and the shell leader fuse was removed. A fire-leak hole was drilled into the shell's casing near the location of the time fuse (which was not altered in any way), see Figure 2. The lift charge was placed into a small plastic bag, the shell leader was inserted into the bag and the bag was tied shut. The bag of lift powder was then inserted into the plastic lift cup of the shell. For each size fire-leak hole, a total of at least 6 test shells were prepared. A height calibrated video recording was made to document the burst height of the shells as they were fired, see Figure 3. Individual burst heights were estimated to approximately 1 foot (.31 m). This was easily accomplished when the burst was well separated in time and space from the muzzle flash from the mortar, such as shown in Figure 3. When the burst was not well separated from the muzzle flash, it was considerably more difficult to estimate the burst height. However, as a result of having analyzed many test firings, subtle differences in the light intensity and duration were found that allowed reasonably certain burst heights to be estimated.

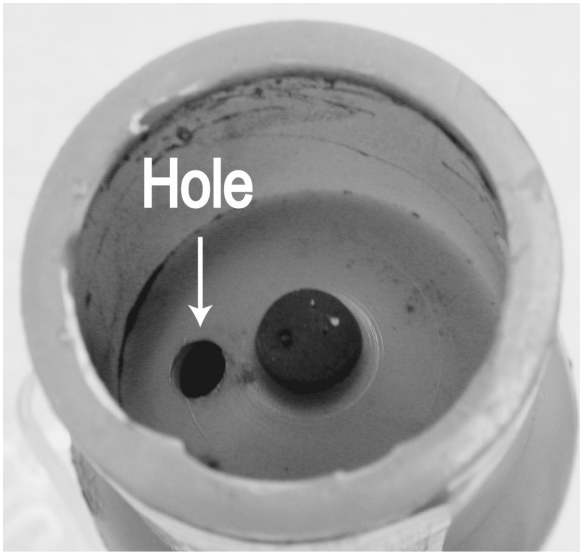

Figure 2. A photograph of the inside of the lift cup of a test shell, showing the primed time fuse (center) and the large 0.20 inch (5.1 mm) fire-leak hole (slightly to the left of center).

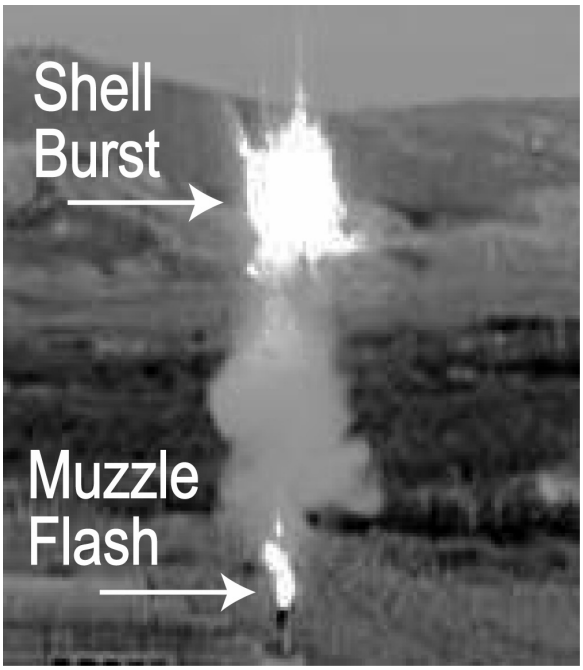

Figure 3. A video image (1 video field; 1/60 s) capturing the burst of a test shell at a height of approximately 7 feet (2.1 m) above the muzzle of the mortar.

Burst Height Results

The results of the test firings are reported in Table 1 and Figure 4. The most significant observation is that surprisingly large fire-leak holes needed to be drilled through the shell casing to cause the shells to explode at about the mouth of the mortar. (In the case of the shell burst shown in Figure 3, the fire-leak hole in the shell was 0.17 inch (4.3 mm) in diameter, nearly as large as that shown in Figure 2.) It is thought that the primary reason it required such a large hole to cause shells to burst near the muzzle of the mortar, lies in the nature of the break charge. For the

most part there was no break charge; there was only the prime on the outside of the many small stars, plus a relatively small amount of dust from the prime, to serve as the break charge. The relatively slowly reacting contents of the shells would be expected to produce only a modest amount of gas to burst the shells. Thus, while the presence of a large fire-leak hole would initially allow the entrance of a relatively large amount of fire into the shell, to rapidly ignite its contents, that same large hole would then allow the escape of a relatively large amount of burst gas prior to the shell exploding. This was confirmed in some of the video records of the testing, wherein some of the ascending shells occasionally appear to have fire jetting from their fire-leak holes prior to the shells exploding.

In looking at the graph of the data, probably the most striking feature is the large uncertainties in the average burst height reported. The variability is thought to be the result of a combination of the difference between the various shells in the Holiday shell kits, combined with the intrinsic high variability of the ignition and propagation processes. The result is a fairly large degree in uncertainty of the exact nature of the trend line shown in Figure 2. (Had it been necessary to determine a more exact dependence of average burst height as a function of the size of the fire-leak hole, certainly many more test shells would have needed to have been fired.)

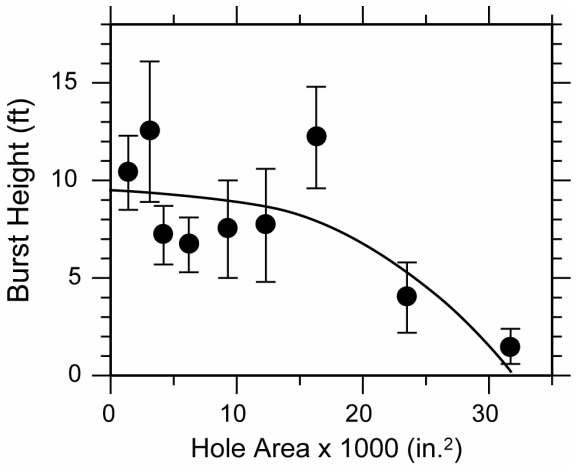

Figure 4. Graph of fire-leak hole area versus average shell burst height for Holiday test shells, including standard error bars.

Measurement of Burst and Exit Times

To better understand the burst height test results, some additional testing was performed. In one series of tests, the burst times for the 2¼-inch (57-mm) Holiday shells were determined (i.e., the time taken for the shells to explode after their contents were ignited). To accomplish this, a technique that had proven effective in previous measurements was employed (see reference 4 for more detailed information). The first step was to install and seal an electric match

Table 1. Burst Height Data for Holiday Test Shells with a Fire-Leak Hole in their Shell Casing.

Test No.	Hole Diameter		Hole Area		Burst Height[(a)]		Standard Deviation[(b)]		Standard Error[(c)]	
	(in.)	(mm)	(in.^{2})	(mm)^2	(ft)	(m)	(ft)	(m)	(ft)	(m)
1	0.043	1.09	0.0014	2.29	10.4	3.17	4.2	1.3	1.9	0.6
2	0.062	1.57	0.0031	5.08	12.5	3.81	9.6	2.9	3.6	1.1
3	0.073	1.85	0.0042	6.88	7.2	2.20	3.4	1.0	1.5	0.5
4	0.089	2.26	0.0062	10.16	6.7	2.04	3.4	1.0	1.4	0.4
5	0.109	2.77	0.0093	15.24	7.5	2.29	6.1	1.9	2.5	0.8
6	0.125	3.18	0.0123	20.16	7.7	2.35	7.1	2.2	2.9	0.9
7	0.144	3.66	0.0163	26.71	12.2	3.72	6.4	2.0	2.6	0.8
8	0.173	4.39	0.0235	38.51	4.0	1.22	4.5	1.4	1.8	0.5
9	0.201	5.11	0.0317	51.95	1.5	0.46	2.3	0.7	0.9	0.3

a) Average burst height for the series of firings.

b) One sigma standard deviation, using the (n – 1) method.

c) One sigma standard error is the standard deviation divided by the square root of the number of measurements in the average.

(Daveyfire A/N 28 B) into the wall of the casing of each of six test shells, such that the match tip protruded approximately ¼ inch (6.4 mm) into the shell's interior. Then two wraps of thin wire were attached to the exterior of the shell casing, such that one wrap was at a 90 degree angle to the other. By monitoring their continuity, the wires provided a means to detect when the shell casing burst. During the actual testing, an electronic firing and timing device was used to measure the burst times. This device had a 10 kHz clock that started when the firing current was applied to the electric match, and the clock stopped when a break in the wires encircling the shell was detected. (The level of current used to fire the electric matches had previously been determined to be sufficient to fire them in less than 0.001 second.) Burst times were found to range widely, from 0.014 to 0.078 second, and they averaged 0.033 second.

In another series of tests, the time taken for 2¼-inch Holiday shells to exit their mortar after igniting their lift charges was determined. To accomplish this, again a previously reported technique was employed.[4] The lift charge was removed from each of six test shells and the powder put into a small plastic bag. An electric match (Daveyfire A/N 28 B) was inserted into the bag, which was then sealed and inserted into the shell's lift cup. Each test shell was loaded into a mortar, after which a trip wire was tightly installed across the muzzle of the mortar. The same firing and timing device described above was used to fire the shell and measure its exit time from the mortar (i.e., the time between igniting the lift charge and the breaking of the trip wire). Again the individual times were found to range fairly widely, from 0.029 to 0.047 second, and they averaged 0.038 second.

In the context of the issue of shells exploding in their mortars, another piece of information is needed. Based on several earlier studies, it is known that there is an extended interval of time after the lift powder has started to burn and before a noticeable pressure rise takes place in the mortar. Typically this time interval is about half of the total time taken for a shell to leave the mortar, and measurements of the mortar pressure profiles for the Holiday shells revealed time delays of the same magnitude. Thus, the interval of time when there is a significant pressure gradient inside the mortar that can be effective in forcing flaming lift gasses through the fire-leak holes in the test shells is only approximately 0.019 second (0.038 s / 2 = 0.019 s)

Using these test results, on average if the effective amount of fire leaking into the interior of the Holiday shell is approximately the same as that produced by an electric match, the shells will not explode until about 0.014 seconds after they have left the mortar (0.033 s – 0.019 s = 0.014 s). Assuming the muzzle velocity of the Holiday shell follows the same trend as larger shells; this time interval corresponds to a distance of a few feet above the muzzle of the mortar. Thus, based on the combined results of the average time measurements, the burst height results reported above (Table 1 and Figure 4) seem reasonable.

Tests Using Other Burst Charges

If test shells having burst times that are less than those for Holiday shells were used, then the size of the fire-leak hole needed to produce an in-mortar explosion should be smaller. As confirmation of this, additional Holiday shells were prepared using two different types of contents. In one brief series of tests empty casings were filled with 1.3 ounces (36 g) of Black Powder (Goex, 4FA). In another brief series of tests 0.3 ounce (8 g) of a flash powder (70:30, potassium perchlorate and dark pyro aluminum) was used with an additional 1.0 ounce (28 g) of weight added to the test shells. The results of these tests are summarized in Table 2.

Based on a single measurement, a Black Powder filled shell had a burst time of a little less than half that of normal Holiday shells. Correspondingly, the area of the fire-leak holes that resulted in the shells exploding while they were still inside their mortars was also found to be about half that for normal Holiday shells. Based on a single measurement, a flash powder filled shell had a burst time of a little less than a third that of normal Holiday shells. This was surprising and thought not to be truly representative because previous burst time measurements of salutes had produced substantially shorter burst times. That the single measurement of salute burst time was not an accurate result was supported by the observation that the area of the fire-leak hole that consistently resulted in the salutes exploding while they were still inside their

Table 2. Test Results for 2¼-inch Shells Using Other Burst Charges.

Test Shell Type	Shell Burst Time[(a)] (s)	Fire-Leak Hole				Test Results
		Diameter		Area		
		(in.)	(mm)	($in.^2$)	(mm^2)	
Normal Holiday Shell	0.033	0.20	5.1	0.031	50.8	Shells burst at the approximate muzzle of the mortar.
Black Powder filled Shell	0.015	0.12	3.0	0.012	19.7	One of three shells exploded inside the mortar.[(b)]
		0.16	4.1	0.020	32.8	Two of three shells exploded inside the mortar.[(b)]
Flash Powder filled shell	0.010	0.06	1.5	0.003	4.9	Three of three shells exploded inside the mortar.[(b)]

a) This is for a shell without a fire-leak hole in the casing.

b) These explosions were powerful enough to destroy the mortars.

mortars was less than a tenth that for normal Holiday shells. (Further testing was not performed because of a shortage of Holiday shells to use in that testing.)

Conclusion

The testing reported in this article confirms and quantifies the earlier report of experiments in which seemingly "incredibly large holes" needed to be drilled into small plastic fireworks shells to have those shells burst before exiting their mortar.[7] More importantly, the results of the studies on small plastic firework shells are useful in providing some of the basic information needed to more definitively quantify the difference between the causes of so-called flowerpots and muzzle breaks, even for larger display firework shells. However, as the Black Powder and flash powder filled shell tests show, the results depend on the nature of the aerial shell being considered, and these fire-leak hole data should not be expected to apply quantitatively to larger display shells. Further testing is underway using larger fireworks aerial shells and the first of that work was subsequently reported.[9]

Acknowledgements

The authors are grateful to L. Weinman for providing comments on an earlier draft of this article, to R. Brown and G. Hanson for commenting on this article and for providing insights into the mechanism of flowerpot malfunctions, and to Daveyfire for providing the electric matches used in this study.

Notes and References

1) A common definition for a flowerpot is: "A type of aerial display shell malfunction where the shell bursts with relatively low power within a mortar. It produces an upward spray of ignited stars and other effects, ….".[3]

2) A common definition for a muzzle break is: "A malfunctioning aerial shell which bursts just as it leaves the mortar, scattering high velocity burning stars and other material in all directions near ground level.[3]

3) K. L. and B. J. Kosanke, et al., *The Illustrated Dictionary of Pyrotechnics*, Journal of Pyrotechnics, Inc., 1996.

4) K. L. Kosanke, "Hypothesis Explaining Muzzle Breaks", *Proceedings of the Second 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.

5) This theory was supported in one case by the post event examination of a muzzle breaking shell's time fuse and a portion of the shell casing. The fuse was found to have been bent over and flattened to the extent of being pressed into the outer layers of

the shell casing. More significantly, the fuse was also mostly pulled out of its mounting in the wall of the shell casing. (G. Hanson, Precocious Pyrotechnics, USA, personal communication, 1992.)

6) Note that data supporting the thought of shell fuses occasionally being pulled out when a shell fires was presented in a recent article by M. Speers ("Reasons for Fuse Failure and Drift Distance of Spherical Fireworks Shells", *Journal of Pyrotechnics*, No. 17, 2003).

7) These were plastic cylindrical shells with lengths greater than their diameter, and which ranged in size from 32 to 50 mm in size. (R. Brown, Hands Fireworks, Canada, personal communication, 1992.)

8) Prior to regulation by the US Consumer Product Safety Commission, these shell kits were considered consumer fireworks.

9) K. L. and B. J. Kosanke, "The Effect of Intentionally Caused Fire Leaks into 3-Inch Display Firework Aerial Shells", *Fireworks Business*, No. 249, 2004; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 7 (2003 and 2004)*, Journal of Pyrotechnics, 2005.

An earlier version appeared in *Fireworks Business*, No. 242, 2004.

Typical Mortar Recoil Forces for Spherical Aerial Shell Firings[a]

K. L. Kosanke and L. Weinman

(Included in the text of this article are a series of notes. These notes present ancillary information that may be of interest to some readers but are not strictly needed within the context of this article. Thus readers should feel free to ignore the notes unless they desire more information.)

One of the more common requests for information regards the recoil force produced when aerial shells are fired from mortars. Generally the concern is whether some support structure (e.g., roof top, platform or barge deck) will safely accommodate the dynamic load produced as shells of various sizes are fired from mortars placed upon the support structure. Providing a precise answer can be a complex engineering problem, requiring information that is not readily available. However, providing reasonable estimates for the recoil forces produced by the firing of typically performing aerial shells is a relatively easy matter. This article provides those approximate values for typical 3- through 12-inch (75- through 300-mm) spherical aerial shell firings. (These values are only for single break spherical shells; they are not for cylindrical shells or for so-called stacked, double-bubble, or peanut spherical shells.)

Pressure is defined as the force applied per unit area, thus in the English system it has units such as pounds (force) per square inch (area). Accordingly, to calculate the total force (F) produced by a pressure acting on some surface, simply multiply the pressure being applied (P) by the area (A) over which it is acting, i.e.,

$$F = P \times A \qquad (1)$$

In the case of an aerial shell firing, if P is the pressure developed inside the mortar[b] and A is the inside cross-sectional area of the mortar, a reasonable estimate of recoil force can be calculated using equation 1.[c] There is no net contribution to recoil force produced by the pressure acting radially on the inside walls of the mortar. This is because the force against each small portion of mortar wall is balanced by an equal but opposite force on the portion of mortar wall directly across from it.[d] Accordingly, all that is needed to produce the estimates of recoil force is knowledge of the pressure profile in the mortar (i.e., internal mortar pressure as a function of time) and the inside cross-sectional area of the mortar (calculated using the internal diameter of the mortar).

Figure 1 illustrates internal mortar pressure as a function of time during the firing of a typical 4-inch (100-mm) aerial shell. First there is an extended period of time (t_0 to t_i) during which there is effectively no pressure rise inside the mortar. This length of time is commonly 0.01 to 0.02 second. This corresponds to the time taken for fire to spread among and ignite the grains of lift powder, before there is sufficient gas production to cause a detectable pressure rise in the mortar. After that, there is a rapidly accelerating increase in mortar pressure up to some peak value, generally occurring over a period of 0.005

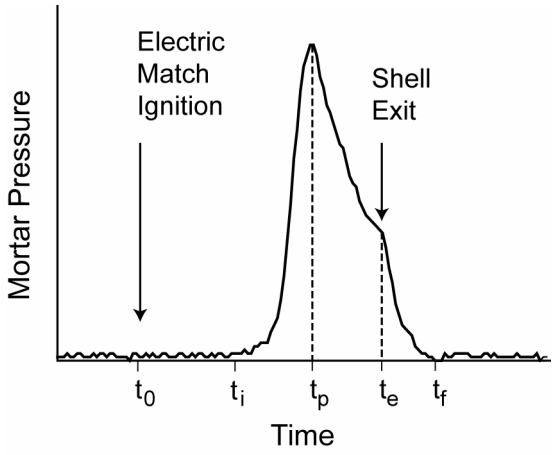

Figure 1. A somewhat typical internal mortar pressure profile during the firing of an aerial shell.

to 0.01 second (t_i to t_p).[e] Next, as the shell accelerates upward (increasing the volume below the aerial shell) and the rate of gas production begins to lag, mortar pressure typically drops during the time before the shell exits the mortar (t_p to t_e). This pressure drop generally continues for 0.005 to 0.01 second.[f] Finally, the exiting of the shell causes an even more precipitous drop in mortar pressure back to ambient levels over a time period of 0.005 to 0.01 second (t_e to t_f). The total duration of the pressure pulse (t_i to t_f) typically ranges from 0.02 to 0.03 second.

While the pressure developed in mortars during a shell firing does depend on shell size, both the general shape of the pressure profile and its duration are mostly independent of shell size.[g] Peak mortar pressures were measured during the firing of 136 spherical aerial shells (ranging in size from 3 to 12 inches [75 to 300 mm]) and were found to be well fitted by a simple linear relationship with shell size.[1] Specifically, the peak pressure was found to increase by approximately 13.6 psi per shell inch (94 kPa/25 mm), as is shown in column 2 of Table 1. Using equation 1, these peak pressures can be converted to peak recoil forces, simply by multiplying peak pressure by the inside cross-sectional area of the mortar, see columns 3 and 4 of Table 1.

For most support structures (e.g., a reasonably substantial building roof) the response of the structure to the recoil force of a mortar firing will not be proportional to the peak force but rather to the impulse delivered.[i] (The impulse delivered is equal to the product of the average force exerted, times the total duration of the force.[j]) In testing it has been found that the average recoil force is approximately 45% of the peak force, mostly independent of shell size. Accordingly, the average force reported in column 5 of Table 1 is just 45% of the peak force value for that size shell in column 4. It has also been found that the typical duration of the recoil

Table 1. Mortar Pressure, Recoil Force and Impulse for Various Size Aerial Shell Firings.

Mortar Size [ID]		Peak Pressure (i)	Mortar Area (ii)	Peak Force (iii)	Average Force (iv)	Impulse (v)	Equivalent 4 foot drop (vi)
(in.)	(mm)	(psi)	(in.^{2})	(lbf)	(lbf)	(lbf s)	(lbf)
3.0	75	41	7.1	290	130	3.3	7
4.0	100	54	13.	700	320	7.9	16
5.0	125	68	20.	1,400	630	16	32
6.0	150	82	28.	2,300	1000	26	52
8.0	200	106	50.	5,300	2400	60	120
10.0	250	136	79.	11,000	5000	120	240
12.0	300	163	110.	18,000	8000	200	400

i) From reference 1, to the nearest 1 psi. Note to convert from psi to kPa, multiply by 6.9.

ii) Mortar Area, $A = \pi \times d^2/4$, where d = internal mortar diameter. Note to convert from in.^{2} to cm^2, multiply by 6.4.

iii) Peak Force, F = (Peak Pressure) × (Mortar Area) = $P \times A$. The values of peak force are reported to only two significant figures. Note to convert from lbf (pound force[h]) to N, multiply by 4.45.

iv) In examining a number of mortar pressure profiles, the average force exerted over the duration of the mortar's recoil was typically found to be approximately 45% of the peak force produced. The value for each average force in Table 1 is equal to 45% of the Peak Force for that size shell and is reported to only two significant figures. Note to convert from lbf to N, multiply by 4.45.

v) Impulse = (Average force) × (Typical recoil duration), where the typical duration was found to be approximately 0.025 second. The values of impulse are reported to only two significant figures. Note to convert from lbf·s to N·s, multiply by 4.45.

vi) This is the weight of a solid object that, if dropped from a height of 4-feet (1.2 m) on to the support structure, will deliver the same impulse as the firing of that size of a typical single-break spherical aerial shell. This weight in pounds is numerically equal to twice the impulse given in column 6 of Table 1. Values are given to two significant figures, but rounded to next largest pound. (See note k for an explanation.) Note to convert from lbf to kg, multiply by 2.2.

force is approximately 0.025 second.[k] Thus the recoil impulse for each size of typical spherical shell (column 6 of Table 1) is the average pressure value of column 5 multiplied by 0.025 second.

Note that the mortar recoil impulse values (column 6 of Table 1) approximately double for each increase in shell size. This means that the stress delivered to a support structure also more or less doubles with each incremental increase in shell size. That is to say, the firing of a 5-inch (125-mm) spherical shell from a mortar will typically deliver about twice the stress (impulse) as firing a 4-inch (100-mm) shell. While this is useful information, it says nothing about whether the support structure is sufficiently strong to safely withstand the intended size of shell firings. To make that determination, a structural engineer will need to be consulted to consider data such as in Table 1. However, to provide points of comparison with which most readers will be familiar, column 7 has been included in the table.[l] These are solid weights that, when dropped from a height of four feet (1.2 m), will deliver approximately the same impulse as will typically be produced by the firing of that size single-break spherical aerial shell.

