Pyrotechnic Literature Series No. 8

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

Table of Contents — Part 5

Biographical Information on Ken and Bonnie Kosanke

Ken has a Ph.D. in physical chemistry and post-doctoral training in physics. He has directed numerous research projects and served as the Quality Assurance Manager for a government subcontractor. Bonnie has a M.S. in Biology and Computer Science. She has extensive experience conducting and directing research and as a computer scientist. Today they operate a pyrotechnic research facility located on 80 acres in Western Colorado. In addition to test ranges and an explosion chamber, there are chemistry, electronics, and video labs, fabrication shops, and assembly buildings.

In the past they have commercially manufactured fireworks and operated a fireworks display company. They have both served as officers and on numerous committees of the Pyrotechnics Guild International. Currently they serve on Technical committees of the National Fire Protection Association. They also lecture and consult in pyrotechnics.

Together they have published more than 200 articles on fireworks, pyrotechnics and explosives. They published, *The Illustrated Dictionary of Pyrotechnics*, *Lecture Notes for Pyrotechnic Chemistry,* and *Lecture Notes for Fireworks Display Practices*. Bonnie publishes the *Journal of Pyrotechnics*. Ken served for many years as a senior technical editor for *Pyrotechnica* and for the *Pyrotechnics Guild International Bulletin.*

CAUTION

The experimentation with, and the use of, pyrotechnic materials can be dangerous; it is felt to be important for the reader to be duly cautioned. Anyone without the required training and experience should never experiment with nor use pyrotechnic materials. Also, the amount of information presented in these articles is not a substitute for the necessary training and experience.

A major effort has been undertaken to review this text for correctness. However, it is possible that errors remain. Further, it must be acknowledged that there are many areas of pyrotechnics, fireworks in particular, for which there is much "common knowledge", but for which there has been little or no documented research. Some articles herein certainly contain some of this unproven common knowledge. It is the responsibility of the reader to verify any information herein before applying that information in situations where death, injury, or property damage could result.

An earlier version appeared in *Journal of Pyrotechnics*, No. 7, 1998.

Development of a Video Spectrometer

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ABSTRACT

A simple, low-cost visible light spectrometer, consisting primarily of a video camcorder and an inexpensive diffraction grating, was assembled and found to be of use in work to improve colored pyrotechnic flames. This instrument is all that is needed to collect and store useful, qualitative flame color information. With this simple instrument, the nature of color agents and the sources of interfering chemical species can be determined.

If semi-quantitative data is needed, a video frame grabber and personal computer can be employed. These allow more accurate identification of wavelengths of spectral features (lines and bands). It also makes possible the determination of relative intensities of spectral features. If quantitative intensity data is needed, a suitable calibration source is necessary and calibration corrections must be applied to the intensity data.

In a brief study using the video spectrometer, it has become clear that much of the difficulty in achieving high quality green and blue colored flames is often the result of impurities present in the raw chemicals. Specifically, the presence of sodium and calcium can act significantly to shift green flame colors toward yellow and blue flame colors toward white.

Keywords: spectroscopy, flame color, video

Introduction

The quality and range of colors produced in fireworks has improved significantly in recent years. However, there continues to be considerable interest in further improving colored flame formulations. To date, most efforts have been hindered by the lack of a satisfactory and affordable spectrometer. Without spectral information it is all but impossible to identify the sources of undesirable interferences acting to reduce color purity. Without information about the emitting species present and their relative spectral intensities, researchers are reduced to using little more than trial and error to guide their efforts. (For more information on the physics and chemistry of colored flames, see Modules 6 and 7 in reference 1.)

This article is one of a series being written to share information on the development of a simple and inexpensive, yet surprisingly effective, instrument to collect spectral data. The instrument not only produces reasonably high-resolution spectra, it simultaneously records a series of spectra from the base of a flame to its tips, and does so continuously throughout the period of burning. The apparatus is referred to as a "video spectrometer". The concept was developed and the work initiated at roughly the same time both by the Kosankes and by T. Wilkinson. Since that time, there has been collaboration; however, the development has proceeded along slightly different paths. The work being reported herein and in an earlier article[2] is primarily that of the Kosankes, whereas the work of Wilkinson will possibly be reported in a subsequent article.[3]

The philosophy expressed in the design and application of the video spectrometer has cost, simplicity, and adequacy as central tenets. That is to say, almost everything in this article could be done better with greater expenditures of time and money. However, when adequate results could be achieved using inexpensive items, or using equipment that is already likely to be available, that is what was done. For example, the instrument is constructed using a standard video camcorder because it produces acceptable results, is compact, and is commonly available.

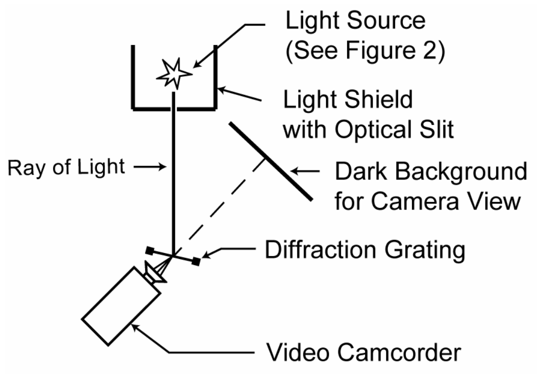

Figure 1. View of the elements comprising the video spectrometer in the horizontal plane (not to scale).

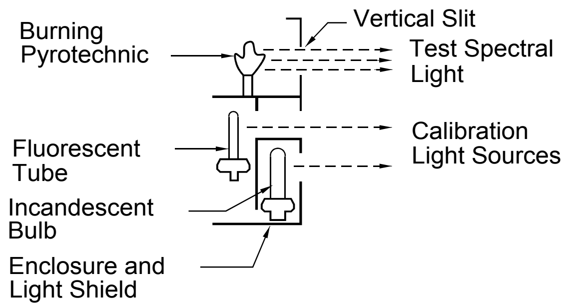

Figure 2. Vertical cut away view, illustrating the arrangement of light sources for the video spectrometer (two calibration sources plus a pyrotechnic flame).

Similarly, a very inexpensive diffraction grating and standard home light sources are used because they are adequate to the task.

Occasionally in this article, alternatives in equipment or methodology are mentioned. For example, the use of a black and white video camera is recommended to overcome some of the problems associated with internal light filters in a color video camcorder. However, most times the reader is left to think of alternatives and ponder their relative merits.

The Instrument

The key components of the video spectrometer and their arrangement are illustrated in a plan view in Figure 1. Light from the calibration sources passes through a slit with a fixed-width of approximately 3 mm. The test source has a manually adjustable slit width ranging from 0 to 3 mm and can be adjusted to control the light intensity from the source. (Typically a width of approximately 1 mm is appropriate.) From there the light travels a distance of approximately 2 m, where it passes through an inexpensive transmission diffraction grating mounted to the lens of a home video camera (camcorder), with the grating aligned vertically (to produce a horizontal dispersion).

Spectral resolution is improved if the diffraction grating is positioned at an angle approximately midway between the camera and the light sources. This angling of the diffraction grating is facilitated with a filter holder such as the "Cokin Creative Filter System",[4] which is designed to accommodate multiple glass plate filters. The diffraction grating can be inserted somewhat diagonally into the filter holder by using the different grooves on opposite sides of the filter holder. The holder slips onto an adapter ring mounted to the camera lens, making it easy to remove when the camera is used for other applications. This mounting system also facilitates the vertical alignment of the grating because the whole filter assembly is designed to rotate somewhat freely on its adapter ring. (This is especially convenient for those video cameras where the whole lens rotates as the camera is focused.)

The physical arrangement of light sources in the vertical plane is shown in Figure 2. Uppermost is the test source, typically a burning pyrotechnic composition. Below the test source is a pair of calibration light sources. The bottom light source is a clear-glass, 60-watt incandescent light bulb with a vertical tungsten filament.[5] This provides a continuous spectrum of colored light, probably best described as a "gray body" spectrum.[6] Behind and above it is a small fluorescent bulb (Sylvania[7] DULUX–S, CF1306/841). Figure 3 is an example set of spectra recorded with the video spectrometer. (For ease of reproduction in this article, all spectra have been rendered as negative grayscale images.) Uppermost is the spectrum of a burning red star. Below that is the spectrum of the Sylvania fluorescent bulb. On the bottom is the continuous spectrum from the incandescent light.

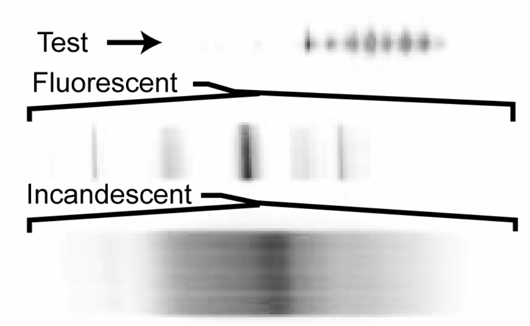

Figure 3. Example of a video spectrometer image (red star plus two calibration spectra) presented as a negative grayscale image (3 mm slit widths).

The calibration light sources are useful, but not essential for most purposes. The fluorescent source can provide wavelength calibration information. But since colored light spectra contain sufficiently prominent and well identified features (atomic lines and molecular bands), the spectra themselves could be used for approximate wavelength calibrations. The incandescent source can provide intensity calibration information. However, for most investigations with the video spectrometer, intensity calibration is not necessary. Beyond their potential use for calibration, the lamps provide a convenient light source for setting up and adjusting the video camera.

Table 1. Wavelength and Relative Intensity of the Major Spectral Features in Figure 3.

Wavelength (nm)(a)	Peak Power (W/nm)(a)	Total Power (W)(b)	Total Intensity (Relative)(c)
404	1.4	7.0	11
436	7.9	15.3	37
487	1.2	9.4	20
546	8.9	51.4	100
612	9.2	31.0	54
708	.5	3.4	5

(a) As reported by Sylvania for the spectral resolution seen in Figure 4.

(b) Areas under the curve for the spectral features.

(c) Relative peak areas corrected for energy (wavelength), using $E \propto 1/\lambda$, and normalized to 100 for the 546 nm peak.

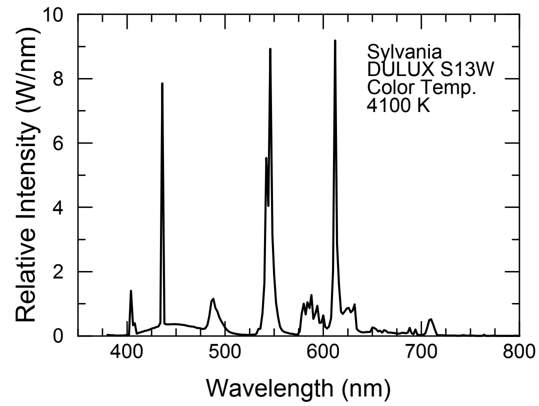

Figure 4. Light spectrum provided by Sylvania for their DULUX–S, CF 13 DX/841 fluorescent light.

Figure 4 is a reproduction of the fluorescent light spectrum provided by the manufacturer. Table 1 is the authors' attempt to quantify the wavelength and intensity of the spectral features for use as a calibration reference. Table 2 has been included as an aid to the reader in correlating the spectral wavelengths reported in this article with perceived color.

The slit was located in the vicinity of the source for several reasons. With the slit a long distance from the camera, it can be opened much wider than if it were near the camera. This makes it easier to adjust its width and to have separate test and calibration slits. If the slit were too near to the camera, it would not be possible to focus the camera on it as required, and only a small portion of the grating and camera lens would be

Table 2. Approximate Wavelengths Associated with Various Colors of Light.[6]

Perceived Color	Approximate Wavelengths (nm)
Red	700 to 610
Orange	610 to 590
Yellow	590 to 570
Green	570 to 490
Blue	490 to 450
Violet	450 to 400

used. Further, localized imperfections in the grating and lens could degrade spectrometer performance. Most importantly, with the slit attached to the holder of the test flame source, it is trivially easy to control its orientation so that light from the central portion of the flame is directed to the grating and camera.

To collect spectral data with usably accurate intensities, one must not over-load the charge coupled device (CCD) of the video camera with an over bright image. Apparent source brightness should be controlled by adjusting the test source slit width, the distance between the source and slit, the distance from the slit to the camera, or any combination of the three. Also the video camera's iris control should be set to manual and adjusted to control the apparent source brightness.

The resolution achieved by the video spectrometer is determined by the convolution of the slit width and the characteristics of the diffraction grating and video system. For any given camera, narrowing the slit and "zooming in" for a close-up view increases the resolution up to some value that is limited by the quality of the diffraction grating. The grating used in this case has a moderately high number of lines (530 lines per mm) but is quite inexpensive (< $2).[8] The resolution achieved is more than adequate for use in pyrotechnics. As a test of the resolution, a neon discharge tube was used as the test source with a slit width of 1 mm. A spectral resolution of 2–3 nm at a wavelength of 600 nm was achieved, see Figure 5. (Note that the top portion of Figure 5 is an expanded view of the neon spectrum, accomplished by using the video camera's telephoto capability to zoom in on just the red portion of the neon spectrum.) This resolution is sufficient to allow the identification of rather narrowly spaced atomic lines, whereas most pyrotechnic spectral intensity will appear as much broader molecular bands. (For more information on spectral types and pyrotechnic spectra see Modules 6 and 7 of reference 1.)

Not shown in Figure 1 is a large screen video monitor connected to the video camcorder. While it is possible to set up and use the video spectrometer using only the small eyepiece monitor on the camera, it is much more convenient to have a large screen monitor that can be viewed throughout the work area. Although colored spectra are attractive, the intrinsic resolution of the chromance (color) signal is significantly less than that for the luminance (black and white intensity) signal. Accordingly, fine tuning the video spectrometer (and data processing) is facilitated by operating the video monitor in a black and white (gray scale) mode.

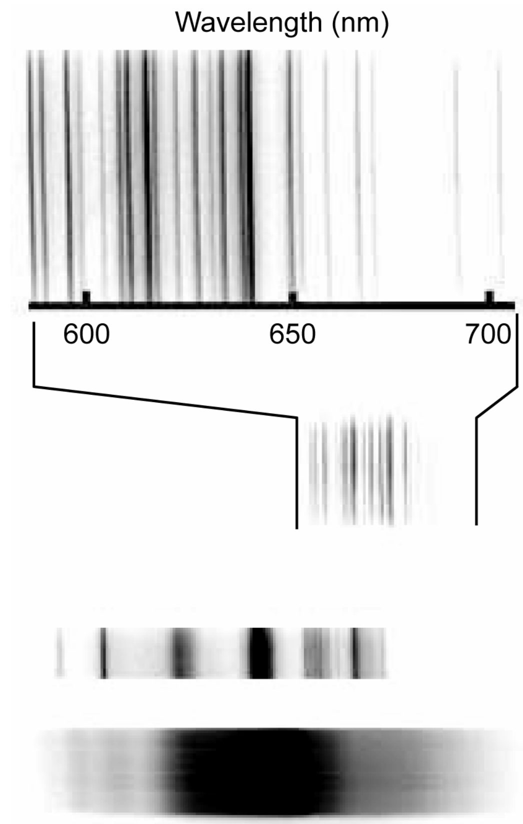

Figure 5. Upper: View with video camera "zoomed in" on the neon spectrum (1 mm slit width). Lower: The two calibration spectra (on the bottom) plus the neon spectrum (above).

Data Capture

Preparation for the collection of spectral data requires some adjustment of the instrument. First, set up the video camcorder with the diffraction grating in place and aim the camera directly at the light source slit(s). With the work area moderately dark and an operating light source located directly behind the slit, set the camera's focus control to manual and adjust the focus for a sharp image of the slit. Then aim the camera to the side (pan) just enough for the spectral image to become visible. At this time, using the wide angle / telephoto ("Zoom") control, adjust the size of the image so that the spectrum from the incandescent light nearly fills the width of the image area. (If a light source that produces reasonably narrow features is used, such as a fluorescent bulb, fine tune the camera's focus for the sharpest spectral image.) Finally, if the camera has an electronic iris control, set it to manual and adjust it such that the brightness of the image is not excessive. The light produced by pyrotechnic flames is quite bright, and it may be necessary to fine tune the iris adjustment or narrow the test source slit to keep the camcorder CCD from being overloaded. Also, the exposure should be set for 1/60 second (in the US); this will eliminate potential problems with flickering of the electric lamps.

The bulk data capture mechanism is the video recorder of the camcorder itself. As a test sample of pyrotechnic composition is burned, an essentially continuous collection of flame spectra (60 video fields per second), including any audio commentary by the experimenter, is preserved for later reproduction and processing. In addition, because the slit can be oriented along the length of the flame from its base to its tip, a series of spectra at varying distance along the flame are also recorded. This is potentially useful because of differences in the chemical species and temperatures present at various points in the flame.

As always it is necessary to follow all safety procedures, such as limiting the presence of combustible materials in the work area and employing air handling equipment to remove combustion products from the burning compositions.

Qualitative Data Processing

If only qualitative spectral information is needed, then simply playing back the recorded spectra may be sufficient, possibly using the pause capability of the recorder to hold the video image for more thorough examination. For this type of data interpretation, generally only approximate wavelengths are determined, and no correction is made for the sensitivity of the camera as a function of wavelength. Figure 6 presents two examples, a red and a blue color flame spectrum. (Note that calibration spectra have been removed from Figure 6 for simplicity of presentation, and a nanometer wavelength scale has been added.) The red flame spectrum is the same as that presented in Figure 3, and it obviously dominates in the longer wavelength (red) end of the spectrum. The color of the blue flame is not as pure. In the blue flame spectrum there are strong bands in the short wavelength (violet–blue) end of the visible spectrum. However, there are also strong bands near 500 nm (green) and even features near 600 nm (orange). These non-blue features in this blue flame act to seriously reduce the purity of its color.

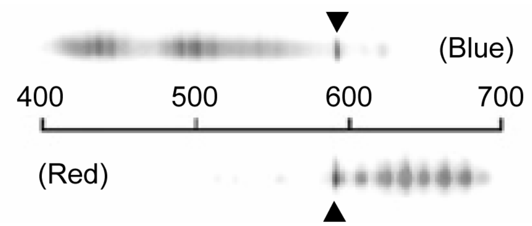

Figure 6. Examples of blue (above) and red (below) flame spectra, with the calibration spectra removed, a wavelength scale (in nm) added, and the Na-lines (589 nm) annotated (▲).

In Figure 6, the wavelength scale was established using the known spectral features from the fluorescent light, specifically the peaks at 436 and 612 nm. The accurate positioning of the wavelength scale was then accomplished using the very narrowly spaced sodium doublet lines (▲) at 589 nm, clearly visible in the test spectra. The sodium doublet lines are present in essentially all pyrotechnic flames due to trace amounts of sodium in the chemicals used.

An acceptable alternative wavelength calibration method is to use the prominent known spectral features present in the test spectra themselves. To facilitate use of this, Table 3 was complied. It lists the wavelengths and relative intensities of prominent features in pyrotechnic colored flame spectra.[9–11] In addition, many other spectral features are possible, most notably features from various oxides. However, in typically formulated colored flame compositions, they are relatively weak features.

Table 3. Identification of Some Major Spectral Features Grouped by Chemical Species and Band Group.

Source[a]	Wavelength (nm)[b]	Relative Intensity[c]
SrCl	689	< 1
	674–676[d]	5
	661–662[d]	10
	649	4
	636	10
	624	2
SrOH	608–611[d]	10
Sr[e]	461	10
CaCl	633–635[d]	1
	621–622[d]	10
	618–619[d]	10
	605–608[d]	1
	593	10
	581	4
CaOH	644	2
[Ref. 10]	622	10
	602	2
	554	5
Ca[e]	442–445[d]	10
Na	589	10
BaCl	532	3
	524	10
	521	1
	517	2
	514	10
	507	1
BaOH [Ref. 10]	513 488	10 8
CuCl[f,g]	538	2
	526	4
	515	2
	498	4
	488	8
	479	5
	451	1
	443	6
	435	9
	428	7
	421	4
CuOH	537	10
[Ref. 10]	530	9
	524	9
	505	6
	493	5
Cu[e]	522[d]	10

(a) Unless otherwise indicated, these data are taken from reference 9.

(b) Wavelengths are only reported to the nearest nm.

(c) The reported relative intensities are normalized to 10 for the strongest emission within a group of features from each chemical species. Different band groups for the same chemical species are separated by a single solid line in the table. Because intensities are normalized within each group and because the manner of excitation for the spectra in the literature is generally different than that for pyrotechnic flames, it cannot be assumed that the intensities listed in the table will be those observed in pyrotechnic flames.

(d) When two or more spectral features are within about 2 nm of each other, they are listed as a single feature showing a range of wavelengths and with the combined intensity of the features.

(e) Other weaker atomic lines occurring in the visible range are not reported.

(f) Pearse and Gaydon[9] report six groups of bands for CuCl; however, the bands in only three of the groups were seen in flame spectra examined for this article. Also they appear to have collectively normalized the intensities of the bands (i.e., the strongest band in each group is not set to 10).

(g) Shimizu[11] reports a total of 31 bands for CuCl; only the 10 strongest of those correspond to wavelengths reported by Pearse and Gaydon.

Figure 7 is a comparison of the spectra of two burning orange stars. The lower spectrum is from a standard formulation based on a calcium salt, and the upper spectrum is from a formulation producing a visibly more attractive orange flame. In the lower spectrum, the emission bands observed are those characteristic of calcium monochloride, a band from calcium monohydroxide and the sodium doublet lines at 589 nm. The same features are present in the upper spectrum; however, also visible are three features near 520 nm, which are the strongest bands from barium monochloride. Obviously then, the improvement in the orange color was accomplished by using a small amount of a barium salt to shift the composite calcium color point from reddish orange to orange. (A similar approach is described in reference 12; a discussion of color mixing and composite colors is discussed in Module 6 of reference 1.)

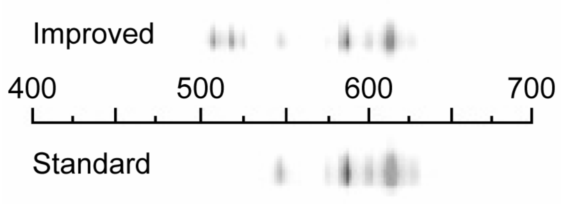

Figure 7. Comparison of spectra from two orange stars. The upper spectrum has green bands to improve the orange color.

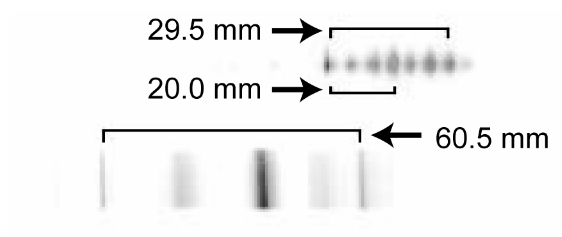

Figure 8. Example of approximate method for determining unknown wavelengths.

Semi Quantitative Data Processing

If more quantitative spectral information is desired, one can capture the video data using a personal computer. The spectra for this article were collected with the inexpensive (but quite effective) Snappy® software / hardware system.[13] Computer capture allows for the production of hard copy printouts of the spectral images, such as those presented in this paper. Also disk files of the video images can be created for use in data processing or for archival purposes.

To identify unknown spectral features, fairly precise identification of their wavelengths is helpful. Because the relationship between wavelength and screen location is essentially linear, only two spectral features of known wavelength are needed to establish a scale factor (the wavelength in nm per millimeter separation on the printout). The peaks at 436 and 612 nm in the fluorescent calibration spectrum are convenient for this purpose. By simply measuring the physical distance in millimeters between the two features on a paper printout of the spectrum and dividing (612 – 436 =) 176 nm by the measured physical distance, one establishes the scale factor in nm per mm. This same scale factor applies to all spectra recorded, providing no changes are made to the camera setup. The most convenient method to locate oneself on the test spectrum is to use the sodium doublet lines at 589 nm. If the physical distance from the sodium lines to an unknown feature in the test spectrum is measured, its corresponding wavelength can be determined by simply multiplying the distance just measured by the scale factor and adding to or subtracting from 589 nm, depending on whether the unknown feature lies to the higher or lower wavelength side of the sodium lines.

This type of approximate wavelength calibration is illustrated in Figure 8. In this case, from the full size printout of the spectra, the distance between the 436 and 612 nm features in the fluorescent light spectrum was measured as approximately 60.5 mm. Thus the scale factor is 2.91 nm/mm (176 × 60.5). In the test spectrum, the distances from the sodium doublet line to two of the features are 29.5 and 20.0 mm. Thus they correspond to wavelength displacements of 86 nm (2.91 × 29.5) and 58 nm from the 589 nm sodium doublet, or wavelengths of approximately 674 nm (86 + 589) and 647 nm. From Table 3, it is fairly obvious that these must be the SrCl bands listed as 674 – 676 and 649 nm. As a practical matter, this method only allows identification of wavelengths to within a few nanometers. This is due to difficulty in visually determining the points of peak intensity for the features seen on the spectrum printout.

Adobe PhotoShop®[14] is a popular digital image processing program. Although not its normal function, it offers the ability to produce intensity data from the spectra captured on a personal computer. One uses the "color-picker" (densitometer) intensity function, found on the "Info Pallet", on the spectral areas of interest to generate intensity versus image position data. This position data can then be used to determine screen position (wavelengths) more accurately. The procedure used is the same as suggested above; however, instead of making physical measurements with a ruler, the locations of screen pixels corresponding to the highest intensity for spectral features are used. In addition, although labor intensive, it is possible to use the Adobe intensity function to produce an intensity versus wavelength graph of the spectrum. Starting on one side of the screen image, intensity readings are recorded manually

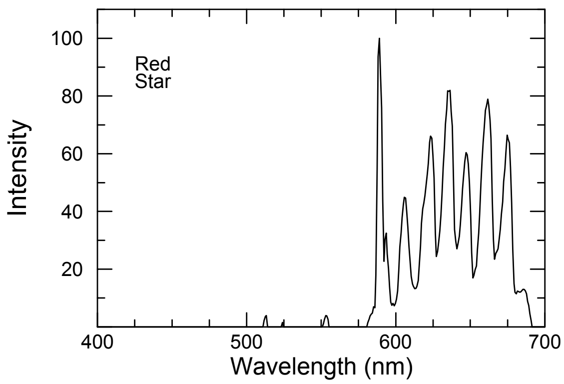

Figure 9. Example of the spectrum from a red test star.

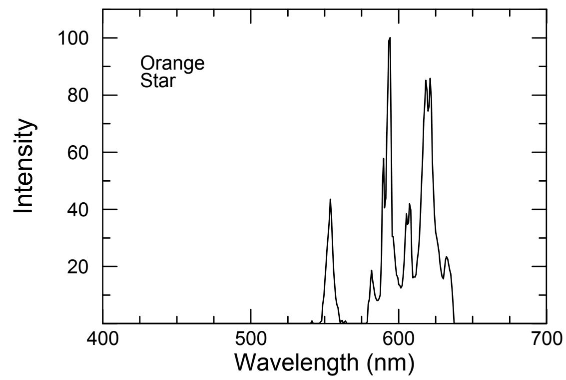

Figure 10. Example of the spectrum from an orange test star.

as one moves from pixel to pixel across the image. Then these data are plotted to produce a graph of intensity (density) versus screen location. By knowing the wavelengths of at least two features in the spectrum, one can convert the screen locations to wavelengths. In a trial of this method it took about 30 minutes to produce and graph the data from a single spectrum.

Un-Scan-It Gel®[15] is a software package intended for computerized density scanning of gel electrophoresis plates. However, it works wonderfully to digitize video spectrometer data captured on a personal computer. It also allows intensity calibration of the image, plotting the results, integrating peak (band) intensities, and dividing the length of the flame into multiple separate spectra. With Un-Scan-It, the time to produce an intensity versus screen position graph and store the data is about one minute. Snappy and Un-Scan-It were used to produce the graphs in the remainder of this paper, including a series of example color flame spectra. The test stars[16] used to produce these spectra are based on ammonium perchlorate, hydroxy-terminated polybutadiene (HTPB), and a color agent. The spectra are presented in Figures 9 through 12 with their peak intensities normalized to 100.

As an example of the utility of having the spectral data in graphical form, consider Figure 13. This presents two similar appearing green flame spectra. These spectra were produced as a test of the hypothesis that replacing some of the ammonium perchlorate with potassium perchlorate would improve the green flame color. Both formulations used the same chemical color agent, barium nitrate; however, the new (im-

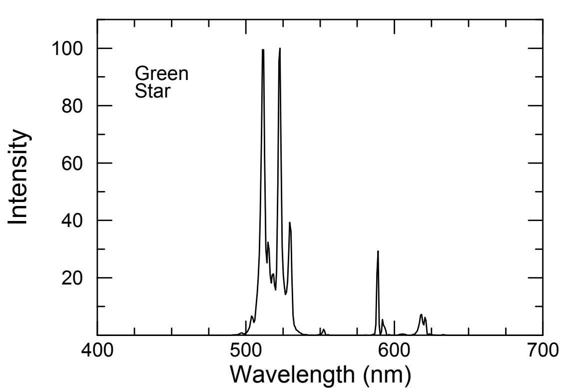

Figure 11. Example of the spectrum from a green test star.

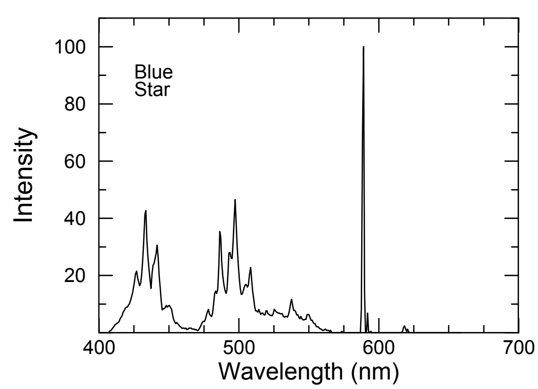

Figure 12. Example of the spectrum from a blue test star.

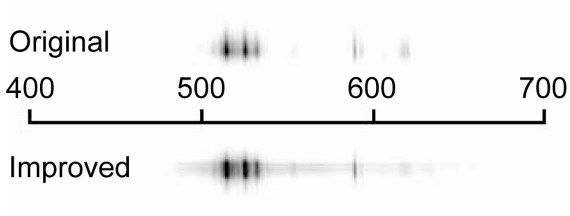

Figure 13. Comparison of the spectra from two green star formulations. The upper one appeared noticeably more yellow.

proved) formulation was prepared a couple of years after the first. The improvement to the color was obvious, as perceived by a panel of viewers; the original formulation appeared noticeably more yellow. In Figure 13, the most obvious difference seen in the "Improved" spectrum is the presence of a weak continuum for the "Improved" formulation. The reason for this is not entirely clear, but presumably it is a result of the incandescence of liquid potassium chloride particles in the flame or from potassium ion recombination (see Modules 6 and 7 of reference 1). Regardless of its source, the presence of the continuous emissions could only act to reduce flame color purity, contrary to what was observed. The second most obvious difference in the improved formulation is the increased intensity of the green bands (from BaCl, see Table 3). This is presumably the result of an increase in flame temperature. However, these greater intensities should only cause an increase in brightness and not an improvement in color, unless there is a perceived increase in the green intensities relative to interfering features (i.e., the line from sodium and bands from CaCl).

Figure 14 presents graphs of the spectra from Figure 13. The presence of the continuum and the increase in intensity noticed in Figure 13 are confirmed. Table 4 is a listing of intensities of

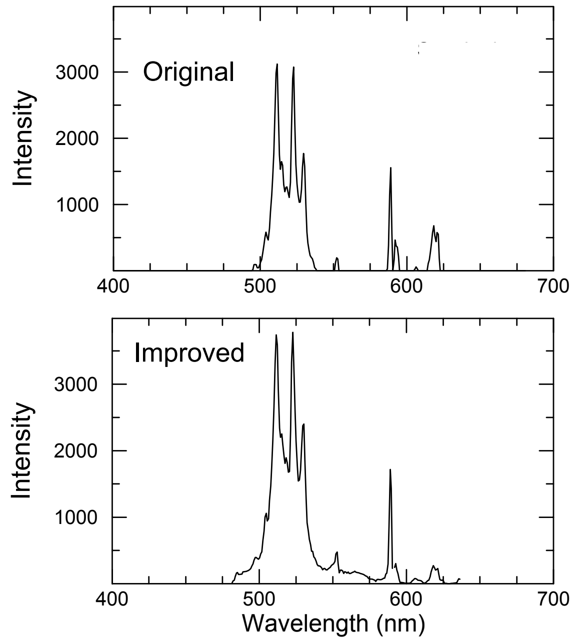

Figure 14. The two green spectra as in Figure 13, but rendered as graphs.

key spectral features. The presence of the continuum and the increase in intensity are confirmed. However, notice in the improved star formulation that the normalized intensity of the sodium doublet is reduced by about 5%, and the calcium monochloride bands are reduced by about 50% as compared with the original formulation.

Thus spectral analysis suggests that it is unlikely the visible improvement in flame color is the result of substituting potassium perchlorate for some of the ammonium perchlorate as hypothesized. It is more likely that, over the two year time span, chemicals from different lots (or suppliers) were being used and the different lots had differing amounts of interfering chemicals.

Table 4. Intensity of Key Spectral Features Seen in Figure 13.

Wavelength (nm)	Intensity (x 1/1000)		Normalized Intensity		Identification of Source	Perceived Color
	Original	Improved	Original	Improved		
507–532	61.2	98.3	≡ 100	≡ 100	BaCl	Green
589	3.7	5.6	6.0	5.7	Na	Yellow
593	1.5	1.3	2.5	1.3	CaCl	Orange
618–622	4.5	3.4	7.4	3.5	CaCl	Red

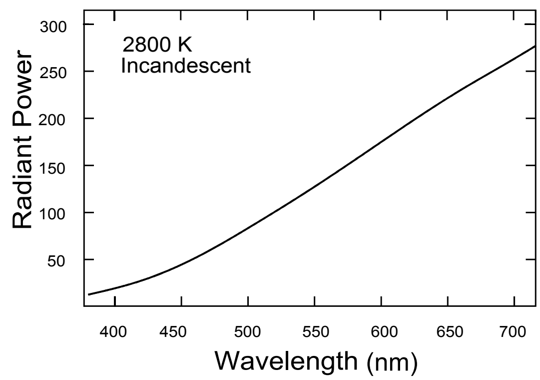

Figure 15. Spectral energy curve of typical 2800 K tungsten lamp.

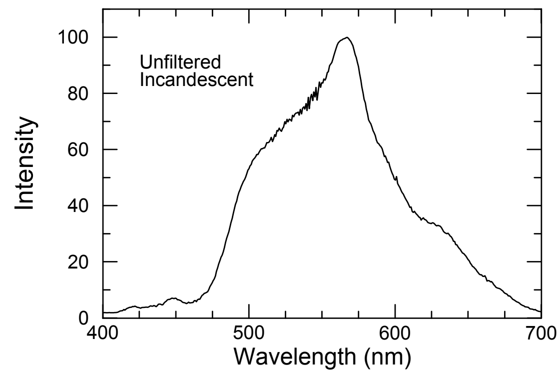

Figure 16. The observed spectrum of the incandescent calibration light source.

Quantitative Data Processing

The relative intensity data such as demonstrated in the green example can be very useful. However, when reasonably-accurate, absolute-intensity results are needed, an intensity calibration is necessary. The need for this calibration is a result of the way in which the camcorder prepares its composite color image. Internal light filters differentiate between the three primary video colors. These filters, in combination with an internal infrared filter and the wavelength dependent sensitivity of the CCD, produce a wide deviation from constant light sensitivity across the color spectrum.

The needed calibration information might be acquired using the fluorescent light source and the spectral data provided by the lamp's manufacturer. However, there are not many useful spectral features in the light output, and there is no guarantee that each bulb produces spectra identical to that reported by the manufacturer. A somewhat better alternative is to use the spectrum from an incandescent bulb as shown in Figure 2. (Obviously, still better would be to use a black body source or a spectrally calibrated lamp.)

A 60 W tungsten filament is expected to produce a color temperature of approximately 2800 K.[17] Figure 15 is a graph of radiant power as a function of wavelength for a color temperature of 2800 K.[18] However, the spectrum recorded with the video spectrometer, Figure 16, is grossly different than that of Figure 15. Originally it had been hoped that the two spectra would be similar enough that the needed correction would simply require applying a set of wavelength-dependent correction factors. However, the magnitude of the correction required in the region from 650 to 700 nm is too extreme for this method. The grayscale image captured using Snappy is only 8-bit data (intensities ranging from 0 to 255). With correction factors exceeding 50 being needed, the resulting intervals between successive values would be unacceptably large. Accordingly, another method was sought.

A more constant sensitivity as a function of wavelength would be obtained with a black and white video camera. However, that would be an additional purchase for many potential researchers and would probably require the use of a separate video recorder. Another alternative would be to use a still camera and black and white film. But for a short duration light source, only a few spectral images could be recorded, and because of the flame's flickering (movement behind the slit) they might not be typical of what is being produced. Another drawback of using film is the time delay in developing it, thus making set up and adjustment more difficult than with the video camera.

A coarse initial correction for intensity was attempted using externally mounted light filters. A pair of rose colored filters (GamColor[19] polyester color filters #105 and #130) reduced the sensitivity in the green region and improved the observed continuous spectrum sufficiently to allow final correction using reasonably small numerical calibration factors. Figure 17 is the

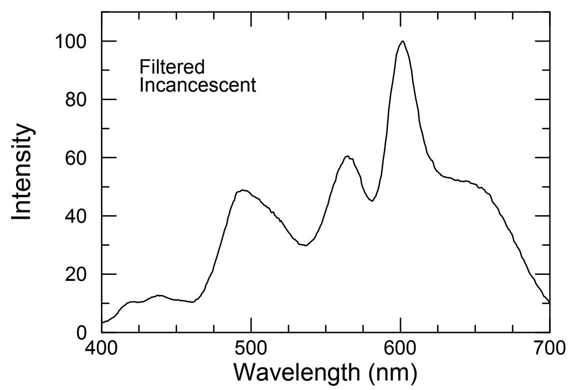

Figure 17. The filtered spectrum of the incandescent calibration light source.

filtered continuous spectrum. Figure 18 is a graph of the intensity calibration factors which successfully reproduce the 2800 K spectrum (Figure 15).

As of this writing, no studies have been conducted using intensity-corrected spectra. However, studies to measure the temperature of glitter spritzel (dross particles) and flash temperatures may be initiated soon. For that work, fairly accurate spectral intensities will be needed.

Conclusion

Although still in an early stage of development, the video spectrometer has already proven useful. For example, a recent gathering of flame color researchers were able to conclude that many of the problems preventing the better colored flame formulations from producing high purity colors, stem from impurities in the chemicals used. (Most notably the presence of sodium and calcium caused problems.)

Probably the most significant advantage of a video spectrometer in studying flame color formulations is its relatively low cost, assuming a camcorder and personal computer are already available. Also, its ability to continuously record very short duration spectra is ideal for pyrotechnic flames. Finally, the ability to look simultaneously at various points along the length of a flame is a feature generally absent from even high quality commercial spectrometers.

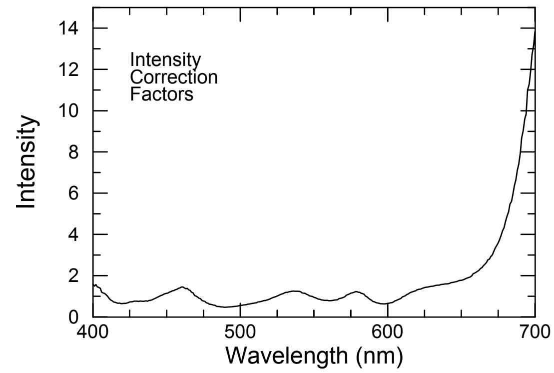

Figure 18. Intensity calibration factors for the filtered spectra.

Clearly further improvements can be made in the hardware and operation of the video spectrometer. This work is shared in the hope that others would find the video spectrometer useful and would further develop the instrument.

Acknowledgments

The authors gratefully acknowledge the assistance of S. Anderson in the preparation of the test stars used in this article and J. La Marca for providing the GamColor filters. The authors wish to acknowledge the technical assistance of W. Meyerriecks, S. Anderson, W. Smith, T. Wilkinson, L. Weinman, and D. Dolata.

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Measurements of Glitter Flash Delay, Size and Duration

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ABSTRACT

A brief series of measurements were made on the flashes produced by a simple glitter formulation. In part this was done as a test of one theory for the chemistry of glitter. However, this was also done to produce some intrinsically interesting data that have not been previously reported. It was observed that both increasing the percentage of aluminum in the formulation and decreasing the particle size of the aluminum, decreased the delay time before the appearance of the glitter flashes. Both the size and duration of glitter flashes increased for flashes with greater delay. It was also observed that there was a rapid increase in temperature just prior to the onset of the flash event.

Introduction

Glitter effects are one of the most attractive in fireworks. Several theories have been proposed for its chemistry and are discussed in a review article by one of the authors.[1] One reason for conducting the work reported in this article was to collect some information to test one of those theories; however the thorough discussion of the theory is left to the review article. For the most part, this article simply presents the results of the study without an attempt to interpret them.

Experimental

To keep the chemistry simple and make the results unambiguous, a fairly simple glitter formulation was used. The basic formulation is given in Table 1 and is similar to one suggested by Fish.[2]

Table 1. Basic Test Glitter Star Formulation.

Ingredient	Parts
Potassium nitrate	54
Charcoal (air float)	11
Sulfur	18
Sodium bicarbonate	8
Dextrin	4
Aluminum(a)	(a)

(a) Various types and amounts of aluminum were used.

The mixture of ingredients without aluminum was prepared in sufficient quantity to make many small batches of test stars. Each batch of composition was dampened with 10% distilled water. The stars were made as cylinders ¼ inch (6 mm) in diameter and approximately ½ inch (12 mm) in length using a compacting force of approximately 50 psi. A relatively small diameter was chosen for the test stars to limit the number of glitter flashes produced per unit time, which facilitated their observation and counting. On average approximately 550 glitter flashes were observed for each test star burned.

One series of test stars was made with a spherical atomized aluminum having an average particle size of approximately 12 microns (Alcoa S-10). For these stars, the percentage of aluminum in the composition was 5, 7 or 10 percent. For another series of test stars, the aluminum was

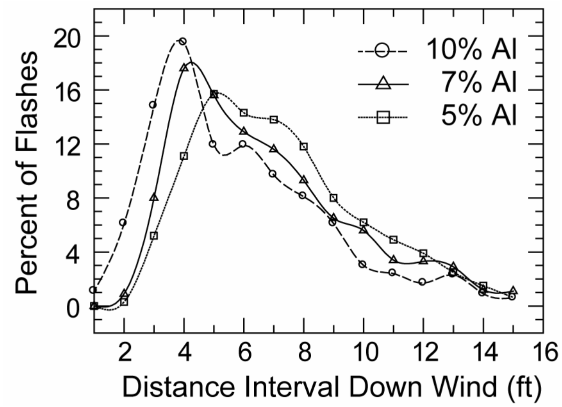

Figure 1. Graph of the percent of glitter flashes occurring as a function of down wind distance, for various aluminum concentrations.

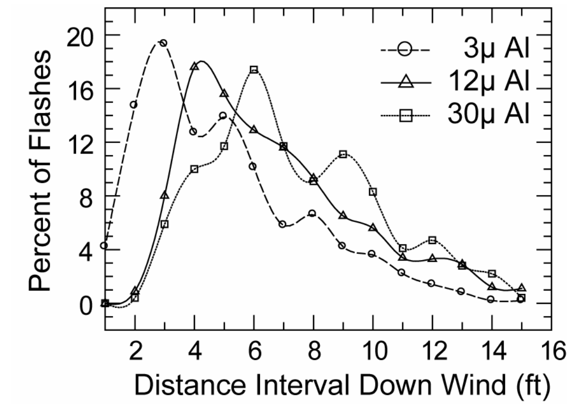

Figure 2. Graph of the percent of glitter flashes occurring as a function of down wind distance, for various aluminum particle sizes.

held constant at 7 percent, but the average particle size of the atomized aluminum was 3, 12 or 30 microns (using Valimet H3, Alcoa S-10 and Valimet H30, respectively).

The test stars were burned under one of two conditions. In some instances they were burned at a height of approximately 11 feet (3.3 m) and the dross droplets allowed to fall vertically under the influence of gravity. However, in most cases the test stars were burned in a horizontal air stream moving at approximately 60 ft/s (18 m/s), causing the dross droplets to be carried down wind. The air stream was allowed to diverge shortly after the point where the star was burned. Thus the wind speed gradually fell to an average of approximately 35 ft/s (11 m/s) over the range of the observed glitter flashes. The air temperature was relatively cool, approximately 45 °F (7 °C) for the gravity driven tests and 35 °F (2 °C) for the wind driven tests.

Under either test condition (gravity or wind) glitter flashes occurring at greater distances from the test star correspond to greater delay times. However, for simplicity in reporting the results of this study, for the most part, only delays in terms of distances are given. For a given delay distance, this is the distance from the burning star to the center of a one-foot (0.3-m) interval over which observations were made. For example, flash events reported for a down wind distance of 4 feet (1.3 m) are those occurring between 3.5 and 4.5 feet (1.1 and 1.4 m) from the star.

The percent of flashes versus down wind distance curves were produced using a cubic spline function. This method was chosen because the level of precision of the data is not great and because the intrinsic shape of the curves is unknown. Accordingly, it is not intended to imply that any undulations seen in the graphs are real.

Results

The effect of varying aluminum concentration (5, 7, and 10 percent) is shown in Figure 1. For this formulation, increasing aluminum concentration decreased the typical delay of the glitter flashes. This is seen in both the down wind distance at which the maximum number of flashes occurs and in the average distance traveled before the flash reaction, see Table 2. The effect of varying the particle size of the

Table 2. Summary of Approximate Glitter Flash Distance Information for Variations in Formulation.

Aluminum Variation	Glitter Flash Distance	
	Peak (ft.)	Average (ft.)
5%	5.1	7.1
7%	4.3	6.7
10%	3.8	5.8
3 μ	2.9	5.0
12 μ	4.3	6.7
30 μ	6.0	7.3

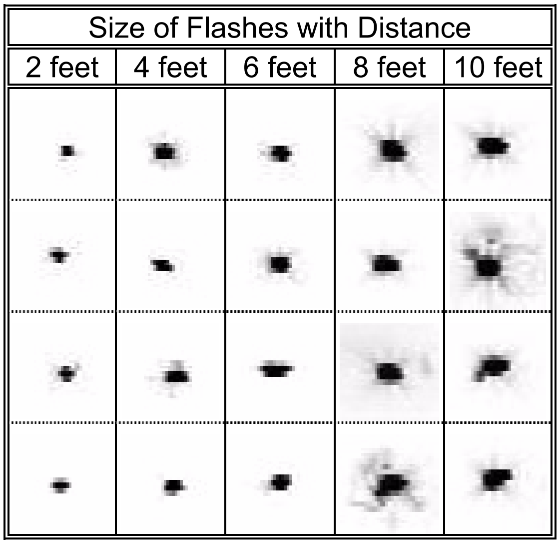

Figure 3. Examples of typical glitter flashes as a function of distance from the star (negative black and white images).

Table 3. Average Glitter Flash Duration as a Function of Down Wind Distance.

Down Wind Distance (ft)	Ave. No. Fields	Ave. Flash Duration (ms)[a]
4	1.20	2.8
6	1.20	3.8
8	1.32	5.5
10	1.48	7.5
12	1.52	10.2
14	1.86	13.3

(a) Values were calculated using the curve fitted flash durations from Figure 4.

atomized aluminum (3, 12 and 30 micron) is also shown in Figure 2. For this test, increasing particle size increased the typical delay of the glitter flashes. It is possible to interpret both sets of data (effects of concentration and particle size) as glitter delay increasing as the result of decreasing the total surface area of aluminum in the composition.

Although not the primary purpose of these measurements, some other interesting observations were made. Considering the likely dross droplet velocities in the air stream, it is possible to estimate the time elapsed before the glitter flashes occur, based on the distance they traveled. In this case it was simply assumed that droplet speed during the first foot traveled was half that of the air stream. Thereafter, droplet speed was assumed to equal that of the air stream at each point. Accordingly, for the formulations tested, it is estimated that the peak number of glitter flashes are typically occurring roughly 0.1 second after leaving the burning star. Similarly the average time to the occurrence of the glitter flashes is roughly 0.2 second.

There appears to be a relationship between the time interval before flash occurrence and the physical size and duration of the flash. The size relationship is demonstrated in Figure 3, which presents 1/60 second negative black and white images of typical glitter flashes. Here the flashes are organized by distance from the burning star (using 7 percent of the 12 micron aluminum) in a gravity driven test. (As in the air stream driven case, there is a functional relationship between increasing distance and increasing time.) In Figure 3, the actual size of each image area is approximately 10 inches (0.25 m); thus the size of the flashes ranges from about 1 inch (25 mm) for those flashes occurring soon, to about 3 inches (75 mm) for those flashes occurring later.

There also appears to be a correlation between the observed duration of the glitter flashes and the distance from the burning star (delay time). This was established by observing the number of successive video fields (each 1/60 second) during which individual flashes were visible. For each down wind distance from test stars, 25 observations of the duration of flashes were made, and an average duration was calculated. These data are listed in Table 3 and graphed in Figure 4. Using a statistical model wherein a glitter flash can initiate at any time during the 1/60 second image interval, it can be estimated that

$$D = \frac{N-1}{60}$$

where D is the approximate average flash duration and N is the average number of video fields over which glitter flashes are seen. Using this relationship, average flash durations were calculated as a function of distance in the air stream from the burning star. These flash durations ranged from approximately 3 to 13 ms (Table 3).

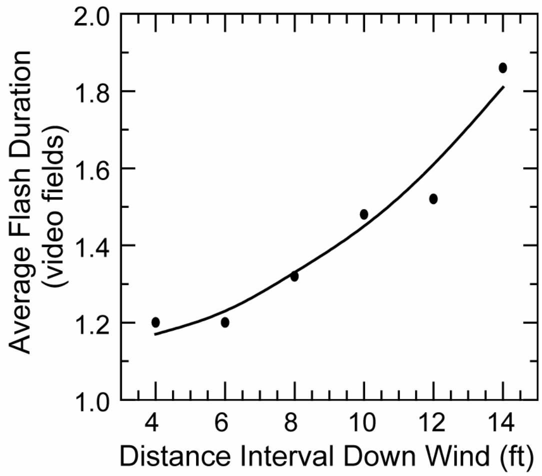

Figure 4. Graph of the average number of video fields for glitter flashes as a function of distance.

Figure 5 is a composite negative black and white image of a glitter dross droplet traveling to the left, until the time when it is just beginning to flash. The figure is composed of a series of individual 1/60 second (17 ms) video fields; however, to help identify the passage of time and the progress of the droplet, every other video image was omitted. Note that the intensity of the emitted light is roughly constant until about the last three images, where its intensity (darkness) noticeably increases. Figure 6 is a graph of this dross droplet's image intensity prior to the onset of the flash reaction. In Figure 6, all of the video images were captured and analyzed, not just the half presented in Figure 5. The light intensity at first remains fairly constant and then rapidly increases just prior to the onset of the flash reaction.

Light intensity is a function of temperature, thus the temperature of the glitter dross droplet is increasing just prior to the flash reaction.

Figure 5. Composite image of a glitter dross droplet just prior to the start of the flash reaction.

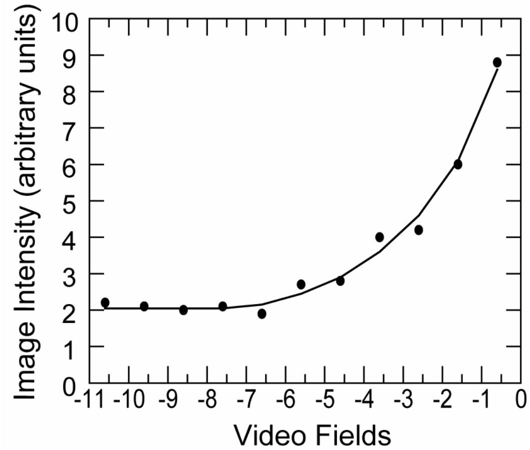

Figure 6. Graph of video image intensity of the dross droplet from Figure 5.

However, at this time, the response function (intensity versus wavelength) of the video camera is not known. Thus it is not possible to assign temperatures to the dross droplet. (There are plans to make such measurements in the future.)

Conclusion

The results reported in this article are somewhat interesting on their own and do provide potential insight into the control of the glitter flash reaction. However, they also provide a basis to draw an inference regarding the chemistry operating in the glitter phenomenon. However, the discussion of glitter chemistry is left for another article by one of the authors.[1]

The results presented are based on only a limited amount of data and for only one type of formulation. Further, in some cases, assumptions and approximations have been made. Thus a good measure of caution is warranted before drawing firm conclusions from these results.

Acknowledgments

The authors wish to acknowledge D. Tygett of Valimet for providing samples of their H3 and H30 aluminum. The authors are also grateful to S. Anderson for providing technical and editorial comments on this article.

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Lift Charge Loss for a Shell to Remain in Mortar

K. L. Kosanke

I recently needed an estimate of the amount of lift powder that would have to be missing from a spherical aerial shell, for it to remain in its mortar upon firing. Since that apparently has never been reported in the literature and because it was easy to determine, a brief study was conducted to discover this. Although there is little reason for the typical pyrotechnist to need the answer to this question, nonetheless it is a somewhat interesting number; thus, the motivation for this short article.

In this study, only plastic spherical aerial shells were tested and the mortars used were all high-density polyethylene. Information about the materials and conditions for the tests are listed in the table below. Each shell size was test fired using Goex 4FA fireworks (blasting) Black Powder. However, because smaller shells are often lifted using finer grained powder, the 3- and 4-inch spherical shells were also tested using Goex 2Fg sporting grade Black Powder. In each case the lift powder was placed in a small plastic bag with a Daveyfire SA-2000 electric match. The bag of lift powder was then taped directly to the bottom of the test shells, thus providing little dead space below the shell other than that resulting from its spherical shape. The shell weights and nominal lift weights were those used in previous studies, and are felt to be typical for spherical shells. The temperature during the tests was approximately 70 °F (21 °C). For each size shell, a series of test firings was conducted, each time adjusting the amount of lift powder until a quantity was found that was just sufficient to cause the shell to clear the top of the mortar upon firing.

For the conditions of these tests, it required an average of approximately 14 percent of the nominal lift charge weight to cause the test aerial shells just barely to exit the mortar. There is no estimate of the statistical uncertainty for these results because of the limited number of tests performed.

I am grateful to Alan Broca of Daveyfire, Inc. for supplying the electric matches used in this study.

Shell Size (in.)	3	4	5	6
Mortar. Length. (in.)	2.22	22.5	26.5	26.5
Mortar Diameter (in.)	2.98	3.91	4.93	5.93
Shell Weight (lb.)	0.30	0.80	1.5	2.5
Shell Diameter (in.)	2.62	3.72	4.68	5.63
Nominal Lift Weight (oz.)	0.5	1.0	1.7	2.7
Minimum 4FA Lift to Exit (oz.)	0.09	0.13	0.25	0.36
Percent of Nominal	18	13	15	13
Minimum 2F Lift to Exit (oz.)	0.07	0.11	—	—
Percent of Nominal	14	11	—	—

To convert inches (in.) to mm, multiply by 25.4.

To convert pounds (lb.) to g, multiply by 454.

To convert ounces (oz.) to g, multiply by 28.

An earlier version appeared in *Proceedings of the 4th International Symposium on Fireworks*, 1998.

Configuration and "Over-Load" Studies of Concussion Mortars

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ABSTRACT

Although concussion mortars have been used for many years at band concerts and in theatrical performances, there has been relatively little investigation of the effectiveness of their basic design. Measurements of the effect of two modifications of the design of concussion mortars indicate that significant improvements in their performance were achieved; however, only for light powder loads. Though somewhat disappointing, these designs may be of use in situations where increased loudness of report is needed without an increase in smoke production. Measurements were also made of the effect of loading materials (whether inert, a fuel, or an oxidizer) on top of a commonly used concussion powder. It was found that all of these produced increased sound output. However, this seemed to be mostly the result of added confinement of the concussion powder.

Introduction

This is the third in a series of articles examining the performance of concussion mortars. The first article[1] investigated air blast pressure (sound pressure level), internal mortar pressure, and mortar recoil force as functions of the load mass of one type of concussion powder. The second article[2] was a comparative study of air blast pressure and internal mortar pressure for a collection of six commercially produced concussion powders. In the present article, the effect of two modifications of the standard concussion mortar design were investigated. In addition, so called "over-load" studies were conducted. In this context, over-load refers to the practice of placing an increment of some other material on top of (over) the normal charge of concussion powder (load). The motivation for the study was to determine the extent to which these materials might act to modify and potentially improve the performance of concussion mortars.

Background

In its most common form, a concussion mortar consists of a thick cylindrical steel bar, welded to a heavy base plate. The mortar contains a combustion chamber (barrel), typically produced by drilling a hole on-axis into the top end of the steel bar. The basic mortar used in this study was 2 inches (50 mm) in outer diameter, with a 1-inch (25-mm) hole drilled to a depth of 4.5 inches (115 mm). The construction of the mortar is illustrated in Figure 1, which also shows it loaded with a charge of powder and an electric match for ignition.

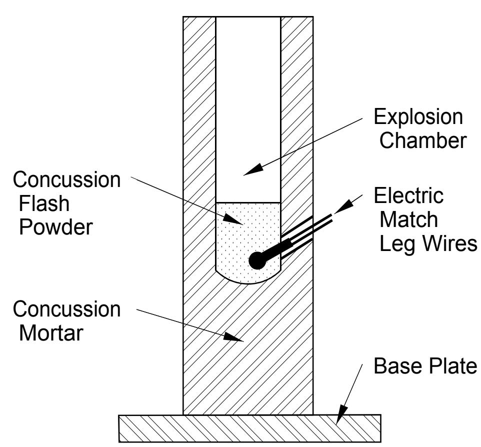

Figure 1. An illustration of the construction and setup of a concussion mortar.

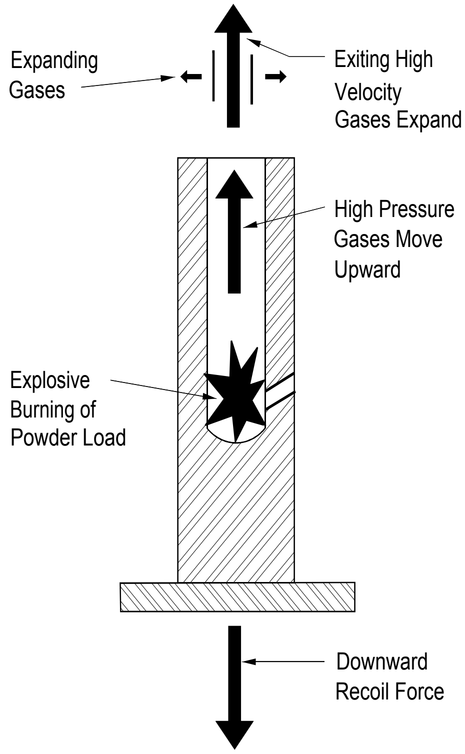

Figure 2. An illustration of the firing of a concussion mortar.

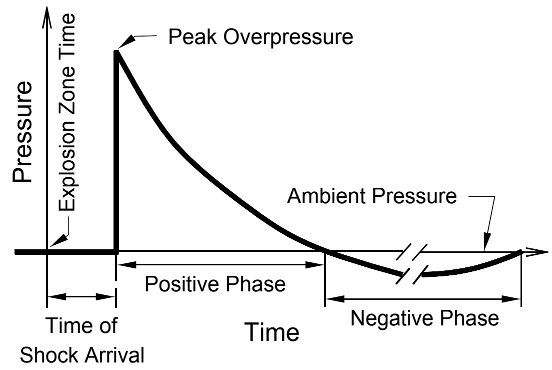

Figure 3. An illustration of a typical overpressure profile (blast wave) produced by an explosion.