For example, from the last column of Table 1, if the support structure can safely withstand the drop of a fairly rigid[m] 7-pound (3.2-kg) mass from a height of four feet (1.2 m), then it can probably survive the firing of a typical 3-inch (75-mm) single-break spherical aerial shell. If you can do the same with a 400 pound (182 kg) rigid mass, then the structure can probably survive the firing of a typical 12-inch (300-mm) spherical aerial shell. However, it is important to consider that:

1) It is implicitly assumed that the size (diameter) of the mass that is dropped is approximately the same as that of the bottom of the mortar being considered.
2) The data in Table 1 is for the firing of *typical single-break spherical aerial shells*,[a] which means that roughly half of the shell firings must be expected to produce forces greater than those presented in Table 1. And some properly functioning single-break spherical shells will produce twice the average recoil force.
3) The values in Table 1 do not take into consideration the possibility of aerial shell malfunctions, which could produce forces substantially in excess of those listed.
4) It is a standard engineering practice to design-in a safety margin of at least two or three.

Although this article provides some approximate guidance regarding mortar recoil forces[n] and the needed strength of support structures for the safe firing of single-break spherical aerial shells,[o] note that neither author is a mechanical or structural engineer. Thus a mechanical or structural engineer needs to be consulted prior to relying on the information presented in this article.

Acknowledgments

The authors are grateful for the comments and suggestions of K. Mniszewski and B. J. Kosanke.

Notes

a) Recent measurements of the mortar pressures produced upon firing spherical aerial shells suggests that some manufacturers are using significantly more lift powder. The result is that the previously reported typical mortar pressures[1] may presently under estimate the pressures now typically being produced. If this is now the case, then the "typical mortar recoil forces" being reported in this article are also under estimates.

b) In this case it is gauge pressure (i.e., the pressure over and above atmospheric pressure), and not absolute pressure, that is used to calculate the resulting force.

c) At least two other factors act to slightly modify the recoil force predicted by equation 1. First, upon firing an aerial shell, there is an upward rush of gas escaping through the gap between the shell's casing and the mortar wall. Some of the motion of this gas flow is communicated to the wall of the mortar. The result of this first factor is that a small upward force is produced that slightly counteracts the much more substantial downward recoil force being produced. The second factor is a result of the constriction provided by the aerial shell that acts somewhat as a plug nozzle in a rocket motor, such that some added thrust may be produced by the escap-

ing lift gas (i.e., the thrust coefficient may be slightly greater than 1.0). The result of this second factor is that a little greater downward force may be produced. For the purpose of this article, both of these minor effects are ignored.

d) The net result of the balanced (equal and opposite) forces on the mortar wall is to produce a tensive force (called hoop stress) in the wall of the mortar. This is only a concern when that force is greater than the tensile strength of the mortar, in which case the mortar will burst. For information on calculating burst strength of pipes (i.e., mortars) see any standard engineering text or any edition of the *Machinery's Handbook* (published by Industrial Press, Inc.) under "strength of materials".

e) Some have attributed this effect to so called "choked flow", apparently thinking that once the velocity of escaping gas reaches the speed of sound and no longer increases, the gas flow ceases to increase even as the pressure continues to increase. There is a limit to gas flow *velocity* at the point of constriction posed by the aerial shell, when that flow velocity reaches the speed of sound under the conditions in the mortar. Nonetheless, because the *density* of the gas continues to increase with pressure, the *mass flow rate* continues to increase even though the velocity of the flow does not. (For more information about choked flow, see reference 3.)

f) With some types and granulations of lift powder, the rate of rise in mortar pressure will be less, and the aerial shell may exit the mortar while the pressure is still increasing. In that case there will be no time interval between the peak recorded pressure and the exit of the shell (i.e., the time from t_p to t_e can be zero).

g) The shape, magnitude and duration of the pressure profile depends on factors such as the characteristics of the lift charge (e.g., its granulation and to a lesser extent its mass), temperature, dead volume under the shell (also called loading space), the mass of the shell, and the size of the gap between the shell and mortar wall.

h) In the Imperial (English) System of units, the pound unit can be either a unit of force or a unit of mass. To help avoid confusion, the abbreviation for pound force is lbf.

i) When a force is applied to a structure, the response of the structure depends on whether the duration of the applied force is greater than or less than the resonant period of the structure.[2] If the duration of the applied force is long in comparison to the resonant period, the response is proportional to the peak force. If the duration of the applied force is less than the resonant period, the response of the structure is proportional to the impulse delivered. Over the course of many measurements of pressure profiles during the firing of aerial shells,[1] it was found that the total duration of the pressure pulse in the mortar (i.e., the duration of the recoil force produced) averaged approximately 0.025 s, and the duration was found to be essentially independent of shell size. For most supporting structures, resonant periods are probably at least 10 times longer, especially for substantial (i.e., massive) structures. Thus the duration of mortar recoil events is much shorter than the resonant period of typical structures, and the structure's response to mortar recoil will be proportional to recoil impulse and not peak recoil force.

j) More correctly from a mathematical standpoint, when pressure is not constant, impulse is equal to the integral of ($P\,dt$).

k) In note g, it was mentioned that there are a number of factors that affect peak pressure and the duration of the pressure pulse. However, in terms of impulse, these factors are less important. This is because those things that tend to increase peak pressure also tend to decrease the duration of the pressure pulse, thus tending to cancel-out the overall effect on impulse.

l) The impulse (I) delivered in stopping a moving object is equal to its momentum (M) since its final velocity is zero. Momentum is equal to the mass (m) of the object times it velocity (v). Further, mass is equal to an object's weight (w) divided by the acceleration due to gravity (g), and the velocity of an object that is dropped is equal to the accelera-

tion due to gravity times the time (t) the object is falling. Thus,

$$I = M = m \times v = \left(\frac{w}{g}\right)(g \times t) = w \times t \qquad (2)$$

The distance (h) an object will fall during a time interval, equals one half the acceleration due to gravity times the square of the time during which it fell. Thus:

$$h = ½ \times g \times t^2 \qquad (3)$$

Solving for t.

$$t = \left(2\left(\frac{h}{g}\right)\right)^{1/2} \qquad (4)$$

For a weight dropped from a height of 4 feet (1.2 m), with the acceleration due to gravity of 32 feet per second squared (9.8 Nm/s^2), the time taken is ½ second.

$$t = \left(\frac{8}{32}\right)^{1/2} = ½ \text{ second} \qquad (5)$$

Thus, substituting for time (t) back into equation 2, the momentum (and impulse) produced by a weight dropped from a height of 4 feet (1.2 m) is numerically equal to one half of that weight. Drops from any other height can be considered in a similar fashion. (For a more complete discussion consult any college level general physics text.)

m) The duration of the recoil force from firing an aerial shell is quite short (approximately 0.025 second, with the peak force coming early and lasting much less than the total duration). A fairly rigid mass is specified as the test object because it is thought that dropping a fairly rigid object will generate a force profile somewhat similar to that of a shell firing. To the contrary, a non-rigid mass such as a sand bag may deliver the same impulse as that of a rigid mass, but the duration of force produced will be longer for the sand bag as its contents shift upon impact. Accordingly, depending on the detailed nature of the supporting structure, the sand bag probably will not produce a stress on a support structure sufficiently similar to that of a shell firing.

n) Subsequent to writing this article, the authors found some published data on the recoil forces produced by large caliber spherical aerial shells. Those data were found to be in reasonable agreement with the estimates included in this article.[4]

o) Regarding the firing of single-break cylindrical shells some very limited testing suggests that the mortar pressures developed are roughly double that of spherical shells of the same size. Thus as a rough approximation, the values given in Table 1 would need to be doubled for the firing of typical single-break cylindrical shells.

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An earlier version appeared in *Fireworks Business*, No. 243, 2004.

Indoor Pyrotechnics – A Brief Cautionary Message

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The forensic science community has had a long-standing interest in the analysis of the residues deposited after the deployment of devices whose operation involves a controlled explosion. For example, testing for the residues of the compounds of lead, barium, and antimony, used in the primer of small-arms ammunitions, may be required on the hands and clothing of individuals to determine whether they may have discharged, or otherwise had contact with, a firearm. As an extension of research in the area of gunshot residue analysis, recent work dealing with the examination of residues from various pyrotechnic devices [1–3] has revealed some trends in the chemical composition of the residues of pyrotechnic devices. A survey of the composition of the starting components and residues from 150 small, consumer grade pyrotechnic devices purchased in the United States revealed that more than 30% of the devices contained some proportion of lead, 5% contained antimony, and 80% contained barium.[3] These devices included fountains, wheels, and ground spinners that are likely to be used in family fireworks displays in close proximity to the spectators.

An examination of 18 consumer grade pyrotechnic devices, manufactured around the world and submitted for testing prior to acceptance for marketing in Canada, revealed that more than 60% contained lead, 50% contained antimony, and more than 75% contained barium.[24] Further, another device, designed for use as a proximate audience item and marketed as appropriate for indoor use, was found to contain lead, barium, and antimony.[2,4]

Many of the products of combustion of pyrotechnic devices will be released as gasses rather than particulates (i.e., smoke), and the method for residue analysis used in this study does not permit a conclusion regarding what proportion of the starting material consisted of heavy metals, but the widespread finding of lead in these devices, particularly in a device designated for indoor use, is a concern.

The particular item designated for indoor use is apparently no longer being sold, so the primary concern is not the current use of these items by unsuspecting pyrotechnists.[5] Rather the concern is that some suppliers have sold (and possibly still are selling) items for indoor use, without knowing whether their chemical ingredients are suitable for indoor use.

As Canadian regulations do not permit the use of lead in indoor devices, it is unlikely that any domestic manufacturer would declare a product containing lead compounds as appropriate for indoor use.[6] Lead has been observed in devices from a number of countries in the world and it is possible that the specific item in this instance was manufactured abroad and only repackaged and labeled in the US.

This occurrence serves as a reminder to importers of proximate audience pyrotechnics intended for indoor use that regulations on the composition of pyrotechnic devices are not universal and that they have a responsibility to verify whether or not the products of combustion from those items are reasonably safe and in compliance with local regulations.

Notes and References

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

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3) M. Trimpe, "Analysis of Fireworks for Particles of the Type Found in Gunshot residue (GSR)", presentation at the American Academy of Forensic Sciences 53rd Annual Meeting, Seattle, Washington, 2001.

4) Residue particles from this device were identified using an automated scanning electron microscope operated in backscatter imaging mode. This mode allows the system to screen out organic debris particles and light elements, such as carbon, sulfur, aluminum, etc., to search for the presence of heavier elements. Using energy dispersive X-ray spectroscopy (EDS), a total of approximately 9200 particles were analyzed for the chemical elements they contained. Of these particles, it was found that a little over 25% of them consisted of lead, antimony, barium, or some combination thereof. Lead particles accounted for the majority of this group of particles.

5) As some pyrotechnists might have some of these items in their inventories, note that the item was labeled as "Glittering Crackle Mine". If they wish, anyone having items with this name may contact author Kosanke at 970-245-0692 for further identifying information.

6) In the US, according to NFPA-1126 (*Standard for the Use of Pyrotechnics before a Proximate Audience*), responsibility for deciding what chemical compositions are acceptable for use in indoor proximate audience pyrotechnics is left with the manufacturer (or importer). However, approval of indoor proximate audience pyrotechnic devices for transportation is facilitated by a manufacturer following the requirements of APA 87-1 (Standard for Construction and Approval for Transportation of Fireworks, Novelties and Theatrical Pyrotechnics), which does not include lead compounds on the list of Standard Fireworks Chemicals. The effect is that an indoor pyrotechnic device using a lead compound requires a more costly and involved method to obtain approval for transportation. The net result is that, while the use of lead compounds in indoor proximate audience pyrotechnics in the US is not expressly prohibited, it is discouraged.

An earlier version appeared in *Fireworks Business*, No. 243, 2004.

Manual Firing Delay Times for Aerial Shells

K. L. and B. J. Kosanke

Introduction

As used in this article, the definition of "manual firing delay time" is the time interval between the manual ignition of the tip of the shell leader delay element and when the aerial shell fires from its mortar. This delay time is of interest in the context of the delay time requirement in the National Fire Protection Association's *Code for Fireworks Displays* (NFPA-1123).

Prior to the 1990 edition of NFPA-1123, the requirement for delay times for the manual firing of shells was that:

"The length of exposed black match on a shell shall not be less than 3 in. (76 mm) .... Also, the delay time between the ignition of the tip of the exposed black match and ignition of the lift charge shall not be less than four seconds ...."

In the 1990 and more recent editions of NFPA-1123, the requirement was changed to:

"... the time delay between igniting the tip of the shell's fuse and the firing of the shell shall not be less than 3 seconds or more than 6 seconds."

In 2003 the NFPA code was in the process of revision, and it was the authors' suspicion that many display fireworks aerial shells in use at the time did not successfully meet the stated requirement for manual firing delay times. Thus a brief study was undertaken to produce the data needed to establish whether it was appropriate to consider 1) revising the requirement in the 2005 edition of NFPA-1123, or 2) encourage manufacturers to better meet the existing requirement. (Certainly, if the requirement were current being met, there would be no need to do either.)

As a significant cost saving measure, aerial shells were not actually fired in this study. The justification for this is based on the following logic. The total manual firing delay time is as the sum of two times: 1) the time for the delay element of the shell leader to burn; and 2) the combined time for the quick match portion of the shell leader to burn, ignite the lift charge, and for the shell to exit the mortar. Since the second of these two times had previously been measured[1] (and is summarized in the paragraph below), there was only a need to measure the burn time of a collection of delay elements and then add the two times together to produce a good estimate of manual firing delay times.

One of the configurations used in the earlier measurements of electrical firing times had the electric match installed at the beginning of the quick match portion of the shell leader, labeled as position number 1 in Figure 1. In these tests, shell leaders from a total of 6 different manufacturers were used to fire 24 shells while measuring the time delay between the ignition of the

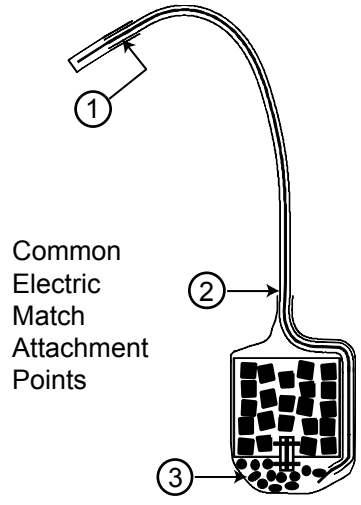

Figure 1. Illustration of the typical points of attachment of electric matches for electrically fired aerial shells.

electric match and the exit of the shell from its mortar. (See reference 1 for details.) The result was an average firing time of 0.33 second. (This average time approximates the second of the two times identified in the above paragraph.)

For an aerial shell fired using a delay element such as exposed black match, the firing time might be found to be slightly shorter than 0.33 second because of the more vigorous burning at the point of ignition of the quick match as compared with ignition produced by an electric match. (See Figure 2 for an example of the large amount of fire produced near what would be the starting end of the quick match portion of a typical shell leader.) However, as will be seen, a suspicion that the actual manual firing burn time may be slightly shorter turns out to be of little consequence for the purpose of this investigation.

Figure 2. Photograph of the flame and sparks projecting to the right from the end of approximately one inch of quick match ignited by black match (on the left) as the delay element of a shell leader.

Testing and Results

Having previously measured one of the two times needed to answer the question posed for this study, what remained was to determine the burn time of the delay element (plus approximately one inch (25 mm) of quick match) of a collection of shell leaders. In that effort, the burn time of a total of more than 120 delay elements with short sections of quick match (approximately 1 inch long) were measured. In all tests each delay element was in the same physical condition as received; however, in no case was the delay element in less than reasonably good condition. The results of the testing are summarized in Table 1.

The initial testing used two types of black / quick match. The first one, labeled as "Prec. Pyro." in the table, was from fairly recent production by Precocious Pyrotechnics and was chosen because it was among the most fiercely burning products available. The second one, labeled as "Unknown", was chosen because it was one of the more mildly burning products available.

For the initial portion of this study, 10 doubly long test segments of both the fast burning and the slow burning match were prepared; then each of these initial segments was cut in half, with each half being placed into one of two separate groups. This was done to help assure that any systematic differences in the performance of the quick match along its length would not distort the results of the measurements.

In the first test series only one of the two sets of fast burning quick match was used and had been conditioned by having been stored for an extended period of time at approximately 60 °F (50 °C) and approximately 30% relative humidity. (Throughout this study, the segments of quick match conditioned in this way are indicated as "Dry" in the descriptions in Table 1.) Prior to testing each of 10 segments, three inches (75 mm) of black match were exposed by pulling it partially from the match pipe. The exposed black match was positioned approximately horizontally and without being in contact with anything that might alter its burn time. The tip of the black match was carefully ignited using a small torch and the segment was allowed to burn while being video taped. The burn time of each segment was determined by means of a frame by frame playback of the tape. The average burn time was 1.06 seconds. As a result of this first test it was also established that the standard error[2] in the average burn times was approximately 0.25 second. Thus it was decided that measuring approximately 10 fuse segments would be sufficient for the purpose of this study. As a base line for further measurements, one of the two sets of 10 fuse segments from the slower burning quick match were prepared and tested as described for the fast burning match. The average burn time was 3.44 seconds.

Next a brief investigation was undertaken to determine the extent to which humidity exposure affected the burn time of the black match. The second set of 10 segments from the fast quick

match and the second set of 10 segments from the slow quick match were placed into a chamber, which was humidity controlled to approximately 85% relative humidity, for 5 days. (See reference 3 for a more complete description of the method for humidity conditioning.) Following humidity conditioning the segments were burned and timed as described above. It was determined that while there was a slight lengthening of the burn time with exposure to relatively high humidity (approximately 10%), given the statistical uncertainty of the measurements, it was concluded that this burn time difference was not sufficient such as to require exposing subsequent test samples to high humidity.

The third series of tests was conducted to determine the extent to which the orientation of the black match delay element affected its burn time. For these tests, two sets of 10 black match segments from both the fast and the slow quick match were prepared and burned as described above. However for these tests the segments

Table 1. Results of Measurements of Aerial Shell Delay Element Burn Times.

Description [a]	Number Tested	Delay Element Burn Time (s)				Total Delay [b] (s)
		Shortest	Longest	Average	Std. Dev.	
Prec. Pyro. – Dry – 3"	10	0.53	2.77	1.06	0.81	1.39
	10	0.67	2.93	1.22	0.72	1.55
Prec. Pyro.– Humidified – 3"	10	0.46	2.87	1.29	0.72	1.62
Prec. Pyro.– Dry – 3" – Up	10	0.60	2.80	1.29	0.62	1.62
Prec. Pyro.– Dry – 3" – Down	10	0.67	2.13	1.17	0.63	1.50
Unknown – Dry – 3"	10	2.93	4.23	3.44	0.37	3.77
Unknown – Humidified – 3"	10	0.70	4.97	3.58	1.09	3.91
Unknown – Dry – 3" – Up	10	2.94	3.73	3.49	0.26	3.82
Unknown – Dry – 3" – Down	10	1.60	2.94	2.26 [c]	0.44	2.59
Jumping Jack – Dry [d]	10	1.53	3.20	2.28	0.44	2.61
Thunderbird – Dry [e]	6	3.73	5.90	4.74	1.03	5.07
Wizard – Dry [f]	5	0.87	2.67	1.83	0.65	2.13
Lido – Dry [g]	6	5.37	4.00	4.89	0.50	5.22
Sunny – Dry [g]	6	4.40	5.97	5.15	0.61	5.48

a) In each case the black match delay elements were in reasonably good condition. Unless otherwise noted, the delay elements were conditioned by an extended exposure to approximately 30% relative humidity and were burned in a horizontal position. The notation "humidified" indicates that the fuse was conditioned for 5 days at approximately 85% relative humidity. The notation "up" or "down" indicates that the fuse was burned in a vertical position; "up" indicating that the burning proceeded in an upward direction and "down" for burning proceeding in a downward direction.

b) The total firing delay time is the burn time of the delay element plus the average delay time from the previous study of delay time with an electric match installed at the start of the quick match. In 30 test firings using shell leaders from a variety of different manufacturers, the delay time averaged approximately 0.33 second. Accordingly, each reported "Total Delay" time in this table is 0.33 seconds longer than the average "Delay Element Burn Time" reported in this table.

c) Quite a lot of dross formed during burning and dropped down the burning strand to ignite more of the exposed match more quickly.

d) The delay element was black match with a dusted piece of tissue and loose string tie at the point of becoming quick match. The average length of black match was 3.1 inches.

e) The delay element was flat black match and covered with pasted paper at the point of becoming quick match. The average length of black match was approximately 2.8 inches.

f) The delay element was black match, which was unconstricted and uncovered at the point of becoming quick match. The average length of black match was approximately 3.5 inches.

g) The delay element was a single strand of heavy visco-like fuse, approximately 5/32 inch (4 mm) in diameter. The connection at the point of attachment with the quick match was closed with a pasted wrap of paper.

were held vertically (instead of horizontally) while being burned. One set of fuse segments from each type quick match was burned from the bottom upward and the second set was burned from the top downward. The average upward burn time for the slow burning black match was approximately unchanged compared with burning it horizontally; whereas for the fast burning match, the average upward burn time was approximately 10% longer. To the contrary, average downward burn time for the fast burning black match was unchanged compared to when burned horizontally; whereas for the slow burning match, average downward burn time was approximately 30% shorter. Obviously the two types of black match responded differently to each other when being burned vertically rather than horizontally. To avoid having to test all types of shell leaders in multiple orientations, and because it is thought to more nearly represent the typical firing orientation, it was decided that the remaining testing should all be conducted with the delay elements positioned horizontally.

In the remaining tests, the delay elements and approximately one inch of shell leader from 5 other manufacturers were harvested for testing as described above. The delay elements used by three of these manufacturers were exposed lengths of black match, whereas the other two manufacturers used a single strand of thick visco-like fuse having a substantial powder core.[4] The average burn time for the different manufacturers' delay elements ranged widely, from approximately 1.8 to 5.2 seconds.

Conclusion

The overall average manual firing delay time estimated for shell leaders from the seven sources of fuse tested is approximately 3.7 seconds. While this is within the NFPA-1123 range of from 3 to 6 seconds, if the burn time for the shell leaders from those two manufacturers using the heavy visco-like delay elements are not included, the average manual firing delay time for the remaining five manufacturers (those using black match delay elements) is only 3.0 seconds. This suggests that perhaps half of the display aerial shells using black match delay elements, fire in less than the minimum 3 second NFPA-1123 requirement.

Thus it could be concluded that either the NFPA-1123 firing delay time requirement needed to be adjusted, or a number of conventional shell leader manufacturers need to modify their products to be in compliance with the delay time requirement. However, it is not the purpose of this article to recommend a specific solution, but rather only to identify a potential problem deserving attention. (Note that the Technical Committee on Pyrotechnics of the NFPA subsequently decided to modify the delay time requirement in the 2005 edition of the code to 2 to 6 seconds.[5])

Acknowledgments

The authors are grateful to L. Weinman (Schneier / Weinman Consultants) for commenting on an earlier draft of this article and to Marc Williams (Night Music) for supplying some of the shell leaders using in the testing.

References and Notes

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2) The standard error of the average is the standard deviation of the series of measurements (calculated using the $n - 1$ method) divided by the square root of the number of measurements in the average.

3) K. L. and B. J. Kosanke, "Quick Match; A Review and Study", *Proceedings of the 4th International Symposium on Fireworks* (1998); also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)*, Journal of Pyrotechnics, 2005.

4) The use of this type of delay element has become increasingly common in recent years.

5) NFPA-1123 (2006) *Code for Fireworks Display*, National Fire Protections Assoc.