Upon ignition, because of the confinement provided within the combustion chamber, the concussion powder burns explosively, see Figure 2. The high internal pressure causes the combustion products (gases and solid particles) to be accelerated upward. As the gases exit the end (mouth) of the mortar, they expand to produce a shock wave that is heard and felt by the audience. As a result of the ejection of combustion products, a downward recoil force is produced.

Figure 3 illustrates a theoretical air blast (overpressure) profile. Before the arrival of the blast wave, there is no indication (with respect to pressure) that an explosion has taken place or that the blast wave is approaching. When the leading edge of the shock wave arrives, it produces an essentially instantaneous rise in pressure from ambient to some maximum value. Thereafter, the pressure decays much more gradually back to ambient pressure. This portion of the blast wave is referred to as the positive phase. Following the positive phase, there is a negative phase, during which pressure drops below ambient. In essence, this is caused by over expansion of the gases, wherein the outward rush of air continues beyond that necessary to relieve the pressure produced by the explosion. Thus, a partial vacuum forms at the seat of the explosion, producing the negative phase of the blast wave. This is less extreme than the positive phase and lasts longer.

The sound qualities of potential interest with regard to the firing of concussion mortars are sound pressure level, loudness and tonal quality. Except for a few brief comments in this article, readers wishing more information are referred to a previous article in this series,[2] or to reference texts on the subject.[3–5] Sound pressure level (SPL, in decibels, dB) is a physically measurable quantity and can be calculated from air blast overpressures. There is a logarithmic relationship between blast pressure and SPL. Loudness (*N*, in sones) is a subjective measure of sound level, dependent on the processing of nerve impulses by the brain. The loudness scale is linear, such that a sound with a loudness value twice that of another sound will be perceived by a typical listener to be twice as loud. The tonal quality of the concussion mortar sound may also be of interest. That is to say, does the sound produced tend toward being a sharp crack or a more mellow boom? The feature of a blast wave that is conjectured to correlate with perceived tonal quality is the duration of the positive and negative phases. All else being equal, shorter phase durations are expected to be heard more nearly as sharp cracks,

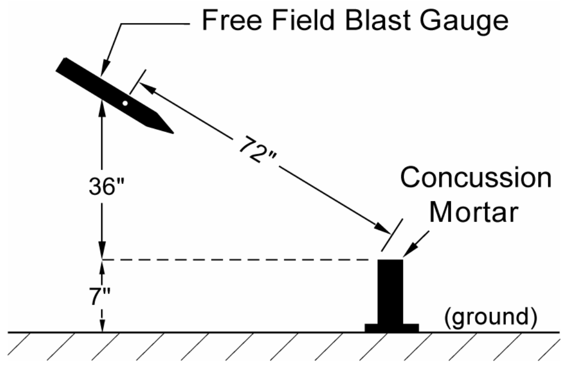

Figure 4. An illustration of the physical setup for one detector used to collect concussion mortar overpressure data. (Not to scale.) (For conversion to SI units, 1" =25.4 mm.)

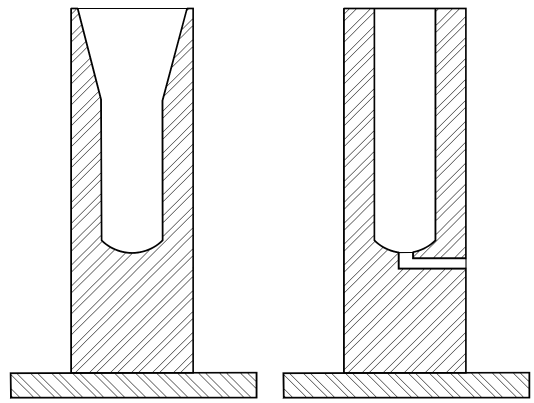

Figure 5. Illustrations of the "trumpet" and "confined match" concussion mortar configurations.

and longer phase durations, as more mellow booms.

Experimental Method

Data was recorded outdoors in a large open space, with the concussion mortar placed with its base directly on the ground. Air blasts (overpressures) produced by the firing of the concussion mortar were measured using two piezoelectric free field blast gauges (PCB Piezotronics model 137A12). The physical arrangement for one of the detectors with respect to the concussion mortar is shown in Figure 4. The second detector was positioned at the same height but at twice the total distance, 144 inches (3.65 m), from the muzzle of the mortar. The electrical overpressure signals were amplified (PCB Piezotronics model 480D09 amplifying detector power supply) and digitally recorded (Fluke model 99 oscilloscope).

In the first portion of this study, combinations of two new configurations to the basic mortar design were investigated. One new configuration was a modification to the bore of the concussion mortar, such that the last 1.5 inches (38 mm) tapered from 1.0 inch (25 mm) to a diameter of 1.75 inches (44 mm). This is illustrated in Figure 5 and is referred to as the "trumpet mortar" configuration in this article. The idea for this configuration originated with M. Grubelich and T. DeWille[6] and was proposed as a way of increasing sound output for low mass powder loads. The other new configuration was a modification of the electric match hole. A 0.22-inch (5.6-mm) hole was drilled 0.25 inch (6.4 mm) deeper into the bore of the mortar, and an intersecting 0.16 inch (4.1 mm) hole was drilled from the side of the mortar. This configuration is also illustrated in Figure 5 and is referred to as the "confined match" configuration. The idea for this configuration originated with the Kosankes as a way of achieving reproducible positioning of electric matches, which was needed for other planned concussion mortar studies. Because of the close fit of the electric match in its hole, it was necessary to insulate the match head contacts to prevent occasional misfires due to short circuiting. This was accomplished either with a single wrap of tape or by dipping the match heads in nitrocellulose lacquer.

In all cases in this study the concussion powder used was Pyropak Concussion Powder supplied by Luna Tech, Inc. This is a fuel-rich powder based on magnesium and strontium nitrate.[2] Similarly, all of the electric matches used in this study were Pyropak ZD matches.

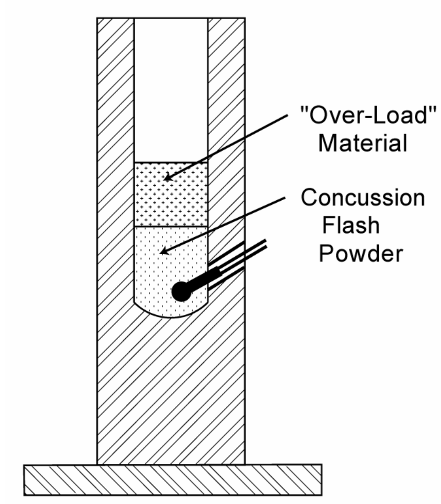

Figure 6. An illustration of the use of "over-load" materials in a concussion mortar.

In the second portion of this study, so called "over-loads" were studied. In each case some other material was placed over the normal load of concussion powder, see Figure 6. A variety of over-load materials were tested. These materials fell into three categories: relatively inert materials, used to provide added confinement of the concussion powder; fuels that might react after mixing with oxygen in the air above the concussion mortar; and oxidizers that might react with the excess magnesium (vapor) produced when firing Pyropak concussion powder. (Pyropak concussion powder has approximately 50% excess of magnesium fuel, which normally reacts in the air above the mortar producing light and possibly additional sound output.[1]) More information about the over-load materials and the reasons for their selection will be given when discussing the results.

The presence of statistical noise in the blast overpressure data sometimes makes it difficult to determine accurately the peak overpressures and durations of the positive phase. This is especially true for light (low mass) powder loads. For example, see the top graph in Figure 7, which is for the firing of a 7 g powder load as recorded by the near blast wave detector. To facilitate unbiased and consistent interpretation of the data, it was decided to digitally filter the data using a 15 coefficient digital finite impulse response 20 dB/octave filter, which began its

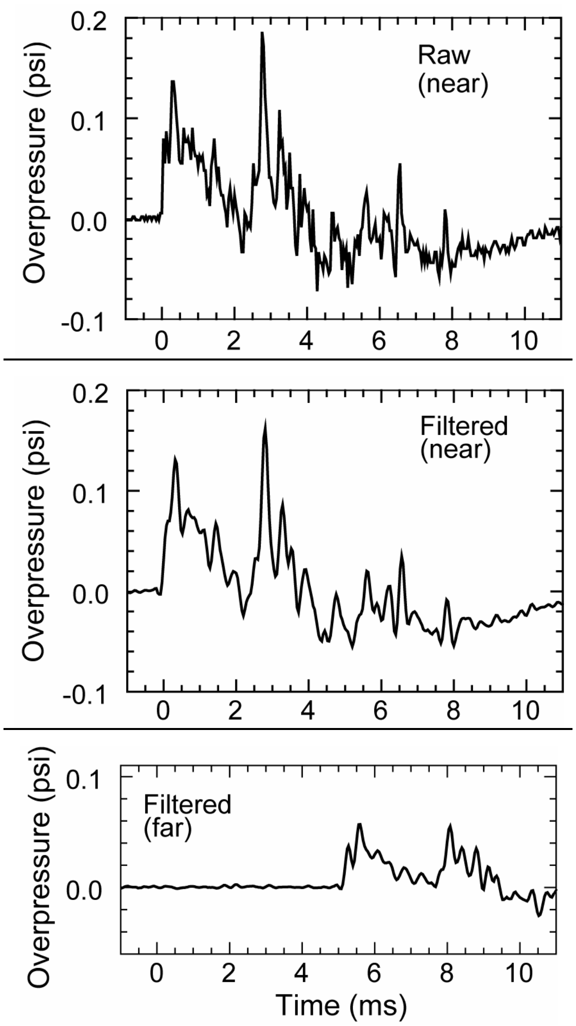

Figure 7. Raw and filtered blast pressure data from the firing of a 7 g concussion powder load.

rolloff at 10% of the Nyquist frequency for the data rate.[7] The middle graph in Figure 7 is the original data after being filtered. The initial small dip in the filtered data, just before the onset of the leading edge of the blast wave, is an artifact of the filtering process and should be ignored. However, the prominent features seen in the "Filtered (near)" data are felt to be real and not just lower frequency statistical noise. This view is supported by the observation that the data recorded for the "Filtered (far)" detector appears to be quite similar, although reduced in amplitude and delayed in time as expected (see the bottom graph of Figure 7). Figure 8 is a similar set of raw and filtered data; however this time for a more substantial powder load (28 g). This graph has more nearly the shape expected for a blast wave. The feature seen in the graph about 1 ms after the arrival of the blast wave has been shown to be reflections from the holder of the detector, although that reflection seen in Figure 8 appears more prominent than most. The need for filtering the data from heavier loaded mortar firings is significantly less than for the light loads. However, in an attempt to produce consistent results, all data sets were filtered.

For this article, peak blast pressure was taken as the maximum pressure observed in the filtered data. The duration of positive phase was taken to be one data point (0.04 ms) less than the time interval between when the positive excursion of the unfiltered pressure data reached 10% of its peak value and the first negative excursion in the filtered data. Pressure impulse was simply the area under the positive phase waveform as seen in the filtered data.

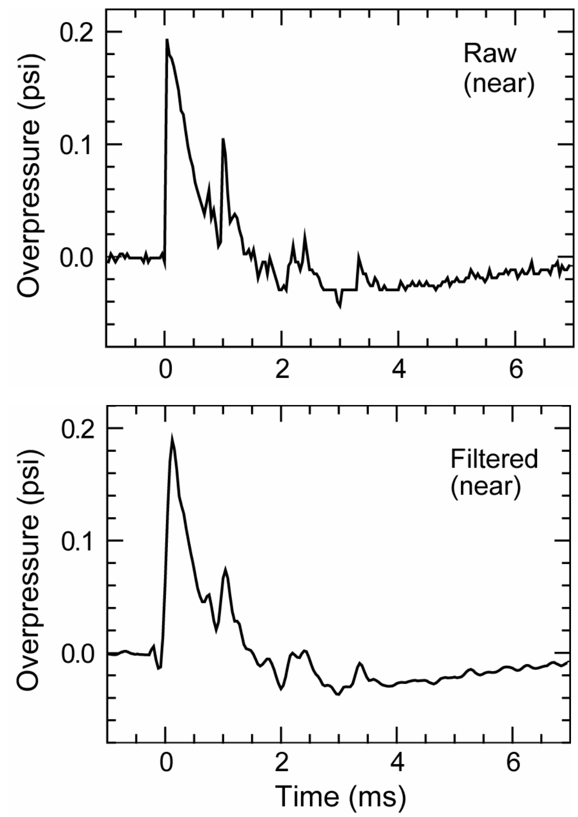

Figure 8. Raw and filtered blast pressure data from the firing of a 28 g concussion powder load.

Results

For each mortar configuration, powder load, and over-load condition examined, three repeat measurements were made. Table 1 presents a listing of the results of those measurements. However, because average results are presented in the process of discussing the various sets of test conditions, Table 1 appears appended to the end of this article. Further, the degree of statistical precision in these measurements is not high, and accordingly, the accuracy of the averages reported below, is relatively low, and it is only the general magnitude of the various effects that should be relied upon in drawing conclusions.

If human hearing of concussion effects occurs as presumed, then: greater peak pressures correspond to louder sounds; greater pressure impulses correspond to greater total energy production; and longer and shorter positive phases correspond to more mellow and sharp sounds, respectively.

Trumpet Mortar Effect

Table 2 presents a summary of the results comparing the trumpet configuration with the regular mortar design, both with the electric matches in the standard Luna Tech match hole location. For the lightest load (7 g), note that: there was an approximate doubling of both the peak pressure and pressure impulse for the trumpet mortar, while the duration of positive phase decreased by about one third. Since pressure and impulse both increased by approximately the same amount, this suggests there was a greater production of sound energy from the same amount of powder (i.e., greater efficiency). For this to be consistent with the observation of a decrease in positive phase duration, there must also have been a change in the shape of the blast wave. For heavier loads (14 and 28 g) some differences were observed between the blast waves from regular and trumpet mortars. However, these differences seem to be primarily a statistical artifact.

Table 2. Average Trumpet Mortar Effect Using Standard Electric Match Location.

Mortar Position →	Near Mortar (72")			Far Mortar (144")		
Test Variable →	**Peak Pressure** (psi)			**Peak Pressure** (psi)		
↓ Test Condition →	Regular	Trumpet	% Change	Regular	Trumpet	% Change
7 g	0.10	0.21	+110	0.036	0.072	+100
14 g	0.85	0.72	–15	0.36	0.39	+8
28 g	1.75	1.97	+13	0.66	0.73	+11
Test Variable →	**Pressure Impulse** (psi ms)			**Pressure Impulse** (psi ms)		
↓ Test Condition →	Regular	Trumpet	% Change	Regular	Trumpet	% Change
7 g	0.08	0.18	+110	0.050	0.075	+50
14 g	0.58	0.62	+7	0.29	0.34	+17
28 g	1.09	1.03	-6	0.53	0.58	+9
Test Variable →	**Positive Phase** (ms)			**Positive Phase** (ms)		
↓ Test Condition →	Regular	Trumpet	% Change	Regular	Trumpet	% Change
7 g	2.1	1.5	–29	3.0	1.8	–40
14 g	1.5	1.7	+13	1.7	2.1	+24
28 g	1.7	1.4	–18	1.5	1.7	+13

For conversion to SI units, 1 psi = 6.89 kPa, 1" (inch) = 25.4 mm.

For more specific information of the test conditions, see Table 1 and its notes.

Confined Match Effect

Table 3 presents a summary of the results of the effect of changing the electric match hole from the standard Luna Tech position on the side of the mortar to the new confined match location. For the lightest powder load (7 g), note that: the peak pressure nearly doubled, the

Table 3. Average Match Hole Effect Using the Standard Concussion Mortar Shape.

Mortar Position →	Near Mortar (72")			Far Mortar (144")		
Test Variable →	**Peak Pressure** (psi)			**Peak Pressure** (psi)		
↓ Test Condition →	Standard	Confined	% Change	Standard	Confined	% Change
7 g	0.10	0.18	+80	0.036	0.067	+86
14 g	0.85	0.63	–26	0.36	0.31	–14
28 g	1.75	1.61	–8	0.66	0.69	+5
Test Variable →	**Pressure Impulse** (psi ms)			**Pressure Impulse** (psi ms)		
↓ Test Condition →	Standard	Confined	% Change	Standard	Confined	% Change
7 g	0.08	0.13	+62	0.050	0.065	+23
14 g	0.58	0.55	–5	0.29	0.30	+3
28 g	1.09	0.97	+11	0.53	0.51	–4
Test Variable →	**Positive Phase** (ms)			**Positive Phase** (ms)		
↓ Test Condition →	Standard	Confined	% Change	Standard	Confined	% Change
7 g	2.1	1.6	–24	3.0	1.8	–40
14 g	1.5	1.7	+13	1.7	2.0	+18
28 g	1.7	1.4	–18	1.5	1.4	+7

For conversion to SI units, 1 psi = 6.89 kPa, 1" (inch) = 25.4 mm.

For more specific information of the test conditions, see Table 1 and its notes.

Table 4. Average Combined Trumpet Mortar And Confined Match Effects.

Mortar Position →	Near Mortar (72")			Far Mortar (144")		
Test Variable →	**Peak Pressure** (psi)			**Peak Pressure** (psi)		
↓ Test Condition →	Reg./Std	Trum./Conf	% Change	Reg./Std	Trum./Conf	% Change
7 g	0.10	0.27	+170	0.036	0.10	+180
14 g	0.85	0.71	–16	0.36	0.32	–11
28 g	1.75	1.84	+5	0.66	0.69	+5
Test Variable →	**Pressure Impulse** (psi ms)			**Pressure Impulse** (psi ms)		
↓ Test Condition →	Reg./Std	Trum./Conf	% Change	Reg./Std	Trum./Conf	% Change
7 g	0.08	0.17	+110	0.050	0.081	+62
14 g	0.58	0.59	+2	0.29	0.35	+21
28 g	1.09	1.04	–5	0.53	0.58	+9
Test Variable →	**Positive Phase** (ms)			**Positive Phase** (ms)		
↓ Test Condition →	Reg./Std	Trum./Conf	% Change	Reg./Std	Trum./Conf	% Change
7 g	2.1	1.3	–38	3.0	1.5	–50
14 g	1.5	1.9	+27	1.7	2.3	+35
28 g	1.7	1.5	–12	1.5	1.6	+7

For conversion to SI units, 1 psi = 6.89 kPa, 1" (inch) = 25.4 mm.

For more specific information of the test conditions, see Table 1 and its notes.

pressure impulse increased by a little less than half, and the duration of positive phase decreased by about one third. As in the case of the trumpet mortar configuration, there does seem to have been an increase in energy production. However, because peak pressure increased somewhat more than pressure impulse, some of the increase in peak pressure came as a result of a decrease in the positive phase duration. The differences, between the blast waves produced with the electric matches in the standard and confined locations, observed for the higher powder loads (14 and 28 g) seem to be statistical in nature. Thus, as with the trumpet mortar configuration, the effect of the confined match configuration seems to be limited to the lightest powder loads.

Combined Trumpet Mortar and Confined Match Effect

Table 4 presents a summary of the combined effect of using the trumpet mortar and confined match configurations. For the lightest powder load (7 g), note that: the peak pressure nearly tripled, the pressure impulse nearly doubled, and the positive phase duration decreased to about half. For heavier loads, the differences seem to be primarily statistical in nature. These results are generally consistent with what would be expected, based on the study of the individual effects.

Over-Load Effects

Table 5 presents a summary of the effect of over-loads that mostly provided a confinement effect. For these tests, materials were chosen that were not expected to participate in an exothermic chemical reaction. In the first case, perhaps not literally meeting the definition of an over-load, two thicknesses of gaffer's tape were applied across the muzzle of a mortar loaded with 7 g of concussion powder. In the trials for two other materials, the load of concussion powder was 14 g. In one case, there was an over-load of 7 g of a fine fluffy aluminum oxide powder. In the other case the over-load was a loose fitting wooden plug (bullet?), also with a mass of 7 g. For each over-load tested there was an increase in peak blast pressure (roughly 25 to 60%), however, without a significant increase in pressure impulse. Thus, there was no added energy release in the blast wave. The increase in peak pressure is a result of a corresponding

Table 5. Over-Load Confinement Effect.

Mortar Position →	Near Mortar (72")			Near Mortar (72")		
Test Variable →	**Peak Pressure** (psi)			**Peak Pressure (psi)**		
↓ Test Condition →	Without	With	% Change	Without	With	% Change
7 g + Tape (×2)	0.10	0.15	+50	0.04	0.06	+50
14 g + 7 g Al_2O_3	0.63	0.85	+35	0.31	0.37	+19
14 g + 7 g Plug		1.13	+79		0.45	+45
Test Variable →	**Pressure Impulse** (psi ms)			**Pressure Impulse** (psi ms)		
↓ Test Condition →	Without	With	% Change	Without	With	% Change
7 g + Tape (×2)	0.08	0.08	0	0.05	0.04	–20
14 g + 7 g Al_2O_3	0.55	0.63	+15	0.30	0.32	+7
14 g + 7 g Plug		0.65	+18		0.33	+10
Test Variable →	**Positive Phase** (ms)			**Positive Phase** (ms)		
↓ Test Condition →	Without	With	% Change	Without	With	% Change
7 g + Tape (×2)	2.1	1.5	–29	3.0	1.6	–47
14 g + 7 g Al_2O_3	1.7	1.7	0	2.0	1.7	–15
14 g + 7 g Plug		1.3	–24		1.6	–20

For conversion to SI units, 1 psi = 6.89 kPa, 1" (inch) = 25.4 mm.

All tests were conducted using the regular mortar design with the confined match configuration. For more specific information of the test conditions, see Table 1 and its notes.

decrease in positive phase duration (roughly 10 to 40%).

Table 6 presents a summary of the effect of over-loads of aluminum metal powder (which has the capability of acting as a fuel in a reaction with atmospheric oxygen). Except for the 28 g over-loads, increases in peak pressure ranged from about 30 to 75%, increases in pressure impulse ranged from about 20 to 50%, and no systematic effect was seen in positive phase durations. Accordingly, it would seem that at least some of the aluminum powder is contributing to sound production. Also, it is expected that the reaction of excess fuel with air oxygen produces a brighter flash of light; however, no attempt was made to measure this effect.

For the 28 g over-loads in both the regular and trumpet mortars, there was an approximate doubling of both peak pressure and pressure impulse, coupled with increases in positive phase duration ranging from about 20 to 50%. A check in Table 1 for the results for the individual firings, confirms that the increases in positive phase are quite consistent and thus probably not likely to be merely a statistical artifact. Such an increase is in contrast with what has been seen in other cases (mortar configurations or over-loads) where there have been increases in sound level (peak pressure). Typically in those cases there was a reduction of positive phase duration or at best no systematic effect. However, in this case, there is an increase in sound output, apparent mellowness of that sound, and presumably the light produced a potentially desirable combination.

Table 7 presents a summary of the effect of over-loads with the capability of reaction with the excess fuel (magnesium) in the Luna Tech concussion powder. At high temperatures, sulfates act as oxidizers, especially with active metal fuels such as magnesium.[8] Further, the combination of magnesium and magnesium sulfate has shown the ability to produce powerful explosions with the potential for use as a flash powder.[8,9] Accordingly, the use of calcium and magnesium sulfate as oxidizing over-loads was investigated. When using these materials, there was observed an increase of about one third in peak pressure, little if any increase in pressure impulse, and a small decrease in positive phase duration. In comparing these results with those

Table 6. Average Over-Load Fuel Effect.

Mortar Position →	Near Mortar (72")			Far Mortar (144")		
Test Variable →	**Peak Pressure** (psi)			**Peak Pressure** (psi)		
↓ Test Condition →	Without	With	% Change	Without	With	% Change
14 g + 7 g Al	0.63	1.05	+67	0.31	0.50	+61
14 g + 7 g Al + 2% Cab		0.83	+32		0.39	+26
14 g + 7 g Al (H2)		1.00	+59		0.41	+32
14 g + 14 g Al		1.12	+78		0.52	+68
14 g + 14 g Al + 2% Cab		0.99	+57		0.48	+55
14 g + 28 g Al		1.40	+120		0.64	+110
14 g + 7 g Al, Trum.	0.71	1.00	+41	0.32	0.50	+56
14 g + 14 g Al, Trum.		1.41	+99		0.59	+84
14 g + 28 g Al, Trum.		1.19	+68		0.59	+84
Test Variable →	**Pressure Impulse** (psi ms)			**Pressure Impulse** (psi ms)		
↓ Test Condition →	Without	With	% Change	Without	With	% Change
14 g + 7 g Al	0.55	0.75	+36	0.30	0.40	+33
14 g + 7 g Al + 2% Cab		0.70	+27		0.36	+20
14 g + 7 g Al (H2)		0.66	+20		0.34	+13
14 g + 14 g Al		0.77	+40		0.44	+47
14 g + 14 g Al + 2% Cab		0.80	+45		0.44	+47
14 g + 28 g Al		1.16	+110		0.66	+120
14 g + 7 g Al, Trum.	0.59	0.80	+36	0.35	0.43	+23
14 g + 14 g Al, Trum.		0.86	+46		0.48	+37
14 g + 28 g Al, Trum.		1.10	+86		0.62	+77
Test Variable →	**Positive Phase** (ms)			**Positive Phase** (ms)		
↓ Test Condition →	Without	With	% Change	Without	With	% Change
14 g + 7 g Al	1.7	1.5	–12	2.0	1.7	–15
14 g + 7 g Al + 2% Cab		2.2	+29		2.6	+30
14 g + 7 g Al (H2)		1.7	0		2.1	+5
14 g + 14 g Al		1.6	–6		1.8	–10
14 g + 14 g Al + 2% Cab		1.7	0		2.1	+5
14 g + 28 g Al		2.5	+47		2.7	+35
14 g + 7 g Al, Trum.	1.9	1.6	–16	2.3	1.9	–17
14 g + 14 g Al, Trum.		1.5	–21		2.2	–4
14 g + 28 g Al, Trum.		2.5	+32		2.7	+17

For conversion to SI units, 1 psi = 6.89 kPa, 1" (inch) = 25.4 mm.

Except as noted, all tests were conducted using the regular mortar design with the confined match configuration. For more specific information of the test conditions, see Table 1 and its notes.

found in Table 5 for unreactive over-loads, it would seem that if any reaction was occurring between the excess magnesium (vapor) fuel and the oxidative over-loads, it did not contribute significantly to sound production.

The high fluorine content of Teflon makes it a powerful oxidizer in combination with active metal fuels such as magnesium. So much so that these are the primary components used in military infrared decoy flares.[10] The use of Teflon as an over-load material produced an

Table 7. Over-Load Oxidizer Effect.

Mortar Position →	Near Mortar (72")			Far Mortar (144")		
Test Variable →	**Peak Pressure** (psi)			**Peak Pressure** (psi)		
↓ Test Condition →	**Without**	**With**	**% Change**	**Without**	**With**	**% Change**
14 g + 7 g $CaSO_4$	0.63	0.91	+44	0.31	0.39	+26
14 g + 7 g $MgSO_4$		0.92	+46		0.38	+23
14 g + 7 g Teflon		0.91	+44		0.39	+26
Test Variable →	**Pressure Impulse** (psi ms)			**Pressure Impulse** (psi ms)		
↓ Test Condition →	**Without**	**With**	**% Change**	**Without**	**With**	**% Change**
14 g + 7 g $CaSO_4$	0.55	0.59	+7	0.30	0.32	+7
14 g + 7 g $MgSO_4$		0.61	+11		0.32	+7
14 g + 7 g Teflon		0.73	+33		0.40	+33
Test Variable →	**Positive Phase** (ms)			**Positive Phase** (ms)		
↓ Test Condition →	**Without**	**With**	**% Change**	**Without**	**With**	**% Change**
14 g + 7 g $CaSO_4$	1.7	1.5	–12	2.0	1.7	–15
14 g + 7 g $MgSO_4$		1.4	–18		1.5	–25
14 g + 7 g Teflon		1.6	–6		1.6	–20

For conversion to SI units, 1 psi = 6.89 kPa, 1" (inch) = 25.4 mm.

All tests were conducted using the regular mortar design with the confined match configuration. For more specific information of the test conditions, see Table 1 and its notes.

effect similar to that of the other potential oxidizers, with the exception that some of the added sound production is probably the result of its reaction with magnesium. Evidence for this is the increase in pressure impulse by one third.

Conclusion

As mentioned above, significant variations were often observed for measurements made under apparently identical conditions. Accordingly, any minor effects observed may merely be statistical in nature (may not be real), and only those results that are fairly certain will be addressed in this section.

The only concussion powder used in these tests was Luna Tech's Pyropak Concussion Powder. This is a fuel-rich powder that uses a nitrate oxidizer, which is fairly unique among commercial concussion powders.[2] Accordingly, the results reported from this study, may not apply to the use of other concussion powders.

Both the trumpet and confined match configurations produced significantly increased peak air blast pressures (louder sounds), but only for the lightest powder loads (7 g). This seems to have been the combined result of somewhat greater sound producing efficiency (increased pressure impulse) and a consequence of a decrease in positive phase duration. When a trumpet mortar with the confined electric match feature was tested, there was a further significant increase in sound output, but again only for the lightest powder loads. However, to put this into perspective, the sound output from 14 g of concussion powder in a standard mortar is substantially greater than that produced by 7 g of powder in a trumpet mortar with a confined electric match. Accordingly, the only obvious situation where the achievements of the new mortar configurations would be preferred over using a larger load of concussion powder would be in cases where the production of smoke needed to be minimized.

The use of aluminum metal powder overloads probably does produce a brighter flash of light upon firing, but that was not measured in this study. Regarding sound output, for light powder loads (7 and 14 g) it was found that the use of aluminum metal powder over-loads did not produce substantially greater output than that accomplished with an over-load of an equal mass of unreactive material. There was, however, the potentially useful observation that the 28 g over-loads produced blast waves with noticeably greater sound pressure and also longer positive phase durations.

The use of oxidative over-loads also produced results fairly similar to using unreactive material. This was a surprise, it was thought there was significant potential for a powerfully explosive reaction between the excess vaporized magnesium and these oxidizers.

Acknowledgments

The authors wish to acknowledge the following companies for providing materials used in this study: Luna Tech for supplying the concussion powder and electric matches, Alcan-Toyo for supplying their aluminum metal powder No. 105, and Valimet for supplying their H-2 aluminum metal powder.

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Table 1. Results from Individual Tests of Mortar Configurations and Over-Load Conditions.

Mortar Position →	Near Mortar (72")			Far Mortar (144")		
Test Variable →	Peak P.	Impulse	Pos. Ph.	Peak P.	Impulse	Pos. Ph.
↓ Test Condition	(psi)	(psi ms)	(ms)	(psi)	(psi ms)	(ms)
7g, Regular, SH[b,c]	0.088	0.066	2.2	0.036	0.028	2.3
	0.093	0.093	2.4	0.031	0.067	4.4
	0.116	0.095	1.8	0.042	0.055	2.4
14g, Regular, SH[b,c]	0.91	0.55	1.3	0.38	0.29	1.5
	0.81	0.55	1.5	0.35	0.29	1.6
	0.84	0.63	1.8	0.35	0.30	2.0
28g, Regular, SH[b,c]	1.99	1.16	1.6	0.79	0.56	1.6
	1.57	1.01	1.7	0.61	0.50	1.5
	1.69	1.11	1.7	0.59	0.54	1.5
7g, Regular, NL[a,b]	0.17	0.11	1.3	0.059	0.054	1.4
	0.16	0.11	1.6	0.055	0.060	1.9
	0.21	0.18	1.8	0.087	0.081	2.0
14g, Regular, NL[a,b]	0.54	0.56	1.7	0.29	0.30	1.9
	0.68	0.49	1.6	0.32	0.28	1.9
	0.68	0.59	1.8	0.33	0.32	2.3
28g, Regular, NL[a,b]	1.60	0.91	1.2	0.73	0.49	1.2
	1.38	0.95	1.9	0.57	0.51	1.6
	1.85	1.06	1.2	0.78	0.53	1.4
28g, Regular, TH[k,l]	1.41	0.88	1.4	0.58	0.51	1.9
	1.37	0.84	1.4	0.60	0.53	2.2
	1.47	0.84	1.3	0.63	0.52	1.9
7g, Trumpet, SH[b,c]	0.17	0.12	1.4	0.061	0.058	1.7
	0.24	0.20	1.7	0.087	0.094	2.2
	0.21	0.15	1.4	0.067	0.072	1.6
14g, Trumpet, SH[b,c]	0.72	0.58	1.8	0.38	0.33	2.0
	0.80	0.67	1.6	0.43	0.35	2.0
	0.64	0.60	1.8	0.35	0.33	2.4
28g, Trumpet, SH[b,c]	1.90	1.06	1.5	0.69	0.58	1.8
	1.90	1.08	1.6	0.74	0.60	1.8
	2.11	0.94	1.0	0.77	0.57	1.4
7g, Trumpet, NL[a,b]	0.25	0.18	1.6	0.094	0.082	1.4
	0.30	0.17	1.2	0.125	0.087	1.4
	0.25	0.15	1.2	0.082	0.075	1.7
14g, Trumpet, NL[a,b]	0.84	0.58	1.7	0.37	0.35	2.1
	0.74	0.58	1.7	0.34	0.35	2.1
	0.56	0.62	2.2	0.25	0.34	2.6
28g, Trumpet, NL[a,b]	1.83	1.05	1.6	0.64	0.55	1.7
	1.86	1.11	1.5	0.64	0.58	1.8
	1.82	0.95	1.4	0.78	0.54	1.4
7g, Regular, SH, Tape[b,c,h]	0.16	0.068	1.8	0.061	0.057	1.9
	0.16	0.087	1.2	0.065	0.039	1.2
	0.14	0.079	1.5	0.054	0.036	1.6
14g + 7g Al, Reg., NL[a,b,d]	1.09	0.75	1.6	0.54	0.41	1.8
	0.99	0.72	1.4	0.49	0.39	1.5
	1.07	0.77	1.6	0.48	0.41	1.8

Table 1. Results from Individual Tests of Mortar Configurations and Over-Load Conditions. (Continued)

Mortar Position →	Near Mortar (72")			Far Mortar (144")		
Test Variable →	Peak P.	Impulse	Pos. Ph.	Peak P.	Impulse	Pos. Ph.
↓ Test Condition	(psi)	(psi ms)	(ms)	(psi)	(psi ms)	(ms)
14g + 14g Al, Reg., NL[a,b,d]	1.11	0.74	1.6	0.51	0.43	1.6
	1.11	0.78	1.6	0.56	0.45	2.2
	1.13	0.80	1.7	0.50	0.43	1.6
14g + 21g Al, Reg., NL[a,b,d]	1.20	0.95	1.6	0.57	0.51	2.6
14g + 28g Al, Reg., NL[a,b,d]	1.53	1.13	2.5	0.69	0.67	2.8
	1.58	1.20	2.2	0.69	0.69	2.7
	1.08	1.14	2.8	0.55	0.62	2.6
14g + 7g Al, Trum., NL[a,d,k]	0.72	0.84	2.0	0.44	0.48	2.4
	1.20	0.82	1.4	0.56	0.42	1.7
	1.08	0.74	1.4	0.50	0.39	1.7
14g + 14g Al, Trum., NL[a,d,k]	1.43	0.93	1.9	0.59	0.50	2.2
	1.26	0.85	1.3	0.59	0.50	2.2
	1.55	0.81	1.3	0.58	0.44	2.1
14g + 28g Al, Trum., NL[a,d,k]	1.27	1.23	2.6	0.64	0.67	2.6
	1.30	1.08	2.4	0.61	0.59	2.6
	0.99	1.00	2.6	0.53	0.61	3.0
14g+7g Al+Cab, Reg., NL[a,b,e]	1.04	0.71	1.6	0.50	0.39	1.7
	0.87	0.70	1.7	0.40	0.40	2.1
	0.57	0.68	3.2	0.27	0.30	4.0
14g+14g Al+Cab,Reg., NL[a,b,e]	1.11	0.78	1.6	0.56	0.45	2.2
	0.89	0.81	1.8	0.39	0.44	2.0
	0.97	0.82	1.8	0.48	0.42	2.2
14g + 7g Al (H2), Reg., NL[a,k,m]	0.69	0.49	2.3	0.35	0.26	2.6
	1.20	0.76	1.4	0.43	0.40	1.9
	1.12	0.74	1.4	0.44	0.37	1.7
14g+7g Al_2O_3, Reg., NL[a,b,f]	0.82	0.64	1.6	0.36	0.32	1.6
	0.93	0.64	1.8	0.37	0.33	1.8
	0.79	0.60	1.6	0.39	0.32	1.8
14g + 7g Plug, Reg., NL[a,k,n]	1.28	0.70	1.2	0.50	0.33	1.4
	1.05	0.61	1.3	0.41	0.32	1.7
	1.07	0.65	1.3	0.43	0.34	1.6
14g + 7g $MgSO_4$, Reg., NL[a,b,j]	0.99	0.62	1.3	0.39	0.32	1.4
	0.94	0.63	1.6	0.38	0.33	1.6
	0.82	0.57	1.3	0.37	0.32	1.5
14g + 7g Teflon, Reg., NL[a,b,j]	0.75	0.69	1.8	0.36	0.39	1.8
	1.14	0.72	1.2	0.43	0.41	1.5
	0.83	0.78	1.7	0.37	0.40	1.6
14g+7g $CaSO_4$, Reg., NL[a,b,g]	0.92	0.62	1.4	0.39	0.33	1.6
	0.88	0.57	1.3	0.39	0.31	1.8
	0.92	0.59	1.8	0.40	0.32	1.6

(a) The electric match hole was in the new location (NL), below the bottom of the combustion chamber in the "confined match" configuration as shown in Figure 5.

(b) The electric matches used were Luna Tech ZD matches (supplied in early 1996) and appear to have smaller tips than those supplied in 1997.

(c) The electric match hole was the standard hole (SH) installed by Luna Tech on the side of the mortar as shown in Figure 1.

(d) The aluminum metal powder used was product number ATA-105 (6 micron, atomized), supplied by Alcan-Toyo.

(e) The aluminum metal powder used was product number ATA-105 (6 micron, atomized) supplied by Alcan-Toyo, blended with 2% M-5 Cab-O-Sil from Cabot.

(f) The Al_2O_3 was a very fine powder.

(g) The $CaSO_4$ was fresh (dry) Plaster of Paris, from a local hobby shop.

(h) Two layers of gaffer's tape were crossed over the top end of the mortar.

(i) The Teflon (polytetrafluroethylene) was a very fine powder.

(j) The $MgSO_4$ (anhydrous) was prepared by reacting $MgCO_3$ with H_2SO_4 and drying at 220 °C.

(k) The electric matches used were Luna Tech ZD matches supplied in 1997 and appear to have larger heads than those supplied in early 1996.

(l) The electric match hole was located 2-1/4 inches (80 mm) down from the muzzle of the mortar, which placed it approximately 1/4 inch (9 mm) below the top of the powder load.

(m) The aluminum metal powder used was product number H-2 (2.5 micron, atomized) supplied by Valimet.

(n) A wooden plug weighing approximately 7 g and with a tapered end (to prevent jamming in the bore of the mortar) was made from 7/8-in. (31-mm) dowel stock.

An earlier version appeared in *Proceedings of the 4th International Symposium on Fireworks*, 1998.

Quick Match — A Review and Study

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ABSTRACT

Several factors affect the burning of quick match. A brief study was conducted to determine the general magnitude of the effects produced by those factors, singly and in combination. For high quality quick match, under the conditions of these tests, it was determined that tight string ties, damage to the Black Powder coating and exposure to high humidity had the potential to slow the burning of quick match. However, no single performance risk factor was observed to be sufficient to produce either a significant hang fire or a failure of the quick match to propagate. To the contrary, however, typically a synergistic effect was produced by combinations of risk factors. For example, combinations of two risk factors produced short hang fires, and combinations of all three risk factors produced occasional misfires.

An examination of the extent to which moisture is gained by the materials used to make quick match suggested that the use of synthetic (plastic) string could significantly reduce moisture adsorption. This should reduce the degradation of the performance of quick match that has been exposed to high humidity. Also long duration hangfires could possibly be eliminated because this string does not tend to smolder like cotton string. Finally, there was a brief examination of the time taken for the strings in black match to lose their strength after the flame front had passed. It was found that it may occasionally be possible for one shell firing in a chain to pull apart the fusing of the next shell in the series.

Introduction

Although some interesting new fusing technologies have recently been introduced (No-Match™[1] and Sticky Match™[2]), quick match continues to be widely used in fireworks, mostly for aerial shell leaders. While many in the fireworks trade have extensive practical knowledge regarding the performance of quick match, relatively little quantitative information has been published. Several years ago, a study was conducted to investigate quick match burning under various conditions. This article reports those results, specifically: the effectiveness of methods used to slow the burn rate of quick match, the effect of risk factors (such as powder loss and exposure to high humidity) on its performance, how a combination of risk factors can account for its failure to function properly on occasion, some suggestions for possible improvement of quick match, and the length of time its strings retain significant strength after the fuse burns. However, before presenting those discussions, this article sets the stage by discussing the construction and manner of functioning of quick match.

Construction and Manner of Functioning

Typically quick match consists of black match within a thin loose fitting sheath of paper. (However, on occasion other materials such as plastic tube or even metal tubing are used). Generally the paper sheath is called the "match pipe" and sometimes quick match is called "piped match". See Figure 1 for the appearance of black match and quick match. The match pipe can be pre-made and a length of black match slipped into it. Although this works well

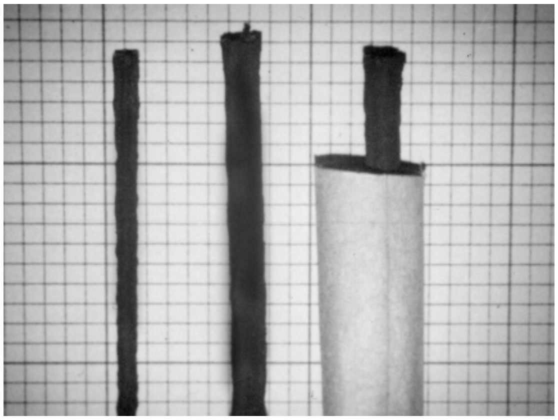

Figure 1. Two examples of black match (left) and an example of quick match (right).

for making short lengths of quick match, such as needed for shell leaders, longer lengths, such as needed for fusing lancework, would need to be spliced together. As an alternative, and the method most commonly used commercially in the US, the match pipe is formed in a continuous process around a very long length of black match. Traditionally, the match pipe included an inner wrap of thin wax-impregnated paper for moisture protection of the black match core. More recently, some manufacturers have used plastic laminated paper,[3] plastic-covered tape[4] or other similar means to provide a greater level of moisture protection.

Black match most commonly consists of a collection of thin strings, usually cotton or cotton / polyester blends that have been coated with a slurry of Black Powder with a binder in water. Manufacturers may use commercial meal Black Powder, a mixture of commercial powder and rough (handmade) powder, or rough powder alone. Typically, the individual strings are pulled over a number of rollers immersed in the slurry, then brought together as a bundle and pulled through a funnel shaped orifice to remove the excess Black Powder mixture. The wet black match is usually wound on a frame for drying before it is used to make quick match. However, some oriental manufacturers use wet, or at least damp, black match to make their quick match. One variation in making black match is to apply a dusting of meal powder to the black match while the match is still wet. This so-called "dusted" match is reputed to ignite easier and burn faster when made into quick match.

Black match typically burns at approximately one inch per second (25 mm/s). The same black match, when loosely sheathed to make quick match, typically burns more than 100 times faster, at 10 to 20 feet per second (3–6 m/s). The authors have heard three explanations for the accelerated burning of black match when wrapped to make quick match, specifically:

1) The black match burn rate increases because of its being starved for oxygen under the paper wrap.

2) The increase in black match burn rate is the result of burning under increased pressure because of the paper wrap.

3) The burn rate increase is the result of contained gases traveling along the enclosed space between black match and the paper (i.e., in essence a transition from parallel burning to propagative burning induced by the presence of the paper wrap).

In large part, the first explanation can be quickly dismissed on theoretical grounds; there is no scientific basis for pyrotechnic burning accelerating because of a deficiency of oxygen. Clearly Black Powder is not dependent on atmospheric oxygen for burning. Moreover, atmospheric oxygen is a more energetically favored source of oxygen than potassium nitrate. Thus, if anything, its availability can only serve to increase burn rate. However, the main reason for rejecting this explanation is that it is contrary to common experience. For example, consider a case where a thin trail of fine (mixed particle size) commercial Black Powder is burned on a surface. The rate of burning will be inches per second (100's of mm/s). However, when this same powder is tightly wrapped with threads to make visco fuse or when well compacted into a casing as a rocket motor, its burn rate falls to less than half an inch per second (about 10 mm/s). This slowing is contrary to the prediction of accelerated burning when Black Powder is starved for oxygen by encasing it.

The second explanation for high burn rates of quick match at least has a potential theoretical basis to support it; burn rate generally accelerates in response to increasing ambient

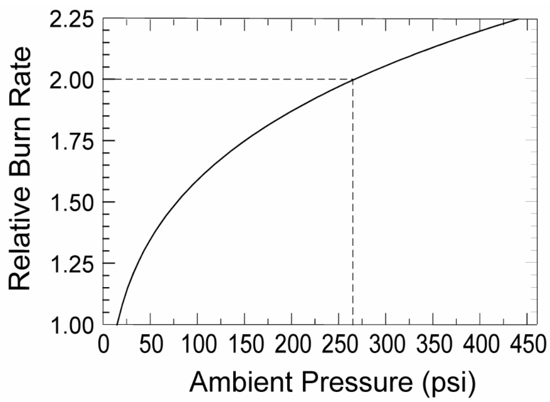

Figure 2. Graph of Black Powder burn rate as a function of ambient pressure (note that 1 psi = 6.9 kPa).

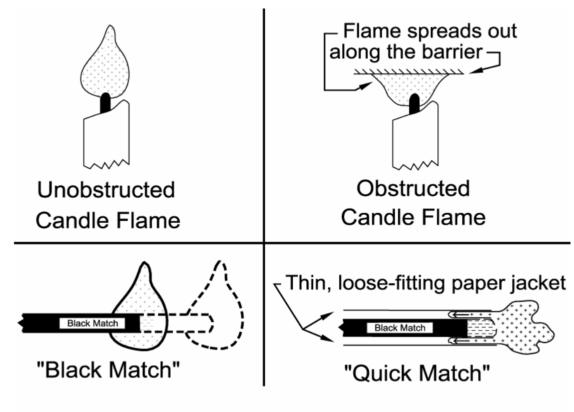

Figure 3. The analogous burning of a candle and black match without and with the presence of an obstruction.

pressure. This is expressed in the burn rate or Vieille equation:[5]

$$R = A\ P^B$$

where R is linear burn rate, P is ambient pressure, and A and B are constants.

For Black Powder, burn rate increases with pressure as shown in Figure 2 (based on the constants given by Shidlovskiy[5]). Two things should be noted in Figure 2: first, ambient pressure must rise to approximately 265 psia (1.8 MPa) for the burn rate of Black Powder to double; and second, the effectiveness of rising pressure to increase burn rate lessens with increasing pressure. Obviously, the pressure increase needed to even double the burn rate for black match is much greater than could ever be contained by the paper match pipe, let alone the horrendous pressure increase needed for a 100 fold increase in burn rate. Accordingly, this second possible explanation for the increased burn rate of quick match must also be rejected.

In essence, the third explanation for the accelerated burn rate of quick match is that there is a transition from parallel to propagative burning. This explanation was presented by Shimizu,[6a] without specifically using the terms parallel to propagative burn type transition. (For a more complete discussion of these terms, see reference 7.) Shimizu's explanation uses the analogy of a candle flame. When a barrier obstructs a candle flame, see Figure 3, the flame tends to spread out along the barrier. He likens the unobstructed candle flame to the burning of black match. When the black match has burned to the start of the match pipe, the pipe at least temporarily obstructs the flame. Some of the flame is deflected out the end of the match pipe, but some flame is also deflected into the "fire path" between the match pipe and black match. The flame entering the match pipe causes the ignition of an additional amount of Black Powder on the surface of the black match. Because more black match has ignited, additional flame is produced. Some of this flame exits the match pipe, and some penetrates further into the match pipe igniting still more black match, thus producing even more flame. The process continues to accelerate as the flame races through the fire path between the black match and match pipe. In the process, the pressure inside the match pipe does increase slightly, but much less than that needed to explain even a small fraction of the increase in the rate of burning. Nonetheless, the increase in pressure has important ramifications. The acceleration of the burning of black match can only increase to the point where the internal pressure exceeds the strength of the match pipe, at which time the pipe ruptures and further acceleration of burning ceases.

In addition to there being a sound physical basis for believing Shimizu's explanation, he conducted supporting experiments. In these tests, the paper match pipe was replaced with thin metal tubes.[6a] As expected, the burn rate increased beyond that found for paper-piped quick match because of the higher pressures

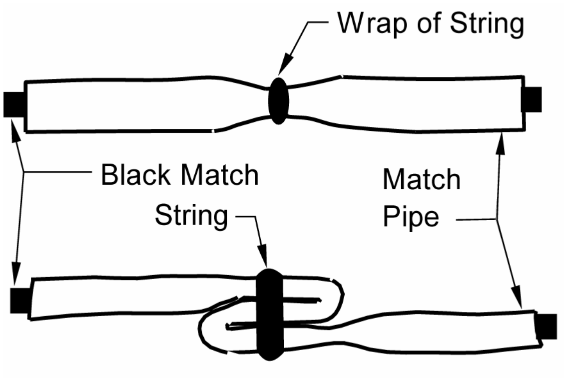

Figure 4. Illustration of two common methods used to slow the burn rate of quick match.

tolerated by the metal tubes before their rupturing. Further, the authors' studies of quick match reported in this article support or are consistent with Shimizu's explanation.

Methods to Slow Quick Match Burning

Lengths of quick match typically burn at 10 to 20 feet per second (3–6 m/s). However, sometimes this is faster than desired, such as when firing a barrage of chain-fused aerial shells. Quick match burns rapidly because fire (burning gas) races down the "fire path" between the black match and the loose fitting match pipe, and therein lies the answer to slowing its rate of burning. Whenever the fire path in quick match is tightly closed, its burning must temporarily transition back from propagative burning (fast) to parallel burning (slow). Ofca[8] calls such delays "choke delays".

A number of similar methods are used to close the fire path of quick match. Probably the most common is simply to tie a string (or light cord) very tightly around the quick match at the point where a momentary slowing is desired. The string collapses the paper match pipe compressing it tightly against the black match. Accordingly, the quick match burning propagates rapidly along its fire path until the point where it is tightly closed by the string. At that point it must burn slowly, layer by parallel layer under the string and compressed match pipe. Then, when the fire path re-opens, the burning again propagates rapidly. For this method of slowing

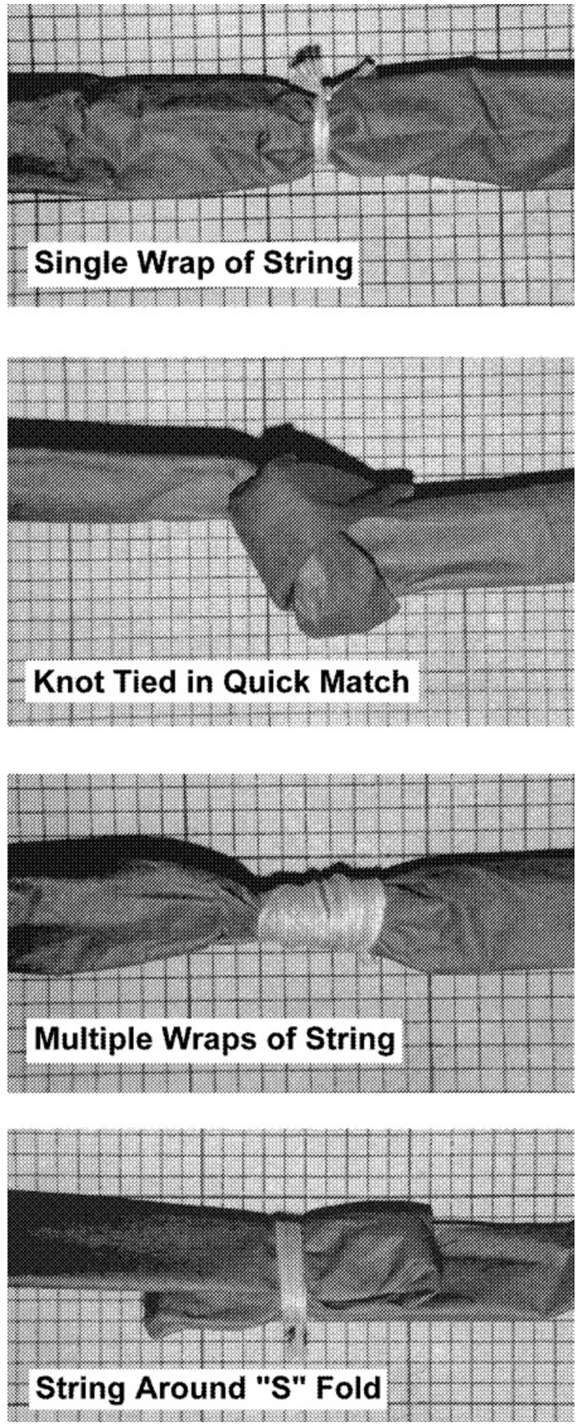

Figure 5. Photos of common methods used to slow the burning of quick match.

to be successful, the fire path must be totally closed. Otherwise some fire will race through any small gap between the black match and match pipe, and there will be much less slowing of the burning.

Table 1. Quick Match Delay Times.

Condition	Burn Times (seconds/60)[a]			Average[b] Delay Time (s)
	Longest	Shortest	Average	
Unaltered	21	17	19	≡ 0.0
Single string tie	45	21	33	0.2
Quick match knot	52	30	44	0.4
"S" tie	79	26	48	0.5
Cable tie	100	24	47	0.5
½" string wrap	109	42	65	0.8

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the large variations observed in burn times for the same conditions, the reported averages (in seconds) must be seen as approximate values and are only reported to the nearest 0.1 second.

Several common methods to close the quick match fire path are illustrated in Figures 4 and 5. Instead of tying a string tightly around quick match, other items such as plastic electrical cable ties can be used. Another method is simply to tie the quick match itself into a tight knot. If a longer delay is desired, more than one tie can be made around the quick match, or a long continuous wrap of string can be used, or the quick match can be tightly tied in the shape of an "S" with string.

Unless noted to the contrary, the same method of measuring burn times was used throughout this study. In each case, three measurements of burn time were made for each condition being tested. Approximate burn times were determined by videotaping the burning of quick match sections and counting the number of 1/60-second video fields, while viewing the tape in slow motion. Each 16-inch (400 mm) long test section of quick match had an additional 4 inches (100 mm) of black match exposed on the end for ignition. Timing started with the first indication that burning had propagated to the inside of the match pipe (i.e., when the flame from the burning black match became distorted by the paper match pipe). Timing stopped at the first sign of fire or significant sparks projecting from the other end of the quick match section. Unless noted to the contrary, the quick match used in these tests was produced by Valet Manufacturing,[9] which had been stored for more than a month at 75 ºF and 35% relative humidity. The reason for choosing Valet quick match was that it is generally believed to be of high-quality and because a moderate quantity was available in the lab for testing. However, because more testing was performed than originally anticipated, the supply of quick match from Valet was exhausted and quick match from Primo Fireworks (now out of business) was substituted.

The results of the tests of quick match slowing methods are reported in Table 1. In each case the longest, shortest, and average times of three separate tests are reported. The relative unpredictability of these slowing methods can be approximated by comparing the longest and shortest burn times for the various methods. In part the differences must be the result of variations in the length of tightly compressed match pipe around the black match. Further, the variability was probably exacerbated to some extent by the low relative humidity, causing the match pipe paper to be relatively stiff and unyielding, making it difficult to achieve a tight closure of the match pipe around the black match.

The subject of humidity will be specifically addressed below; however, humidity can affect the amount of delay commonly achieved using the various quick match slowing methods. For quick match that has been subjected to high humidity for a few days, the delays reported in Table 1 can be twice as long. Another factor affecting the amount of delay achieved using the various methods is the quality of the quick match. Quick match that is fiercely burning,

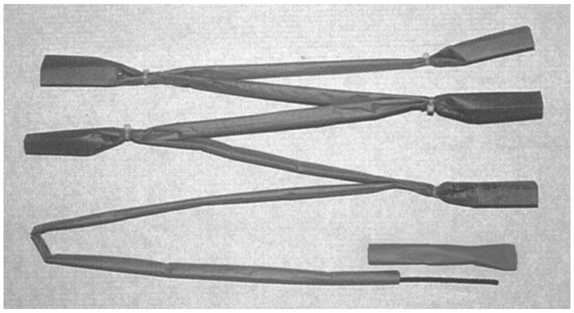

Figure 6. Photo of a short "finale chain", shown with "buckets" for attaching shell leaders.

with a heavy powder coating and a thick match pipe, is the most difficult to slow.

To some extent, an operator can control the speed of a finale during the chaining operation. Figure 6 shows a short finale chain with paper wraps (often called "buckets" and made from coin wrappers) that are used for attaching the quick match to the leaders of shells in the chain. Figure 7 shows a cut away illustration of one bucket. At the chain end of each bucket (left in Figure 7), if the string is tied VERY tightly, a brief delay will be introduced (such as suggested in Table 1). Whereas, if the buckets are only tied tight enough to minimally hold the fusing together, there will be significantly less delay at each tie point. Note: To secure such a connection, some operators augment the string tie with a small amount of glue between the match pipe and bucket.

When longer delays are needed, it is possible to add a length of time fuse such as shown in Figure 8. Here a length of time fuse has been cut, punched and cross-matched (usually with thin black match). The length of time fuse between the cross-matched points determines the amount of delay that will be produced. The piece of time fuse is inserted into a very thin-walled paper tube, typically made with two or three turns of Kraft paper. The time fuse is tied into place near both of its ends. To install the delay element, first cut the quick match to be slowed into two pieces and expose its black match by tearing back the match pipe roughly one inch (25 mm). Then insert the two ends of quick match into the two ends of the delay element and tie them securely. It is important that

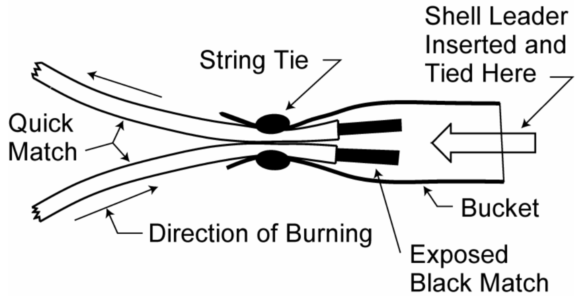

Figure 7. Cut away illustration of one "bucket" in a finale chain.

the string ties on the time fuse are quite tight to keep fire from passing under the strings and skipping around the time fuse.

As one gains experience with a particular supplier's quick match and the methods of slowing quick match burning, it should be possible to control its burn rate to accomplish most needs, providing a high degree of timing precision is not essential.

Effect of Powder Loss

Damage to the Black Powder coating on the black match is reputed to degrade the performance of quick match. Further, severe damage is sometimes given as a reason for quick match failure (a hangfire or misfire). One example of how such powder loss might occur would be the result of extreme and repeated flexing of the quick match in one area, such as from very rough handling. For these tests, damage to the black match coating was introduced by repeatedly drawing approximately 2 inches (50 mm) of its length (near the middle of the quick match

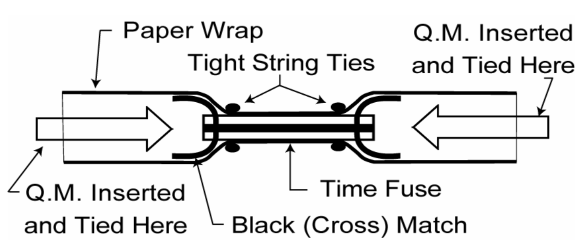

Figure 8. Cut away illustration of method for attaching a length of time fuse to quick match (Q.M.= quick match in illustration).