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A Brief Description of the Construction and Function of Common Electric Matches

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ABSTRACT

A simple description of the construction and the physical principles governing the function of common electric matches and some implications of these principles for testing and firing them are presented.

Keywords: electric match, heat resistance, current, volt, pyrogen

Introduction

This article offers a brief and not overly technical description of how typical electric matches function. It is hoped that this information will be of assistance to those who use them. As a general aid to readers with somewhat limited technical experience, a series of definitions have been included at the end of this article. Because the information presented in this article can be found in numerous texts, except for some direct quotes included in the definitions, specific references are not cited in this article.

In concept, the basic operation of an electric match is quite simple. An electric current is passed through the resistance of the bridgewire. Over time, as energy is dissipated in the bridgewire, it heats-up. A portion of that heat is transferred to the chemical composition (pyrogen) of the electric match. When the pyrogen reaches its ignition temperature, it reacts to produce the desired output of fire from the electric match.

An Idealized Electric Match

Figure 1 is an illustration of a cross sectioned idealized (i.e., imaginary) electric match. The adiabatic barrier is meant to imply that, for the purposes of this example, no thermal energy (heat) may flow through the barrier, not even into the electrical conductors by means of conduction through the ends of the bridgewire. In the center of the bridgewire is a *very small* amount of pyrogen in intimate contact with the bridgewire. It will be assumed that the contact is sufficiently good such that the temperature of the pyrogen is always equal to the temperature of the bridgewire. It will also be assumed that the amount of pyrogen is so small that its heat capacity is a negligible addition to that of the bridgewire.

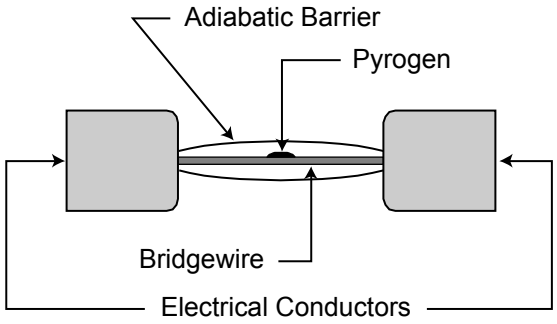

Figure 1. Illustration of an idealized (i.e., imaginary) electric match.

Given the conditions descried above, and after providing somewhat typical physical characteristics for the system, it is possible to calculate the minimum energy needed to function (fire)

this ideal device. Specifically, it will be postulated that:

- The bridgewire:
  - Diameter (d_{bw}) is 0.025 mm
  - Length (l_{bw}) is 2.0 mm
  - Density (ρ_{bw}) is 8.0 g/cm^3
  - Specific heat capacity (C_{bw}) is 0.46 J/g°C (independent of temperature)

  The ambient temperature (T_a) is 27 °C (81 °F).
- The ignition temperature for the pyrogen (T_{ig}) is 327 °C

Using this information some useful calculations can be performed. First, the mass of the bridgewire (m_{bw}) is simply the product of its density and its volume (V_{bw}),

$$\begin{aligned} m_{bw} &= \rho_{bw} \cdot V_{bw} = \rho_{bw}\left(\pi \cdot \frac{d_{bw}^2}{4} \cdot l_{bw}\right) \\ &= \left(\frac{8.0\ \text{g}}{\text{cm}^3}\right)\pi\frac{(0.0025\ \text{cm})^2}{4}(0.20\ \text{cm}) \quad (1) \\ &= 0.0000079\ \text{g} \ \ (\text{i.e., } 7.9\times10^{-6}\ \text{g}) \end{aligned}$$

The amount of energy (J_{bw}) required to raise the bridgewire temperature by one degree Celsius (1 °C) is just the product of its specific heat capacity (C_{bw}) and its mass (m_{bw}),

$$\begin{aligned} J_{bw} &= C_{bw} \cdot m_{bw} \\ &= (0.46\ \text{J/g°C})(7.9\times10^{-6}\ \text{g}) \quad (2) \\ &= 3.6\times10^{-6}\ \text{J/°C} \end{aligned}$$

Since the pyrogen needs to be raised from ambient temperature to its ignition temperature to cause its ignition, the electrical energy required for ignition is (J_{ig}),

$$\begin{aligned} J_{ig} &= (T_{ig} - T_a)\ J_{bw} \\ &= (327\ \text{°C} - 27\ \text{°C})(3.6\times10^{-6}\ \text{J/°C}) \quad (3) \\ &= 1.1\times10^{-3}\ \text{J} \ \ (\text{i.e., } 0.0011\ \text{J}) \end{aligned}$$

In calculating the *minimum* energy required to function this idealized electric match, note that no consideration needed to be given to bridgewire resistance, the voltage applied, the current flowing, or time to ignition. When performing this type of analysis only the mass, specific heat capacity, and ignition temperature are needed to determine the minimum firing energy. Any combination of the applied voltage, total circuit resistance, electric current and time that provides the minimum firing energy will cause the functioning of this idealized electric match.

A More Nearly Real World Electric Match

Figure 2 is an illustration of a cross section of a more nearly real world electric match, and for which there are both similarities and differences from the ideal case. The most important differences are that there is no adiabatic barrier to preclude the escape of thermal energy and by no means does the pyrogen present a negligible contribution to the heat capacity of the bridgewire. (Complicating the situation is that typically the thermal characteristics of the pyrogen are not well known.) There also exists a heat transfer path out the ends of the bridgewire into the electrical contacts. However, this path is generally considered to be negligible, provided that the length of the path is a minimum of approximately 6–12 wire diameters to each of the electrical contacts. Thus, allowing for an additional distance of 5–10 bridgewire diameters at the center of the electric match, if the total bridgewire length is approximately 25 times its diameter, then the loss of heat through its electrical contacts will be negligible.

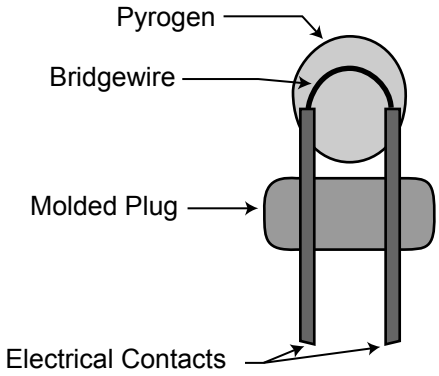

Figure 2. An illustration of a more realistic electric match.

For this more realistic electric match, the primary added consideration is the additional energy required to heat that portion of the pyrogen in immediate contact with the bridgewire while

at the same time this thin layer of pyrogen is transferring heat further outward into the bulk of the pyrogen. Taking a somewhat simplified approach to the problem, at any given time the net amount of thermal energy having accumulated in the thin layer of pyrogen in immediate contact with the bridgewire (J_{net}) is simply the difference between the energy into (J_{in}) and the energy out of (J_{out}) that pyrogen layer.

$$J_{net} = J_{in} - J_{out} \tag{4}$$

The total energy into (or out of) the layer is the rate of energy (i.e., power) being supplied (or leaving) multiplied by time. However, because the rates of energy into and out of the pyrogen layer are not constant over time, this problem must be treated as an integral equation from calculus. While this approach could be taken, it would not be consistent with the "not overly technical" approach promised for this article.

Instead, consider the following analogy, pouring water into a bucket with a hole in its bottom. At any time the amount of water in the bucket will be the difference between the amount of water that has been put into the bucket, minus the amount that has leaked out. (In this analogy, the amount of water in the bucket represents the amount of thermal energy in the layer of pyrogen closest to the electric match bridgewire.) If one adds water very slowly to the bucket, because the water is leaking out as fast as it is being added, only an insignificant amount of water will accumulate in the bucket no matter how long the process continues. If the rate of pouring into the bucket is increased, more water will begin to accumulate in the bucket (i.e., the pyrogen will get hotter). However, as the level of the water in the bucket increases, so does the rate at which it leaks out of the hole. Accordingly, even after adding water for a long time, it may not continue to accumulate to the point of the bucket becoming full (i.e., the pyrogen may not get so hot as to ignite). At some further increased rate of adding water to the bucket, continuing to add water will eventually cause to bucket to fill completely. However, the length of time required to fill the bucket depends on the size of the bucket and the size of the hole. In this analogy, the way to fill the bucket using the least amount of water, is to pour the water into the bucket very rapidly, before much water has a chance to leak out.

For an electric match, the rate of adding thermal energy *(W)* is equal to the current through the bridgewire (I_{bw}) times the voltage drop across the bridgewire (E_{bw}). However, from Ohm's law, the voltage drop across any resistance is equal to the current through the resistance times the value of the resistance ($E = I \cdot R$). Thus, in the case of the bridgewire, the rate of adding thermal energy equals the current through the bridgewire squared (I^2), times the resistance of the bridgewire (R_{bw}).

$$W = I_{bw} \cdot E_{bw} = I_{bw}^2 \cdot R_{bw} \tag{5}$$

Further, the amount of energy added (J) is the rate of addition (W) multiplied by time (t).

$$J = W \cdot t = I_{bw}^2 \cdot R_{bw} \cdot t \tag{6}$$

Following the thinking of the leaky bucket analogy, if the rate of adding energy to the bridgewire is too low (i.e., the rate of adding water to the bucket is too low), the pyrogen layer directly against the bridgewire will heat-up a little, but it will never become hot enough to ignite (i.e., the bucket will never get full) no matter how long the electrical energy is supplied. Although not strictly correct, for the purposes of this discussion the resistance of the bridgewire will be considered to remain constant during the heating process of this particular electric match. With this assumption, referring to equation 5, only the current determines the rate of energy being added to that electric match, and if that current is too low, the electric match will fail to ignite no matter how long the current is applied. The maximum electric current that fails to be capable of igniting the pyrogen even after some specified (long) time, may be called the *no-fire current* for that electric match under a specific set of conditions.

As the amount of electric current passing through the bridgewire is increased beyond the no-fire current level, there will come a time when the electric match will ignite providing one is willing to wait long enough. (In the leaky bucket analogy, this corresponds to the minimum rate of adding water that will eventually cause the bucket to fill completely.) This minimum electric current, that will eventually cause the ignition of an electric match, may be called the *all-fire current* for that electric match under a specific set of conditions.

The least amount of energy needed to ignite the electric match occurs when that energy is supplied very quickly (i.e., when the water is poured very quickly into the leaky bucket so that almost none has a chance to leak out). Using equation 6 above, this *minimum firing energy* can be calculated for a specific electric match.

Some of the principles discussed above are illustrated in Figure 3, which is a graph of firing time as a function of applied current for a generic electric match. Note that the curve takes the approximate shape of a hyperbola. At low currents, the firing time is effectively infinite (i.e., the electric match never ignites). As higher currents are applied, some electric matches fire but on average it takes a relatively long time. As still higher currents are applied, the average time to fire becomes less. However, as the applied current continues to be increased, while the firing times still decrease, the amount of decrease becomes smaller and smaller. Finally, when the applied current becomes very large, there comes a point where the firing time has become essentially constant, because the time for thermal energy to 'leak' away before the device fires has become negligible.

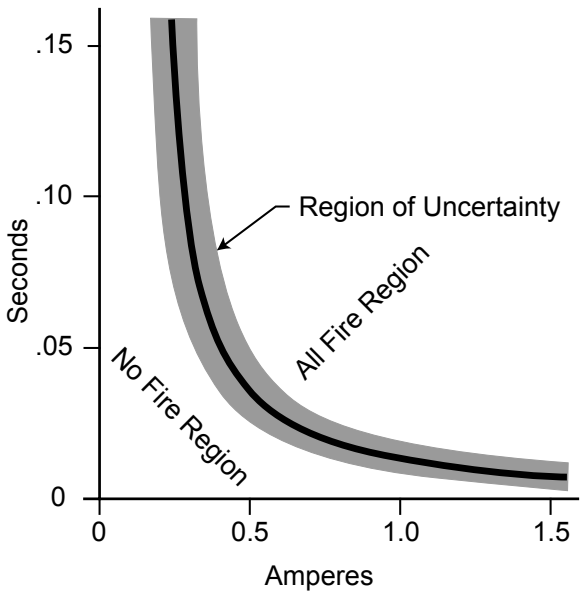

Figure 3. Firing time as a function of applied current for one type of electric match.

No-Fire Current

In Figure 3, the left and lower edge of the shaded band is an estimate of the no-fire current for this particular electric match, under the test conditions used. However, just specifying the no-fire current of an electric match does not fully define its firing characteristics. To be fully definitive, one also needs to consider both the time during which the current is applied and the thermal environment of the electric match. For example, even applying a minimal test current will cause the match composition to begin to heat up. If that electric current is maintained long enough, and if the heat being produced is allowed to accumulate because the electric match is extremely well insulated, eventually the pyrogen could reach its ignition temperature. (Note that when information about time and thermal environment is not specifically provided, a time of application of 5 to 10 seconds and a thermal environment of free air at 20 °C are typically meant to be implied.)

Because it cannot be absolutely assured that no electric match of a given type would ever ignite if a current equal to its no-fire current were applied, the maximum continuity test current is generally required not to exceed 20% of the no-fire current stated by the electric match manufacturer. (Note that some manufacturers may not specify the no-fire current for their electric matches. However, in all cases strict adherence to a manufacturer's maximum test current is required.)

All-Fire Current

In Figure 3, the right and upper edge of the shaded area is an estimate of the all-fire current for this particular electric match, under the test conditions used. As with the no-fire current, the same cautions apply to interpreting the meaning of this all-fire current. Changes in test conditions and variations in the performance of an individual electric match can significantly alter the all-fire current value. For example, the type of electrostatic discharges commonly produced by individuals as they work, may produce electric currents many times greater than the all-fire current. Yet very few, if any, standard electric matches will fire from such an electrostatic discharge pulse passing through the bridgewire. This is because the duration of the current pulse

is very short, typically less than a few microseconds in duration, and so has little total energy.

Because it cannot be absolutely assured that all electric matches of a given type will always ignite if a current equal to their all-fire current were applied, the recommended individual electric match firing current is typically about 40% above the all-fire current stated by the manufacturer, and the recommended series firing current is typically about double the all-fire current. (Note that this corresponds to supplying electric power at a rate that is two and four times that at the all-fire current, respectively, see equation 5.)

Additional Considerations

The shaded area in Figure 3, between the no-fire and all-fire currents, is a region of uncertainty, wherein it cannot be absolutely assured whether or not any individual electric match, of the type being considered, will ignite.

For the purposes of this discussion, a *good* electric match will be defined as one for which the thermal contact between the bridgewire and the pyrogen is completely effective, and a *bad* electric match will be one for which the thermal contact is imperfect or incomplete. Within the context of these definitions, note that a good electric match will require a greater firing energy to function than will a bad device. This is because, at normal firing current levels, the good device will transfer more heat away from the critical interface between the pyrogen and bridgewire, before that pyrogen heats up sufficiently to ignite. Whereas, in the bad device, the voids, cracks, decoupling, etc. serve to impede the heat flow away from the interface. As a result, that portion of the pyrogen still well coupled to the bridgewire will reach its ignition temperature sooner, thus requiring less total energy to function the electric match.

Following the good/bad terminology of the previous paragraph, consider an *extremely bad* electric match, one in which there has been a total decoupling of the pyrogen from the bridgewire. This can, and often does, happen because of applying a somewhat too low (or an intermittent) firing current. In that case, the pyrogen in contact with the bridgewire is raised more slowly than intended toward its ignition temperature, and the pyrogen may decompose without actually igniting. As a result of gas produced in this process, a tiny gap can form between the pyrogen and the bridgewire, thus thermally isolating the bulk of the pyrogen from the heat of the bridgewire. In some cases when this occurs the decoupling may be so severe that the bridgewire may become sufficiently far out of contact with the bridgewire, that the bridgewire may actually heat to its melting temperature and burn out (*fuse*) without transferring sufficient heat to ignite the pyrogen. Nicks in the bridgewire, poor welds, solder voids, and switch chatter are frequent causes of such malfunctions. Nicks in the bridgewire, poor welds and solder voids also have the potential for reducing the electric current flowing in the firing circuit because of significantly greater electric match resistance. So called switch chatter can be the result of a physical bouncing of the switch contacts upon closure or because of dirt or oxidation on the surfaces of the switch contacts, either of which has the potential to reduce the intended firing current.

The term “volts to fire” is meaningless unless details of the complete firing system are specified, including all of the wiring and connectors. This is because the resistance of all the firing lead wiring, the connection resistances and the internal resistance of the battery (if used) all affect the voltage required to produce the required firing current through the bridgewire. However, it might be appropriate to speak of “volts to fire” for a bare electric match head, or some other well specified condition.

The term “firing energy” is only meaningful if the rate of delivering that energy (i.e., power) is also specified. Using equation 6, a continuity test current of only 0.02 ampere through a 2 ohm bridgewire for about 20 minutes is found to deliver 1 joule of energy to the bridgewire and pyrogen. By comparison, most electric matches are considered to require a firing energy of approximately 0.02 joule (0.5 ampere through 2 ohms for 0.05 second).

Conclusion

While electric matches are simple devices, like so many other simple devices, they require the user to have some basic knowledge to truly understand and properly use them. It is hoped

that this article has provided a reasonable amount of that information.

Possibly Useful Definitions

To make these definitions more user friendly, there is necessarily some redundancy of the information. Those definitions in quotes are taken from the *CRC Handbook of Chemistry and Physics*, 62nd edition, 1981.

adiabatic: "A body is said to undergo an adiabatic change when its condition is altered without gain, or loss, of heat." In the case presented in this article, this does not include the heat generated within the bridgewire by the passage of electric current.

ampere: The unit of electric current, for which the abbreviation A may be used, and the symbol *I* is commonly used in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

bridgewire: A small diameter, relatively high resistance, conductor in an electric match. Commonly, bridgewires have a diameter of approximately 0.025 mm and are made of the alloy Nichrome.

calorie: A unit of heat energy, which has fallen into disfavor, is commonly abbreviated cal, and which is equivalent to 4.18 joules (J) (the currently more favored unit).

current (electric)**:** "The rate of transfer of electricity…." The unit of electric current is an ampere, for which the abbreviation A may be used, and the symbol *I* is commonly used as current in equations.

electric detonator: An electrically actuated device producing a detonation that is used to initiate another detonating explosive. These devices are not usually used with pyrotechnic devices. An electric detonator may contain an electric match.

electric match: A small electrically activated device producing a small ignition pulse (flame) used to ignite pyrotechnic devices. (Note: A "**squib**" is **not** an electric match, but a device having a greater energy output, which may be designed and used for propulsion, actuation, or ignition. While it may contain an electric match, the terms should not be confused or interchanged.)

electric potential: (Also potential difference and related to electromotive force or voltage). The unit of electric potential is the volt, for which the abbreviation V may be used, and the symbol *E* is commonly used as potential difference in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

energy: "The capability of doing work." In this article, the symbol for energy is *J*, and the unit of energy may be joules (J) or calories (cal).

heat: "Energy transferred by a thermal process."

heat capacity: "The quantity of heat required to increase the temperature of a system or substance by one degree of temperature. It is usually expressed in calories per degree centigrade or joules per degree Celsius." (See specific heat capacity.)

joule: A unit of energy, including thermal energy, abbreviated as J. A joule is equal to one watt second, and equals 0.24 calorie.

ohm: The unit of electric resistance is the ohm, for which the abbreviation Ω (Greek capital letter omega) is commonly used, and the symbol *R* is commonly used in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

Ohm's law: Expresses the direct relationship between current (*I*), potential difference *(E),* and resistance (*R*) in an electric circuit. A common form of Ohm's law is expressed by the equation,

$$I = \frac{E}{R}$$

power: Is the time rate of energy transfer or production. A common unit of power is the watt, which is commonly abbreviated as W, defined as one joule per second, and the symbol *W* may be used for power in equations. In an electric circuit, the amount of power produced is equal to the product of current (*I*) through the circuit and potential difference (*E*) across the circuit,

$$W = I \cdot E \text{, or } W = \frac{J}{t}$$

pyrogen: An energetic mixture of chemicals used to produce heat, flame, or similar.

resistance: "…is a property of conductors depending on their dimensions, material and temperature which determines the current produced by a given difference of potential." The unit of resistance is the ohm, which is commonly abbreviated as Ω (Greek capital letter omega), and the symbol *R* is commonly used in equations. When an electric potential (voltage) of one volt is applied to a circuit with a resistance of one ohm, a current of one ampere will flow.

specific heat capacity: Heat capacity per gram (g) of material, commonly using the units of joules per gram-degree Celsius (J / g-°C), and the symbol *C* is commonly used in equations.

squib: (Also electric squib) A device containing an electric match plus a pyrotechnic base charge, generally contained in a small metal tube.

temperature: "Temperature may be defined as the condition of a body which determines the transfer of heat to or from other bodies." Note: The units of temperature may be degrees Fahrenheit (°F), degrees Celsius (°C) or Kelvin (K) (by custom, when using K the word degree is not used). Modern technical usage tends toward using either °C or K. The temperature scales may be converted as follows:

$$°F = 32 + \left(\frac{9}{5}\right) °C$$

$$°C = \left(\frac{5}{9}\right) (°F - 32)$$

$$K = °C + 273.15$$

time: Time is usually expressed in seconds, for which the abbreviation s may be used, and the symbol *t* is commonly used as time in equations.

volt: "The unit of electric potential difference…", for which the abbreviation V may be used, and the symbol *E* is commonly used for voltage in equations.

watt: The unit of electric power, which is commonly abbreviated as W, and corresponds to the production or consumption of energy at the rate of one joule per second.

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A Report on the Fireworks Accident at Carmel, Western Australia

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ABSTRACT

The investigation into an accident at Carmel, Western Australia in March 2002 found that the magnitude of explosions occurring in licensed and unlicensed storage areas was significantly greater than would have been expected from the UN hazard classification of items stored within them. Use of revised UN default classification tables for the items in storage, instead of the previous classification, goes toward accounting for the violence of the explosions. The official report into the accident makes a number of recommendations that are of direct international relevance, such as a minimum safety distance of 400 m (from residential housing or defined vulnerable facilities) for licensed UN Hazard Division 1.1 magazines regardless of mass of contents (above 50 kg minimum), removal of a concession that allows for the temporary storage of fireworks in unlicensed areas for up to 14 days prior to a display, the adoption of the UN default classification table throughout Western Australia and the importation of incorrectly classified fireworks to be made an offence.

Keywords : Carmel explosion, UN hazard classification, safety distance, unlicensed storage

Introduction

On 6th March 2002, a fireworks storage facility at Carmel, near Perth in Western Australia, was severely damaged by a number of explosions and fires. There were three major explosions, occurring over a period of 14 minutes, which resulted in the total destruction of some storage units and serious damage to a number of others. Significant damage was caused to several houses and structures in the vicinity of the site, and shrapnel pieces produced by the explosions were found several hundreds of metres away from the explosion sites. The incident did not result in death or injury, but this can only be regarded as being fortunate.

The incident was thoroughly examined by the statutory investigatory body (the Department of Mineral and Petroleum Resources (MPR), Western Australia), which published a detailed report[1] of the incident in a commendably thorough, well documented and timely manner (the report was published in July 2002). In addition to containing a description of the events at the facility and in its vicinity, the report makes a number of recommendations, the implementation of which may have significant consequences for the worldwide pyrotechnic community.

This paper briefly describes the events at Carmel and also briefly examines the recommendations made by the investigatory body. Some of the nine main recommendations made in the MPR report are intended for introduction within the state of Western Australia, some are directed toward federal implementation across Australia and a number are of potential worldwide applicability. This report of the incident and presentation of the recommendations arising from an incident at Carmel is consistent with this Journal's commitment to the advancement of pyrotechnics through the sharing of information.