Table 2. Burn Times of Test Segments of Quick Match Suffering Serious Powder Loss.

Condition	Burn Times (seconds/60)[(a)]			Burn Time Change[(b)]
	Longest	Shortest	Average	
Undamaged	21	17	19	≡ 0%
2" Damaged	16	15	16	–15%
6" Damaged	17	13	15	–20%
Undamaged[(c)]	24	19	21	≡ 0%
2" Washed[(c)]	26	20	24	15%
6" Washed[(c)]	37	34	36	70%

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the variations observed in burn times for the same conditions, the reported average percentage change must be seen as approximate and are only reported to the nearest 5%.

(c) Quick match was from Primo Fireworks.

test segment) over a 0.25 inch (6 mm) diameter mandrill. After each pass, the direction of the bending was changed by rotating the quick match approximately 90°. The process continued until the paper match pipe was so distressed that its tearing was imminent. (Note that this amount of damage to the black match core is more than would be expected from even the roughest handling of aerial shell leaders.) After this treatment, the length of quick match was held vertically and repeatedly tapped to cause as much as possible of the loosened black match coating to fall out of the match pipe. On average, approximately 0.3 g of powder was removed from each damaged quick match segment. A second set of test samples were similarly prepared, except that approximately 6 inches (150 mm) of its length was damaged by being drawn over the mandrill. In this case, approximately 0.7 g of powder was removed from each test segment. The results from these tests are shown in the top half of Table 2, along with burn times for undamaged quick match segments.

Because the observed differences in burn time were small, one cannot be quantitatively certain of these results. Nonetheless it seems likely that the damaged quick match segments actually burned slightly faster than undamaged quick match. Certainly, the damage did not cause the segments to burn significantly slower; even though the damage was severe and much of the loosened powder had been removed. In these tests, it seems obvious that sufficient powder remained attached to the black match for it to function well. If there actually was a burn rate increase, it may be the result of a residue of loosened powder coating the black match and the inside of the match pipe, or an increase in the ease of ignition of the black match coating because the remaining powder had been broken into small pieces.

In another series of tests, this time using quick match manufactured by Primo Fireworks, the effect of even more extreme black match powder loss was studied. In these tests, quick match segments were prepared in which there was a complete loss of black match coating for approximately 2 and 6 inches (50 and 150 mm). This was accomplished by first sliding the length of black match out of the match pipe. The black match coating was then removed from a length of the match, initially by crumbling off a much as practical, and then by washing the strings. Care was taken to prevent wash water from contacting the rest of the black match and to limit the migration of water into the black match through the strings. The lengths of black match were then dried at approximately 70 °F (21 °C) and 35% relative humidity for a week, before being reinserted into the match pipe. The burn testing proceeded as normal, with the results reported in the lower half of Table 2.

While there was a slowing of the burning, under the conditions of the tests, it is apparent that the flame front successfully jumped the lengths of string with no coating. However, it is expected that having an open end to the match pipe aided the propagation of flame over the uncoated sections of the black match.[6b] Accordingly, it should not be assumed that such severe removal of the black match coating would necessarily result in successful propagation in a length of quick match that has a closed end such as is normal for shell leaders. Nonetheless, that the segments of quick match with 2-inch (50-mm) lengths of washed string propagated fire with only a slight increase in burn time, and that the segments with 6 inch (150 mm) of washed string propagated fire with less than a doubling of the burn time are interesting observations.

The results from these two series of tests seem to be convincing evidence that for otherwise excellent quality quick match, as a single factor, it is unlikely that even the most severe physical damage to the black match coating will cause the failure of the match to propagate fire. However, it is important to note that this is not to say that such damage, in conjunction with other problems, does not contribute to failures of quick match (a situation that is investigated later in this article).

Effect of Humidity

Absorbed moisture has the potential to reduce the burn rate of quick match because thermal energy is wasted in heating and vaporizing the moisture. (See reference 10 for a more complete discussion of the factors affecting burn rate.) A series of tests were conducted to determine the effect on the burn rate of exposure of unaltered quick match to higher humidities. Also examined was the approximate length of time of exposure needed to reach a steady state condition.

The constant humidity chambers (hygrostats) used in this study were simply constructed using plastic containers approximately 14 by 10 by 6 inches (360 by 250 by 150 mm) purchased from a discount store. These boxes were chosen because their lids fit well and the seal could be made fairly tight by placing weight on the lid. For humidity control, two small trays were placed inside each plastic box. Each tray was filled with a saturated aqueous solution of either ammonium nitrate, sucrose (table sugar) or potassium sulfate. At the temperature of the lab (≈65 °F or ≈18 °C), the theoretical relative humidity maintained by these solutions should have been approximately 66, 85 and 97%, respectively.[11,12] (For more complete information on this method of producing constant relative humidity environments, see reference 13.) The quick match segments to be subjected to the various humidities were placed into the chambers.

The relative humidity in the lab during the period of the measurements was about 35%. Because the chamber lids were removed to load and remove the samples, and because the lids on the chambers did not provide perfect seals, the relative humidities maintained inside the chambers were less than their theoretical values and they varied somewhat during the course of each day. The relative humidities actually maintained within the chambers were measured using a digital hygrometer (Davis Instruments, model 4080). Those values averaged approximately 64, 78 and 90% for the three chambers.

The results of burn tests of these humidity-conditioned quick match segments are reported in Table 3. As can be seen, the range of values for the same conditions is quite wide as compared to the effects being measured (i.e., statistical precision is limited). Nonetheless some things are certain under the conditions of these tests. In all cases the quick match segments successfully propagated fire. However, exposure to high levels of humidity significantly slowed the burning of quick match, and greater slowing was produced as the level of humidity exposure was increased. Also, for these short open ended segments, the effect of the exposure apparently reaches a steady state within approximately 5 days.

Table 3. Burn Times of Unaltered Quick Match Segments Exposed to High Humidity.

Relative Humidity	Burn Times (seconds/60)[(a)]			Burn Time Percent Change[(b)]
	Longest	Shortest	Average	
35%, > 30 days	21	17	19	≡ 0
64%, 2 days	22	17	20	10
64%, 5 days	30	14	24	30
64%, 7 days	28	16	23	20
78%, 2 days	37	22	31	60
78%, 5 days	32	22	29	50
78%, 7 days	34	21	28	50
90%, 2 days	39	28	34	80
90%, 5 days	50	29	40	110
90%, 7 days	48	31	41	120

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the very wide variations observed in burn times for the same conditions, the reported percentage differences in burn time must be seen as approximate and are only reported to the nearest 10%.

Effect of Combined Risk Factors

In earlier sections of this article, methods for slowing quick match burning (by fire path closure) and the effects of powder loss and humidity exposure were reported. In some respects, these are each potential risk factors for the proper performance of quick match. This section presents information on the effects of some combinations of these individual risk factors.

In the current tests, the same constant humidity chambers described above were used. In all cases, unless otherwise noted, the humidity exposure was for at least 5 days. Two of the techniques for slowing the burning of quick match were reexamined for quick match exposed to high humidity. The first technique was that of tying a knot in the quick match. This was chosen because the stiffness of the low humidity quick match segments had made tying a tight knot difficult, and thus possibly less effective than it might have been. The second technique was that of tying a string tightly around the quick match. This was chosen because it is probably the most commonly used method to slow the burning of quick match and because the normal use of quick match for shell leaders commonly requires tying string around the quick match. Burn times from the previous tests (35% relative humidity) and for the high humidity (78% relative humidity) tests are presented in Table 4 ("Knot in Quick M." and "String Tied").

Exposure to 78% relative humidity was previously observed to increase quick match burn times by approximately 50% (see Table 3). In the present test, the slowing produced for humidity-exposed quick match tied in a knot was approximately 40%, essentially what might be expected. However, the extreme increase in burn time, approximately 300% (> 1.5 s), observed for the string tie method was surprising. This is approximately six times the magnitude of the effect that might have been expected from combining the separate effects. This observation is especially significant because such string ties are commonly used (in securing shell leaders to cylindrical aerial shells, bags of lift powder, and finale chain buckets) and because exposure to such levels of humidity is quite common. Thus, it seems clear that short delay hangfires can be produced by nothing more than prolonged exposure to moderately high humidity and any tight string ties normally around shell leaders.

Previously, the effect of the loss of some or all of the black match coating was investigated. In one series of tests, the black match coating

Table 4. Burn Times of Quick Match in Various Conditions upon Exposure to High Humidity.

Condition and Humidity	Burn Times (seconds/60)[a]			Burn Time
	Longest	Shortest	Average	% Change[b]
Knot in Quick M., 35%	52	30	44	≡0
Knot in Quick M., 78%	87	41	62	40
String Tied, 35%	45	21	33	≡0
String Tied, 78%	162	103	137	320
6" Damaged, 35%	17	13	15	≡0
6" Damaged, 64%	30	18	22	50
6" Damaged, 78%	32	25	27	80
2" Washed, 35%[c]	26	20	24	≡0
2" Washed, 78%[c]	74	36	50	110
6" Washed, 35%[c]	37	34	36	≡0
6" Washed, 78%[c]	∞[d]	68	71[e]	100[e]
String Tied, 35%	45	21	33	≡0
2" Dam., S. Tied, 35%[f]	65	30	45	40
2" Dam., S. Tied, 64%, 2 D.	69	34	52	60
2" Dam., S. Tied, 64%	∞[d]	44	107[e]	220[e]
2" Dam., S. Tied, 78%, 2 D.	∞[d]	89	115[e]	250[e]
2" Dam., S. Tied, 78%	∞[d]	∞	∞	∞
2" Washed, S. Tied, 35%	∞[d]	∞	∞	∞

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the large variations observed in burn times for the same conditions, the reported average percentage differences must be seen as approximate and are only reported to the nearest 10%.

(c) The quick match was from Primo Fireworks.

(d) The infinity symbol (∞) was used to indicate that the burning did not propagate to the end of the segment.

(e) The average difference in burn times was calculated using only the results from the two tests in which the burning successfully propagated to the end of the segment.

(f) Two inches (50 mm) of damaged black match in the quick match, around which a string is tightly tied, was exposed to 35% relative humidity. (Note that listings below also indicate when there were only two days (2 D.) of exposure at the higher humidities.)

was loosened from 6 inches (150 mm) near the middle of the quick match segment. This was accomplished by repeatedly drawing the quick match over a mandrill, followed by removal of the loosened powder. The results of the original tests, and the results for identically prepared segments conditioned in the humidity chambers, are reported in Table 4 (labeled as "Damaged"). As expected, there was an increase in the burn times of the quick match segments. However, the amount of increase for the humidity exposed segments (found to be 50% and 80%) was nearly twice that previously found for humidity exposure alone (which was 20% and 50%).

Also previously, the complete loss of short lengths of black match coating was investigated. To accomplish this total loss of powder from a portion of its length, the black match was removed from the match pipe, some of the coating was removed by physically crushing the black match, and then the strings in that area were thoroughly washed and then dried for a week. For the additional testing reported here, quick match segments were initially prepared as before, but were then conditioned by placing them into the humidity chambers. The quick match used in these tests was from Primo Fireworks. The results for these tests are reported in Table 4 (labeled as "Washed"). Exposure to high humidity increased the burn times of the quick match segments, and again the increase in burn time (≈100%) was approximately twice that previously found for humidity exposure alone (50%). However, note that on one occasion the burning of a humidity-conditioned quick match segment was incomplete, failing to propagate past the washed section.

In another series of tests, the combined effect of having the quick match segments suffer the loss of some of its black match coating (using the method described previously), tightly tying a string around the quick match in the area where the powder coating was damaged, and subjecting the segments to high humidity was studied. The results are listed in Table 4 (labeled as "Dam., S. Tied"). For these tests, the burn time for dry undamaged quick match segments with a string tied tightly around them was chosen for reference. As reported earlier, when the only factor was partial black match powder loss, there actually was an average 15% decrease in the burn time. However, in the current study, the burn time for the combination of the string tie and coating loss increased by 40%. When the effect of high humidity was included, the effect was extreme (> 200%), and there were numerous propagation failures.

Finally, reported in Table 4 (labeled as "Washed, S. Tied") are results for another test, wherein segments with 2-inch (50-mm) washed sections were tested after tightly tying a string around the quick match in the area of the washed section. Under these extreme conditions, it was expected that there would be a consistent failure to propagate.

Under the conditions of tests reported earlier in this article, it would seem that high quality quick match can generally suffer any of the individual performance risk factors (closure of the fire path, powder loss, or high humidity) without a serious loss of performance. However, combinations of the risk factors apparently act synergistically to cause much greater loss of performance, sometimes including a total failure of quick match to propagate fire. Of course, one reason this is significant is the hazards posed when aerial shells hangfire or misfire.

Hangfires and Misfires

Probably the most notable malfunctions of quick match, especially when used as aerial shell leaders, are hangfires and misfires.

> *Hangfire - A fuse ... which continues to glow or burn slowly instead of burning at its normal speed. Such a fuse may suddenly resume burning at its normal rate after a long delay. ... If the hangfire goes completely out (is extinguished), it is termed a misfire.*[14a]

An aerial shell hangfire is hazardous because of its unpredictability. The shell could fire at any time, up to a limit reputed to be 30 minutes or more. An aerial shell misfire is a problem because of the necessity to eventually unload the mortar. It is not the purpose of this article to discuss how these malfunctions should be handled once they occur, but rather to suggest some things that might be done by the shell manufacturer and display operator to reduce the likelihood of their occurrence. If the results reported earlier in this article are generally applicable, a solution to hangfires and misfires is to eliminate situations where multiple risk factors could occur, and even the individual risk factors as much as practical.

In the normal course of its use, it is necessary to make connections to lengths of quick match, for example, when attaching shell leaders to the top of cylindrical shells or to plastic bags of lift powder, and when chain-fusing aerial shells. Typically, string or other ties are used around the quick match for attachment. The strength of the attachment (that keeps the connection from pulling apart) is a result of the tightness of the string tie. It was determined above that a tight tie at a point where there is serious damage to the coating on the black match can cause a malfunction (especially when the quick match has also been exposed to high humidity). However, there are measures that can be taken to limit this potential problem.

Some manufacturers[15] insert an additional short length of black match into the end of the quick match where a tie will be made (or use two strands of black match the whole length). This accomplishes two things. Assuming the inserted black match is in good condition, it is assured that at least that piece of black match will have a good powder coating where the tie is made. Also, with two side-by-side pieces of black match, it is nearly assured that even a tight tie will not completely close the fire path between them.

Some manufacturers do not rely on a single tight tie to hold quick match to finale chain buckets or top-fused aerial shells. Rather they use multiple moderately snug ties, or a combination of a moderately snug tie and a small amount of adhesive applied to the paper at the point of connection. In addition to reducing the likelihood of completely closing the fire path of the quick match, this provides a strong and reliable connection (not likely to be pulled apart accidentally). Note that a strong coupling can have important safety ramifications. By itself, an undetected partial slippage of the shell leader from the its point of connection to a top-fused aerial shell could cause a hangfire or misfire. Similarly, if a finale chain pulls apart while firing, it may cease firing, typically causing someone to approach and re-ignite the chain.

During the summer months, exposure to high humidity may be inescapable. With high quality materials and manufacturing techniques, high humidity alone is unlikely to cause quick match malfunctions. However, exposure to high humidity has serious deleterious effects when combined with other quick match performance risk factors. Thus, as a minimum, nothing should be done to exacerbate the situation. For example, magazines should be kept as dry as practical. This is particularly important if the aerial shells are not of the highest quality and may already have other performance risk factors present. At the display site, measures should be taken to limit exposure to high humidity. For example, boxes of aerial shells should not be placed directly on the ground for long periods of time, and most certainly they should not be placed directly on the ground and then covered with a tarp, thus trapping the shells in a high humidity environment.

The testing performed for this article, used only high quality quick match. Thus the results reported can not be assumed to apply to lower quality material. For example, it was observed that even severe damage to the powder coating on the black match, in the absence of exposure to high humidity, did not result in propagation failures. It is likely that this is a result of one characteristic of high quality quick match—its black match is made using multiple strands of string, each of which is well coated with composition before being drawn together to form the black match. To the contrary, in recent years some of the aerial shells imported from China have used a single coarse cord for the black match, which is only coated on its outside, and to which there is rather poor adhesion of the powder to the cord. This product would not be expected to be nearly as forgiving with respect to rough handling, especially in conjunction with any other risk factors.

Moisture Absorption by Quick Match Components

It had been observed that moisture absorption as a result of humidity exposure can seriously affect the performance of quick match. Accordingly, it seemed appropriate to examine the moisture absorption problem more closely by testing the materials used to make quick match. For this, the same constant humidity chambers were employed; however, three additional relative humidities were used. The chemical solutions in these additional chambers were saturated solutions of sodium chloride, potassium nitrate, and barium chlorate. At the temperature of the lab (≈65 °F or ≈18 °C), the theoretical relative humidities for these solutions would be approximately 75, 93, and 94%, respectively.[10,11] Under actual conditions, the relative humidities were measured as averaging approximately 72, 86, and 88%, respectively.

The test samples for this study were either lengths of black match harvested from various manufacturers' quick match or the individual materials used in making quick match. The black match samples had been stored for an extended period of time at approximately 35% relative humidity and were not dried further

Table 5. Percentage Weight Gain of Various Sources of Black Match Exposed to Increasing Relative Humidities.

Source[a]	Percentage Sample Weight Gain at Humidities Listed					
	64%	72%	78%	86%	88%	90%
Mantsuna	1.3	1.3	1.4	1.5	2.1	2.5
Wandar	2.1	2.4	3.3	3.5	4.1	5.2
Angel Brand	1.9	2.1	3.1	4.1	---	5.4
Temple of Heaven	2.5	2.9	3.0	3.7	5.2	5.6
Primo (dusted)	2.7	3.0	3.9	4.8	5.1	5.8
Horse Brand	3.1	3.3	4.8	4.9	5.4	5.8
Onda	2.6	2.8	4.0	5.1	---	6.2
Yung Feng	3.1	3.3	4.8	5.6	6.0	6.7
Val-Et	3.1	3.3	4.3	5.0	5.3	7.1
Primo (undusted)	3.0	3.6	4.1	4.7	5.7	7.1
Average Gains	2.5	2.8	3.7	4.3	4.9	5.7

(a) All quick match samples dated to approximately 1992.

prior to testing. About 5 grams of sample material was weighed and placed into the constant humidity chambers. The samples were weighed daily to monitor their absorption of moisture as a function of time. For most materials, there was little absorption after the first full day and no further absorption after 2 days. However, the total time of exposure in the humidity chambers was always at least 4 days. In a few cases (e.g., where the samples liquefied) absorption continued for several days and the time of exposure was extended appropriately. Once data collection was completed at one humidity, the sample was placed into the next higher relative humidity chamber, and the measurements continued.

The samples of black match were harvested from aerial shell leaders that were available for use in the laboratory in 1994; some of the shells were then already several years old. Certainly it cannot be assumed that the black match samples used in this study are representative of what that manufacturer may have been using on all of their products or are using today. The percentage weight gains for the test samples of black match, exposed to the various relative humidities, are presented in Table 5. As can be seen, most samples gained between 5 and 7% at the highest relative humidity examined. Note that the Mantsuna black match gained less than half that of any other sample. (The reason for this will be discussed later.)

The average sample weight gain as a function of relative humidity exposure is graphed in Figure 9. Note that the weight gained is an accelerating function of humidity as it approaches 93% relative humidity. This is the humidity at which potassium nitrate becomes deliquescent and liquefies as a result of drawing extreme amounts of moisture from the air.

To study the weight gains of the individual materials used to make quick match, sample materials were dried for 24 hours at approximately 175 °F (80 °C) then humidity conditioned in the same manner as the black match

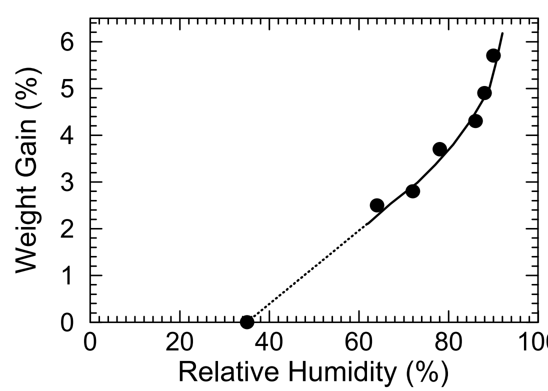

Figure 9. Average percentage weight gain as a function of relative humidity exposure above 35% relative humidity.

Table 6. Percentage Weight Gain of Various Materials Used To Make Quick Match When Exposed to Different Relative Humidities for Five Days.

Material	Percentage Sample Weight Gain at Humidities Listed					
	64%	72%	78%	86%	88%	90%
Goex Meal Powder	1.2	1.2	1.2	2.1	2.3	2.8
Hand Mixed Meal	1.0	1.0	1.2	2.1	2.1	2.6
Charcoal + Sulfur[(a)]	3.4	3.6	3.8	4.2	4.3	4.8
Potassium Nitrate, AR[(b)]	0.0	0.0	0.0	0.0	0.0	0.0
Potassium Nitrate, w/AC[(c)]	0.0	0.0	0.2	0.9	1.3	1.8
Potassium Nitrate, K-P[(d)]	0.2	0.2	0.3	1.5	2.1	2.2
Dextrin	8.9	11.2	14.0	22.3	(e)	(f)
Gum Arabic	11.8	13.9	15.7	16.8	(e)	(f)
CMC[(g)]	21.5	26.5	35.5	52.7	(e)	(f)
PVA[(h)]	5.7	7.9	10.4	16.8	(e)	18.5
HCE[(i,j)]	12	17	26	38	(e)	(e)
SGRS Waxy[(i,k)]	11	13	16	20	(e)	(e)
SGRS Quick[(i,k)]	12	14	16	19	(e)	(e)
Cotton String	5.4	5.9	7.2	9.5	10.0	10.8
Synthetic String[(l)]	0.0	0.0	0.0	0.0	(e)	0.0
30# Kraft Paper	6.7	7.8	10.3	13.2	(e)	15.1

(a) Air float charcoal and sulfur in a weight ratio of three to two. Supplied by Service Chemical.[17]

(b) Potassium nitrate analytic reagent grade.

(c) Potassium nitrate with anticake, as supplied by Service Chemical.[17]

(d) Agricultural grade potassium nitrate, “K-Power”.

(e) Data not taken for this relative humidity.

(f) Sample liquefied.

(g) Sodium carboxymethylcellulose, a water-soluble, thixotropic binder.

(h) Polyvinyl alcohol, a water soluble binder.

(i) The relative humidities to which these samples were exposed were slightly different from those of the other data in this table. The reported percentage weight gain was adjusted slightly by the authors in an attempt to correct for this humidity difference.

(j) Hydroxyethylcellulose, a modestly water-soluble, thixotropic binder.

(k) Soluble glutinous rice starch (SGRS), supplied in two varieties, “Quick” and “Waxy”.

(l) The synthetic string had the physical appearance of cotton string. Unfortunately, the type of plastic used to manufacture the string is not known.

samples. These weight gain results are presented in Table 6. Both Goex[16] Black Powder and the rough mixed ingredients, gained essentially the same amount of moisture, approximately 2.5% at the highest humidity. Given that the mixture of air float charcoal and sulfur constitute one fourth of Black Powder, they account for about half of the moisture absorbed by the samples of Black Powder and rough powder (1/4 of 4.8% = 1.2%). High purity (Analytic Reagent grade) potassium nitrate was not observed to gain any moisture. The less pure grades of potassium nitrate, the commercial grade with anticake and the agricultural grade, absorbed about 2% moisture.

Manufacturers of black match in this country usually add dextrin or starch (binders) to the Black Powder or rough powder used to make black match. As can be seen, both dextrin and two rice starches absorb a significant amount of moisture. In this study, six other binders were examined for their tendency to absorb moisture. The other binders were gum Arabic (more commonly used in the past in fireworks), sodium carboxymethylcellulose (CMC, a thixotropic binder that is occasionally used in manufacturing black match), polyvinyl alcohol (PVA, occasionally used in fireworks), hydroxyethylcellulose (a thixotropic binder, potentially useful in fireworks), and two forms of soluble glutinous rice starch (SGRS, commonly used in products manufactured in the far east). If the goal is to make black match that is less sensitive to high humidity, it would seem that PVA and gum Arabic might be considered as an alternative binder. However, neither offers much improvement considering that only small amounts of binder are typically used.

In Table 6, note that the cotton string which is used in most high quality black match is another important contributor to moisture absorption. In contrast, notice that string made from synthetic (plastic) material, does not absorb moisture. This string appears identical to cotton string (but is noticeably stronger). Synthetic string can be identified by placing it near a flame, where unlike cotton string, it first melts before it burns with a sooty flame. The use of such non-cotton string, may pose a problem regarding difficulty in wetting the string during the black match coating process. However, the use of a small amount of surfactant in the slurry of composition should solve that problem. Recall that the test sample of black match from Mantsuna absorbed less than half the moisture of the other samples. This black match is made using such non-cotton (plastic) string and demonstrates that high quality match can be made using it. In addition to high humidity resistance, another even more important potential advantage of using non-cotton string is that it does not tend to smolder, or burn somewhat like a punk, as does cotton string. Of course, this is important because it should significantly reduce the likelihood of hangfires.

Considering the amount contained in quick match, Kraft paper was the component found to be the greatest absorber of moisture. However, that may only have a relatively minor effect on the performance of quick match in an unconstricted match pipe. This is because, unlike the string in black match, the paper is normally not in intimate contact with the black powder. Accordingly, when the black match composition burns, the moisture containing paper match pipe may not be as effective in wasting the thermal energy being produced. However, when string ties are made around the match pipe, there will be contact between the paper and black match. In that case, the damp paper could have a greater effect. For example, recall the much greater delay reported earlier in this article when a string was tied around quick match and exposed to high humidity.

Survival Time for Strings in Black Match

One reason given for the practice of securing finale chain fusing to mortar racks is that, as shells fire, their shell leaders may sometimes pull apart the fusing to yet unfired shells later in the chain. The only way this can occur is if there is sufficient physical strength remaining in the paper match pipe or in the string of the black match, for a short time after the burning of quick match. A brief study was conducted to determine approximately how long after quick match burns that the string in its black match retains significant physical strength.

There is a basis for believing that the black match strings survive for a short time after quick match burns. In the burning of quick match, a flame front races down the fire path formed between its black match core and its paper match pipe. In this process, a small amount of time is required for the black match coating to be consumed and the strings in the black match to be exposed. Accordingly, the strings are not immediately subjected to high temperatures, and they must retain a significant portion of their strength for a brief time after the flame front has passed.

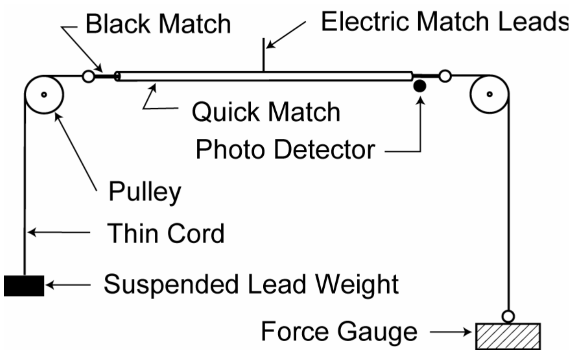

Figure 10. Illustration of the apparatus used to determine black match string failure times.

The apparatus for this study is illustrated in Figure 10. In the center is a 16-inch (405-mm) length of quick match, with approximately 2 inches (50 mm) of black match protruding from each end. Small loops were formed on the ends of the black match to attach thin cords used to apply tension to the black match. The thin cords were each run over small pulleys, where one cord was attached to a piezoelectric force gauge, and the other cord was attached to a suspended lead weight of approximately 2 pounds (≈1 kg mass). Accordingly, as long as the black match in the quick match remained intact, there was approximately a 2 pound (1 kg) tension being applied to the force gauge. The means of igniting the quick match was an electric match inserted through the match pipe at the approximate center of the quick match segment. At one end of the match pipe, a cadmium sulfide photo detector was mounted for the purpose of detecting when the flame front exited the match pipe. (Note that it is not clear whether the detector responded to visible light from the flame or infrared light from hot gases ahead of the flame front.)

A digital oscilloscope was used for timing the events during the tests. The oscilloscope was triggered by the application of current to the electric match. (The level of electric current had previously been determined to be sufficient to cause the firing of the electric match in less than 1 ms.) The outputs from the photo detector and the force gauge were recorded by the oscilloscope. The time of occurrence for each event was read from the oscilloscope traces by knowing the horizontal sweep rate.

The cotton string was found to be a significant absorber of moisture. Thus, it might be expected that the period of time after burning during which it retains its strength was a function of relative humidity exposure. Accordingly, for these determinations measurements were made for each of three humidity exposure conditions. The quick match used in these tests was manufactured by Primo Fireworks and had been stored for more than a month at 35% relative humidity. After being made up as test segments, some were conditioned for 5 days by being placed into humidity chambers at approximately 64 and 78% relative humidity. The test results are presented in Table 7.

For the segments conditioned at 35% relative humidity, the black match strings held the weight for approximately 1/3 second after firing the electric match. In this case, the average time difference between detecting fire exiting the match pipe and the strings failing was approximately 1/4 second. Consistent with what was found in earlier testing, exposure to higher humidity increased the burn time of the quick

Table 7. Black Match String Break Time as a Function of Humidity Exposure.