Brief Summary of the Carmel Incident

A comprehensive report and examination of the incident is contained in an official MPR report.[1] The description in this paper is a brief summary of those events. However, it should be acknowledged that much of the information in this summary and in the MPR report relies heavily on statements provided by the operators of the facility. In some instances, record keeping was not sufficiently detailed to confirm the statements from the operators. In other instances, the physical evidence is contrary to the statements of the operators. The net result is that the conclusions presented in this article and MPR report cannot be considered absolutely reliable. Also, while one of the authors of this paper has had discussions with one of the on site investigators of this incident, it must be acknowledged that the authors have neither inspected the site nor participated in the investigation of the incident.

The facility at Carmel was operated by a fireworks importer and display company. As such, the main business activity of this company was the storage and preparation of fireworks intended for public displays. Pyrotechnic items for those displays were imported into Australia for storage at Carmel; from there, they would be taken to display sites throughout the country. The first firework storage license for the Carmel site was issued in 1985, and this was subsequently altered and added to several times prior to the incident.

There were four licensed storage magazines (termed M1 to M4) present on the site. The details of these magazines are given in Table 1, and their distribution around the site is presented in Figure 1.

The normal practice in the days prior to a display was to remove the required items from magazine storage to temporary preparation areas for sorting, assembly, preparation and dispatch to the display venue. The temporary preparation areas used consisted of freight containers, termed FC1 to FC4 in Figure 1. Use of such temporary areas for processing and storage was permitted at the time of the incident, although the incident report notes that the regulatory body was unaware of the placement on-site of container FC4.

The trigger for the chain of events that led to the explosions at Carmel reportedly started in Shed 2. Container FC3 was primarily used for the storage of mortars and the preparation of various display pieces. The shed in which FC3 was located was used for the storage of unfired ground pack tubes, full ground packs (also called cakes or cake items), rolls of quick match, lances and portfires. On the morning of 6th March 2002, it is estimated that Shed 2 contained a range of items, such as confetti bombs, quick match, fountains and a quantity of electric fuseheads (electric matches).

Reportedly, as a 25-shot ground pack was placed on a bench within Shed 2, a shot initiated. This initiated the rest of the shots within the pack. Within a few seconds, burning stars ejected from the ground pack initiated other items stored within the container and the shed. The staff pre-

Table 1. Licensed Magazines at Carmel Site.

Magazine	Description[a]	Licensed Capacity[b]	Estimated Content (NEQ)[c] on 6 March 2002
M1	10 t steel container	5000 kg HD 1.4	700 kg ground-level items
M2	10 t steel container	5000 kg HD 1.4	725 kg ground packs
M3	Steel container	300 kg HD 1.3	941 kg aerial shells (up to 300 mm) and salutes (up to 75 mm)[d]
M4	Steel container	1500 kg HD 1.3	1626 kg (aerial shells, up to 400 mm)

a) t = metric ton.

b) HD = hazard division.

c) NEQ = Net Explosive Quantity (mass of explosive material in items, excluding packaging).

d) The initial contents estimate is given. The contents were later reported to be 300 kg.[1]

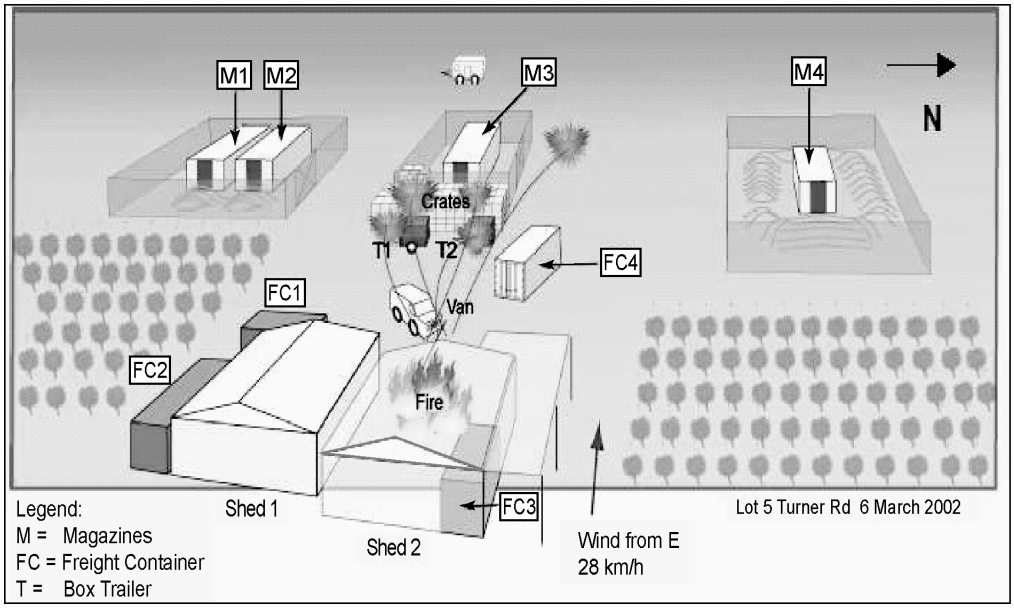

Figure 1. Outline plan of Carmel site (during initial phase of incident).

sent within the shed quickly assessed the situation as being out of control and left the building. Many burning items were observed coming out of the shed through the open door in the direction of container FC4. Soon the adjacent shed was also ignited by the fire, which spread to containers FC1 and FC2, eventually completely destroying them.

Witnesses reported seeing effects from ground packs being fired through the roller door of the shed towards container FC4. This container, the placement of which was unknown to the licensing authority, was positioned 16 m from the door of Shed 2 with the doors of FC4 opening in the direction of Shed 2. There were plastic crates, empty cardboard boxes and a quantity of wooden stakes stored close to the container walls. It is likely that stars from the ground packs struck and ignited the combustible material. Based on witness statements that the doors of FC4 were closed at the time, the ignition of the contents of FC4 would seem to have been as a result of the ignition of its contents from the heat conducted through the steel walls of the container. This is known to be sufficient to ignite the contents of such containers, and the effects of external fires on fireworks stored in steel ISO containers have been recently described in this Journal.[2] However, there is physical evidence that suggests one of the doors of FC4 was at least partially open at the time. If that was the case, the fairly rapid ignition of the contents of FC4 is even more understandable.

Shortly after the ignition of materials inside FC4, it exploded violently, sending a large quantity of steel shrapnel pieces toward magazines M2 and M3. These magazines were penetrated by the shrapnel pieces, and their contents were initiated by impact, friction or heat from the impacting fragments or, more likely, from a combination of these mechanisms. Around 5 minutes after the explosion in FC4, the contents of M2 underwent a partial detonation or a rapid deflagration. There was insufficient evidence to determine which of these explosion mechanisms was responsible for the resultant pressurization of the steel container, which failed at its welded seams. Some parts of the structure, such as roof panels and doors, were projected a short distance, and the remaining burning contents were ejected from the container.

Eleven minutes after the partial destruction of M2, magazine M3 was completely destroyed by a large explosion of unexpected violence. The investigation attributed this explosion to the partial detonation or rapid deflagration of the contents. Witnesses reported a large fireball (approximately 100 m in diameter), and a large cloud of smoke following this explosion. Small pieces of hot shrapnel were projected several

hundred meters from the magazine site by the explosion in M3. Only the floor of M3 remained – the door (weighing 170 kg) was projected 370 m and the roof (380 kg) was found 295 m away. The rest of the magazine had fragmented.

Hot fragments from the explosion of M3 penetrated magazine M1, initiating its contents. No explosion occurred in this magazine, but its contents were consumed by fire. The air blast from the explosion of M3 toppled M1 over by 90 degrees.

Magazine M4, which was protected by a surrounding earth mound, was unaffected by fire or explosion. It is considered that this was due to

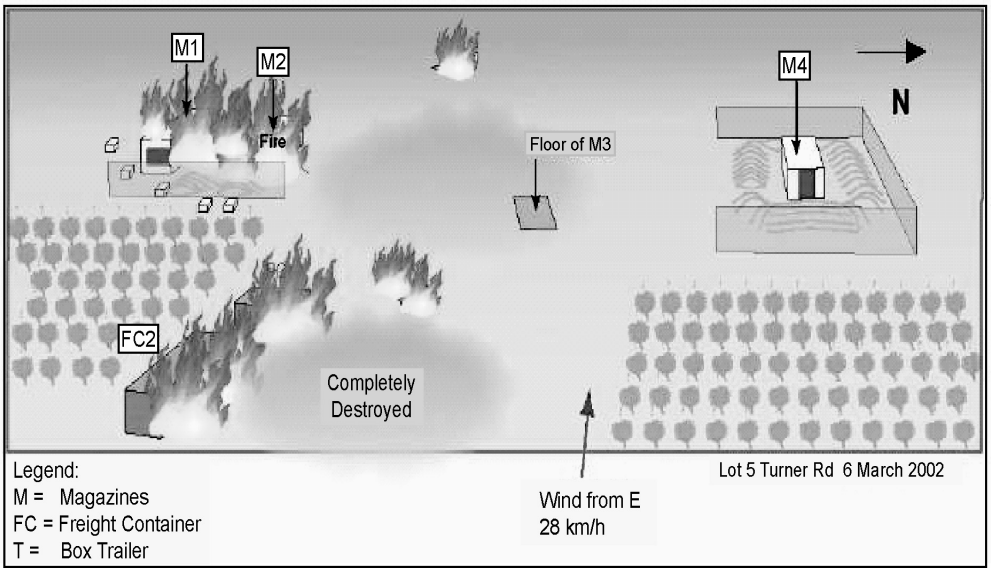

Figure 2. Location of structures following explosions.

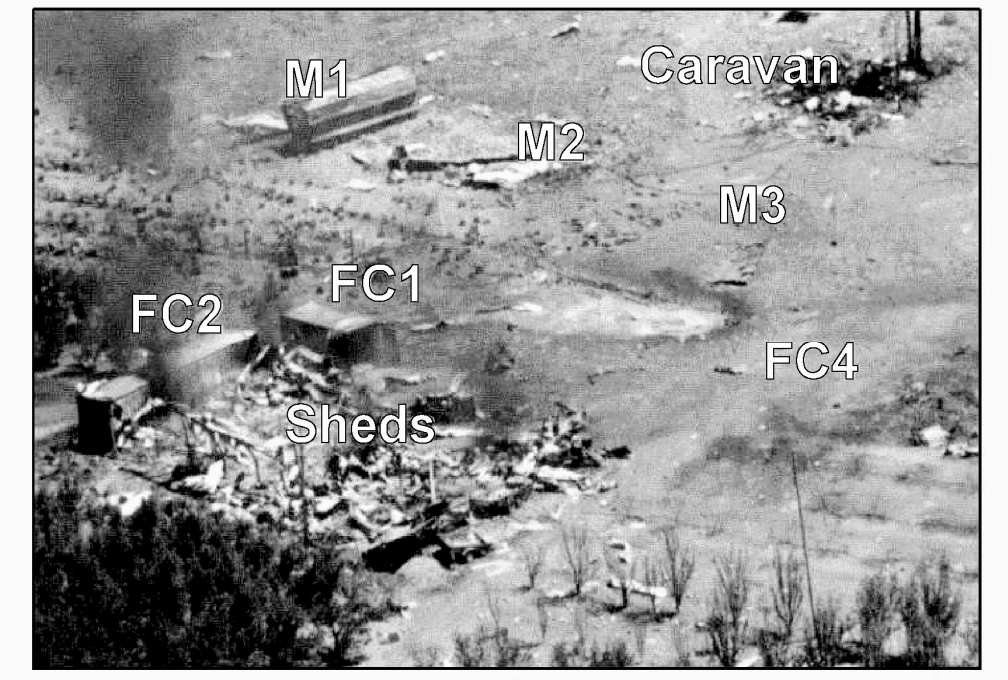

Figure 3. Aerial photograph of site following explosions.

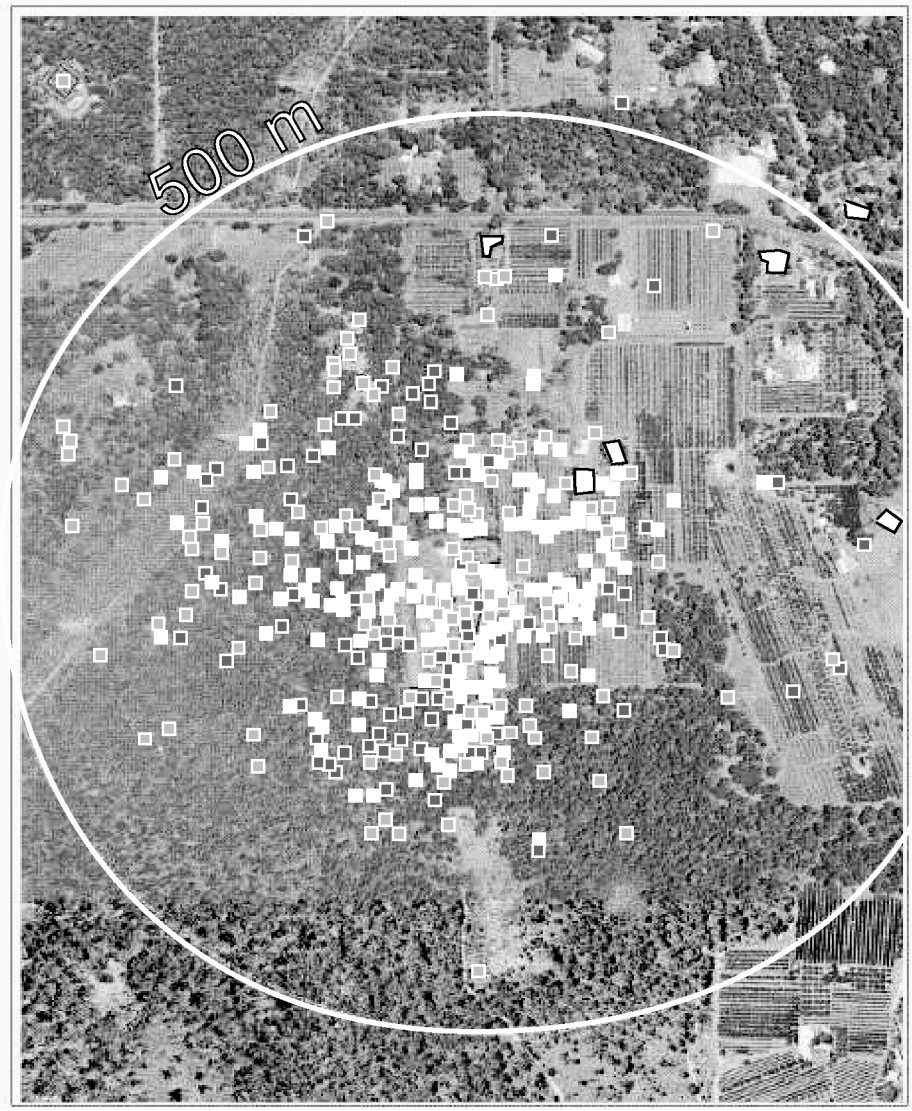

Figure 4. Combined distribution of shrapnel pieces.

the protection from flying shrapnel afforded by the earth mound.

Several bush fires started in the locality as a result of shrapnel and burning fireworks. The local fire service did not fully extinguish all fires started by the incident until the following day.

The remaining structures at the site are shown in Figure 2. A photograph of the damage is shown in Figure 3.

In addition to the damage at the site of the facility, damage to houses and other structures was reported up to a distance of 4.5 km from the facility. Most of the shrapnel was within 500 m of the facility. Figure 4 shows the distribution of fragments produced in the course of this incident.

Cause of Initiation of the First Ground Pack

The sequence of events culminating in the series of explosions at the site reportedly began with the ignition and firing of a single tube in a 25-shot 30-mm ground pack. The circumstances leading to this event merits a closer examination, since there was no obvious means of initiation.

The ground pack in question was one of a batch that had failed to fire at a previous display.

The packs were intended to be fired electrically, but they had failed to do so. The reason for failure at these displays is not known. Reportedly the packs were being adapted for hand-firing at a future display, and a key part of the modification process was the removal of the electric fusehead from the main fuse.

An operator would remove the metallic foil from the top of the ground pack tubes and then remove the electric fusehead from the ground pack. The pack would then be picked up by a second operator, who would transport the pack to another part of the working area, prior to refusing. Reportedly the pack in question ignited at the point when it was placed onto the ground by the second operator.

The investigation was not able to determine the reason why the shot initiated. Fuseheads are known to be quite sensitive to accidental ignition; however, most of the various possible modes of ignition involving the fusehead would be eliminated since reportedly no electric fusehead was present in the pack at the time of its initiation. Electrostatic discharge from the operator was considered to be unlikely in the belief that any such charge would likely have been dissipated during the handling of previous packs, and a discharge would have been expected at the point of picking up the pack, not when it was set down.

One possibility for the ignition of the ground pack is that there was displacement of some composition from within the ground pack, possibly caused by removal of the fusehead or disintegration of some of the several clay plugs present in the pack. This composition could then have become trapped between other materials (such as tissue paper and cardboard) within the pack. The impact from placing the pack onto the bench may then have been sufficient to ignite the composition.

The Subsequent Fires and Explosions

Following the ignition of the first shot in the first ground pack, the rest of the shots in the pack fired, projecting burning stars throughout Shed 2. This shed, which was not a licensed magazine, contained a considerable amount of pyrotechnic and other flammable material. There were at least 144 75-mm diameter aerial shells, some 15 to 20 ground packs, 25 cases of confetti bombs, 2000 electric fuseheads, some boxes of surplus quick match and assorted tubes from small ground pieces. There was also a substantial quantity of empty cardboard boxes and other combustibles in the shed at the time.

There are contradictory witness statements as to the contents of container FC4. Some state that there were no fireworks at all stored inside the container and that only packaging material was stored there. One witness statement suggests that a moderate quantity of pyrotechnic material (about 450 75-mm shells and 30 100-mm aerial shells) was stored in FC4, and that these shells were close packed instead of being in their original packaging. The violent explosion which destroyed the container within a few minutes of the incident starting in Shed 2 would suggest that the latter statement is a better reflection of the true situation.

The explosion that destroyed container FC4 was a mass explosion characteristic of high explosives of hazard division (HD) 1.1 rather than an event in the manner expected of fireworks of HD 1.3 (i.e., a minor blast and/or projection hazard but no mass explosion hazard). Previous tests described in this Journal[2] have illustrated the expected results from the initiation of a considerable quantity of HD 1.3 material inside a steel freight container, where mass explosion was not observed.

That a mass explosion did occur inside FC4 might be explained by (a) the 75-mm shells present in the container being close-packed (108 shells per box instead of 72), and (b) there may have been some salutes (which are now considered to exhibit HD 1.1 behavior) amongst the shells, as was normal company practice.[1] However, the absence of definitive information on the contents of the container makes it difficult to accurately establish the cause of the mass explosion, and the reported contents of FC4 seems inconsistent with the power of the explosion. This stresses the need for accurate record keeping if post-incident investigations are to produce reliable recommendations to prevent future incidents.

The explosion that resulted in the structural failure of magazine M2 was somewhere between the behaviors expected for HD 1.1 and HD 1.3. The magazine was known to contain mainly

boxed ground packs (HD 1.4) and had an overall NEQ estimated at 725 kg. One of the firework types stored in M2 had a report as its main effect, and it is now accepted that such items can exhibit HD 1.1 behavior.[3] This may explain the unexpected violence of the event that partially destroyed the magazine.

Magazine M3 was destroyed by a very large explosion, characteristic of a detonation of a large quantity of HD 1.1 material. The magazine had an estimated 941 kg (NEQ) of up to 300-mm aerial shells and up to 75-mm salutes. According to the incident report, the blast took the authorities and the industry by surprise, since the items stored in M3 were all considered to be in HD 1.3 display fireworks.

The classification of some firework types was investigated following the Enschede disaster in the Netherlands in May 2000, and it was found that some high energy firework types tested as HD 1.1 under the UN testing regime[3,4,5] rather than HD 1.3. If these findings, which are summarized in Table 2, are applied to the contents of M3, then the hazard classification of the contents changes significantly.

Under the revised classification scheme given in Table 2, the contents of M3 would have been regarded as HD 1.1. The size of the explosion, which was thought to be from an estimated 941 kg of HD 1.3 material, is perhaps less surprising if it is thought to have come from 941 kg of HD 1.1 material. It should be stated that the firework company provided an NEQ estimate of 941 kg for magazine M3 early in the investigation, but this was revised downwards to 300 kg at a later date.[1]

Magazine M1, which reportedly contained material, mostly ground packs, with a NEQ of 700 kg classified as HD 1.4, was severely damaged by fire during the incident, but it was not destroyed by an explosion. The report considers it likely that a mild deflagration, consistent with HD 1.3 behavior, occurred within M1 as a result of its contents being initiated by hot fragments from M3. The magazine was licensed for the storage of HD 1.4 material, but reference to Table 2 shows a revised classification of HD 1.3 for ground packs, and the events within M1 are consistent with this revised classification.

Magazine M4, which contained much more material than M3, was left relatively unscathed by the events on the rest of the site. The earth mound around it reduced the likelihood of fragment impact. One wall of the magazine was struck by shrapnel, but the wall was not penetrated and the contents did not ignite.

In summary, the magnitude of the explosions came as something of a surprise to the regulatory authorities. The classifications of the items stored at the site were HD 1.3 and 1.4, for which no mass explosion would have been expected. However, if the revised classifications and the conditions of storage are taken into account, then the observed mass explosions may be explained. According to the classifications given in Table 2, magazines M1 and M2 would have had a classification of HD 1.3 (rather than HD 1.4) and magazines M3 and M4 would have had a classification of HD 1.1 (rather than HD 1.3).

The revised UN classification scheme alluded to in Table 2 is subject to revision, and it is not expected to be published until late 2004 at the earliest.

Table 2 Revised Firework Classifications Arising from Enschede Investigation Findings.[1,3,5]

Firework Type	"Old" UN Classification	Revised UN Classification
Report shells (all sizes)	1.3	1.1
Color shells (200 mm or greater diameter)	1.3	1.1
Color shells (below 200 mm diameter)	1.3	1.3
Roman candles (less than 50 mm diameter)	1.4	1.3
Boxed ground packs – report as primary effect	1.3	1.1
Boxed ground packs – color as primary effect	1.3	1.3

Report Recommendations

Nine specific recommendations were made in the incident report. Those recommendations and brief comments by this paper's authors follow:

Recommendation 1: Fireworks operators worldwide note the unforeseen explosions witnessed at the Carmel facility and conduct risk assessments of all their activities in preparing fireworks for displays and prepare Safe Operating Procedures for these activities.

Risk assessment is a key part of reducing the risk associated with any activity to a level which is as low as reasonably practicable (ALARP). This approach has been adopted in a number of countries.[6,7] The initiation of the ground pack, which triggered the whole sequence of events described in this paper, illustrates that the unexpected may occur at any time, so proper and thorough risk assessment should always incorporate such events. In addition, the consequences of unexpected initiation should be taken into consideration during the assessment of risk – in this case, the positioning of freight container FC4 may have been changed if the risk assessment had considered the possibility of an initiation of the type experienced.

Recommendation 2: That fireworks operators worldwide store all their fireworks in licensed magazines and not in preparation areas.

Short-term storage in unlicensed areas was permitted in Australia at the time of the incident. The incident report makes it clear that storage in unlicensed areas (Shed 2 and container FC4) was the major contributory factor in the escalation of the incident.

Recommendation 3: MPR considers what action, if any, is warranted in relation to compliance issues at the storage facility.