Measurement and Humidity	Time (s)			Average Time Difference (s)
	Longest	Shortest	Average	
First Light, 35%	0.16	0.07	0.13	—
String Break, 35%	0.41	0.28	0.35	0.22
First Light, 64%	0.28	0.10	0.20	—
String Break, 64%	0.52	0.39	0.46	0.26
First Light, 78%	0.30	0.22	0.27	—
String Break, 78%	0.56	0.48	0.51	0.24

match (in this case there was an approximate doubling of burn time resulting from exposure to 78% relative humidity). However, exposure to higher humidity also increased the time before the strings failed; for both 64 and 78% relative humidity, the strings failed after about 1/2 second. However, each time, the net result was that the strings failed approximately 1/4 second after detecting fire exiting the match pipe.

Given the time taken for an aerial shell to exit a mortar,[18] the survival time of the black match strings after the burning of quick match may be minimally sufficient to occasionally allow a firing shell to pull apart the fusing of other yet unfired shells. However, a detailed discussion of this question is more complex than it might at first appear and is beyond the scope of this article.

Conclusions

The information about quick match performance presented in this article may be substantially more complete than has appeared elsewhere in print. Nonetheless, this study was limited in both scope and depth. There is much more that should be researched and reported about quick match and its occasional malfunctions (hangfires and misfires). Accordingly, great care should be taken in drawing definite conclusions from the information in this article. The results reported are reasonably accurate but may only be correct for the materials and conditions used in these studies.

Acknowledgments

The authors gratefully acknowledge Bill Ofca and Garry Hanson for their technical review of an early draft of this article, and Larry Homan, Dan Hyman, and Marc Williams for reviewing the present article.

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An earlier version appeared in *Proceedings of the 4th International Symposium on Fireworks*, 1998.

Pyrotechnic Primes and Priming

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ABSTRACT

If a pyrotechnic item fails to ignite when intended, it is a failure. It makes no difference that had it ignited; it would have produced a spectacular display or a life-saving distress signal. Primes and priming techniques are important in producing high quality pyrotechnic effects, because it is through their use that reliable ignition can be achieved.

In this review article, after presenting some basic information, propagation energy diagrams are explained and used to discuss the role and manner of functioning of pyrotechnic primes. In the course of the discussion, a number of ignition and propagation problems will be investigated and solutions demonstrated. The article concludes with a discussion of some basic prime formulations and methods for their application.

Introduction

A pyrotechnic prime is a composition applied to the igniting surface of the main pyrotechnic composition, to enhance the probability of successful ignition. Figure 1 illustrates the basic manner of use of a prime layer to aid in the ignition of an aerial signal flare and a fireworks gerb. In the simplest terms, the characteristics of a good prime are that:

- It is easily ignited (but not so much so that accidental ignition is likely).
- It generates abundant thermal energy upon burning.
- It has an efficient mechanism for energy feedback to unignited composition.

Before the discussion of primes and priming techniques, a review of pyrotechnic ignition and propagation is appropriate (for a more complete discussion, see reference 1). Following this is a discussion of propagation energy diagrams of the type introduced by Shimizu.[2]

Pyrotechnic Ignition and Propagation

Pyrotechnic materials are said to exist in a "meta-stable" state. That is to say, under normal circumstances they are stable (they do not spon-

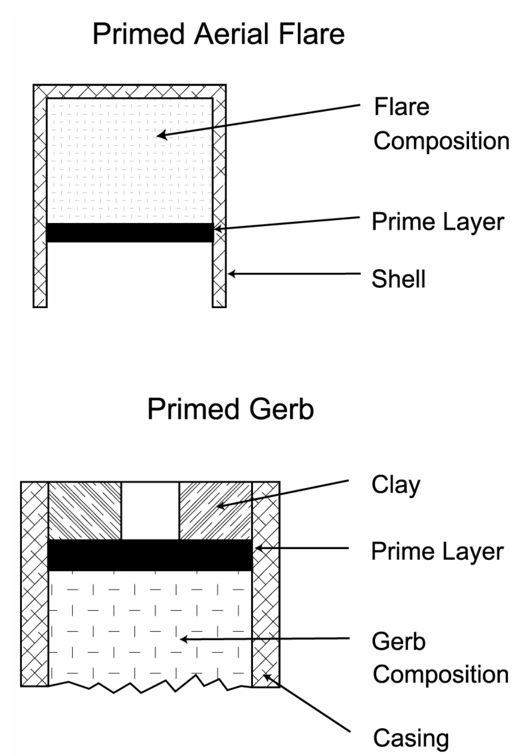

Figure 1. Illustration of a prime layer on an aerial signal flare and a fireworks gerb.

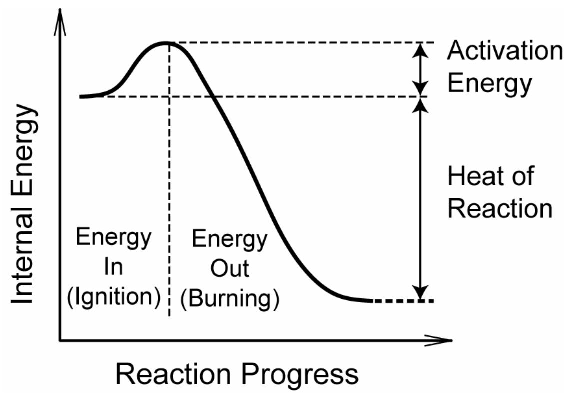

Figure 2. Changes in internal energy as a pyrotechnic composition ignites and burns.

taneously ignite). However, once ignited, the combustion reaction is self-sustaining, producing an excess of thermal energy. Pyrotechnic materials do not spontaneously ignite under normal conditions because the ignition process first requires the input of energy into the composition to raise its local temperature. Once ignited, pyrotechnic combustion reactions can be self sustaining, because there is a net production of energy as the composition burns. This two step energy relationship is illustrated in Figure 2, which tracks the internal energy of a tiny portion of pyrotechnic composition during its ignition and burning. The first step, when energy is added to the composition, is seen as an increase in the internal energy of the material. Within the formalism adopted for this article, the minimum energy required for ignition is called the "activation energy" for the pyrotechnic composition and is abbreviated as E_a. The requirement of an input of energy to cause the ignition of a pyrotechnic material, allows pyrotechnic compositions to be safely made and stored prior to use. If it were not for this activation energy barrier, fuels and oxidizers would ignite on contact. In the simplest of terms, it is possible to think of activation energy as the energy needed to raise a tiny portion of the material to its ignition temperature. The second step in Figure 2, when the burning composition produces energy, is seen as a decrease in internal energy. The net amount of energy produced during burning is the "heat of reaction" for the composition, abbreviated as ΔH_r (In modern parlance, heat of reaction is more properly termed enthalpy of reaction).

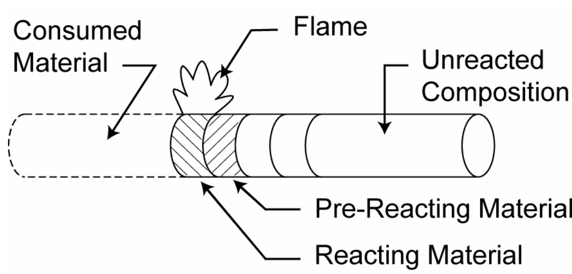

Figure 3. Burning "propagating" along a stick of pyrotechnic composition.

In terms of chemistry, the process of ignition and burning can also be considered as two steps. The first step can be thought of as when chemical bonds are being broken between individual atoms in the tiny particles of fuel and oxidizer. This requires the input of energy (the activation energy). In the second step, new chemical bonds are formed between individual fuel and oxidizer atoms forming the products of the reaction. This bond forming produces energy which flows from the chemical system (the heat of reaction). If the new chemical bonds (fuel to oxidizer) are stronger than the original bonds, more energy is produced than is consumed, and there will be a net production of energy. Note that for pyrotechnic materials, the bonds within fuel and oxidizer particles tend to be weaker than the new bonds formed during burning, and this is the reason these materials produce energy upon burning.

In the simplest of terms, pyrotechnic propagation can be thought of as continuing self-ignition. To illustrate this, consider Figure 3, which is a sketch of a stick of burning pyrotechnic composition, and which can be thought of as a series of thin disks of material. The composition to the far left in Figure 3 has already been consumed by burning. The disk, designated as "reacting" layer, has ignited as a result of having received its needed activation energy. As this layer of material burns it produces energy, most of which is lost to the surroundings. However, some of the thermal energy produced is transferred to the next thin disk, designated as "pre-reacting" material. If the amount of energy delivered to the pre-reacting layer exceeds its activation energy requirement (i.e., it receives more energy than is required for its ignition) then it too will burn. If this process is repeated for each successive disk of composition, the burning will propagate through the entire stick of pyrotechnic material.

It is possible to quantify the requirement for propagation in what might be called the "propagation inequality". Propagation within a pyrotechnic composition will continue only so long as the amount of energy fed back to the next layer (E_f) exceeds its activation energy requirement

$$E_f > E_a \quad (1)$$

The amount of energy fed back equals the heat produced (heat of reaction) times the fraction of that energy being fed back (F_{fb})

$$E_f = \Delta H_r \times F_{fb} \quad (2)$$

Thus the propagation inequality becomes

$$\Delta H_r \times F_{fb} > E_a \quad (3)$$

So long as the inequality is met, a pyrotechnic composition will propagate. However, if anytime during its burning, the inequality fails to be met, burning will cease at that point.

There are three mechanisms by which energy can be transferred from reacting to pre-reacting layers: conduction, convection and radiation. In conduction, thermal energy, as atomic and molecular vibrations, is passed along from hotter to cooler regions. The factors maximizing conductive heat transfer are those things that increase thermal conductivity, for example having compacted composition, the use of metallic fuels, and the presence of metal casings or core wires around or within the composition. In convection, hot gases penetrate the composition along the spaces between grains (generally called "fire paths"). The factors maximizing convective heat transfer are those things that allow for gas penetration, for example having uncompacted composition and granulated or cracked masses of composition. In radiation, thermal energy is passed from hotter to cooler regions as long wavelength light (infrared). The factors maximizing radiative heat transfer are those things that facilitate the emission and absorption of thermal energy, for example having abundant incandescent particles (solid and liquid) in the flame and using a dark colored or black pyrotechnic composition.

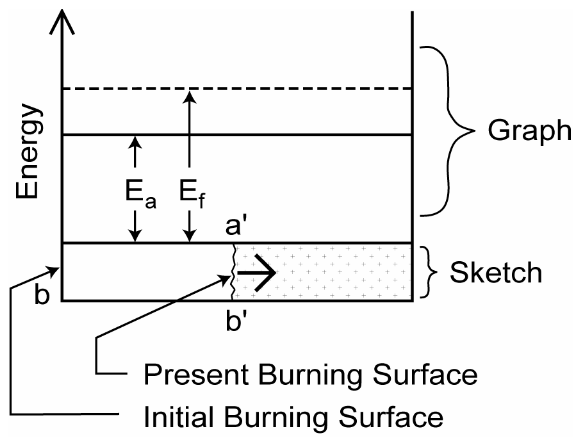

Figure 4. Illustration of Shimizu's Ignition and Propagation Energy Diagram.

Given the relationship in equation 3, it is clear that the factors favoring propagation are: high heat of reaction (much thermal energy produced), a relatively large fraction of energy fed back (efficient energy feedback), and low activation energy (low ignition temperature and low specific heat of the composition). When the propagation inequality is just barely met, burning proceeds feebly and is easy to extinguish. When the inequality is abundantly met, the burning proceeds fiercely and is difficult to extinguish.

Propagation Energy (Shimizu) Diagrams

The nature of ignition and propagation problems and how priming can overcome these problems can be difficult to comprehend. However, a qualitative understanding can be facilitated through the use of propagation energy diagrams, such as used by Shimizu.[2] These diagrams are a clever combination of a sketch and a graph. See Figure 4. The lower portion of the diagram is simply a sketch of a stick of pyrotechnic composition as in Figure 3. The composition is shown as initially having a burning surface *a-b*, which has burned to the current burning surface *a'-b'*. Above the sketch is a graph of energy as a function of distance along the composition. Here the two terms from the propagation inequality, equation 1, are charted. The energy being fedback, E_f, is shown as a

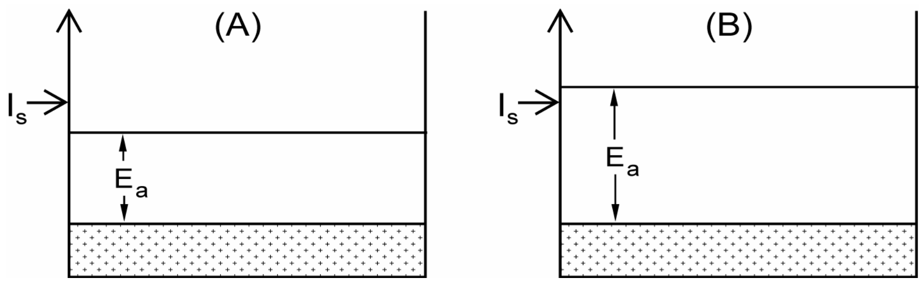

Figure 5. Illustration of varying activation energy requirement for ignition.

dashed line. Activation energy, E_a, is shown as a solid line.

When the process of ignition is discussed, the amount of energy (ignition stimulus) being delivered to the exposed surface of the composition is shown as an arrow from the side, labeled I_s in Figure 5. The source of the ignition stimulus can take any of several forms. It could be direct thermal energy, such as provided by a burning fuse. However, it could also be mechanical energy such as from impact or friction, or electrical energy such as from an electrostatic discharge.

Consider the two cases illustrated in Figure 5. In case **A**, the activation energy required for ignition is relatively low, well below the amount of energy being supplied by the ignition stimulus. In this case, ignition of the composition is assured. (For simplicity, the amount of energy fed back during burning has not been shown.) However, in this case, since the activation energy requirement is quite low, it is possible that accidental ignition could result from unintentionally supplying sufficient energy during the preparation or loading of this composition. In case **B**, the activation energy requirement is quite high and exceeds the level of the ignition stimulus. In this case, the pyrotechnic composition will not be ignited by this level of stimulus.

In Figure 6, propagation is considered for three compositions with varying activation energy needs. In each case, it is assumed the ignition stimulus exceeds the activation energy requirement and has not been shown. In case **C**, the activation energy needed is greater than the amount of energy being fed back (solid line is higher than dashed line). Accordingly, even though the ignition stimulus is sufficient to cause ignition of a small portion of the composition, it will fail to propagate once the stimulus ends. As soon as the input of ignition energy has ended, burning must cease.

In case **D**, the activation energy requirement is less than in case **C**. Now, slightly more energy is fed back to pre-reacting layers than is needed to cause their ignition. Accordingly, there will be propagation of burning throughout the length of composition. However, because there is only a slight excess of thermal energy being fed back, the burning will be feeble and the flame will be relatively easy to extinguish.

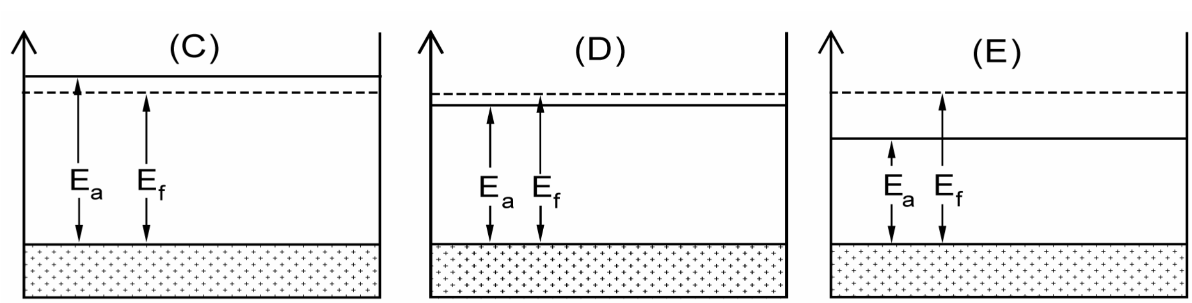

Figure 6. Illustration of the effect of varying activation energy on propagation.

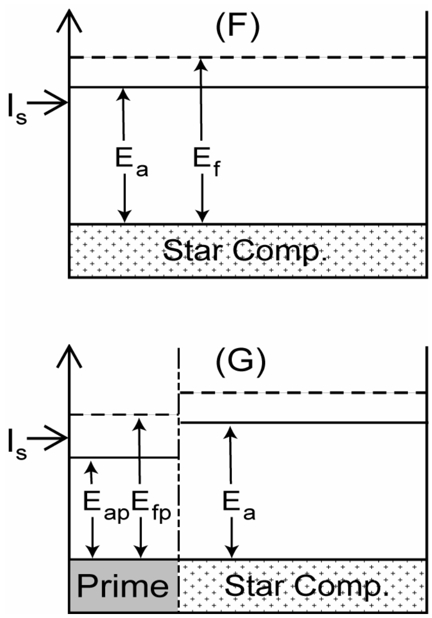

Figure 7. Illustration of how priming aids ignition.

In case **E**, there has been a further reduction of the needed activation energy, with a relative abundance of energy being fed back to pre-reacting layers. As a result, propagation is assured and burning will proceed vigorously.

Basic Priming Situations

The role of a pyrotechnic prime is to help assure the ignition of the main pyrotechnic composition. Consider the situation illustrated in case **F** of Figure 7. For the purpose of this example, the pyrotechnic composition might be for a signal flare or a fireworks star. Based on what was discussed above, if this composition were successfully ignited, it would propagate successfully and burning would be fairly vigorous. (Ample energy would be fed back, E_f, compared with that needed for propagation, E_a.) However, the level of ignition stimulus, I_s, is not sufficient to accomplish ignition, it is less than E_a. In this case it is irrelevant how well the item was capable of functioning had it ignited, since it does not ignite.

Now consider case **G**, this has the same main composition and ignition stimulus as in case **F**. However, a prime layer has been included (thickness exaggerated). Note that the activation energy requirement for the prime is less than that of the main composition. Accordingly, the ignition stimulus is now sufficient to achieve ignition. Further, the prime will successfully burn to the interface with the main composition, E_{fp} is greater than E_{ap} (the subscript "*p*" denotes the prime composition). At the interface between the compositions, burning continues because the energy supplied by the prime, E_{fp}, also exceeds that needed for ignition of the star composition, E_a. In this case, the use of a layer of prime was successful in causing the ignition of the main (star) composition.

There are many times when different pyrotechnic compositions are in contact and when successful performance depends on the burning of one composition to successfully ignite the next. One example would be in a thermite grenade, where the delay column must eventually ignite the thermite composition. Another example would be in a color changing fireworks star,

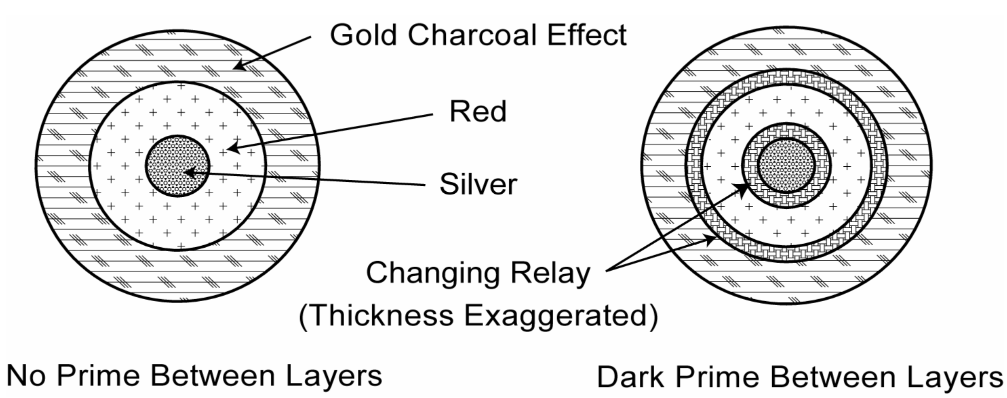

Figure 8. Illustration of the cross section of color changing fireworks stars.

where a burning outer layer of composition must ignite the inner star composition. (See Figure 8.) In fireworks there can also be aesthetic reasons for using a special prime between compositions of color change stars. These special prime compositions are ones that burn with the emission of very little visible light and may be called “dark prime” or “color change relay”. The first aesthetic problem is that when the star burns through the interface, for a brief time, both compositions will be burning. At best this will produce an output that is some mixture of the two intended effects, which may not appear as a crisp and clean change. Further, sometimes neither effect will be successfully produced by the mixed burning compositions.

A second aesthetic reason is that as a practical matter, it is not possible to make color change stars so perfectly and ignite them so consistently that all stars burn through the color change at the very same instant. Human perception is such that a momentary random dimming of a collection of burning stars as they are changing color is less noticeable than having a mixture of stars burning to produce two different colors at the same time. As a result, the effect of using a dark prime layer, even when there is no need in terms of successful propagation, is to create the illusion of a perfectly synchronized and precise color change. Figure 9 is an example of a competition grade aerial shell burst, in which the stars used a layer of dark prime. In this time exposure photograph, note the brief periods of no light emission between the production of the color and comet spark effect.

Some propagation scenarios are illustrated in the diagrams in Figure 10. In case **H**, burning will successfully pass the interface between the two compositions because E_{f1} is greater than E_{a2}. (The subscripts *1* and *2* denote compositions type 1 and 2.) If the order of the two compositions is reversed, which would be the case for a color change from something like willow to silver flitter, a situation like the diagram shown as case **I** results. This time the burning will not pass through the interface between the compositions because E_{f2} does not exceed E_{a1}. The solution to this problem can be to include a prime layer between the two star compositions,

Figure 9. Demonstration of the use of a “dark prime” in a color changing fireworks star.

as illustrated in case **J**. This time the burning composition 2 will ignite the prime layer, $E_{f2} > E_{ap}$, and the burning prime will ignite composition 1, $E_{fp} > E_{a1}$.

Typically for military applications a prime will be specially formulated for each use. However, in some fireworks applications, it is common to create the prime by simply mixing compositions 1 and 2 in roughly equal proportions. When the two compositions are chemically compatible, the resulting mixtures tend to have an activation energy requirement and energy feedback that is approximately midway between the two. (See reference 3 for some information regarding pyrotechnic chemical compatibility.)

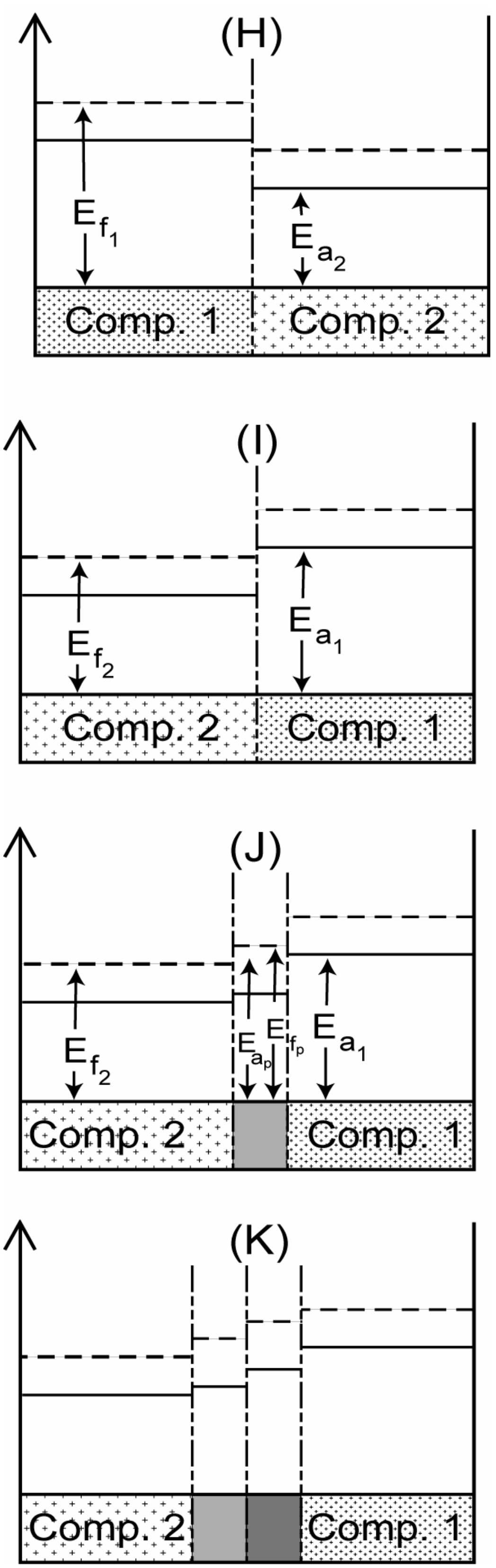

Figure 10. Potential successful and unsuccessful burning of pairs of pyrotechnic compositions.

Probably the most common use of such "composition mixture" primes is in the rolling of color changing stars. However, in some instances the gap between the energy fedback by the first composition and the needed activation energy of a second composition is too large to be reliably spanned through the use of a single intervening prime layer. Such a difficulty can be overcome simply by using more than one prime layer, each formulated to bridge part of the gap. In fireworks this can be accomplished by varying the ratio of the two compositions in the mixture. For example, instead of using about 50% of each composition, one could first use a mixture of 67% of the first composition and 33% of the second. This could be followed by a mixture of 33% of the first composition and 67% of the second composition; such a 2-layer prime is illustrated as case **K** in Figure 10. In principle, the use of successive layers of variously formulated primes can be used to successfully span any gap between E_f and E_a.

Other Propagation Problems

There are a series of other propagation problems that can be visualized through the use of propagation energy diagrams. Although not all of these are problems to be solved through the use of primes, for completeness, they are nonetheless included in this article.

Many pyrotechnic devices are made using solvents added to the pyrotechnic composition. This may be done to activate a binder, to temporarily suppress sensitivity to accidental ignition, to minimize dust production while loading, or to facilitate compaction of the composition to greater density. If use of the pyrotechnic device is attempted while it still contains a significant amount of this solvent, there can be a failure of the item. The basic reason for this is shown in Figure 11, which illustrates the process of raising such a composition to its ignition temperature (T_i). As thermal energy is added, at first its temperature rises with a slope dependent on the rate energy is supplied and the heat capacity of the composition. However, when the boiling point of the solvent is reached, for a period of time the temperature remains nearly constant because the added thermal energy is being consumed in the process of evaporating

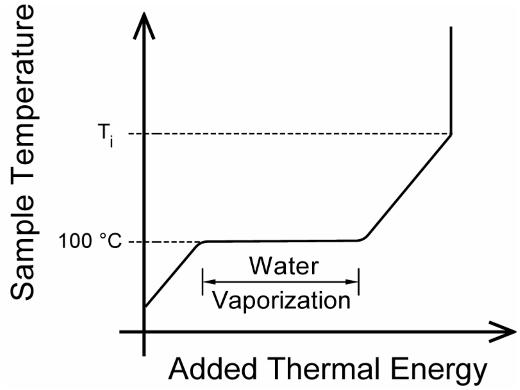

Figure 11. Illustration of the energy consumed by vaporizing water from a moist composition.

the solvent. Once the solvent has been eliminated, the temperature of the composition again rises toward the ignition temperature. Obviously, in this case considerably more thermal energy was required to reach the ignition temperature. In effect, such a solvent containing composition has a significantly higher activation energy requirement, which is dependent on the amount of solvent it contains.

When a pyrotechnic item still containing some residual solvent is used, it can fail to burn completely. This can be illustrated using Figure 12, which is a simplified propagation energy diagram for a pyrotechnic device still containing some residual water from the time of its fabrication. The outside of the item (toward the left), where it is exposed to the air, is shown as having dried completely. The inside of the item (toward the right) is shown as being moist as a result of the water added when it was made. In between is a band of composition shown as having increasing moisture content. When this item is ignited, at first, where the composition is dry, it will burn successfully because the energy being fedback exceeds its activation energy requirement. Burning will continue into the zone of increasing moisture content, even though the burning becomes more feeble as the activation energy requirement increases. However, when the point is reached where E_a has risen to equal E_f, burning must cease. Here, the obvious solution is to use no more solvent than necessary and to allow sufficient time for its substantially complete evaporation before its use.

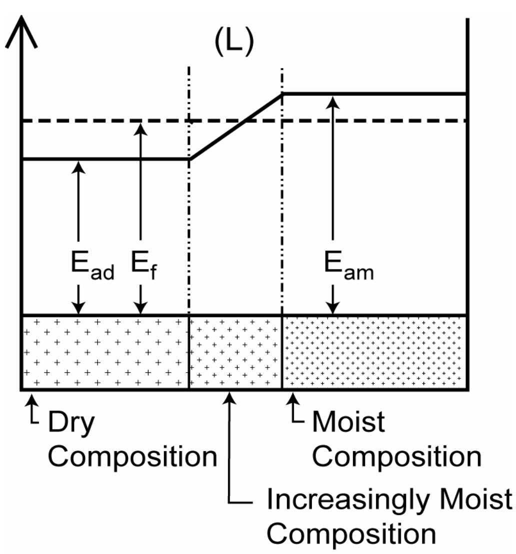

Figure 12. Propagation energy diagram for a progressively moist composition.

The feedback mechanism for some pyrotechnic compositions is primarily thermal conduction. These tend to be compositions that produce essentially no gaseous combustion products, most notably delay compositions used in military devices such as hand grenades. For such items, a crack through or separation of the delay column can result in a failure to propagate past that point. Figure 13 is a propagation energy diagram illustrating the cause of such a failure. When the delay column is initiated, it

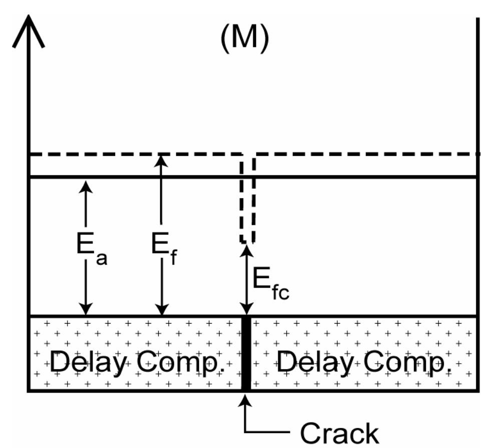

Figure 13. Propagation energy diagram for a delay column with a crack in the composition.