This recommendation is particular to the incident in question, and allows potential legal action (if any) to be taken. While the results of any legal action taken may be of interest to the pyrotechnic community in Australia and elsewhere, comment upon them is outside the scope of this paper.

Recommendation 4: That for the purpose of storage and transport, fireworks in Western Australia be classified in accordance with either UN testing, or by analogy of type using the UN default classification table.

This recommendation deals with the manufacturer self-classification of fireworks that are imported into Western Australia. Such classifications need to be carefully checked as a result of the incident. The notes to the recommendation make it clear that Western Australia should make use of the UN default classification table in its revised form, rather than relying on self-classification from manufacturers. The UN transport classifications for fireworks are not necessarily the same as their storage classifications. This has been addressed in the United Kingdom by the introduction of Hazard Types (HT's),[8] but this approach has not yet been applied in most other countries.

Recommendation 5: For the purpose of licensed storage of fireworks of HD 1.1, separation distances to off-site residential housing shall be in accordance with vulnerable facilities as per Table 3.2.3.2 of Australian Standard 2187.1 – 1998 "Explosives – Storage, Transport and Use Part 1: Storage", except that a minimum separation distance of 400 meters shall apply at all times.

The quantity-distance concept is consistent with common practices for establishing separation distances, and the table cited in this recommendation is similar to those cited elsewhere.[9] However, the minimum distance of 400 meters is the separation distance for 731 kg NEQ of HD 1.1 material. Failing to accept the lesser hazard posed by smaller quantities of HD 1.1 fireworks is tantamount to declaring fireworks to be significantly more hazardous than other HD 1.1 explosives. This is a position that must be hard to defend, especially in this case where the accuracy of statements of the operators regarding the quantities of fireworks present at the Carmel site is in serious question. As a matter of comparison, it might be of interest to compare this 400 meter distance with the amount of HD 1.1 material allowed for storage under the American Table of Distance for Storage of Explosives,[10] which is 4000 pounds (approx. 1820 kg) for unbarricaded magazines and 40,000 pounds (approx 18,200 kg) for barricaded magazines.

Recommendation 6: That MPR develops a Safety Bulletin to inform fireworks operators world-

wide of requirements based on revised classification of fireworks.

The changes to various regulations that are proposed by the recommendations made in the incident report need to be communicated to the industry. This recommendation proposes a mechanism for doing so.

Recommendation 7: That WA (Western Australia) takes a leadership role in discussions with other jurisdictions to adopt a nationally consistent approach to the revised classification of fireworks.

Each State within Australia has its own set of regulations. This recommendation proposes that these regulations are revised to ensure consistency. This approach is likely to be of benefit to the industry, since it can be expensive and time-consuming to deal with, for example, having different regulatory requirements at the place of importation and the place of storage.

Recommendation 8: That MPR amends the Firework Permit application form to enable the checking of safety controls for temporary storage at a display.

It is a requirement in Western Australia that display operators have to apply in advance for a permit for each separate display. This recommendation proposes that the application form is adjusted to incorporate the identification of revised requirements for the temporary storage of fireworks based on changes in classification.

It should be noted that in Western Australia, the use of fireworks by the general public has been prohibited since 1967.

Recommendation 9: That Government gives a high priority to the development of both the Dangerous Goods Safety Bill and associated explosives (incorporating fireworks) and dangerous goods regulations for a number of reasons, in part to put in place appropriate controls for the preparation and assembly of fireworks and to make it an offence to import incorrectly classified fireworks.

At the time of the incident, the main pieces of legislation governing the use and storage of explosives in Western Australia were the Explosives and Dangerous Goods (Explosives) Regulations 1963 and the earlier Explosives and Dangerous Goods Act of 1961. The report recommends a complete revision of these pieces of legislation, since it considers both to be out of date.

Conclusions

There is some uncertainty about the precise cause of the initiation of the first ground pack, the ignition of the contents of FC4, and the quantities of fireworks being stored. That not withstanding, the nature of the explosions in FC4, M2 and M3 surprised many. The magnitude of the explosions was unexpected from material of HD 1.3 and 1.4, but use of a revised UN classification table, in which many items previously considered as showing HD 1.3 behavior have been reclassified to HD 1.1, goes some way to explaining why the magazine contents behaved as they did.

Use of the revised classifications is likely to have significant consequences for the worldwide pyrotechnic community. Such reclassification will place additional restrictions on the storage and transport of a significant proportion of the items in use. This is very likely to adversely affect the business position of the commercial pyrotechnic community, since added expense is inevitable.

Some other aspects of the incident are familiar to the pyrotechnic community. The storage of flammable material near or beside a magazine or storage area is again shown to be incompatible with safe practice. The use of unlicensed and inappropriately located storage areas is shown to be a major contributory factor in the escalation of the incident from a fire in a small area to the final situation described. Finally, some unwise work practices are likely factors in the initiation and spread of the fire and explosions.

Acknowledgements

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9) *Explosives – Storage, Transport and Use, Part 1 – Storage*, Australian Standard 2187.1 – 1998, Standards Australia (see http://www.standards.com.au).

10) *Code for the Manufacture, Transportation, Storage and Retail Sales of Fireworks and Pyrotechnic Articles,* NFPA-1123, National Fire Protection Association, 2003. (As revised and approved by the Institute of Makers of Explosives in June 1991, and as incorporated in the Storage regulations of the US Bureau of Alcohol, Tobacco, Firearms and Explosives.)

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As Defined by Regulation, What Is Fireworks Flash Powder?

K. L. Kosanke and L. Weinman

Although widely used, the term "flash powder" is poorly defined; there is nothing even approaching universal agreement about exactly which pyrotechnic formulations are and are not fireworks flash powders. This would be of some concern under any circumstance; however, it is the use of the term—flash powder—in regulations that greatly magnifies the problem. One might expect that an agency choosing to use the term "flash powder" in their regulations would have a responsibility to provide a reasonably precise definition for it; if not providing a generally applicable definition, then at least a definition for use within the context of the regulations. Unfortunately, this is not the case. Consider the definition published by of the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF or BATFE), the primary regulating authority for the manufacture, storage and use of explosives in the US:

> *55.11 Meaning of terms. Flash Powder. An explosive material intended to produce an audible report and a flash of light when ignited, which includes but is not limited to oxidizers such as potassium chlorate or potassium perchlorate, and fuels such as sulfur and aluminum.*[1]

Note that this definition depends on the "intended" use of the material. This leads one to ask, "intended by whom"; presumably that is the possessor of the pyrotechnic composition (i.e., its maker or the user of the composition). Thus if the possessor of a pyrotechnic composition intends that it be used to "produce an audible report and a flash of light" (and meets the general ingredient requirements) then it is a flash powder. Conversely then, if another possessor of a composition of the **same** formulation does **not** intend it to produce an audible report and a flash of light, then by this definition it must logically be concluded that the composition is **not** a flash powder under ATF regulations. Obviously this is a problem, one should not need to look into the mind of the possessor to determine whether something is a flash powder or not. There should be some objectively quantifiable characteristic (or set of characteristics) that definitively establishes whether something is or is not flash powder, at least for the purpose of regulation.

In the ATF's definition, even if "intended to produce" was replaced with "capable of producing", that does not really solve the problem. This is because just about any pyrotechnic composition is capable of producing an audible report and a flash of light under some set of conditions. For example, consider a Black Powder maroon; upon functioning, this certainly produces both "an audible report and a flash of light", yet it is most doubtful that anyone would classify Black Powder as a flash powder.

It is useful that the ATF provides, to some extent, additional guidance elsewhere in their regulations that further defines the nature of flash powder. The ATF includes flash powder as one example in a list of high explosives.[2]

> *55.202 Classes of explosive materials. (a) High Explosives. Explosive materials which can be caused to detonate by means of a blasting cap when unconfined, (for example dynamite, flash powders and bulk salutes).*[1]

Note that the ATF does not qualify their inclusion of flash powders as high explosives, such as by saying some, many, or most flash powders are high explosives. Accordingly, the ATF has established another necessary condition for a pyrotechnic composition to qualify as a flash powder under their regulations. In addition to the pyrotechnic composition being "intended to produce an audible report and a flash of light", it must also be a high explosive (i.e., it "can be caused to detonate … when unconfined"). Unfortunately, the only way to determine whether or not a pyrotechnic composition detonates when unconfined (i.e., whether or not the pyrotechnic composition qualifies as a flash

powder[5]) is to perform a fairly difficult (i.e., expensive) test. There is another point that needs to be considered regarding the performance of a detonation test, specifically, what is the quantity of material being tested. Consider the following pyrotechnic composition generally recognized to be a flash powder, a composition with 70% fine grained potassium perchlorate and 30% pyro-aluminum. In relatively small quantities, when unconfined this composition will burn without producing an explosion, and if there is no explosion, it certainly did not detonate. Logically then, such small quantities of this composition must not be a flash powder, even though larger quantities of this same composition might be shown to be capable of detonating when unconfined.[2]

If one seeks additional guidance from other authoritative sources regarding an objectively quantifiable definition of flash powder, little if any additional information is found. For example, in their training materials, the Pyrotechnics Guild International uses the definition,

> *Flash Powder. Explosive composition intended for use in firecrackers and salutes. Flash powder produces an audible report and a flash of light when ignited.[9]*

In their fireworks construction standard, the American Pyrotechnic Association does not use the term flash powder. They define two terms "explosive composition" and "pyrotechnic composition". Of these two terms, fairly clearly flash powder is included within the definition of explosive composition.

> *2.6.1 Explosive Composition. Any chemical compound or mixture, the primary purpose of which is to function by explosion, producing an audible effect (report) in a fireworks device.[10]*

Both of these definitions still require one to consider the use to which a pyrotechnic composition will be put, in addition to one or both, producing a flash of light and a report. Unfortunately, none of these definitions provide an objectively quantifiable measure that can be used to establish whether a given pyrotechnic composition is or is not flash powder.

A second article has been prepared addressing the subject of what is flash powder.[11] That follow-on article considers some technical issues relating to the production of "an audible report and a flash of light". It also suggests an approach that might be taken to provide an objectively quantifiable and relatively easy way to determine which pyrotechnic compositions are and which are not fireworks flash powders.

References and Notes

1) Federal Explosives Law and Regulations, ATF p 5400.7 (09/00).

2) Note that one can make the case that there is a lack of research identified by the ATF to support their assertion that flash powders are high explosives.[3] In fact, the most recent and comprehensive published research concluded that the flash powders that were tested (including the most common flash powder formulation) do not detonate and are not high explosives.[4] Nonetheless, for the purpose of the discussion in this article, the ATF's declaration that flash powder is a high explosive will be accepted.

3) K. L. Kosanke, "ATF's Classification of Flash Powder", *Fireworks Business*, No. 158, 1997; also in *Selected Pyrotechnic Publications of K.L. and B.J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999.

4) A. Hahma, "On the Deflagration of Al – $KClO_4$ – Mixtures", *Proceedings of the 3rd International Symposium on Fireworks*, 1996.

5) One of the universally accepted laws of logic is that, if a premise is true, then the contrapositive[6] of that premise is also true.[7, 8] Applying this logic law to the quoted text from the ATF regulations, if it is true that flash powders are high explosives, then any pyrotechnic composition that is **not** a high explosive must **not** be a flash powder.

6) "To form the contrapositive of a given proposition we replace its subject term by the compliment of its predicate term and replace its predicate term by the compliment of its subject term."[7]

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An Interesting New Design???

K. L. and B. J. Kosanke

It is difficult to argue that the quality of Chinese fireworks has not improved greatly over the past 25 years. However, that is not to say that on occasion, one still does not encounter quality related problems, sometimes so extreme that it is hard to believe. The photo in Figure 1 is of a 3-inch (75-mm) aerial shell and is such an example. (The authors encountered this shell several years ago, while working briefly in Australia.) Based on the location of the shell's cross-matched time fuse and suspender ring, the lift cup has clearly been attached to the side of the aerial shell. One might suspect that this was an attempt at a cleaver new design, were it not for the fact that this shell would not fit into a 3-inch mortar, and that the other 71 shells in the case had been constructed normally. Before seeing this shell, who would have believed that such an incredibly obvious error could ever have been made by a worker attaching lift cups, and if made, how could it have escaped the notice of the worker packaging shells to make it through any quality control process!

Figure 1. Photograph of one uniquely constructed 3-inch (75-mm) aerial shell.

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Product Warning !!!

K. L. and B. J. Kosanke

Display operators need to be aware of the potential for some tiger tail comets to produce extremely dangerous fallout. The problem was discovered only recently and was then investigated by the authors on a visit to the display company's facility. The shells in question are 4- and 5-inch (100- and 125-mm) White and Red Tiger Tail comets as shown overall in Figure 1. While all of the shells have the same basic labels, there were slight differences as noted in Table 1. However, in trying to determine whether any particular tiger tail comets have the problems found in the ones being discussed in this article, it is probably wise to consider that Chinese manufacturers frequently subcontract work and otherwise share production. Thus, it is possible that not all of the items labeled and appearing as shown in this article may have a problem, and it is also possible that items labeled and appearing differently may have the same problem described in this article.

Figure 1. Photos of the 5-inch (125-mm) Tiger Tail comets in question. (The 4-inch (100-mm) comets are virtually identical in appearance.)

Table 1. Identifying Label Information Appearing on the Tiger Tail Comets in Question.

Comet Type[a]	Product Code[a]	EX Number[a]	Product Number[b]	Brand Identification[c]
4-inch (100-mm) Red	560	9612098	None	(d)
4-inch (100-mm) White	564	9612099	None	(d)
5-inch (125-mm) Red	560	9612098	K8051	(e)
5-inch (125-mm) White	564	9612099	K8051	Flower Basket

a) As it appears on the small white label as shown in Figure 2.

b) As it appears on the label around the lift cup as shown in Figure 3.

c) As it appears on the label around the lift cup just above the product number.

d) There is no brand indication; however, at the point where the Flower Basket brand marking appears on the 5-inch White Tiger Tail comets, there is a blue spot, slightly darker than the background label color, which obscures the point where the Flower Basket brand marking might otherwise have appeared.

e) There is no brand indication; however, at the point where the Flower Basket brand marking appears on the 5-inch White Tiger Tail comets, there is a reddish pink spot similar in size and color to the background spot behind the Flower Basket brand marking seen on the 5-inch (125-mm) Red Tiger Tail comets. (See Figure 3.)

Figure 2. Close-up image of the product identification label of the comets in question.

Figure 3. Close-up images of the points on the lift cup label where the product number and brand marking appears on some of the comets. The upper image is of the 5-inch Red Tiger Tail comet label; and lower image is of the 5-inch (125-mm) White Tiger Tail comet label. The 4-inch (100-mm) comet labels are not shown.

Traditional tiger tail comet shells are made by completely covering a normally functioning aerial shell with a thick layer of comet composition. (Thus, after the comet composition burns off, the aerial shell explodes, and there is relatively little potential for dangerous fallout.) The items described in this article are being referred to as only tiger tail *comets* (rather than tiger tail *comet shells*) because they do not have a functioning aerial shell at their center. The manner of internal construction of the comets in question is illustrated in Figure 4, shown without their outer paper wrap, lift cup, lift charge and leader fuse. The outer most layer is comet composition; next is a paper casing comprised of a thin layer of pasted kraft paper and a pair of standard chipboard hemispheres; the center of most of the items is filled with what appears to be reddish-orange clay. (However, the centers of the 4-inch (100-mm) Red Tiger Tail comets are empty.) Table 2 presents approximate average dimensions and masses of the various comets in question, and it indicates the type of filler contained within them.

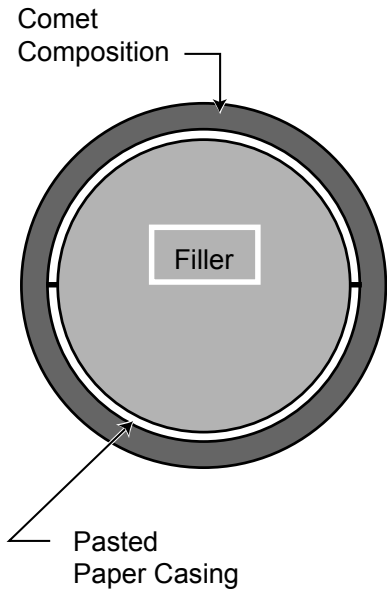

Figure 4. Sketch of the internal construction of the tiger tail comets in question.

The problem with these tiger tail comets is that, after functioning, the inner fully intact sphere falls to the ground with the potential to strike a member of the crew, a spectator, or property. For the 4-inch (100-mm) red comets, with their minimal mass, the consequences of being struck should generally be relatively mi-

Table 2. Dimensions, Masses and Construction Details for the Comets in Question.

Comet Type	Unfired Comet				Inner Sphere				
	Mass [a]		Diameter[b]		Diameter [b]		Mass [a]		Filler
	(oz)	(g)	(in.)	(mm)	(in.)	(mm)	(oz)	(g)	Type
4-inch Red	10.2	290	3.75	(95)	3.35	85	2.3	65	Empty
4-inch White	16.6	470	3.75	(95)	3.35	85	9.2	260	Clay [d]
5-inch Red	27.5	780	4.35	(110)[c]	3.75	95	13.4	380	Clay [d]
5-inch White	30.0	850	4.35	(110)	3.75	95	14.1	400	Clay [d]

a) Masses are rounded to the nearest 0.1 ounce and nearest 10 grams.

b) Diameters are rounded to the 0.05 inch and nearest 5 millimeters.

c) Not specifically measured, but visibly the same as the 5-inch (125-mm) white comets (i.e., 110 mm).

d) This appears to be common, uncompacted clay, loaded into two hemispherical tissue paper bags.

nor. However, the consequences of being struck by one of the clay-filled spheres could be catastrophic. To help quantify the situation a computer model was used to predict the velocity of the various spheres when they impact the ground at the end of their flight. Table 3 presents the velocity results and the corresponding shell energies. As a point of comparison, note that the energy of a fast-ball thrown by a professional baseball pitcher is approximately 80 foot-pounds (110 J). Thus the clay-filled spheres, with impact energies ranging from 150 to 270 foot-pounds (205 to 370 J), have the potential to produce extremely serious (or even fatal) injury as a result of a person being struck with one the spent tiger tail comets.

Table 3. Calculated Impact Velocity and Energy for the Shells in Question.

Comet Type	Impact [a]			
	Velocity		Energy	
	(ft/s)	(m/s)	(ft-lbs)	(J)
4-in. (100-mm) Red	70	20	10	15
4-in. (100-mm) White	130	40	150	210
5-in. (125-mm) Red	140	40	260	360
5-in. (125-mm) White	140	40	270	375

a) Impact values are rounded to the nearest 10 feet per second (5 m/s) or nearest 10 foot-pounds (15 J).

Another point needs to be contemplated; there may be a greater potential for these inner spheres to strike spectators than might be expected. If the comets are fired vertically, experience the same drift as determined for spherical shells of the same size, are among the largest items to be fired in the display, and the display site is only minimally large enough to accommodate the shells being fired, then 5 to 10 percent of the spent comet spheres may fall outside the secured area of the site (i.e., potentially into spectator areas). Further, in some limited testing, the comets fired from angled mortars seem to travel farther than normal dud shells would travel if fired from mortars with the same tilt angle. This too increases the potential for the spent comet spheres to fall into spectator areas. Compounding this potential problem, since comets are not normally expected to produce dangerous fallout, they are often fired from mortars with tilt angles significantly greater than normal shells. Were that to be done with these tiger tail comets, there would be an even greater potential for the spent comet spheres to fall into spectator areas.

If you think you may have some of these troubling tiger tail comets, please test them, under conditions that will safely allow a determination of whether they produce the dangerous fallout reported in this article, prior to using them in displays.

The authors are grateful to L. Weinman for commenting on an earlier version of this article and are especially grateful to the display company for reporting the problem.

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From a Technical Standpoint, What Is Firework Flash Powder?

K. L. Kosanke and L. Weinman

Introduction

In a recently published article on the regulatory definitions of firework flash powder[1] it was concluded that none of those definitions provided sufficient information to objectively establish whether or not a pyrotechnic composition is a flash powder. That is to say, those definitions are all subjective to the extent that they depend on the intended use of the composition and none provide a quantifiable measure that can be used to determine whether a particular pyrotechnic composition is a flash powder. The purpose of the present article is to suggest a general approach that might be used as the basis for producing a quantitative definition of flash powder.

The reason such an objectively quantifiable definition is needed is that – from both a regulatory and safety standpoint – flash powders are treated differently than other pyrotechnic compositions. The rationale for this is that the hazards posed by firework flash powders are generally significantly greater than most other commonly encountered pyrotechnic compositions. Accordingly, both pyrotechnic manufacturers and regulatory enforcement personnel need to be able to unambiguously identify whether a composition is or is not a flash powder.

Background Discussion

Before proposing a possible framework for a quantitative definition of firework flash powder, consider the following non-quantitative definition as a starting point for the discussion.

Firework Flash Powder: Any active metal fueled pyrotechnic composition suitable for use in a firework salute (or firecracker).

In considering this definition it is appropriate to consider why it requires that the pyrotechnic composition be metal fueled. The bright white flash of light characteristic of flash powders is produced by incandescence. At the reaction temperature attainable in pyrotechnic reactions, only solids and liquids incandesce, gases do not. As a practical matter, metal oxides are the only pyrotechnic reaction products that are not gaseous at high temperature. Thus metal fuels need to be present in substantial quantity in flash powders. See Table 1, which is a list of the boiling point of some of the pyrotechnic reaction products. The table has somewhat arbitrarily been divided into species with boiling points above and below 2500 °C. Note that the oxides of zirconium, magnesium, aluminum and titanium top the list.

Table 1. Boiling Point of Some Pyrotechnic Reaction Products.[2]

Reaction Product	Boiling Point (°C)
ZrO_2	≈ 5000
MgO	3600
Al_2O_3	2980
TiO_2	2500–3000
SiO_2	2230
ZnO	1975
K_2SO_4	1689
KCl	1500
K_2CO_3	d > 891(T_m)
H_2O	100

d = decomposes

T_m = melting point

A second requirement for the production of the bright white flash of light characteristic of firework flash powders is a high reaction temperature. To see why this is the case, consider Figure 1, which presents information on the light produced by incandescent bodies at various temperatures.[3] Note particularly the two curves labeled 1727 C and 3727 C. While these two curves correspond to only doubling the absolute temperature, the intensity of light produced in the

visible region increases by a factor of approximately 500. (Because the perception of light by humans follows an approximate logarithmic relation, the perceived brightness produced by an incandescent object at 3727 °C would be quite a bit greater, but it would not be 500 times greater, than the light from the object at 1727 °C.) Note also that at 1727 °C almost all of the emitted light is in the long wavelength (red) end of the visible range, whereas at 3727 °C the wavelengths of light are more nearly balanced across the visible range. The effect is that the perceived color of incandescent light produced at 1727 ºC will be distinctly orangish yellow, whereas that produced at 3727 °C will be perceived as white. Accordingly, to produce a flash of light that is both bright and white, a high reaction temperature is essential.

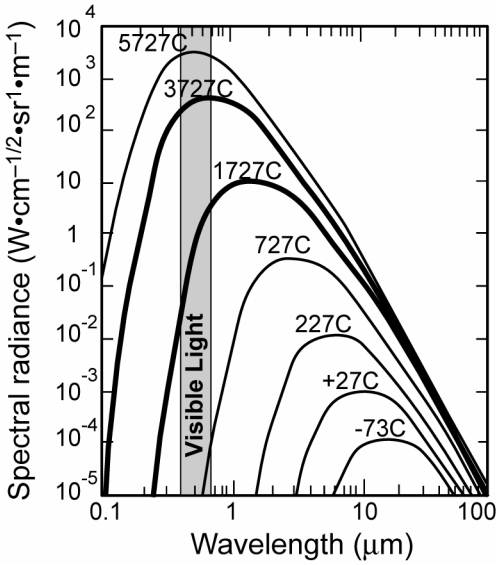

Figure 1. Incandescent emissions at various temperatures. [3]

The reaction temperatures for pyrotechnic compositions depend on a number of factors, but generally by far the most important is the thermodynamic heat of reaction for the composition (now more properly termed enthalpy of reaction). To see why, for the production of high reaction temperatures, it is important that the metal fuel be what is commonly described by a chemist as an active metal, consider the data in Table 2. Listed there are the heats of reaction for the burning of various metals (i.e., their combining with oxygen). The table has somewhat arbitrarily been divided into metals with heats of reaction above and below 500 kJ/mol. Note that titanium, silicon, aluminum and magnesium top the list.

Table 2. Heat of Reaction for the Burning of Various Metal Fuels. [4]

Metal Fuel	Reaction Product	Heat of Reaction (–kJ/mol)
Ti	TiO_2	945
Si	SiO_2	911
Al	Al_2O_3	838
Mg	MgO	602
Fe	Fe_2O_3	412
Zn	ZnO	348
Pb	PbO_2	277
Cu	CuO	157

Obviously metals do not all produce the same amount of thermal energy upon burning. While there is no universally accepted definition of an active metal, one possible definition could be those metals that burn with the production of the most abundant thermal energy. Accepting that definition for this article, those metals near the top of Table 2 would be the most active metals and would produce the highest reaction temperatures (i.e., those most capable of producing the brightest and whitest flashes of light).

The second part of the above non-quantified definition for firework flash powder is that it be suitable for use in a firework salute. In essence this is just saying that the composition must be a reasonably violent explosive such that it is capable of producing the thunderous report (blast wave) expected for firework salutes when only mildly confined in paper casings. To constitute a reasonably violent explosive is saying in effect that: 1) the oxidizer must be reasonably effective, 2) the ratio of ingredients must be approximately correct, and 3) the particle size of the components (most especially the active metal fuel) must be sufficiently small. These are all important factors known to affect reaction rate.[5] Reasonably effective oxidizers include the chlorates, perchlorates and probably the nitrates commonly used in firework. The approximately correct ratio of ingredients would be those reasonably near the stoichiometric ratio of ingredi-

ents. Sufficiently small particle size of ingredients is required such that most of the fuel and oxidizer are fully reacted in the explosion and not blown clear such as in the form of sparks.

Structure for a Potential Quantitative Definition

At this point in the discussion, it seems appropriate to begin the attempt to produce the promised basis for a quantitative definition for firework flash powder. This will be done in the form of an actual definition; however, at this time the specific numbers to be used in the quantitative definition will not be included. (These values will need to be determined as a result of research and a consensus of opinion between representatives of the industry and enforcement agencies.)

Firework Flash Powder: Any pyrotechnic composition containing at least N_1% of a metal powder finer than N_2 mesh.

In terms of metal content, the above suggested definition is essentially that proposed to the US Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) by the American Pyrotechnic Association (APA), which follows:

Flash Powder: Pyrotechnic compositions consisting of one or more oxidizers such as potassium perchlorate, potassium chlorate, ammonium perchlorate, barium nitrate, or potassium nitrate combined with 25% or more by weight of metal powder such as aluminum, magnesium, or magnesium/aluminum alloy ("magnalium") or 30% or more by weight of a combination of metal powder combined with sulfur or antimony sulfide. The term "powder" means material capable of passing through a standard 275-mesh sieve.[6]

While the authors agree in large measure with the APA approach, it is felt that test data needs to be produced before deciding on the exact percentages and particle size, whether nitrates should have different numbers, and what range of metals should be considered. Also thought needs to be given to an additional requirement relating to the explosivity of the actual pyrotechnic composition being considered. (This will be discussed further below.) A definition such as that proposed by the APA has the useful quality of allowing manufacturers to readily know, without the need for testing, whether or not any pyrotechnic composition they make is a firework flash powder and whether or not the regulatory and safety requirements for firework flash powder must be met.

The problem with the authors' definition above is that there are some pyrotechnic compositions that are definitely not flash powders, yet they contain a high percentage of relatively fine metal powder. One example of such a pyrotechnic composition is sparkler composition.[7] Thus some means of excluding such compositions from the firework flash powder definition is needed. It is suggested that there be an additional requirement in the definition of firework flash powder, one relating to the explosivity of the pyrotechnic composition. In the definition to be proposed, this additional requirement is stated as an exception. Thus the additional requirement would not always need to be considered. If a manufacturer is willing to accept that a pyrotechnic composition is a flash powder based on its metal content alone, that is their choice and nothing more would need to be considered. However, for any pyrotechnic composition for which the limits on metal powder content were exceeded, yet the manufacturer believed that composition was not sufficiently explosive so as to constitute it being classed as a flash powder, a relatively simple test could be conducted. That explosivity test would then determine whether that particular pyrotechnic composition was flash powder for the purposes of regulation. A possible expanded definition for firework flash powder follows.

Firework Flash Powder: Any pyrotechnic composition containing at least N_1% of a metal powder finer than N_2 mesh, except when that pyrotechnic composition does not produce an explosion measuring at least N_3 under specified test conditions.

As with determining the values of N_1 and N_2, the value of N_3 and the standard explosivity test conditions will need to be arrived at by consensus. To reach a rational consensus, there will need to be testing of many compositions widely understood and accepted to be firework flash powder and many other compositions widely understood and accepted not to be firework flash powder.

Before completing this article, it is appropriate to include one possible example for the "specified test conditions" mentioned in the above definition. (Certainly a number of other tests might be considered as alternatives.) An apparatus much like a version of a proximate audience concussion mortar might be used, such as sketched in Figure 2. The means of ignition could be a short length of 3/32-inch (2.4-mm) Black Powder visco fuse (also called hobby, cannon or firework safety fuse). This type of fuse is desirable because it is widely available and it provides a persistent ignition stimulus, in contrast with electric matches. In Figure 2, the fuse hole is only very slightly larger than the fuse, such that the fuse will tend to stay in place and relatively little of the test powder will enter the fuse hole. Also, it is suggested that the fuse hole enter at the point where the larger drilled hole – forming the test powder chamber – first begins to taper to its point. This will allow the visco fuse to pass across the chamber, causing the test powder to surround the fuse. The values for N_4, N_5 and the amount of powder used in the test (N_6) will need to be determined by consensus after testing.

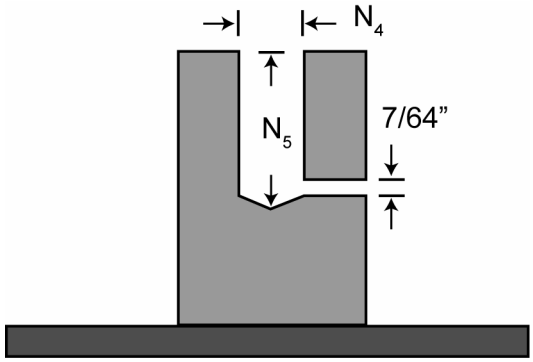

Figure 2. A sketch of one possible approach to a flash powder test unit.

Any test composition that did not produce an explosion would be considered not to be a flash powder. Another possibility is to better quantify the output test such as illustrated in Figure 3. The flash powder test unit would be placed on a flat and relatively smooth hard surface, and the indicator of the power of the explosion could be a measurement of the sound pressure level (dB) produced. Here again, the distances N_7, N_8 and sound pressure level (N_9) will need to be determined by consensus after testing.

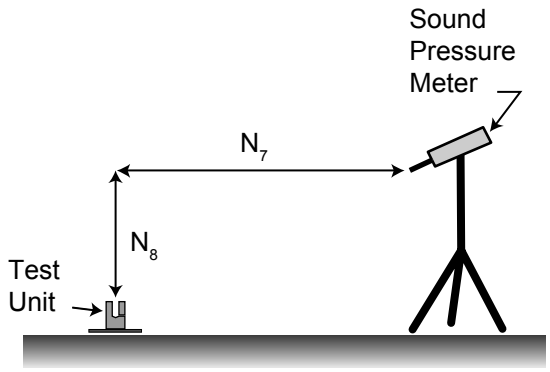

Figure 3. A sketch of the setup of the flash powder test unit and a sound pressure meter.

Conclusion

A quantitative definition of firework flash powders is a complicated and involved subject. There are many issues that need to be considered and some are not strictly of a scientific nature. Some limited research and a third article are being considered that would allow this proposal to be taken to the next level by suggesting some possibly appropriate values for N_1 through N_9, as well as possibly considering other simple test methods.

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Muzzle Breaks That Appear To Be Flowerpots

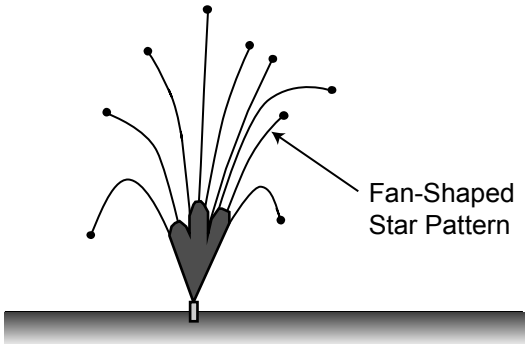
K. L. and B. J. Kosanke

As is sometimes the case when doing research: A) one occasionally discovers something which was not being sought; B) the thing discovered then seems intuitively obvious and one is amazed (and a little embarrassed) not to have figured it out long ago; C) the thing discovered helps to answer some other previously seemingly inexplicable observations; and D) one finds there are some new questions for which no certain answer is immediately available. All four of these happened recently while the authors were investigating the size of hole in the casing of aerial shells (of various sizes) that is needed to produce a fire-leak sufficiently great to cause the shell to explode while it is still inside the mortar.[1,2] During the course of those studies, it was found that a number of events, which visually appeared to definitely be flowerpots, were actually muzzle breaks.

After some introductory information, this article presents a collection of both standard and high frame-rate video images to make the case about muzzle breaks appearing to be flowerpots. An explanation is then offered as to why this should not have been unexpected, and finally the article considers some old and new questions relating to this observation. (While the authors are not aware of these observations having been presented elsewhere in the literature, certainly others may have previously figured this out for themselves.)

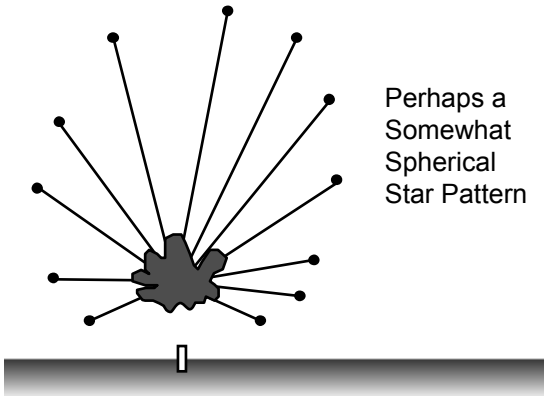
A common definition for a flowerpot is:

A type of aerial display shell malfunction where the shell bursts with relatively low power within a mortar. It produces an upward spray of ignited stars and other effects, as illustrated below[3].



A common definition for a muzzle break is:

A malfunctioning aerial shell which bursts just as it leaves the mortar, scattering high velocity burning stars and other material in all directions near ground level. It appears somewhat like the following illustration.[3]



In the testing being performed, aerial shell malfunctions were caused by piercing the paper shell casing of an aerial shell in the immediate area of their pair of time fuses, to thus allow the entrance of burning lift gases when the aerial shell was fired. The holes were made with mechanically driven awls of various diameters. Figure 1 is a composite image made during one of the test firings. The composite image was made by combining five individual 1/60th second digital video fields, thus spanning a total time interval of 0.083 second. This time interval was chosen because it is only a little less than the time taken for the human brain to process a vis-

ual image.[4] That is to say the composite image of Figure 1 is what a human observer would see as this event occurred. (This was confirmed by the authors when they personally witnessed this and several other similar events.)

The shells used in this testing were 3-inch (75-mm) Thunderbird Color Peony - Gold, product number TRA-105, with approximately 1.3 ounces (37 g) of lift powder. In the case of the shell malfunction presented in Figure 1, the awl was 0.090 inch (2.3 mm) in diameter, which when removed left a hole staying open with a diameter of approximately 0.074 inch (1.8 mm).

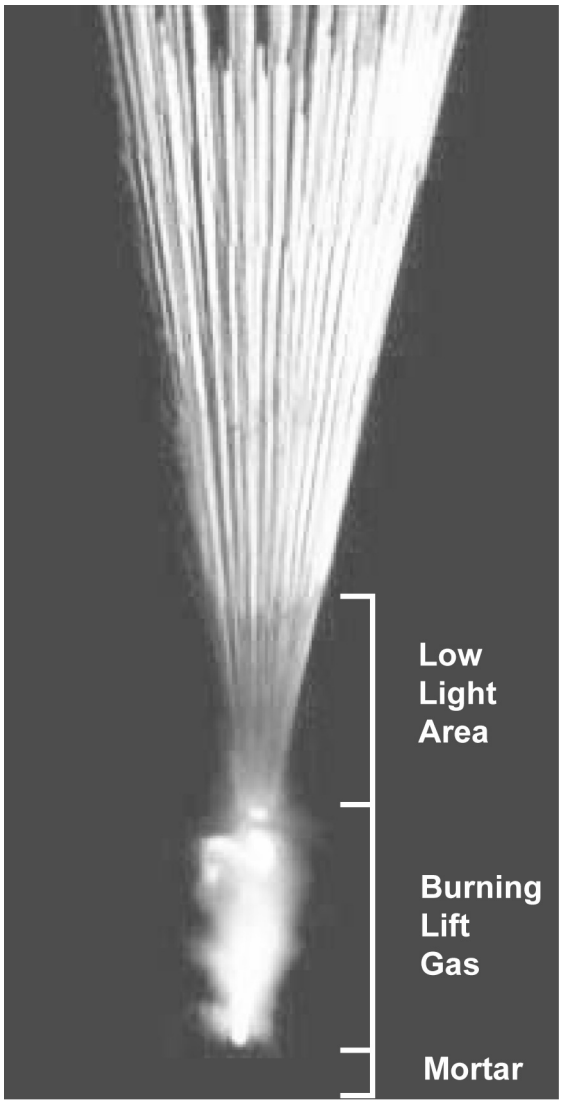


Figure 1. An 83 millisecond composite video image of an intentionally produced aerial shell malfunction.

In Figure 1, the field of view is approximately 30 feet (9 m) vertically and 15 feet (5 m) horizontally. The 24 inch (0.6 m) long HDPE mortar is at the bottom of the image but is not visible in the darkness, and it extended slightly below the bottom of the image. Above the mortar the plume of burning lift gas extends upward approximately 6 feet (2 m). Above this is a low light area extending approximately another 5 feet, where the prime on the stars is burning as the stars proceed upward and outward. Finally the more brightly burning stars are seen to continue approximately another 18 feet (5.5 m) in their upward and outward motion. Upon seeing this image or witnessing the event first hand, few if any practicing pyrotechnists would characterize this malfunction as anything other than what is commonly called a flowerpot.

Recently, to facilitate their fire-leak testing, the authors gained the use of a high frame-rate video system.[5] The early portion of same event presented in Figure 1 is shown in Figure 2 as a collage of six individual images. These video images were acquired at a rate of 2000 frames per second and with a shutter speed of 1/2000 second. The six images shown, selected from a total of nearly 200 video frames spanning the event, were chosen to illustrate some key points during the course of the event. (The identification of what is seen in each image of Figure 1 was made more certain by viewing the entire event several times in slow-motion and by having viewed several other similar appearing events.)

In image 1 of Figure 2, burning lift gas is seen and the aerial shell is approximately 1 foot (0.3 m) above the mortar, as evidenced by the bright and wide plume of lift gas deflecting around the shell. Image 2 was taken 0.0065 second after image 1; the plume of burning lift gas is significantly more pronounced, and the shell has advanced upward another approximately 2 feet (0.6 m). Image 3 was taken 0.0045 second after image 2; the diameter and brightness of the fire above the mortar is seen to increase significantly as a result of the shell breaking approximately 4 feet (1.2 m) above the top of the mortar. Image 4 was taken 0.0155 second after image 3, by which time the star prime has mostly burned away and many of the stars can be seen at the start of forming an almost perfectly symmetric

burst pattern. Images 5 and 6 were taken 0.0100 and 0.0200 second after image 4, where the stars are seen to produce an expanding symmetric pattern of a normally symmetric shell burst. (The total span of time for the series of images in Figure 2 is 46 milliseconds.)

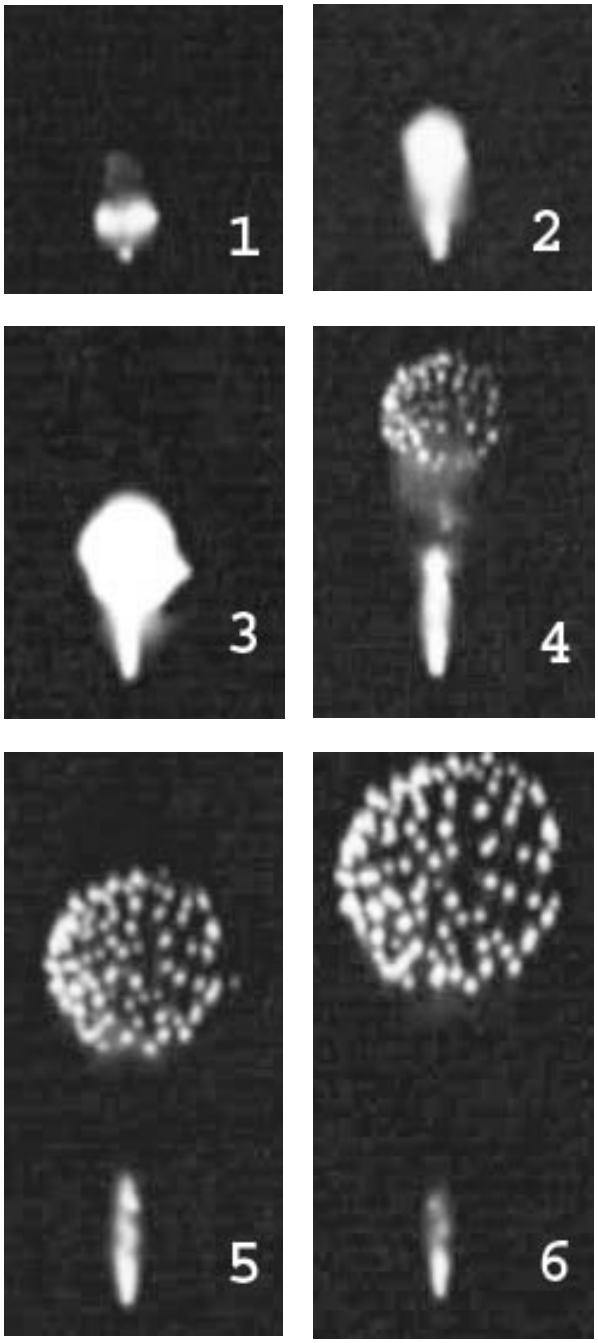


Figure 2. A collection of 6 high speed video images, of the same event presented in Figure 1, spanning an interval of 46 milliseconds.

That the aerial shell exploded after exiting the mortar was confirmed by having monitored the pressure inside the mortar during the shell's firing. When an aerial shell explodes while it is still inside the mortar, the blast wave from the explosion produces a near instantaneous increase in pressure above normal. Figure 3 presents a pair of graphs of mortar pressure as a function of time during the firing of this same type of aerial shell. The upper graph is from the shell firing documented in Figures 1 and 2, wherein the shell exploded after leaving the mortar. In the the lower graph, note the jump in mortar pressure that occurs. In this case, the aerial shell was caused to explode while just barely inside the mortar (by having made a hole in its shell casing using a 0.25-inch awl.)

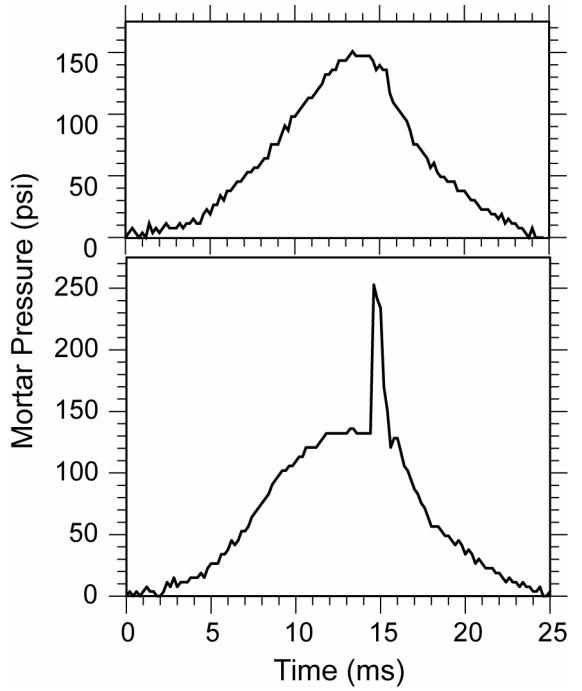


Figure 3. Two graphs of internal mortar pressure during the firing of aerial shells: upper, normal shell firing; lower, shell exploding while just barely within the mortar. Note: 1 psi = 6.9 kPa.

In addition to the strong confirmation offered from the mortar pressure data, the star burst pattern seen in Figure 2 bears added witness to the fact that the shell had exited the mortar before exploding. Consider the three burst patterns presented in Figure 4, which were produced by the

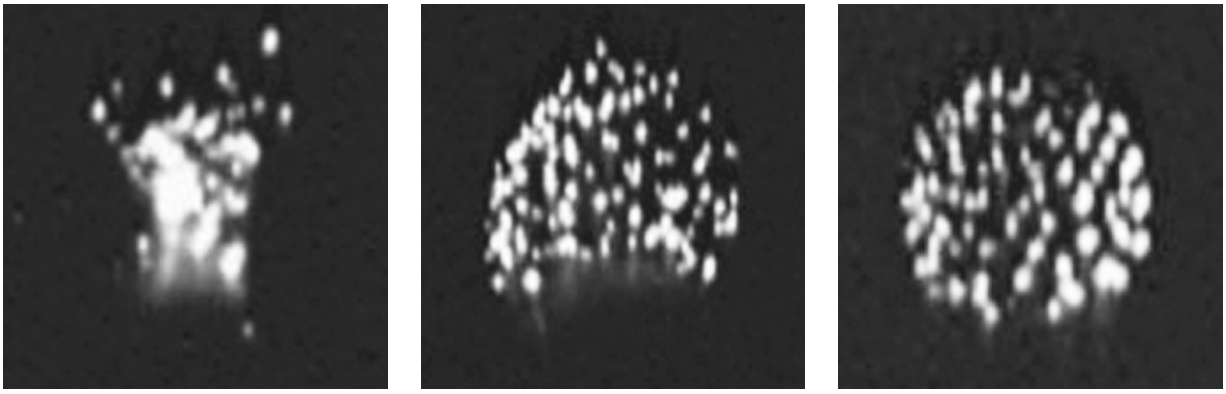


Figure 4. Images of three star burst patterns: (left image) produced by test shells bursting within the mortar, (middle image) just barely above the mortar and (right image) clear of the top of the mortar.

same type of Thunderbird 3-inch (75-mm) aerial shells. The left most image was produced by a test shell that burst a little before exiting the mortar (as was confirmed by monitoring internal mortar pressure). In this case there is a total lack of burst pattern symmetry. The middle image is from a test shell bursting outside, but within a foot or two the top of the mortar. In this case the high pressure lift gas is apparently sufficient to cause the flattening of the bottom of the burst pattern and sometimes a slight bulging out of the top of the pattern. The right most image in Figure 4 was produced by a test shell bursting when several feet above the top of the mortar. Note the near perfect symmetry of this third star pattern, which is essentially identical to that produced by the aerial shell displayed in Figure 2. While these 1/2000 second images are quite distinct from one another, the three events as perceived by a human observer appear essentially identical.