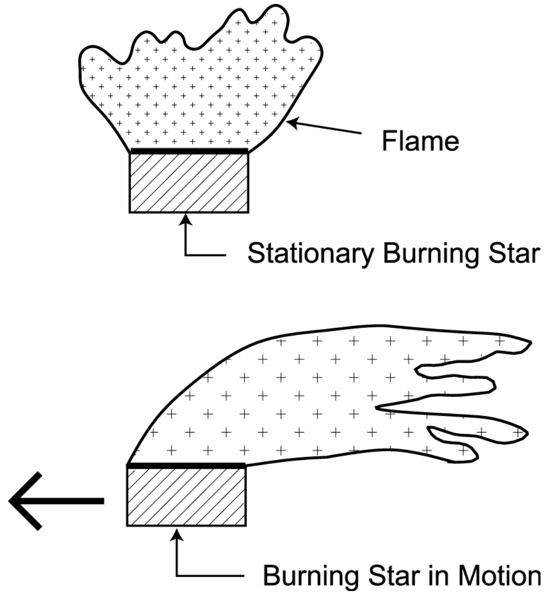

Figure 14. Illustration of a burning fireworks star, when stationary and when moving through the air.

propagates successfully because E_f exceeds E_a. However, at the point of the crack or separation, there will be a substantial decrease in the amount of thermal energy being fedback. This is because the air gap, even if quite narrow, has significantly reduced thermal conductivity. At this point, when E_{fc} falls below E_a, propagation must cease.

In fireworks, a somewhat similar propagation failure can occur as stars are expelled from a Roman candle or hard bursting aerial shell. In these cases, propagation can sometimes fail because E_f momentarily drops below E_a. Figure 14 is an illustration of two burning stars. In the case where the star is stationary, the flame hovers relatively close above the burning surface of the star. This allows ample opportunity for thermal energy to be fedback from the flame to the burning surface via radiation. However, in the case where the star is moving rapidly through the air, the flame will be cooled because of greater mixing with air and will be deflected away from the burning surface. In effect, the amount of thermal energy being fedback to the burning surface will be reduced. Figure 15 is a photograph taken while measuring the explosive force of a bursting fireworks aerial shell. However, it also documents the way the flame trails behind moving stars.

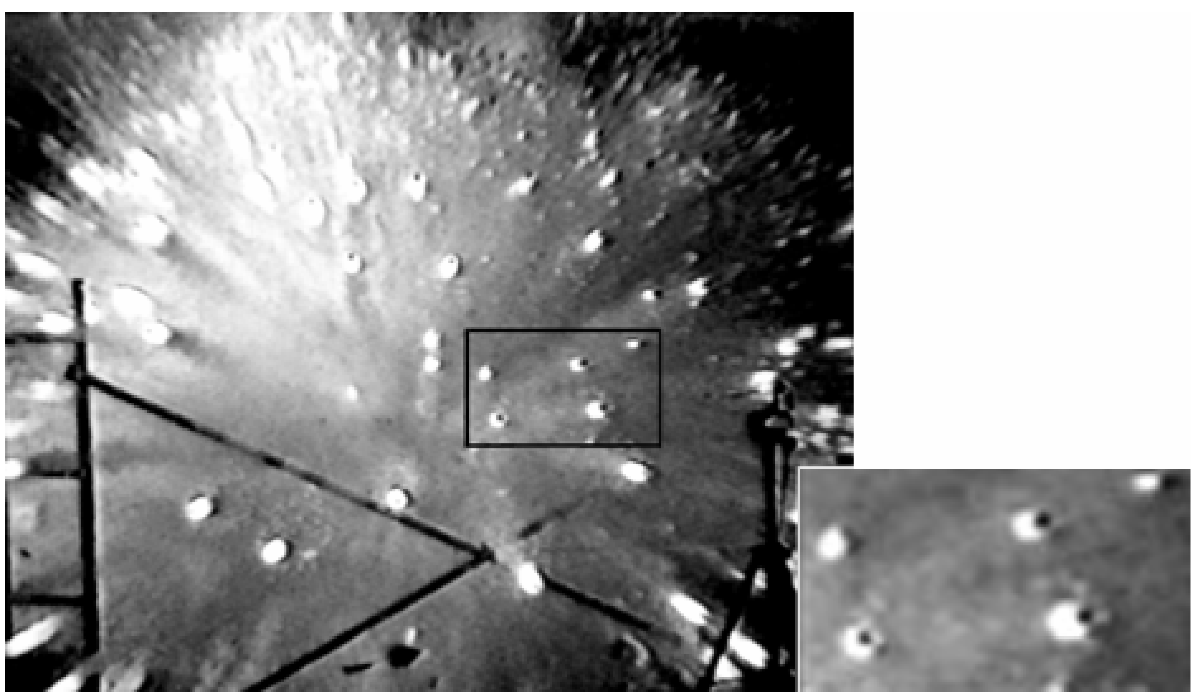

Figure 15. Photo and enlargement taken of a bursting fireworks aerial shell demonstrating the way the flame trails behind the moving star.

Case **N** in Figure 16 is a propagation energy diagram for an unprimed fireworks star as it is expelled from an exploding aerial shell. (Note that the amount of star burning before the shell burst has been exaggerated.) Initially the star ignites and burns because E_f exceeds E_a. However, as the aerial shell bursts, and the star is expelled at high velocity, E_f drops because the flame now trails significantly behind the star. In this case, because E_f falls below E_a, the star is extinguished. (This effect is sometimes referred to as a star being "blown blind".) Note that if the star had somehow managed to stay lit, as aerodynamic drag acts to quickly reduce the speed of the star, and as a result the flame moves back closer to its surface, E_f would increase, soon exceeding E_a and approaching its initial value that is to say, the stars would stay lit.

Unlike the previous two examples of propagation failure, this is a case where priming can help. In case **O** of Figure 16, a layer of prime (thickness exaggerated) has been applied to the star's surface. In this example, when the aerial shell bursts, again there is a drop in the energy fed back (E_{fp}). However, because it is a characteristic of the prime that there is a larger differential between E_{fp} and E_{ap}, this time E_{fp} does not fall below the activation energy requirement of the prime, and the prime layer continues to burn. If the prime layer is thick enough such that the star slows sufficiently by the time the prime layer is depleted, E_{fp} will have risen sufficiently that burning will continue and the star will be consumed in its intended display.

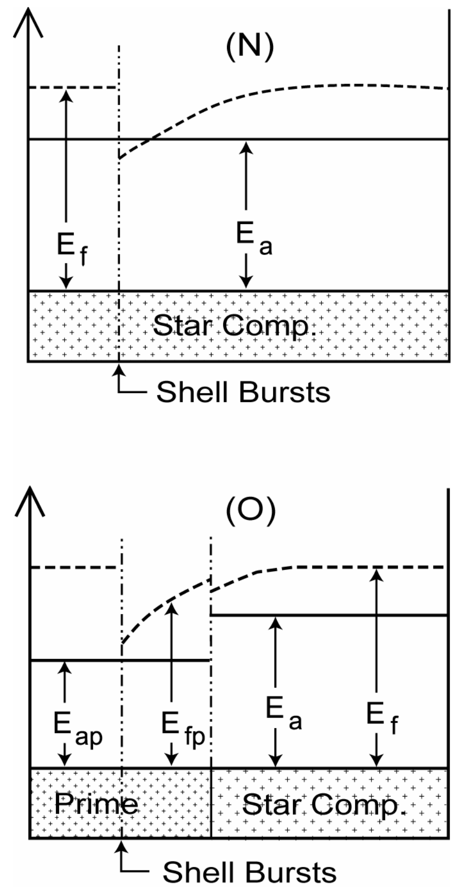

Figure 16. Ignition and propagation energy diagram of unprimed and primed stars as they are expelled from a bursting fireworks aerial shell.

Prime Formulations

The most widely used pyrotechnic primes are based on Black Powder. Some typical applications are in helping assure the ignition of signal flares, fireworks stars and fountains, special effect gerbs, and fusing systems. When cost is not a major consideration, the Black Powder would be commercially manufactured. Where the prime is to be pressed into place, any of the granulated powders in the range of 20 to 60 mesh may be used. Where a slurry is to be prepared, a fine grained powder such as meal D or fine meal will be combined with a suitable binder before use. In fireworks, typically a less expensive "rough powder" will be used. Rough powder is a handmade powder with the same basic formulation as Black Powder (see Table 1) but without the extensive mechanical processing of Black Powder. As a consequence, rough powder has burning characteristics, some of which are inferior to Black Powder, but fully adequate its for use as a fireworks prime.

There are occasions when the thermal output of Black Powder or rough powder may not be adequate to reliably ignite the main pyrotechnic composition. One such example from fireworks is in the priming of some strobe star compositions. A common method for increasing thermal output is the addition of a high energy fuel, such as fine mesh aluminum, to the basic rough powder prime. The choice of aluminum will be effective in increasing the heat of reaction of

Table 1. Prime Formulations (without listing the binder used).

Ingredient	Rough Powder	Enhanced Rough Powder	Potassium Perchlorate Based	Enhanced Perchlorate Based	Dark Prime	Alternate Dark Prime
Potassium nitrate	75	75	—	—	75	78
Potassium perchlorate	—	—	70	70	7	—
Potassium dichromate	—	—	—	+5(c)	—	—
Charcoal (very fine)	15	15	10	10	8	12
Sulfur	10	10	—	—	—	—
Antimony sulfide	—	—	—	—	3	—
Red gum (accroides)	—	—	20	20	2	—
Shellac	—	—	—	—	—	10
Silicon (–200 mesh)	—	+5(b)	—	—	—	—
Reference	Common	Kosanke(a)	Kosanke(a)	Kosanke(a)	Shimizu[4]	Jennings-White[5]

(a) These particular formulations were developed in about 1980; however, it is not intended to imply that similar or identical formulations had not been previously developed and used by others.

(b) The amount of silicon powder used can be varied according to the need. Typically 3 to 10% was found to be effective.

(c) Smaller amounts of potassium dichromate (as little as 1 or 2%) are effective in improving the vigor of the propagation of this prime. Because of the various serious health hazards associated with potassium dichromate,[6] it is advisable to use no more of this chemical than is necessary to accomplish the need.

the prime, and there are instances where this is sufficient. (The use of fine aluminum also tends to increase the light produced, which can be aesthetically undesirable.) Fine mesh silicon is another fuel that can provide the same increase in thermal output and also improve the efficiency of energy feedback. Upon burning silicon forms molten silicon dioxide (glass). This combustion slag can aid in the conduction of thermal energy to the yet unignited composition. One place where such a high temperature slag is particularly effective is where the prime is employed to cause the ignition of material that is not in direct contact with the prime. An example is the prime applied to a Bickford type fuse on the inside of a pyrotechnic device, in which a spray of combustion products from the end of the fuse is intended to provide the ignition stimulus for the device. When silicon is used as an additive in the prime, not only will additional energy be produced, but also molten droplets of glass will be included in the combustion products. The "enhanced" rough powder formulation in Table 1 is an example of such a prime. Note that the amount of silicon used in the prime formulation can be adjusted to meet the need. Note further that the silicon powder has been added to rough powder without reformulating the prime for the maximum production of energy. At the time this formulation was used, this was mostly done for convenience, as a supply of rough powder was already available for other applications, and various amounts of silicon powder could be added to fit the particular need at the moment. The lack of necessity to reformulate the prime tends to demonstrate the efficacy of the prime. However, to some extent, this thermally enhanced prime relays on atmospheric oxygen for complete combustion.

There are times when a nitrate-based prime such as Black Powder is inappropriate; for example when priming a composition including ammonium perchlorate. In this case, when either composition is moistened with water (or more slowly by withdrawing moisture from the air) a double decomposition (metathesis) reaction can occur to form the hygroscopic oxidizer, ammonium nitrate. When this occurs, the application of the prime may prevent the ignition of the device. There are also times when the pres-

Table 2. Prime Formulations.

Ingredient	Starter Mixture[(a)]	Thermite Igniter[(b)]	First Fire[(c)]	Tracer Igniter[(d)]	Magnalium Thermite[(e)]	Hot Perchlorate Prime[(f)]
Potassium nitrate	70	—	—	—	—	—
Potassium perchlorate	—	—	—	—	—	60
Barium peroxide	—	31	—	78	—	—
Iron(II-III) oxide (black)		29	—	—	—	—
Iron(III) oxide (red)	—	—	25	—	75	—
Red lead oxide	—	—	25	—	—	—
Charcoal (very fine)	30	—	—	—	—	15
Calcium resinate	—	—	—	2	—	—
Red gum (accroides)	—	—	—	—	—	5
Aluminum (fine)		40	—	—	—	—
Magnesium (fine)	—	—	—	20	—	—
Magnalium 80:20 (200 mesh)	—	—	—	—	25	—
Silicon (fine)		—	25	—	—	10
Titanium	—	—	25	—	—	—
Zirconium (60–200 mesh)	—	—	—	—	—	10
Reference	Ellern[7]	Ellern[7]	Ellern[7]	Ellern[7]	Jennings-White[5]	Jennings-White[5]

(a) "Sulfurless Black Powder" is typically bound using nitrocellulose lacquer.

(b) A high thermal output, relatively easily igniting, modified thermite used as an ignition mixture for normal thermite.

(c) An easily igniting, high thermal output prime based on Goldschmidt (thermite) reactions.

(d) Good resistance to high speeds through the air, used to prime tracers.

(e) The use of 80:20 magnalium overcomes much of the ignition difficulties of normal thermite, allowing its use as a prime.

(f) Essentially a modification of the potassium perchlorate prime from Table 1 that produces significantly greater thermal output.

ence of sulfur in a prime can be problematic; for example when priming a composition containing a chlorate. In this case, the chlorate and sulfur combination gives rise to concern regarding the sensitivity to accidental ignition. A prime formulation avoiding the use of both a nitrate and sulfur is the potassium perchlorate-based prime in Table 1. This prime is useful in many applications, but it does not offer the same level of burning persistence as Black Powder primes. This can result in problems maintaining the burning of items moving rapidly through the air. When necessary to overcome this problem, a fiercer burning prime will result when a small amount of the burn catalyst potassium dichromate is added to the composition. However, because of the health risks associated with potassium dichromate,[6] appropriate precautions must be employed, and no greater concentration of potassium dichromate than necessary should be used.

Finally in Table 1 are two dark prime (color change relay) formulations. The first formulation is fairly traditional. Whereas the second is simpler and avoids the use of antimony sulfide, which may produce sensitiveness problems when priming compositions containing a chlorate. Another group of prime formulations is presented in Table 2 without comment except for the table notes.

Prime Binding

In most instances, it is necessary to attach the prime composition to something, such as a pyrotechnic device or a fuse. To hold the mass of prime together and in place on the item, some form of binding system must be used. Probably the most common method, especially for fireworks, is to add a small amount (typically about 5%) of an aqueous binder to the prime composition. The binder is activated with the addition of water; the prime is applied to the component being primed and allowed to dry. Dextrin (made from corn or potatoes) is the most common aqueous binder used in Western countries, and soluble glutenous rice starch is the most common in the Orient. In the past, gum Arabic was also commonly used, especially in the manufacture of black match and for priming fuses. Recently, several new families of aqueous binders with variable thixotropic properties are being employed, including polyvinyl alcohol, sodium carboxymethylcellulose, and hydroxyethylcellulose. For these binders, the length of the polymer chain (whether manmade or natural) is selected to control their viscosity and thus their thixotropic properties. Such binders can be useful when it is desired to hold the components of a prime in suspension in a slurry and retard their settling out during use.

Water activated primes require fairly long periods to dry, typically several hours and potentially even days. The drying period must be especially long in some applications, such as when there is a chance that water has migrated from the prime into the powder core of a fuse. To some extent drying time can be reduced when a water plus alcohol mixture (typically 50:50) is employed. Another advantage of a water / alcohol mixture is that surface tension is reduced, making it somewhat easier to mix the solvent into the binder and to coat surfaces with the prime. However, it is thought that the use of alcohol may inhibit the effectiveness of some aqueous binders.

With the wider range of chemicals in use today, and especially with metal fuels, there may be concern about the water reactivity of pyrotechnic compositions. (For more information on potentially hazardous chemical combinations, see reference 3.) One effective solution to this problem is simply to avoid the use of aqueous binding systems. When prime formulations already contain red gum or shellac, typically as fuels, they can also be employed as the binders for these primes when they are activated with a suitable solvent, most commonly an inexpensive alcohol. Both methanol (wood alcohol) and isopropanol (rubbing alcohol) are frequently used. However, methanol vapors are hazardous to breathe, potentially producing optic nerve damage,[8] and isopropanol typically contains up to approximately 30% water. Thus the best choice for an alcohol is denatured ethanol (grain alcohol). When compositions do not already contain an alcohol activated binder, a small amount of such binder can be added to the formulation. Probably the most commonly employed nonaqueous binding system is nitrocellulose lacquer, usually 5 to 10% nitrocellulose in an acetone solution. Typically, the drying time for nonaqueous binding is shorter than for water activated binding systems, and the nitrocellulose lacquer system is especially fast drying. However, some systems, such as red gum activated with alcohol, form a gummy mass and can be especially slow to dry.

All materials, even crystals, are capable of plastic flow under the influence of a sufficiently high pressure. This plastic flow of material can be effective to bind a prime together and to other materials. When a pyrotechnic formulation contains relatively soft materials like shellac, red gum, asphaltum, or sulfur, the pressures required for plastic flow binding are sufficiently low as to be readily accomplished by pressing, even into paper casings. Obviously, because no solvent is involved, no drying time is required for plastic flow binding.

Prime Application Techniques

Often, especially in fireworks, the main pyrotechnic composition is prepared wet, using a solvent to activate its binder. If the same solvent will dissolve the binder in the prime composition, the simplest method of application is to apply loose dry prime composition to the exposed surfaces of the main composition. In so doing, some of the solvent will migrate from the main composition into the prime composition thus activating the binder in the prime composition. Accordingly, when the item dries, some of the prime will then be bound to the surface of the main composition. This “dusting” process can be more thoroughly described using the example of “cut stars” in fireworks. Cut stars are prepared by first forming amply moistened star composition into a “loaf”, which is a solid block of hand-compacted composition. This loaf is then cut using the equivalent of a dull knife, first into slices, and then each slice is diced into cubes. To apply the prime to such stars, first the work surface is dusted with a thin layer of prime composition. When a slice of the star composition is cut from the loaf, it is allowed to fall onto the loose prime composition, some of which will stick to its moist surface. Then additional prime composition is dusted onto the top surface of the slice, to which some will adhere. After dicing the slice of star composition into cubes, to the extent practical, prime composition is dusted onto the freshly exposed surfaces of the cubes. Using dusting to prime pyrotechnic compositions is fairly simple and, providing an excess amount of prime has been used, has the advantage of producing a prime surface which tends to readily take fire. This is because the outer most surface of prime is relatively loose, rough-textured and free from any significant buildup of binder (discussed further below). However, dusting suffers from the disadvantage that generally only a small amount of prime can be made to stick to the surfaces; for most items, this is probably only a few percent by weight.

Some pyrotechnic items, such as color changing fireworks stars, as illustrated in Figure 8, are made as a series of layers, like the structure of an onion. In western countries, the layering process is commonly produced by alternating the application of a spray of water (or other solvent) and dry pyrotechnic composition. The spray of water causes the surface of the item to become sticky, providing a ready surface for the dry composition to adhere. For such items, probably the most effective method of applying the final prime coating is simply to conclude the cumulative layering process with some number of layers of prime. (Similarly, the dark prime between the color compositions can be applied in layers.) The use of a layering process has the advantage of allowing any number of layers of prime to be applied (i.e., any amount of prime to be applied). This can be quite important in some situations; for example, when difficult to ignite and easily extinguished fireworks stars are propelled from hard breaking aerial shells. To maintain their burning, there must be sufficient prime to continue burning until the stars have slowed sufficiently for the star composition itself to be able to remain ignited (as depicted in Figure 16). In these cases, often the outer prime layer may be 10 to 20% by weight of the star. For easy ignition of prime composition applied by layering, it is important that the very last application of dry composition be in excess to what would normally adhere to the surface. This will help produce an outer surface that is rough and mostly free of solvated binder, similar to that described above for prime applied by dusting.

For small completed items and especially fuses, “slurry” priming is often used. In this case, sufficient binder solvent is added to the prime composition to make a thick but flowing slurry. The viscosity of the slurry is controlled by the amount of solvent and the choice of binder (and possibly flow control additives). Viscosity is adjusted to meet the needs of the particular application method, which tends to fall into three categories. In many cases the prime slurry is simply applied by painting using a small brush. Another common method (to apply a more viscous prime slurry) is from a container under pressure, for example using a squeeze bottle such as used for food products like mustard or catsup. This has the advantage of generally allowing the application of a thicker coating of prime than is practical by painting with a brush. The third slurry application method is sometimes used to completely coat the surface of the item or device to be primed. In this case, the item is briefly submerged in the prime slurry, either individually using a forceps (tweezers) to hold the item, or in batches using a course screened basket containing the items. Following the dipping process it is common to dust a layer of dry prime onto the exposed surfaces of the items.

Many pyrotechnic devices have the main pyrotechnic composition compacted using a press. Examples of such items are signal flares, tracers, whistles, fountains, drivers, etc. For

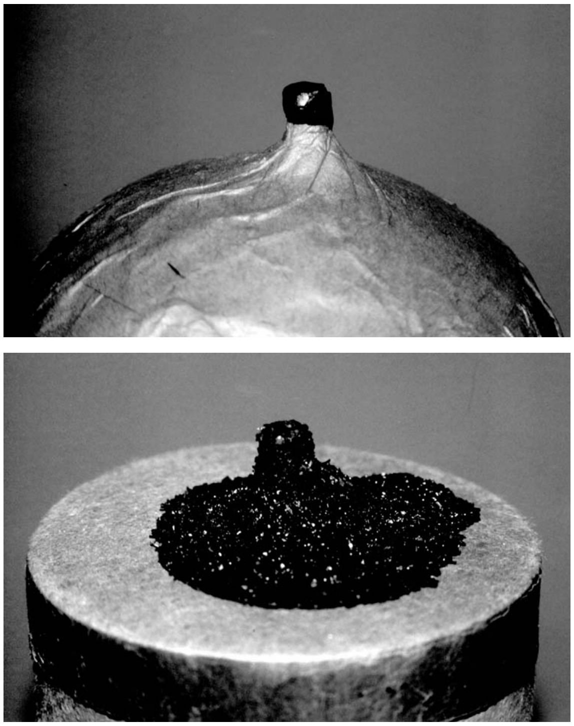

Figure 17. Examples of fuse priming methods with greatly differing probabilities for successful ignition.

these items, it is often convenient to apply the prime layer using compaction (plastic flow binding). In these cases, one or more increments of prime composition are used in the pressing of the item, such as illustrated in Figure 1 for an aerial flare or gerb. For devices made using compaction, this is probably the most common prime application method.

Regarding prime application methods, there are a few additional subjects that should be considered that can greatly affect ignitablitiy. Figure 17 has photographs of two fireworks aerial shells with their Bickford-style timing fuses primed. The shell in the top photo has had a layer of prime painted over the end of the fuse. The shell in the bottom photo has had larger amount of prime applied using a squeeze bottle, then the prime was pressed lightly into a bed of loose granular Black Powder, some of which then adhered to the prime surface.

All else being equal, the larger the primed surface area, the greater the probability it will successfully be ignited by any given ignition stimulus. The reason is simply one of probability. If all locations on the primed surface have

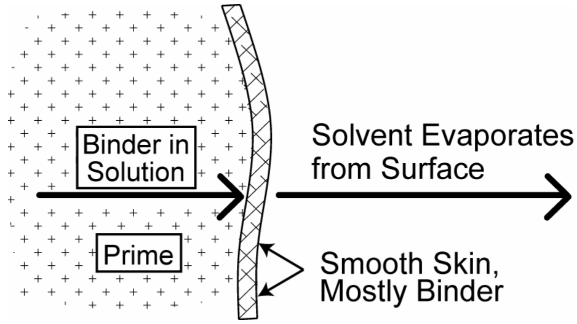

Figure 18. Illustration of the formation of a "skin" of mostly binder on the surface of prime.

an equal chance of being ignited, the probability of ignition increases as the number of locations (surface area) increases. In the upper photo in Figure 17, the total prime surface area is approximately ¼ square inch (1.5 cm^2), while that in the bottom photo has approximately 8 times more primed surface.

The surface texture of the prime coating is also important. Generally, if the surface is smooth and hard, such as pictured for the prime layer in the upper photo of Figure 17, ignition will be more difficult than if the surface is rough, such as for the prime layer in the lower photo. With a rough surface, the tiny exposed points will raise more quickly and to higher temperatures than the bulk of the prime coating. Accordingly, these points are more likely to take fire and cause the rest of the prime to ignite, even when the amount of energy supplied would not otherwise have been sufficient.

Another potential surface problem for prime compositions applied wet with solvents, is that during the drying process a thin layer of binder can form on the surface. As illustrated in Figure 18, this can occur because, as the solvent migrates to the surface, it carries dissolved binder with it. Then as the solvent evaporates, the binder (and other soluble components) are left behind on the surface. This collection of binder can produce a surface that is quite resistant to ignition, both because of its chemical composition and because it can be quite smooth. The likelihood of experiencing this problem can be reduced if a minimum amount of solvent is used, and if the surface is dusted with dry prime composition or granular Black Powder.

Alternatives to Priming

One alternative method applies to Bickford style fuse. It is more common to "cross match" such fuse as shown in Figure 19, than it is to apply a coat of prime composition. In this case a hole has been punched through the fuse, intersecting the powder core of the fuse. Inserted into the hole is a thin piece of black match (cotton strings impregnated and coated with Black Powder). In this case, if any point on the surface of the black match is ignited, quickly the entire black match is consumed and the powder core of the time fuse is ignited.

In some cases, the main pyrotechnic composition of an item itself has ignition and burning properties that are similar to prime compositions. If that is the case, there is no need for the application of a prime to its surface to help insure ignition. Examples of some pyrotechnic compositions that will likely have properties that are sufficiently prime-like are: rough powder-based spark-producing compositions, most fireworks glitter compositions, and chlorate-based colored flame compositions. However, as with prime compositions, consideration must be given to the physical condition of its surface. To achieve successful ignition, rough textured surfaces are preferred to those that are hard and smooth.

Conclusion

Many failures of pyrotechnic items and devices are the result of the inability to cause their ignition at the time of their intended use. Properly formulated and applied pyrotechnic prime compositions when present on the ignition surface can significantly improve the probability of successful ignition. Prime compositions are those that: are easily ignited (have a low activation energy requirement), but not so easily ignited that accidental ignitions are likely; upon burning, produce abundant thermal energy (have high heats of reaction); and have efficient means of feeding thermal energy to the main pyrotechnic composition.

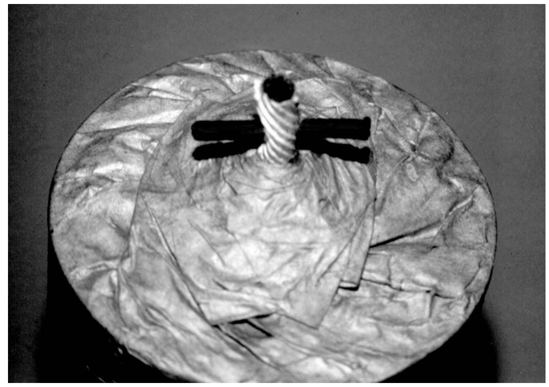

Figure 19. Example of a fireworks aerial shell with a "cross matched" time fuse.

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Dud Shell Risk Assessment: NFPA Distances

K. L. and B. J. Kosanke

There are potential hazards and some level of risk resulting from those hazards associated with all human activities. When the risks are below an acceptable level, those activities are generally considered safe. The hard part is not the estimation of risks; there are relatively simple methods to estimate risk. Rather, the hard part is determining what is an *acceptable level* of risk for an activity. For the most part, this article only addresses the easy part, discussing the relative risks of dud shells falling into spectator areas for different scenarios. The reader is left with the hard part, deciding what level of risk is acceptable and what (if anything) to do about those risks for their displays.

Spectators at a fireworks display may be exposed to a range of potential hazards, only one of which is the possibility of a dud shell falling in their midst. However, while an analysis and discussion of this one risk is intrinsically useful, it can also serve a broader purpose. Namely, to demonstrate how risk assessments are performed and how such information can be used to evaluate and select appropriate risk management strategies for any hazard.

Some fireworks display operators may believe the separation distance requirements of the National Fire Protection Association, in NFPA 1123 (1990 and 1995 editions), are sufficient to assure that dud aerial shells will never fall into spectator areas. Unfortunately, the chance of this happening is not zero; however, the current separation distances do greatly reduce the risk when compared to that for the distances in earlier versions of the code. This article begins the discussion by quantifying and then comparing the spectator risk for displays performed with both the earlier and current NFPA separation distances. (A subsequent article will consider the merits of various mortar placements and tilt angle, and the use of even greater separation distances.)

Drift Distance

For a number of reasons, aerial shells follow a trajectory somewhat different from that predicted by the alignment of the mortar from which it is fired. For example, if an aerial shell is fired from a mortar aligned perfectly vertical and with absolutely no wind, one might predict that it would rise straight up into the air. Further, if the shell failed to burst, that it would eventually fall straight down, landing quite near the mortar from which it left. However, this essentially never happens. One cause for the divergence is the sideways force produced by the tumbling of the shell as it moves through the air. (This is the same force used by a baseball pitcher in throwing a curve ball.) For a dud shell, "drift distance" can be defined as the difference between where the shell is predicted to land, based on simple ballistics, and where it actually falls to the ground, see Figure 1.

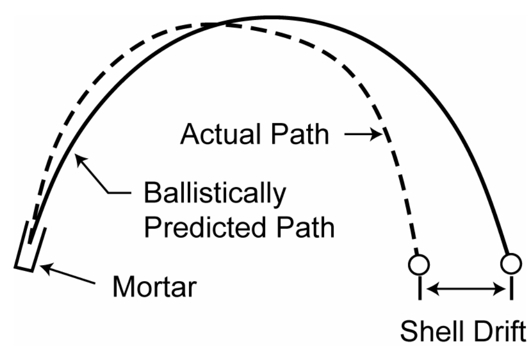

Figure 1. Illustration of drift distance for a dud aerial shell.