The above paragraphs describe what the authors unintentionally learned regarding the appearance of some muzzle breaking aerial shells during the course of testing for other purposes. This was point A mentioned in the first paragraph of this article. Point B was that this observation probably should not have come as much of a surprise. This is because it is reasonably well known that the human brain takes approximately 0.1 second (100 milliseconds) to process a visual image[4] (which is why motion pictures and television sets produce what appear to be continuous motion, when in actuality they are presenting a series of discrete still images). In effect the brain integrates the flow of visual stimuli to form a composite image and is unable to discern events occurring in times less than approximately 100 milliseconds as being separate or individual events. Accordingly, when the stream of images presented in Figure 2 is processed by one's brain (along with those many other images occurring between those included in Figure 2), the result is a perceived image very much like that presented as Figure 1. Had the authors thought carefully and critically about this, they could have figured out long ago that muzzle breaks of this type would appear to a human observer as being flowerpots.

Point C mentioned in the first paragraph was that such a discovery often provides an explanation to one or more previously seemingly inexplicable observations. One such observation is that many flowerpots produce a sound not noticeably louder than a normally firing aerial shell. For a shell actually exploding while being fired and still inside the mortar, this was hard to explain. Surely the exploding shell would add to the normal mortar firing pressure (as demonstrated in Figure 3), and the sound produced by the release of that greater pressure from the mortar should be louder. If so, then why is the sound of a flowerpot often times not noticeably louder? However, if in fact the aerial shell – thought to have been a flowerpot – actually exploded shortly after it left the mortar, while the combined sound produced (the shell exiting and then the shell exploding) would span a little longer time interval, they would not combine to make a louder sound. Similarly, it was hard to explain

why some relatively weak mortars can survive the apparent flowerpotting of powerfully exploding shells without the mortar being damaged or destroyed. Again, if the powerfully exploding aerial shell had actually exited the mortar before exploding, then its not damaging the mortar is certainly understandable.

Point D mentioned in the first paragraph was that a discovery generally leads to one or more not yet definitively answered questions. One such question is, why then do some of those aerial shells that malfunction by exploding just after exiting their mortar present the visual appearance of being a muzzle break and do not appear as flowerpots as in Figure 1? That is to say, what is it about such muzzle breaking shells that causes them to appear as muzzle breaks and not flowerpots? Another question is approximately what percentage of those malfunctions commonly identified as being flowerpots are actually muzzle breaks, and is that percentage a function of shell size? (The authors have some thoughts about these questions but will not speculate until more testing has been conducted.)

Acknowledgment

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An earlier version appeared in *Fireworks Business*, No. 248, 2004.

When Is Wind Speed Excessive for the Safe Display of Fireworks?

K. L. and B. J. Kosanke

While working on the 2006 edition of NFPA-1123 *Code for Fireworks Display*, the Technical Committee on Pyrotechnics of the National Fire Protection Association (NFPA) received a request for a "Formal Interpretation" regarding the 2000 edition of the code. In effect, a request for a Formal Interpretation is a request for the committee to provide clarification or a ruling regarding one or more paragraphs in the code. According to NFPA practice, a request for a Formal Interpretation must always be phrased in such a way that it can be answered either "yes" or "no". This article addresses that request for a Formal Interpretation and was written because: 1) the question being posed was reasonable and important; 2) a simple yes or no will not meet the needs of the requestor; and 3) to stimulate a discussion of the issue, such that the display fireworks industry might then provide guidance to the committee before they address the issue at their next committee meeting.

The paragraph of interest to the requestor was:

> *5.1.4.2 If high winds, precipitation, or other adverse weather conditions prevail such that a significant hazard exists in the opinion of the operator or the authority having jurisdiction, the fireworks display shall be postponed until the weather conditions improve to a reasonable level.*

Apparently because the code gives no guidance as to how much wind is too much wind, the Formal Interpretation requestor asked (yes or no):

> *Given the following conditions: (1) The display site meets the minimum separation distances in Table 3.1.3 and no additional separation distance is provided between the display site and spectator viewing area; and (2) The display site is on the same elevation with the spectator viewing area; and (3) the other minimum code requirements of NFPA 1123 have been met. Is it the intent of paragraph 5.1.4.2 to postpone a fireworks display if the maximum continuous wind speed exceeds 5 mph?*

The requestor then asked the same question, but for 10, 15 and 20 mph (16, 24 and 32 k/hr) wind speeds.

As readers of *Fireworks Business* certainly know, there may be cases where even a 5 mph (8 k/hr) wind might be excessive and yet other cases where a 20 mph (32 k/hr) wind is not excessive (at least in terms of safety). Thus, there are no simple answers for the requestor of the Formal Interpretation, and the requestor is unlikely to find the committee's response will have supplied the information being sought. All this not withstanding, the committee (and the industry) should probably be grateful to the requestor for raising the issue. It is appropriate for the code to provide guidance for the enforcing authority regarding what constitutes excessive wind, and it is likely that such guidance will now be crafted and added as advisory information to the next edition of the code. The remainder of this article is devoted to presenting background information about aerial shell and shell debris ballistics, discussing the specific question about excessive wind, and then suggesting guidance to be considered for possible inclusion in the code by the committee.

Technical Background

If the wind is blowing away from the spectator viewing area (or all spectator viewing areas) the chance of hazardous debris posing a risk to spectators is reduced. If the wind is blowing toward the spectator viewing area (or any spectator viewing area) the chance of hazardous debris posing a risk to spectators is increased. As an additional consideration, the displacement downwind for debris from exploded aerial fireworks

will be much greater than for dud shells. (This is because the mass of the debris is relatively low and their drag coefficient is relatively high, as compared to dud shells). See Figure 1, which is a computer calculation[1] of the trajectory of a typical 6-inch aerial shell fired from a mortar tilted 6.6 degrees into a 40 mph (64 k/hr) wind.[2] Each symbol identifies the location of the aerial shell (triangles) and a substantial piece of debris from the exploded shell (diamonds) after successive one second intervals have elapsed. Note that this mortar tilt angle is sufficient to compensate for the effect of the wind to the extent that the aerial shell reaches its apex directly above the mortar (not considering shell drift[3] from bore balloting[4] and magnus forces). The point of fall of the dud shell (assuming it does not explode near its apex) is calculated to be approximately 200 feet (61 m) downwind from the mortar. The point of fall of a substantial piece of shell debris is approximately 800 feet (244 m) down range (assuming the shell explodes near its apex). (The substantial piece of shell debris in this case has a mass that is approximately 3% of the shell's total mass upon firing, which corresponds to approximately 1/3 of one hemisphere of the shell's casing.) Such a substantial piece of shell debris was chosen because it is about the most massive single piece of debris that is likely to be produced from a normally effective star shell burst. Note that lighter weight shell debris will come to fall even further downwind. (As a point of comparison, this piece of debris will come to fall at a point that is about twice the minimum separation distance (from the spectators to the mortar), which is only 420 feet [128 m].)

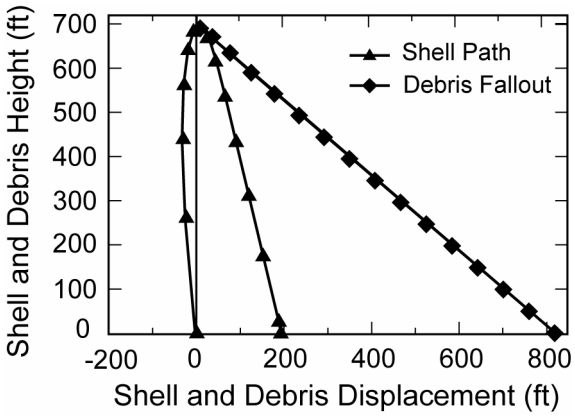

Figure 1. A graphical representation of the trajectory of an aerial shell fired from a mortar angled slightly into a strong wind (40 mph [64 k/hr].

A third category of material might have been considered in Figure 1; that is dud components from exploded shells. Based on their typical mass and size, these dud components would be expected to fall to the ground somewhere between the points of fall of dud shells and the more massive pieces of debris from exploded shells.

Figure 1 helps to make the point that while skilled mortar angling may be able to compensate for the effect of a significant wind on (1) the location of the apex of the shell, (2) the point of fall of a dud shell, or (3) the point of fall of substantial shell debris; it is not possible to fully compensate for more than one of these effects at the same time, as documented in Table 1. A mortar tilt of 13 degrees into the wind will compensate for where a dud shell will land, but the relatively heavy debris will still fall 650 feet (198 m) downwind. To fully compensate for the heavy debris would require a mortar tilt angle of approximately 40 degrees into the wind, but that tilt angle will result in a dud shell falling at a point nearly 600 feet (183 m) up wind.

Table 1. Displacements Downwind for Selected Mortar Tilt Angles into the Wind.

Mortar Tilt Angle (deg)	Displacement Downwind (ft)		
	Shell at Apogee	Dud Shell at Impact	Debris Fallout
6.6	0	195	820
13.0	–115	0	650
39.1	–460	–590	0

(Negative displacements are upwind from the point of discharge.)

The inability to simultaneously compensate for the points of fall for both dud shells and debris, even with the most skilled angling of the mortars, is one reason for concern when attempting to perform a display when there is a significant wind. While on the subject of skilled mortar angling, Tables 2 and 3 are offered for possible assistance. Table 2 gives calculated results for the approximate average downwind displacement in the point of fall of typical dud 3-, 6- and

Table 2. Calculated Approximate Average Downwind Displacement of Dud Spherical Shells Based on Wind Speed.[2]

Wind Speed (mph)	Downwind Displacements by Shell Size					
	3 in. (ft)	75 mm (m)	6 in. (ft)	150 mm (m)	12 in. (ft)	300 mm (m)
0	0	0	0	0	0	0
5	49	15	53	16	56	17
10	98	30	105	32	113	34
15	147	45	158	48	170	52
20	197	60	212	65	227	69
25	245	75	266	81	285	87

(Note, these results are calculated for spherical shells under fairly typical conditions.)

Table 3. Calculated Approximate Average Down Range Displacement of Dud Spherical Shells Based on Mortar Tilt Angle.[2]

Mortar Tilt Angle (deg.)	Down Range Displacements by Shell Size					
	3 in. (ft)	75 mm (m)	6 in. (ft)	150 mm (m)	12 in. (ft)	300 mm (m)
0	0	0	0	0	0	0
2	42	13	74	23	127	39
5	103	31	184	56	314	96
10	201	61	359	109	611	186
15	291	89	520	159	885	270
20	372	113	664	203	1130	345

(Note these results are calculated for spherical shells under fairly typical conditions.)

12-inch (75-, 150- and 300-mm) aerial shells, as a function of wind speed for displays fired from sites approximately 1000 feet (305 m) above sea level. (The amount of displacement for other wind speeds and other size shells can be estimated by interpolation.) Table 3 gives calculated results for the approximate average down range shift in the point of fall of typical dud 3-, 6-, and 12-inch (75-, 150- and 300-mm) spherical aerial shells, as a function of mortar tilt angle (as measured from vertical).

By comparing Tables 2 and 3, one can conclude that the approximate amount of mortar tilt needed to correct the point of fall of dud shells for each 5 mph (8 k/hr) of wind speed is that indicated in Table 4. One complicating factor for making such corrections for wind is the difficulty in accurately achieving such small tilt angles. However, an even greater problem is that it is the average wind aloft, and not that at ground level, that needs to be compensated for. Because of obstructing near surface objects such as trees and houses, the wind speed at ground level will almost always be less than the winds aloft. As a way of crudely estimating wind speed aloft, one might assume as a very rough rule-of-thumb that the wind aloft is about twice the speed at ground level.

Table 4. Calculated Approximate Mortar Tilt from Vertical for Each 5 mph (8 k/hr) of Wind Speed Needed To Compensate for Downwind Displacement of Dud Aerial Shells.

Shell Size		Approximate Mortar Tilt Angle into the Wind (degrees)
(in.)	(mm)	
3	75	2.4
6	150	1.4
12	300	0.9

Discussion

There probably are two main areas in which excessive wind represents a safety concern: 1) when hazardous debris is carried to and falls into a spectator area because of the wind, and 2) when there is a risk of fire that is significantly exacerbated as a result of it being more difficult to control because of the wind.

The first area of concern, hazardous debris reaching spectators, is relatively easy to address. There are three main types of hazardous debris that are of primary concern, debris from exploded shells, dud components from exploded shells and dud (unexploded) shells. Generally of least concern are the debris from exploded shells; the next greater concern is for any dud components from exploded aerial shells; of much greater concern are dud aerial shells (which can cause serious injury if striking a person, or which might ignite upon impact with the ground).

In discussing this, recall that in addition to meeting the separation distance requirement, the requestor of the Formal Interpretation included the provision that the other minimum code requirements of NFPA 1123 (2000) have been met. Accordingly, code paragraphs 2.3.2 and 5.1.4.3 will have been (and presumably are being) complied with. These code paragraphs state that:

> *2.3.2 ... Under no circumstance shall mortars be angled toward the spectator viewing area. ...*; and
>
> *5.1.4.3 ... If any unsafe condition is detected, such as hazardous debris falling into the audience, the spotter shall signal the shooter to cease firing until the unsafe condition is corrected. ...*

That the downwind displacement is greater for the debris from exploded aerials shells than it is for dud components, and it is significantly greater than for dud shells is important in the context of determining when wind speed is too great for reasonable safety. This is because, while the smoldering debris from exploded shells is relatively easy to spot at night, falling dud components and dud aerial shells are not. Thus, before a wind is blowing strong enough to significantly increase the probability of a dud component or a dud shell falling into a spectator area, relatively easily visible smoldering debris will likely be seen to approach dangerously close or into spectator areas, thus causing the display to be halted at that time. That is to say, in the context of this question, if smoldering debris is not being driven into spectator areas by the wind, then neither will the more dangerous dud components.

There is, however, still the question of how one can easily determine, before a display has started, whether a wind blowing toward a spectator area is excessive. In that case, it may be necessary to draw upon the experience of the operator (and hopefully the enforcing authority) as to whether it is safe to begin the display. As an alternative, one or more small caliber test shells might be fired and their performance used as a guide in determining whether it is safe to begin the display. Similarly, displays typically start with relatively small caliber shells, whose debris is generally less dangerous and whose down range displacement by the wind will generally be slightly less than for larger shells. Thus, if there is uncertainty as to whether the wind is excessive, a display might be started, closely observed, and then halted at such time as it becomes apparent that an unsafe condition exists for the firing of larger shells.

The second area of concern regarding potentially excessive wind for a fireworks display is in regard to the potential difficulty in controlling a fire that might be ignited by the display. In this case, both the direction and speed of the wind are important considerations. Wind direction has a controlling effect on what might be set alight by burning or smoldering fallout, and wind speed can strongly affect the rate of spread of a fire once started. Addressing these issues generally lies squarely with the local fire authority,

and it is pretty much their call as to whether the wind conditions are safe enough to proceed with a display from a fire safety standpoint. However, it should be considered that it may be possible to mitigate a fire safety problem by means other than postponing the display.

Suggestion

Because at the time, the Pyrotechnic Committee was nearly beyond the point in the revision process where the public can comment on adjustments made to the code, it seems prudent that the issue regarding excessive wind should only be addressed in Annex A (formerly Appendix A) of the code, which is for non-binding guidance. Accordingly, as a starting point for work by the committee, the following text was offered as a possible annex note to NFPA-1123 code paragraph 5.1.4.2.

> *A.5.1.4.2 In considering when wind speed is excessive for the reasonably safe performance of a fireworks display, there are two primary considerations (1) the potential for an increased risk of hazardous debris from the display falling into spectator areas, and (2) the potential for an increased probability of a fire that is made excessively difficult to control. Under some extreme conditions, winds as slight as 5 mph might pose a problem; while under other conditions winds in excess of 20 mph may not pose a problem.*
>
> *An increased fallout hazard only occurs when the wind is traveling in a direction toward one or more spectator areas. What is probably the least dangerous debris, smoldering remnants from exploding aerial shells, is the type of fallout that is most greatly affected by wind and is the easiest to observe. Accordingly, if such smoldering debris is not seen to fall dangerously near or into any spectator area, the wind is unlikely to be excessive regarding more dangerous fallout from the display. However, when the wind is a problem, there are some possible mitigation strategies that might be considered regarding hazardous fallout. These are: to move the spectators out of the path of the fallout, to redirect the fallout by moving the fireworks or re-angling the mortars, to increase the separation distance between the fireworks and spectators, to modify the content of the display to eliminate the fireworks of greatest concern, and to delay the display until weather conditions have improved.*
>
> *Any increased fire hazard because of the wind is best evaluated by the local fire authority and is not addressed in this code. If the wind is found to be a problem in this regard, some possible mitigation strategies to be considered regarding fire risk are: to water down the areas and items of concern immediately before the display, to modify the content of the display so as to eliminate the fireworks of greatest concern, to increase the amount of fire suppression equipment and personnel in the immediate area, and to delay the display until weather conditions have improved.*

(Any readers wishing to comment regarding this issue, and whose interests are represented by one of the fireworks groups or associations serving on the Pyrotechnics Committee, were encouraged to work through their representatives. Any others wishing to make input were encouraged to communicate with the authors of this article.)

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An earlier version appeared in *American Fireworks News*, No. 277, 2004.

"Warning Extremely Dangerous Directions for Firing"

K. L. and B. J. Kosanke

The title of this very short article is, in effect, a direct quote from a label found on some display firework aerial shells, see Figure 1. As it turns out, the label is more literally correct than might have been intended. Note that one of the instructions is to "LIGHT FUSE BEFORE PUT IN TO MORTAR…" Few if any would argue that users should not be "warned" about such "extremely dangerous directions for firing". As regards this particular label, it would definitely seem to be a good thing that many inexperienced users of display fireworks fail to read (and in this case, rigorously follow) the use instructions accompanying them.

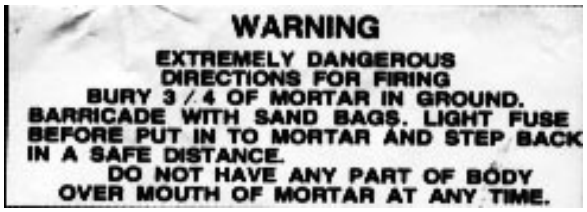

Figure 1. A copy of the warning and direction label found on some display firework aerial shells imported in 2004.

The authors are grateful to Mike Walden (Pyro Shows, Inc.) for finding and reporting the problem with this warning and direction label.

An earlier version appeared in *Fireworks Business*, No. 249, 2004.

The Effect of Intentionally-Caused Fire Leaks into 3-inch Display Firework Aerial Star Shells

K. L. and B. J. Kosanke

This article is the second report on a series of tests to more definitively establish the difference between the causes of so-called *flowerpots* and *muzzle breaks*. A previous article[1] reported on a similar study using 2-1/4 inch (57-mm) plastic aerial shells (formerly classed as consumer fireworks). The current article extends the earlier work by considering relatively high quality, although small, display firework shells. To conserve space and avoid needless repetition, some of the background and supporting information presented in the earlier article will not be repeated in the present article.

The current study, as in the previous study, concludes that quite large fire leak holes are needed to cause the shells to explode while still within the mortar upon their firing. This is significant because it was previously demonstrated that the nature of the break charge substantially affects the size of the hole needed to cause shells to explode within the mortar as they are fired.[1] For example, the presence of a relatively small fire leak hole is sufficient to cause a salute to explode while still well within its firing mortar. This is in contrast with the 2-1/4 inch (57-mm) plastic aerial shells tested previously, which had little if any break powder, and the fire leak hole results for those shells were not considered to necessarily apply to higher quality more powerfully breaking aerial star shells. The display shells in the current study had ample high quality break powder and were reasonably powerfully breaking. (Although testing using larger caliber display aerial shells has not yet been completed, it is appears that rather large fire leak holes are also necessary to cause those larger caliber shells to explode while still inside their mortars as they are being fired.) Thus, as was concluded in past studies of the probable causes of flowerpots and muzzle breaks of star shells,[2] small cracks and holes in those shells have the potential to cause muzzle breaks; however, much more substantial fire leaks (up to and including total casing failures) are required to produce in-mortar shell explosions. (Note that a discussion of the causes of malfunctions described as flowerpots is complicated somewhat by the observation that some muzzle-breaking shells actually give the visual appearance of what would generally be described as flowerpots.[3]

Test Procedure

In the current tests, the shells were 3-inch (75-mm) Thunderbird brand "Color Peony-Gold" product number TBA-105. The shells were approximately 2.68 inches (68 mm) in diameter and of typical paper construction with two time fuses. On average, the shells had a total mass of approximately 4.8 ounces (130 grams), and with approximately 1.3 ounces (36 grams) of lift powder. The shells contained approximately 2.5 ounces (70 grams) of stars that were approximately .032-inch (7.6 mm) in diameter, and approximately 0.64 ounces (18 grams) was rice hull break powder.

To prepare the test shells for firing, their paper lift bag covering and the plastic bag of lift, with the shell leader attached, were removed. A fire leak hole was made in the immediate area of the time fuses of each test shell, using a remotely operated mechanically driven awl. Awl diameters ranged from 0.040 inch (1.0 mm) to 0.23 inch (5.8 mm). Because the shell casings were paper, following removal of the awl, the diameter of the hole remaining open was slightly less than the diameter of the awl. The actual diameters of the fire leak holes were determined by inserting drill stems of various diameters into the hole until the largest one that fit effortlessly was found. The diameter of the fire leak holes ranged from 0.035 inch (0.89 mm) to 0.20 inch (5.1 mm). The shell leaders were removed from the bags of lift powder and replaced with electric matches (Daveyfire AN/28 B). The lift charges were then secured to the bottom of the shells us-

Table 1. Results From Fire Leak Testing of 3-inch (75-mm) Display Fireworks Aerial Shells.[6]

Fire Leak Hole[a]		Shell Burst Height (ft.)			High Speed Video	Mortar Pressure Gauge
Diameter (in.)	Area (x 10^3) ($in.^2$)	Average[a,b]	Standard Deviation[a,c]	Standard Error[d,e]		
0.035	0.96	7.3 (0)	1.0	0.5	Yes	No
0.055	2.4	9.0 (0)	2.5	1.	No	No
0.074	4.3	3.5 (0)	0.9	0.4	Yes	No
0.086	5.8	4.1 (0)	1.5	0.7	No	No
0.11	9.4	3.0 (0)	1.8	0.8	Yes	Yes
0.16	20.	2.4 (0)	1.1	0.5	Yes	Yes
0.20	31.	0.76 (3)	0.9	0.9	Yes	Yes

a) Values reported to two significant figures.

b) The number in parenthesis is the number of shells bursting within the mortar. In calculating the average burst height, a shell burst occurring within the mortar was arbitrarily assigned a burst height of –0.5 foot.

c) The standard deviation was computed using the so-called $n - 1$ method.

d) The standard error of the mean is equal to the standard deviation divided by the square root of the number of measurements being averaged (i.e., in this case the number of measurements was 5).

e) Values reported to one significant figure.

ing a small amount of tape. For each fire leak hole size, five test shells were prepared and fired.

The test mortars were high density polyethylene (HDPE), 22.5 inches (570 mm) long above the mortar plug and 2.93 inches (74.4 mm) inside diameter. For some tests, the mortar was fitted with a piezoelectric pressure gauge. This was done because monitoring the mortar pressure profile as a shell fires provides confirmation as to whether the shell exploded within the mortar as opposed to a few feet above the mortar. (See reference 3 for a demonstration of the spike in mortar pressure when a shell explodes before it has exited the mortar.)

In all cases the testing was documented by video taping using conventional video equipment. However, during the course of the testing, the use of a high frame-rate video system was acquired.[4] This aided in the ability to accurately determine the height above the mortar at which the shell bursts had occurred. However, when shell burst occurred very close to the muzzle of the mortar (within the muzzle flash of a firing mortar), the high speed video provided confirmation as to whether the shell burst occurred just inside or just outside the mortar. This is because of differences in the pattern of the stars produced, which are only discernable using the high frame-rate video system. (See reference 3 for a demonstration of the differing star patters for shell bursts occurring well-outside, just-outside and inside the mortar.)

Burst Height Results

The results of the testing are summarized in Table 1 and Figure 1. As in the previous study, there is a large amount of variability in the burst height data, which is thought to be a reflection of the large variability so often seen in pyro-

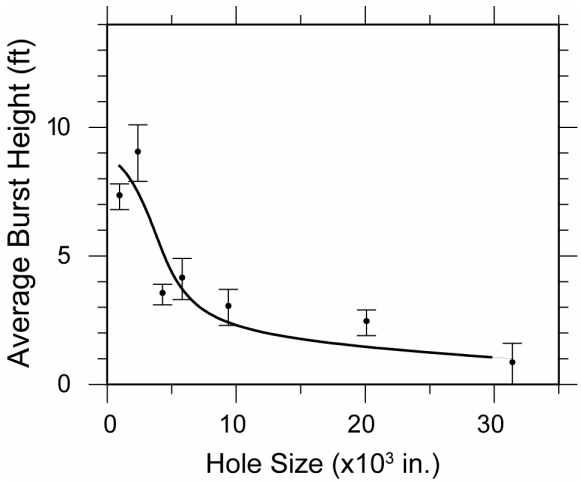

Figure 1. Graph of average burst height as a function of fire leak hole area. (The error bars are the one sigma (1 σ) standard errors reported in Table 1.)[5,6]

technic ignition and propagation. For this reason the location and shape of the average burst height trend line in Figure 1 is relatively uncertain. Had this needed to be determined with greater accuracy, many more test aerial shells (than the five for each size fire leak hole) would have needed to be test fired.

The general shape of the average burst height curve is similar to that found previously for the 2-1/4 inch (57-mm) plastic aerial shells. Both start at roughly 10 feet (3 m) for the smallest fire leak holes (approximately 0.04-inch diameter), then fall to lower burst heights for larger size holes, with shells bursting within their mortars when the fire leak hole diameter reaches approximately 0.2-inch (5 mm) in diameter. However, the approximate hole size where there appears to be a substantial drop in average burst height occurs at approximately 0.06-inch (1.5 mm) for 3-inch (75-mm) display shells whereas a similar drop did not occur until significantly larger fire leak holes (approximately 0.15-inch [3.8-mm]) for the 2-1/4 inch (57-mm) plastic shells. Based on the substantially different types and amounts of break powder for the two types of shells, and the previous testing using various types of break charge, a difference such as this could be expected.

These display aerial shells had more lift charge than thought to be typical of other manufacturers. However, this is not expected to have produced substantially anomalous results. With more lift charge, the mortar pressures were greater than the average of previous measurements. (Peak mortar pressures in this case averaged approximately 110 psi (759 kPa) whereas previous measurements of a variety of shell types produced an average of only approximately 40 psi [276 kPa].). The higher pressure must cause more burning lift gas to pass through a given diameter fire leak hole, which will result in reduced time for the shell to explode. (This effect was demonstrated in the testing reported below.) However, at the same time, the greater mortar pressures will also cause the shells to exit the mortar in less time (also shown below). The result of the shell explosion times and mortar exit times both being reduced must tend to balance each other and should tend to leave the burst height versus fire leak hole diameter data somewhat unaffected.

Measurement of Shell Burst and Mortar Exit Times

To help gain a better general understanding of the flowerpot versus muzzle break processes, measurements were also made of the average time required for a test shell to exit its mortar after having its lift charge ignited and the average time required for a test shell to explode after having its contents ignited. The same methods that have been used successfully in the past[1,2] were employed in these measurements and will not be described again in this article.

The average of five measurements of shell exit time was 0.027 second. This compares with an average of 0.043 second measured previously for a variety of 3-inch (75-mm) display shells.[2] Considering that the current test shells have a greater amount of lift powder than typical, this reduction of approximately 35% in average exit time seems reasonable.

The average of five measurements of shell burst time was 0.065 second. This compares with 0.043 second measured previously for a variety of 3-inch (75-mm) display shells.[2] While this is greater than the average found previously for other shells, it is within the range of those earlier measurements.

In an attempt to quantify the effect of an increased amount of fire leaking into an aerial shell because of the greater than typical mortar pressure found for these test shells, some additional measurements of shell burst time were made. In these tests two electric matches were sealed into the shells at points across from one another in the shell casing, rather than using the single electric match as in previous tests. When this was done, the average shell burst time decreased from 0.065 to 0.042 second, approximately 30% less than when a single electric match was used.

Conclusion

The most significant piece of information gained from this study is that a fire leak hole nearly the same diameter as a typical time fuse must be present to cause the shell to explode while still inside the mortar. Further, based on the mortar pressure profile data, even those shells in this study that did explode inside the mortar did so quite near the top of the mortar.

Accordingly, the results of this study support and help quantify the conclusions presented in reference 2, that relatively small fire leaks must produce muzzle breaks in display aerial star shells, and that flowerpots are the result of very much more substantial fire leaks, up to and including the complete failure of shell casings due to the inertial forces produced by the very great acceleration of aerial shells as they are being fired (accelerations that can exceed 1000 times that of gravity[5]).

To further investigate and document the causes of muzzle breaks and flowerpots, similar studies using larger caliber shells have begun and will be reported when they are completed.

Acknowledgment

The authors are grateful to Larry Weinman (Schneier / Weinman Consultants) for commenting on an earlier draft of this article.

References and notes

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6) For Si Unit Conversions: 1 inch = 25.4 mm; 1 foot = 0.305 m; 1 psi = 6.9 kPa.

An earlier version appeared in *Fireworks Business*, No. 250, 2004.

Fireworks Displays: When Is Safe, Safe Enough?

K. L. and B. J. Kosanke

At a recent meeting of the National Fire Protection Association's Technical Committee on Pyrotechnics, there was a proposal to increase the site size requirement for public fireworks displays from the current 70 feet (21 m) to 100 feet (30.5 m) radius per the largest shell size in inches. It was the consensus of the committee that this was not needed because fireworks displays using the current distances were "safe enough". However, no one was able to substantiate their opinion with data. As part of that discussion the authors offered their own unsubstantiated opinion that it was likely that people were at a significantly greater risk while on the round trip drive to witness a fireworks display, than from the fireworks in the display. After offering some background information, this article presents a calculation of the comparative risks of driving to and attending a fireworks display, estimating that people are at least 7 times more likely to be killed or injured as a result of driving to attend a public display than they are from the fireworks in the public display.

Many dictionaries define the word safe as *free from damage, danger or injury* or *something that involves no risk of mishap or error*. However, according to that definition, no activity ever undertaken by anyone is safe because there is always some chance of injury, mishap or error. To the contrary, most texts on risk management define safe as *when the attendant risks of an activity are broadly considered to be acceptably low*.

One way to evaluate the general acceptability of the risk associated with an activity in question is to compare its risk to the risks of other activities that are demonstrated to be acceptable, based on a general willingness of people to partake in those other activities. For example, people readily accept the risk of driving round trip to attend fireworks displays; thus they obviously find that risk to be acceptable. If the risk of witnessing a fireworks display is of the same order (or less) than that associated with driving to the display, then it can reasonably be concluded that the risk of attending a display is also acceptable (i.e., it is safe).

In determining the risks of driving to and attending a fireworks display a combination of statistics and assumptions must be used. For the calculation of these risks to be accurate, the statistics need to be reliable and the assumptions need to be reasonable. The statistics related to injuries while driving come from the National Highway Transportation Safety Administration (NHTSA). The basic statistic used here is that the overall number of deaths on the highway is 1.50 per 100 million miles (160 million km) traveled. (This is an overall average, independent of the type of road, time of day, and vehicle occupancy load.) The assumptions being made are given below and, in the authors' opinion, those assumptions range from reasonable to quite conservative. (Here conservative is used in the sense of intentionally using assumptions that almost certainly underestimate the fatalities associated with driving to and from public fireworks displays, or over estimating those that occur at displays.) The reason for deliberately using conservative assumptions is try to avoid any argument that the conclusion – viewing a fireworks display presents less risk than driving to attend the display – was merely the result of using assumptions that are favorable to the fireworks industry. Further, anyone wishing to use less conservative assumptions may do so by simply replacing the numbers below with ones of their choosing.

The nature of the assumptions used in this estimate is briefly discussed immediately after each assumption is presented.

1) It is assumed that the accident rate driving to and from a public fireworks display is the same as the overall rate reported by NHTSA. (However, displays occur at night and spectators often drink alcoholic beverages on holidays and at displays. Both of these factors

can reasonably be expected to raise the accident rate associated with driving to or from a fireworks display. Thus using the overall NHTSA accident rate may be unduly conservative.)

2) It is assumed that a typical spectator will travel in a vehicle a distance of 2.5 miles (4 km) to attend a public fireworks display, for a round trip distance of 5 miles (8 km). (This average is thought to be quite low, especially for displays outside of large cities. It has been suggested that an average distance of 5 or 10 miles (8 or 16 km) to a display is a more realistic nationwide estimate.)

3) It is assumed that the total number of public fireworks displays in the US each year in the US is 5,000. (This is thought to be a low estimate. It was calculated assuming that each year there is only an average of 100 displays in each of the 50 states. To the contrary, it has been suggested that there are at least 7,000 to 10,000 public displays per year in this country.)

4) It is assumed that the average number of persons viewing a public fireworks display is 10,000. (This is definitely thought to be quite low as an average.)

5) It is assumed that in recent years, on average one spectator every two years (or ½ person per year) is killed in the US as a result of an accident during a public fireworks display. (Based on the authors' experience and input from knowledgeable industry sources, this is thought to be significantly higher than is actually the case. Nonetheless this will be used for the purposes of this article.)

By combining the highway fatality statistic of NHTSA with assumptions 1 through 4, one can arrive at an estimate of the number of people killed each year driving round trip to public fireworks displays by multiplying 5,000 displays per year, by 10,000 people per display, by 5 miles per person, by 1.5 fatalities per 100 million miles driven. The result is 3.75 fatalities per year associated with driving to view public fireworks displays, as compared with the assumption 5 that one-half person per year (i.e., one person every two years) is killed by the fireworks while attending the display. Accordingly, in terms of fatalities, the risk of driving to a public fireworks display is more than 7 times greater than the risk of actually viewing the display. (When less conservative assumptions are made, the estimated risk of driving is more like 20 times that of viewing.)

To conclude this calculated estimate of the relative risk of attending fireworks displays, one additional assumption needs to be made.

6) It is assumed that the ratio of serious injuries to fatalities is the same for driving and for public fireworks displays. (There seems to be little reason to doubt this approximately correct.)

Thus it can reasonably be concluded that the combined (fatality and serious injury) risk of driving to watch a public fireworks display is more than 7 times the risk of viewing the display. Further, since people readily accept the risk of driving to fireworks displays (i.e., that driving to the display is safe or safe enough) then it must logically be concluded that viewing public fireworks displays – as they are currently being performed – is also safe, or safe enough. That is not to say that efforts to further improve public safety at fireworks displays (or while driving on the highway) should be abandoned, rather that the impetus for substantially tightening the requirements for public fireworks displays needs to be kept in perspective. Changes that are relatively easy to implement or for which there is a substantial increase in safety, should be made. However, changes that are especially burdensome to implement or seriously reduce the public's enjoyment of displays, should be considered carefully before deciding whether they really need to be made.

The authors are grateful to personnel associated with *Fireworks Business* and the American Pyrotechnics Association for providing comments on an earlier draft of this article.

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The Effect on Mortars of Explosions within Them

K. L. Kosanke and L. Weinman

An earlier article[1] that appeared a little over a year ago discussed one type of mortar bursting explosion. The article described a process whereby a sufficiently powerful explosion occurring internally near the muzzle of a high density polyethylene (HDPE) mortar would not only burst the top of the mortar, but could also burst the plugged end of the mortar, frequently leaving the middle section of the mortar fully intact. Since publishing that article, readers posed two questions: 1) do the conclusions of the earlier article apply equally to explosions occurring near the plugged end of mortars; and 2) do the conclusions of the earlier article apply equally to mortars made of other materials. The simple answers to the two questions are no and yes, respectively. However, before addressing these two questions, the current article will very briefly summarize the observations made in the earlier article.

Figure 1 is a photograph of one mortar tested previously with a firework salute exploding after being positioned within the mortar near its muzzle. Clearly, both ends of the mortar have suffered severe damage, with the middle section essentially unaffected. As was explained in the earlier article, the bursting of the top of the mortar was caused directly by the explosion of the salute. Whereas the explosion of the plugged end of the mortar was the result of the blast pressure wave from the explosion traveling down the length of the mortar, reflecting off the mortar plug, and thus nearly doubling the strength of the blast pressure wave such as to also burst the bottom of the mortar. (Readers wishing a more complete discussion with supporting data should consult reference 1.)

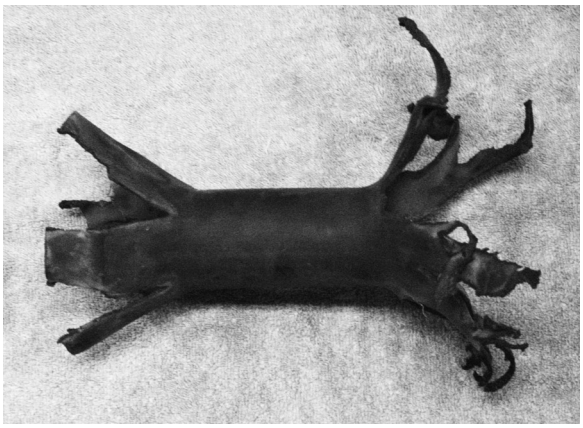

Figure 1. A photograph of a HDPE mortar following the explosion of a salute near its muzzle end (to the right).

Answer to Question 1

When a pressure wave travels along the inside of a pipe of constant dimension, it will diminish somewhat in magnitude as it progresses along the pipe. Over a distance of pipe equal to the length of a mortar the degree of reduction is only modest and for the purpose of this discussion can mostly be ignored. However, when a pressure wave travels along the inside of a pipe where there is a sudden change in the diameter of the pipe, there is an effect that cannot be ignored. Although it is blast waves that are of interest, perhaps the effect can most easily be explained in terms of simple sound waves.

When there is a sudden change in pipe diameter, this corresponds to a change in the pipe's acoustic impedance. A decrease in pipe diameter corresponds to an increase in acoustic impedance; whereas an increase in pipe diameter corresponds to a decrease in acoustic impedance. In both cases, large changes in diameter correspond to large changes in impedance. When a pressure wave reaches a sudden change in acoustic impedance, a reflected pressure wave will develop and will travel back upon the incident wave. The greater the acoustic impedance change, the greater (i.e., stronger) is the magnitude of the reflected pressure wave. When the change is from relatively low to relatively high acoustic impedance (i.e., from relatively large diameter to relatively small diameter), the re-

flected wave will be in-phase with the incident wave, causing reinforcement in the pressure wave at that point. To the contrary, when the change is from relatively high to relatively low impedance (i.e., from relatively small diameter to relatively large diameter), the reflected wave will instead be out-of-phase with the incident wave, thus resulting in a diminution of the pressure wave at that point.

In the case of a firework mortar, when a pressure wave from an explosion near the top of the mortar travels down and reaches the plug in the bottom of the mortar, this is a very great decrease in diameter (effectively to zero), corresponding to a very great increase in acoustic impedance. The result is an in-phase reflection (i.e., a reinforcement or strengthening) of the incident pressure wave at that point. As was demonstrated in the earlier article for a blast wave,[1] this can be sufficient to cause the bottom of a mortar to burst when a reasonably powerful explosion occurs in the top of the mortar, and yet can leave the middle of the mortar fully intact (see Figure 1).

In the case of a firework mortar, when a pressure wave from an explosion near the bottom of the mortar travels up and reaches the muzzle of the mortar, this is a very great increase in diameter (effectively to infinity), corresponding to a decrease in acoustic impedance. The result is an out-of-phase reflection (i.e., a diminution or weakening) of the incident pressure wave at that point. Because of the reduction of the pressure wave at the muzzle of the mortar, there is a reduced likelihood of bursting the top of the mortar. There is a chance that a sufficiently powerful explosion in the lower portion of a mortar could destroy the entire mortar (especially if the explosion occurs up a little way from the bottom of the mortar). However, there is no chance of bursting the top of the mortar if the middle of the mortar is to be left intact. To demonstrate this for blast waves, two tests were performed.

In the first test, using a mortar made with the same type of 2-inch (50-mm) high density polyethylene (HDPE) pipe as was used in Figure 1, a powerful firework salute was exploded in the bottom of a mortar. The salute contained approximately 2 ounces of a high quality flash powder. The result of the explosion is shown in Figure 2. In this case more than 60% of the length of the mortar was destroyed, leaving only approximately 5 inches (125 mm) of the muzzle end of the mortar intact. In the second test, again using the same type of 2-inch (50-mm) HDPE pipe, a 5 ounce (140 g) charge of a commercial high explosive was exploded in the bottom of a mortar. The result of this explosion is shown in Figure 3. In this case more than 80% of the length of the mortar was destroyed, leaving only approximately 2 inches (50 mm) of the muzzle end of the mortar fully intact.

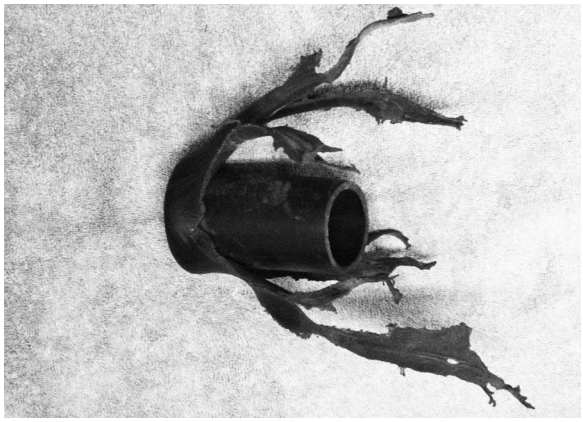

Figure 2. A photograph of a HDPE mortar following the explosion of a powerful salute at its bottom (to the left).

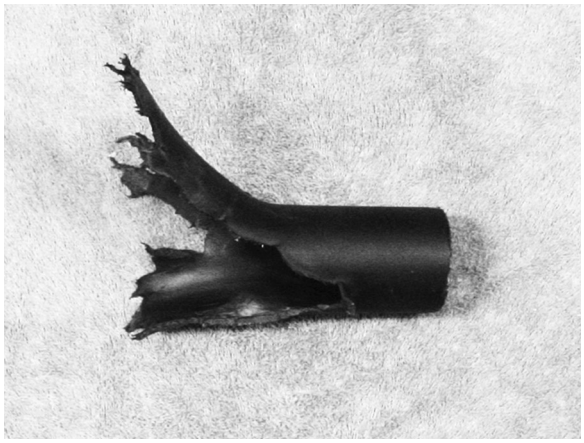

Figure 3. A photograph of a HDPE mortar following the explosion of a very powerful charge of commercial high explosive at its bottom (to the left).

Accordingly the answer to the first question is no, the conclusions of the earlier article do not

apply equally to explosions occurring near the plugged end of mortars. As the result of explosions occurring in the lower regions of mortars, there is no chance of bursting the top of the mortar when the middle portion of the mortar has been left intact.

Answer to Question 2

The same physical principles that are at work within the test HDPE mortars apply to all other mortar materials as well. It is the basic design of the mortar, a tube with only one plugged end that causes this effect. As partial confirmation, note that in a recent series of tests of solid 3-inch (75-mm) cylindrical comets with a disturbing tendency to explode upon firing while still inside their mortars, nine paper mortars received this same type of double ended damage. See Figure 4 for examples of this type of mortar damage, with the mortars from left to right in the photograph suffering increasingly violent explosions.

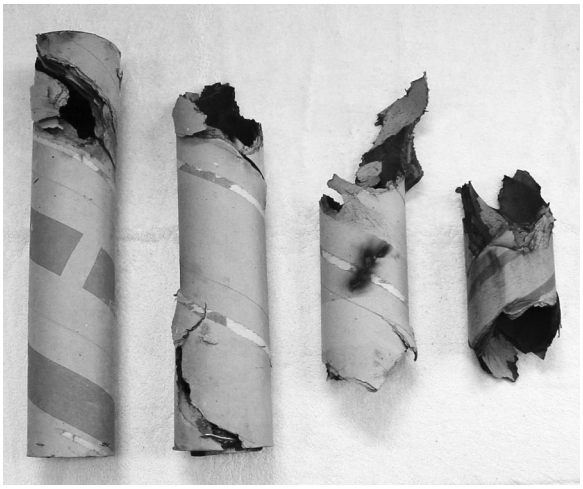

Figure 4. A photograph of a series of paper mortars following internal explosions occurring near their muzzle end.

It is true, however, that the strength of the mortar material does have a significant effect on the power of the explosion needed to produce the damage. Because of the relatively greater strength of steel mortars, many fairly powerful explosions occurring within them produce no visible damage to those mortars. Over the years the authors have observed several steel mortars having burst as the result of an explosion occurring within them. The authors do not recall one that suffered the same type damage as documented in Figure 1. However, the reason is not that steel mortars are not capable of bursting at both ends from explosions near their muzzle ends. In part the reason is that many of those mortar explosions were caused by salutes (or salute containing shells). Salutes that explode within mortars upon firing, almost universally do so when they are still relatively near the bottom of the mortar. Accordingly, these explosive events, while powerful enough to seriously damage (or totally destroy) the mortar, cannot produce double ended mortar damage, as was explained above. Another part of the reason seems to be related to the fact that malfunctioning star shells typically explode near the muzzle of their firing mortars. While occasionally these so called star-shell-detonations are powerful enough to burst the top of their mortar, rarely (if ever) are they powerful enough to also burst the bottom of their mortar, considering that the mortar bottom is substantially strengthened as a result of being solidly welded to a steel plug.

Accordingly, the answer to the second questions is yes, single explosions that burst both ends of the mortars while leaving the middle portions of the mortar intact, are not a direct result of the type of material used to make the mortar.

Acknowledgments

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References

1) K. L. Kosanke and L. T. Weinman, "The Effect of Reflected Blast Waves in HDPE Mortars", *Fireworks Business*, No. 234, 2003; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 7 (2003 and 2004)*, Journal of Pyrotechnics, 2006.