A number of years ago, results from a series of aerial shell drift studies were reported.[1] (While more than 400 test shells were fired in that effort, and while it seems to be the most complete study reported in the literature, the study was not so extensive that the results should be taken as absolutely correct.) In those studies, it was found that dud spherical shells have an average drift distance of approximately 32 feet per inch of shell size. (For example, for three-inch spherical shells, the average dud drift distance is 3 times 32 feet, or approximately 96 feet.) Further, it was found that approximately nine percent of the dud shells fall at more than twice the average drift distance, and that approximately one percent of the dud shells may fall at more than three times the average drift distance.

NFPA Separation Distances

Prior to the 1990 edition of the NFPA code, the minimum separation distances (distance from the spectators to the mortars) were relatively short, see Table 1. With the 1990 edition of the code, the separation distances were increased substantially. For vertically placed mortars the separation distance became 70 feet per shell inch (also shown in Table 1). Obviously, one effect of the increased separation distances is a reduction in the potential risk of dud shells falling into spectator areas. Not obvious, however, is just how significant is that reduction in risk. Much of the remainder of this article will be devoted to estimating the magnitude of this reduction.

Risk Assessment

In performing a risk assessment, consideration is given to both the likelihood (probability) of an event happening and the consequences (level of hazard) of that event, should it occur. [For a more information about performing risk assessments, see reference 2.] To illustrate how a risk assessment is performed, and to provide data for the discussion of separation distances, two scenarios will be considered for a somewhat typical fireworks display. In both cases, for simplicity, it is assumed that: spectators are located in one small area immediately adjacent to the display site, the mortars are placed vertically, there is no wind blowing during the display, and only spherical shells of typical construction are used. In both scenarios each size of mortar is grouped together and placed at the minimum distances from spectators as listed in Table 1. In scenario one, the distances are those from before 1990. Thus the three-inch mortars are all at 50 feet from spectators, the four-inch mortars are at 75 feet, the five-inch mortars are at 100 feet, etc. (see Figure 2). In scenario ttwo, the distances are those from after 1990. Thus, in this scenario all the three-inch mortars are at 210 feet from the spectators, all the four-inch mortars are at 280 feet, all the five-inch mortars are at 350 feet, etc. The number and size of shells in these hypothetical displays were chosen to be fairly typical for a modest size fireworks display, and are given in Table 2.

Table 1. NFPA Minimum Separation Distances.

Shell Size (in.)	Pre-1990 Distance (ft)	Post-1990 Distance (ft)
3	50	210
4	75	280
5	100	350
6	150	420
8	150	560
10	150	700
12	150	840

The consequences of a dud shell falling into spectator areas arise from two potential hazards, from direct impact of a dud with a spectator and from the pyrotechnic output of a shell if it ignites upon impact with the ground. Calculations and measurements suggest the impact velocity of dud shells range from about 90 to perhaps as much as 150 miles per hour, depending on shell size and shape.[3–4] With shells weights ranging from 0.3 to more than 15 pounds, the potential

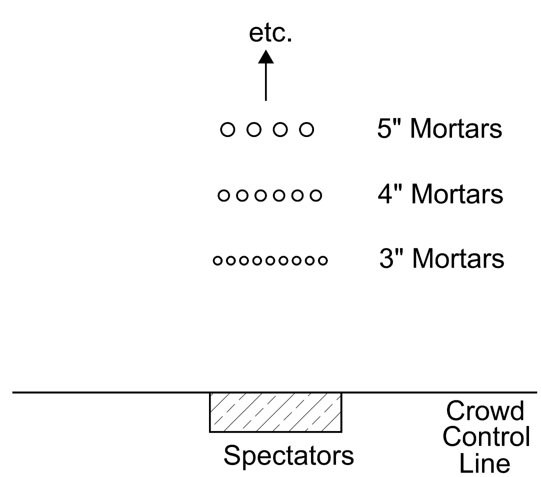

Figure 2. Example of mortar placements for the two scenarios.

Table 2. Dud Shell Risk Assessments for Two Display Scenarios.

Shell Size (in.)	Quantity in Body / Finale	Hazard Scale	Scenario No. 1		Scenario No. 2	
			Probability	Risk	Probability	Risk
3	130 / 100	1	0.81	187	0.06	13.8
4	65 / 0	2	0.73	95	0.06	7.8
5	30 / 0	3	0.71	64	0.06	5.4
6	15 / 6	5	0.60	63	0.06	6.3
8	8 / 0	9	0.73	53	0.06	4.3
10	4 / 0	13	0.79	41	0.06	3.1
12	2 / 1	17	0.85	43	0.06	3.1
			Cumul. Risk	546	Cumul. Risk	39.5

for serious injury or death from the impact of a falling shell is significant.

During measurements to determine spherical aerial shell drift, it was observed that aerial shells smaller than five inches rarely ignite on impact although many shell casings were noticeably damaged (had cracked). For six-inch shells it was found that roughly 10 percent ignited on impact and essentially all shell casings had cracked. For shells larger than eight inches, at least 60 percent of shells ignited on impact and all had seriously damaged casings. However, none of the ignitions observed produced a typically powerful shell burst. In each case, upon ignition, only a fireball was produced with the projection of a few relatively low velocity stars. Nonetheless, for large caliber shells the fire ball dimensions were substantial. Apparently, it was the damage to the shell casings on impact that was the reason for the lack of a typically powerful explosion.

The accident hazard values of Table 2 are relative values, such that values of 2 or 17 are intended to correspond to accidents whose consequences are 2 times or 17 times as severe, respectively, as an accident with a hazard value of 1. In part, the relative hazard scale in Table 2 is a rough estimate based on the information described in the previous paragraphs. However, information from actual accidents, where dud shells have fallen into spectator areas, was also considered in assigning relative severity values. Nonetheless, relatively little time was spent trying to develop a highly accurate hazard severity scale for this example. (Similarly, not much time was devoted to assigning precise probability values, also listed in Table 2.) However, the values in Table 2 are reasonably correct and are adequate for use in contrasting the relative risks of the two display scenarios.

There is no published data to suggest that the probability for any size shell being a dud is different than that for any other size shell. Thus for the purpose of this analysis, it will be assumed that dud probability is independent of shell size. As with hazard values, the probabilities in Table 2 are also relative values. The relative probability values used are just the probabilities for dud shells falling anywhere in a 360 degree circle, beyond the distances being considered. Obviously, because the spectators are assumed to all be in a small area in front of the display and because relatively few shells become duds, these individual probabilities are a gross over estimate. However, since it is only the relative risk between the two scenarios that is of interest, using these relative probabilities is acceptable.

Since the hazard severities listed in Table 2 are relative hazards, and the probabilities are relative probabilities, the resulting risks are only relative risks. For simplicity, in Table 2 and in the remainder of this article, generally the adjective "relative" will not be used but is meant to be implied.

To arrive at the risk for a single shell of any given size, the hazard rating for that size dud shell is multiplied by the probability of a dud shell of that size reaching the spectator area. The combined risk for firing a number of shells of that size is the number of shells times the risk for firing a single shell. Thus the combined risk from firing the 65 four-inch spherical aerial shells at a distance of 75 feet is: 65 shells, times 2 for the hazard, times 0.73 as the probability. This equals 94.9, which is rounded up to 95 in Table 2. Finally, the cumulative risk for each scenario is just the sum of the risks, for firing the numbers of each size shell.

Results

From Table 2, the relative spectator risk from dud shells using the minimum pre-1990 NFPA separation distances (scenario one) is approximately 550, while that using the minimum current NFPA distances (scenario two) is approximately 40. Accordingly, within the context of these two scenarios, using the current NFPA distances should account for more than a 90 percent reduction in the risk from dud shells falling into spectator areas. (Note that large risk reductions are also found when comparing the old and new separation distances in other more realistic scenarios, such as when the spectators are more spread out around the display site.)

Within the scenarios of this article (aerial shells fired vertically at the minimum allowed separation distances), note that it is not the firing of the largest shells that pose the greatest potential hazard to spectators. This is because, for the relative severity scale used, the greater number of small shells fired turns out to be a more significant risk than that posed by the few large shells.

Discussion

When the NFPA Pyrotechnics committee decided to increase the appropriate size of fireworks display sites to 70 feet per shell inch, frankly that was just a good guess, based on the general experience of the committee. At the time, there was no known published data on drift distances for shells, or typical shell burst diameters, or how far down range a shell might be propelled from a misaligned mortar. By the time the code was revised for the 1995 edition, some data had become available that could be used to evaluate the adequacy of the 1990 separation distances. However, more importantly, experience with the new distances was beginning to demonstrate that they were probably sufficient to provide for the "reasonably safe conduct of outdoor fireworks displays". Based on that data and experience, the NFPA Technical Committee on Pyrotechnics chose not to make further changes to the separation distance requirements for the 1995 edition.

The NFPA Committee is now (in 1998) working on the next edition of the code (NFPA-1123). At a recent meeting of the committee's Fireworks Task Group, consideration was given to a proposal (from outside the NFPA committee) to increase the separation distance requirements to 100 feet per shell inch. At that meeting, it was tentatively decided that no increase was needed. In a second article on the risks from dud shells falling into spectator areas, estimates will be made for the effect of such an increase of separation distance. In addition, estimates will be produced and used to investigate the effect of alternate mortar placements and tilt angle.

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Dud Shell Risk Assessment: Mortar Placement

K. L. and B. J. Kosanke

The previous article on this topic[1] discussed the general process by which one performs a risk assessment and then applied it to two fireworks display scenarios. One scenario had mortars of the same size together in groups, with each group located at their pre-1990 minimum National Fire Protection Association (NFPA) separation distances. (See Figure 2 of the previous article if needed.) The second scenario had the same mortar groupings, but this time, each group of mortars was located at their post-1990 NFPA distances.[2] The estimated relative cumulative risks for the two scenarios were 550 and 40, respectively. Accordingly, for these scenarios, the new NFPA separation distances should produce more than a 90% reduction in the risk of dud shells falling into spectator areas.

In the current article, hopefully further insight will be gained by considering a few additional scenarios. To keep from unnecessarily complicating the discussion, each scenario in this article will continue with the same basic assumptions made in the previous article. Each scenario has the same show design (the same number and sizes of shells), has the spectators in small areas immediately adjacent to the display site, and uses the same shell drift data[3] and dud shell hazard scale. Thus the relative risk estimates produced in this article will be consistent with the ones from the previous article.

Recall that the relative risk from firing any single shell is the product of the hazard value times the relative probability of occurrence. To calculate the risk from firing some number of the same size shells, multiply the risk for a single shell firing times the number of shells of that size. Then the cumulative risk for the display is the sum of individual risks from firing each size shells. (For a more complete discussion, see the previous article.[1])

Mortar Placement

Scenario three is more typical of the mortar placements actually used in displays. In this case all the mortars, including finales, are located at the minimum distance required for the largest shell in the display. The risk assessment result for this scenario is 4.8, and the data for this estimate is presented in Table 1.

At a 1998 NFPA Technical Committee on Pyrotechnics meeting, consideration was given to a proposal from a non-committee member that the minimum separation distances be increased from 70 feet per shell inch to 100 feet per shell inch. The committee tentatively decided not to make the change; however, it might

Table 1. Dud Shell Risk Assessments for Three New Mortar Location Scenarios.

Shell Size (in.)	Quantity in Body / Finale	Hazard Scale	Scenario 3 Probability	Scenario 3 Risk	Scenario 4 Probability	Scenario 4 Risk	Scenario 5 Probability	Scenario 5 Risk
3	130 / 100	1	0.000	0.0	0.005	1.2	0.000	0.0
4	65 / 0	2	0.000	0.0	0.005	0.7	0.000	0.0
5	30 / 0	3	0.000	0.0	0.005	0.4	0.000	0.0
6	15 / 6	5	0.001	0.1	0.005	0.5	0.000	0.0
8	8 / 0	9	0.004	0.3	0.005	0.4	0.000	0.0
10	4 / 0	13	0.025	1.3	0.005	0.3	0.001	0.1
12	2 / 1	17	0.060	3.1	0.005	0.3	0.005	0.3
			Cum. Risk	4.8	Cum. Risk	3.8	Cum. Risk	0.4

be instructive to consider what effect using the greater distance would have on the spectator hazard from dud shells. To do this, the cumulative risks for two additional scenarios are estimated. In one case, scenario four, it is again assumed that there are separate groups for each size mortar each of which are positioned at the 100 feet per shell inch distance for that shell size (similar to scenarios one and two). In the other case, scenario five, it is assumed that all mortars, regardless of size, are positioned together at the minimum distance for the largest size shell (similar to scenario three). The cumulative risks for these two additional scenarios are 3.8 and 0.4, respectively, and the data for these are also given in Table 1.

The results for the three new scenarios, compared with two scenarios from the previous article, are discussed below, following presentation of a scenario involving angled mortars.

Mortar Angling

Mortar angling has obvious safety ramifications for the crew performing manually fired displays. This is mostly because dangerous debris from flowerpots and dud shells are propelled slightly away from the crew and unused fireworks. However, the safety ramifications for spectators are less obvious. To examine this, consider the following display scenario. In this case, assume all the mortars are in one large group at the minimum distance for the largest shell size for angled mortars. This corresponds to an offset of 1/3 the NFPA distance toward the main spectator area, with the mortars angled so that the expected point of fall of dud shells is

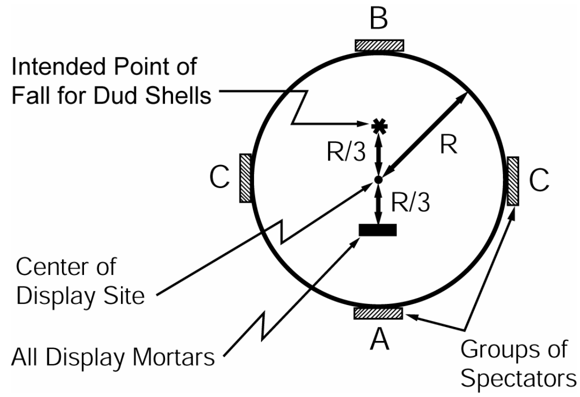

Figure 1. Illustration of scenario six for angled mortars.

1/3 the distance past the center of the display site. This setup is illustrated in Figure 1. For the purpose of simplicity in estimating the relative risk from dud shells, it is assumed there are potentially four small groups of spectators. One group **(A)** is just the same as in each of the previous scenarios. Another group **(B)** is immediately adjacent to the display site in the direction toward which the mortars are angled. The last two groups (both designated as **C**) are immediately adjacent to the sides of the display site. Because the distance from the expected point of fall of dud shells is different for each group, their relative risks are also different. The results for each group are presented in Table 2.

The cumulative risk for the collection of spectators in the four groups depends on the number of people in each group. If there are only spectators in group A, such as might be the case for a display fired from the end of a long

Table 2. Dud Shell Risk Assessments for Angled Mortars, Scenario Six.

Shell Size (in.)	Quantity in Body / Finale	Severity Scale	Spectator Area A		Spectator Area B		Spectator Area C	
			Probability	Risk	Probability	Risk	Probability	Risk
3	130 / 100	1	0.000	0.0	0.000	0.0	0.000	0.0
4	65 / 0	2	0.000	0.0	0.000	0.0	0.000	0.0
5	30 / 0	3	0.000	0.0	0.002	0.2	0.000	0.0
6	15 / 6	5	0.000	0.0	0.010	1.1	0.000	0.0
8	8 / 0	9	0.000	0.0	0.060	4.3	0.002	0.1
10	4 / 0	13	0.001	0.1	0.14	7.3	0.020	1.0
12	2 / 1	17	0.010	0.5	0.20	10.2	0.050	2.6
			Cum. Risk	0.6	Cum. Risk	23.1	Cum. Risk	3.7

Table 3. Summary of Relative Hazard Estimates for the Various Display Scenarios.

Scen. No.	Sep. Distance	Mortar Placement Information	Cum. Risk
1	Pre-1990	Vertical mortars in separate groups by size, each at their minimum distance.	550
2	70 ft/in.	Vertical mortars in separate groups by size, each at their minimum distance.	40
3	70 ft/in.	Vertical mortars all in one group, at the minimum distance for the largest shell.	4.8
4	100 ft/in.	Vertical mortars in separate groups by size, each at their minimum distance.	3.8
5	100 ft/in.	Vertical mortars all in one group, at the minimum distance for the largest shell.	0.4
6A	70 ft/in.	Angled mortars all in one group, at the minimum distance for the largest shell, and spectators only in an area behind the mortars.	0.6
6AC	70 ft/in.	Angled mortars all in one group, at the minimum distance for the largest shell, and spectators in areas behind the mortars and on the sides of the display site.	2.7
6ABC	70 ft/in.	Angled mortars all in one group, at the minimum distance for the largest shell, and spectators on all four sides of the display site.	7.8

pier, then the cumulative risk is 0.6. If approximately the same number of people are distributed evenly between groups A and C, roughly what might be the case for a display fired from a beach, then the cumulative risk would be the average for those three groups or about 2.7 [1/3 × (0.6 + 3.7 + 3.7)]. If approximately the same number of people are distributed evenly between the four areas, the relative hazard for spectators is the average for each of the groups, or 7.8 [1/4 × (0.6 + 3.7 + 3.7 + 23.1)]. These results are discussed further in the next section.

Discussion

Table 3 was prepared to facilitate the interpretation of the results for the various scenarios of this and the previous article. The previous article considered scenarios one and two, with groups of the same-sized mortars each placed vertically at the minimum NFPA spectator separation distances for that size mortar. It was found that scenario two, using the post-1990 distances (70 feet per shell inch), when compared to scenario one, using the pre-1990 distances, resulted in more than a ten-fold reduction in the cumulative hazard from dud shells falling into spectator areas. Specifically, the risk value of 550 was reduced to 40. Further, for these scenarios, it was found that the greatest risk to spectators from dud shells was posed by the smaller rather than larger aerial shells.

In scenario three (from Table 1), again post-1990 spectator separation distances are used. However, this time all of the mortars are assumed to be placed vertically in the same location and at the distance required for the largest size shell. The result is another nearly ten-fold reduction in spectator risk (40 was reduced to 4.8). This demonstrates the important safety advantage of positioning all mortars at the location of the largest mortars. Also in Table 1, note that in this third scenario the small shells no longer present the greatest hazard to spectators. In fact, because of the much greater distance between the small mortars and the spectators, the relative risk from small shells is essentially zero.

This article only considered hazards from dud shells falling into spectator areas. However, similar cumulative risk reductions for other potential safety problems are accomplished when all mortars are at the location required for the largest mortars. These safety problems include, debris from mortar explosions reaching spectators, shells being propelled directly into spectator areas from repositioned mortars, etc.

In addition to the spectator safety advantage of locating all mortars together, at the distance required for the largest size shells, there are operational and potential esthetic advantages as well. For manually fired shows, having firing take place in several different places on the site could require several different firing crews. Further it would be more difficult to artistically coordinate the firing from these various crews. For electrically fired displays, firing from several locations will probably require more and longer cable runs. It would also eliminate the possibility of using sand-boxes with various sized mortars intermixed in the same order as the firing cues for the show. Finally, firing each size shell at the minimum NFPA distances results in all shells bursting at approximately the same height in the sky as viewed by spectators near the display site.[4] This tends to result in shells overlapping their bursts in an unattractive jumble of color and allows the use of a relatively small portion of the sky.

In scenarios four and five, using spectator separation distances of 100 feet per shell inch, it was found that the relative dud shell risks were 3.8 for mortars in separate groups each at their minimum distance, and 0.4 when all mortars are located in one group at the distance required for the largest size. These are each about a ten-fold reduction in risk compared with the same mortar groupings using 70 feet per shell inch. Specifically the cumulative risks drop from 40 to 3.8 and from 4.8 to 0.4 for scenarios two and three when compared to scenarios four and five, respectively. This is a significant risk reduction; however, an important question is whether this further reduction is needed. Is the problem of dud shells falling into spectator areas sufficiently large that additional measures need to be taken? This is not a technical question, and there is not technical answer for it. However, note that the relative risk for 100 feet per shell inch separations with groups of mortars each a the minimum distance (risk value 3.8, scenario four), is about the same as that from 70 feet per shell inch separations with all the mortars at the distance for the largest shell (4.8, scenario three). Accordingly, if some hazard reduction was desired, without having to increase the overall separation distances, the NFPA code could be revised to require that all mortars be placed at or near the distance required for the largest size. Most operators already do this, and these operators must already have the least problem with dud shells potentially falling into spectator areas.

As a final set of scenarios (six-A, six-AC, and six-ABC), the situation of angled mortars was considered. In each case, angling mortars will be safer for a manual firing crew for the reasons discussed above. However, in terms of relative spectator risks from dud shells, the safety ramifications of mortar angling depend on the distribution of people around the display site. When spectators are located all around the site in approximately equal numbers (scenario six-ABC), it is more dangerous for the spectators than is vertical mortar placement (risk value 7.8 versus 4.8 for scenario three). Thus, it can be concluded that when spectators surround a display site in approximately equal numbers, the mortars should generally be angled no more than the minimum needed for crew safety.

When spectators are approximately evenly distributed around half of the display site, behind and to the sides of the mortars (scenario six-AC), the relative risk drops to 2.7 which is lower than for vertical mortars (4.8 for scenario three). In this case mortar angling improves safety for both crew and spectators. When spectators are located only in the area behind the mortars (scenario six-A), then there is an even more significant reduction in risk, to only 0.6. (Note that this is about the same reduction in risk as for scenario five with its separation distance of 100 feet per shell inch.)

Conclusion

In some ways this and the previous[1] article simply stated the obvious (i.e., duds are less likely to fall into spectator areas if the distance to spectators is greater). Also these articles made a number of simplifying assumptions (e.g., all spectators are in small areas immediately adjacent to the display site boundary). However, hopefully the information on the magnitude of the effect of various setups and distances on safety is useful, even if the estimates are based on simplistic scenarios.

There are few if any easy answers in risk management and the hard part is not coming up with relative risk estimates. The hard part is trying to decide when something is safe (i.e., when have the risks associated with an activity been reduced to an acceptable level). Accordingly, the purpose of these articles was not to provide the answers, but rather to provide information to aid display companies in finding their own answers.

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An earlier version appeared in *Journal of Pyrotechnics*, No. 9, 1999.

Performance Study of Civil War Vintage Black Powder

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ABSTRACT

A sample of Black Powder dating to the time of the US Civil War (ca. 1863) was harvested from cannon balls uncovered during an excavation on what had previously been the grounds of the Allegheny Arsenal near Pittsburgh, PA. A portion of this powder was eventually made available for an investigation of its properties. It was found to be in excellent condition, both physically and in its performance. Physically, it is essentially indistinguishable from high quality Black Powder of current production. Its performance under conditions replicating its normal use was only slightly less than that produced by a high quality powder of current production.

Keywords: Black Powder, US Civil War, Bormann fuse, quickness test, Eprouvette

Introduction

The stability and aging characteristics of Black Powder are occasional topics of discussion among pyrotechnists. A related question is, have the performance characteristics of Black Powder changed significantly over the years, possibly as the result of differences in raw materials or manufacturing methods? Having obtained a sample of Black Powder, dating to the time of the US Civil War (ca. 1863), the authors were able to investigate some of those interesting questions. This short article is the first in a series planned to report on those investigations.

Source of Powder Sample

Many of the exploding cannon shells produced by the North during the US Civil War were assembled at the Allegheny Arsenal, located in Pittsburgh, PA.[1] While some of the original site of the arsenal remains as a national historic site, much of it has been developed for other purposes, one of which is a gas (petrol) station. In 1972 there was an excavation at the gas station to install a new fuel storage tank. In the course of that excavation, approximately 1000 explosive cannon balls and rifled shells, dating to the Civil War (ca. 1863), were uncovered.[2] The shells were seized by the police for destruction by a bomb disposal unit. However, some of the shells in the best condition, were saved from destruction. These shells were subsequently provided for analysis.

Since the shells were still potentially explosive, a remotely operated, barricaded, and water-cooled drill press was used to gain entry to the contents of the shells. For some of the shells, it was found that the seals on their fuses had failed. This allowed water to enter during the period of approximately a hundred years that the shells had been buried, thus ruining the powder they contained. However, the 32–pounder cannon balls were exceptions. These had a casing about 6 inches in diameter with a cast iron wall about an inch thick. Contained inside each shell were several pounds of Black Powder in apparently perfect condition, free flowing and showing no sign of deterioration. The lead-based "Bormann" time delay fuses,[3,4a] screwed into these cannon balls, provided sufficient integrity to protect the contents from intrusion of water over the preceding century of burial. It is the Black Powder from some of these 32 pounders that was provided for use in this study.

The organization of this article is such that the results of a series of physical and performance tests are presented, mostly without comment. This is then followed by a discussion of those results.

Physical Testing

A sieve analysis was performed on a sample of the recovered Black Powder, with the results listed in Table 1. Table 2 provides information on various granulations of Black Powder dating to about the time of the US Civil War and for recently produced powders. In comparing the granulations, it must be considered that current sieves have square holes produced by the interwoven wires forming screens, whereas the sieves of the Civil War era had round holes in thin sheet metal.[4b]

Table 1. Sieve Analysis of the Civil War Black Powder Sample.

Mesh[(a)]	Size (in.)[5]	Percent[(b)]
+12	> 0.066	0
–12 +16	0.047–0.066	15
–16 +20	0.033–0.047	45
–20 +30	0.023–0.033	30
–30	< 0.023	10
	Total Percent	100

Note that sieve sizes are US Standard. To convert inches to millimeters, multiply by 25.4.

(a) Minus (–) means the material passes through this mesh sieve. Plus (+) means the material is retained on this mesh sieve.

(b) Rounded to the nearest percent.

The Civil War powder's bulk and grain density were determined and compared with a recently produced powder. A bulk density for the 16- to 20-mesh fraction of the Civil War powder was determined by placing 5.00 g of powder into a 10 cc graduated cylinder (10 mm ID), and vibrating to produce a minimum volume. The bulk volume occupied by the powder was then read to the nearest 0.1 cc. The results were reported in terms of mass per cubic centimeter,

Table 2. Size Ranges of Black Powder Granulations.

Civil War Era[4b] Black Powder	Passing[(a)] (in.)	Retained[(a)] (in.)
Musket	0.06	0.03
Mortar	0.10	0.06
Cannon	0.35	0.25
Current Black Powder[6]	Passing Mesh[(b)]	Retained Mesh[(c)]
2Fg (Sporting)	16 (3%)	30 (12%)
Class 4 (Military)[7]	16 (3%)	30 (5%)
Musket (Military)	14 (3%)	25 (5%)
Fg (Sporting)	12 (3%)	16 (12%)
4F (A Blasting)	12 (3%)	20 (12%)

Note that sieve sizes are US Standard. To convert inches to millimeters, multiply by 25.4.

(a) These are for sieves made with round holes.

(b) Maximum percent retained on this mesh sieve.

(c) Maximum percent passing through this mesh sieve.

see Table 3. Following this, the interstitial sample volume was estimated by determining the volume (to the nearest 0.1 cc) of a light weight oil required to fill the air spaces between the powder grains. To limit possible migration of the oil into the powder grains, a minimum time was allowed to elapse during the measurement. Grain density was then determined after subtracting the interstitial volume from the bulk volume. Similarly, the bulk and grain densities were determined for a sample of Black Powder recently produced by Goex[8] and sieved to the same 16- to 20-mesh range.

Table 3. Density and Moisture Content of Black Powder Samples.

Powder Type (16–20 mesh)	Bulk Density (g/cc)	Grain Density (g/cc)	Moisture (%)
Civil War	0.98	1.67	0.67
Goex	1.03	1.75	0.53
Mil Spec 1962[7]	—	1.69–1.76	< 0.70
Mil Spec 1862[4]	—	≥1.75	—

Figure 1. Photo of Eprouvette,[9] an early Black Powder Tester.

Following the current military protocol for Black Powder moisture determination, samples of both the Civil War and Goex powders were weighed, placed in a 75 °C oven for 4 hours, allowed to cool briefly, then reweighed. The mass loss, expressed as a percentage, is the reported moisture content of the powder. These results are also reported in Table 3.

Performance Testing

An early instrument used to gauge the performance of Black Powder is an "Eprouvette", which is a pistol-like device, see Figure 1. The device has a small combustion chamber into which a charge of Black Powder is loaded. One end of the chamber is blocked with a spring-loaded pivoting baffle, with a ratchet to hold it in position against the closing force of a spring. When the powder is fired, using a standard percussion primer, the force of the explosion is determined by noting the extent to which the baffle has rotated. Five test shots were conducted using the 16- to 20-mesh samples of the Civil War powder and again using current production powder manufactured by Goex. The results, including the averages and their standard errors, are reported in Table 4. (Note that these results are dimensionless.)

A modern test of powder performance is the quickness test.[10] In this test, a small sample of powder is burned in a closed vessel, while recording internal pressure as a function of time. Typically, for this type of test, the level of confinement is sufficient to withstand the pressures produced without venting. However, the instrument used in this study had been assembled

Table 4. Eprouvette Test Results.

Trial	Civil War	Goex
1	4.0	3.5
2	3.5	3.5
3	2.5	2.5
4	2.5	3.5
5	2.5	3.5
Average	3.0	3.3
Std. Error	0.3	0.3

Note that the standard error is the standard deviation, using the n–1 method, divided by the square root of n, the number of measurements.

for use in studying fireworks lift and burst powders.[11] Accordingly, it was designed to operate in a relatively low pressure regime, typically using one of a series of rupture disks that limit the maximum pressure to a few hundred psi (a few MPa). The volume of this quickness tester is quite low (6.3 cc) to allow testing of very small powder samples. The standard procedure with this apparatus is to crush the powder sample using a mortar and pestle, then load 0.15 g of the 60- to 100-mesh fraction into the combustion chamber for test firing. In each case, ignition is accomplished using a tiny hot-wire igniter.[12]

In this study of Civil War Black Powder the standard method described above was used. Figure 2 is an example of the pressure versus time data from one quickness test. The figure also

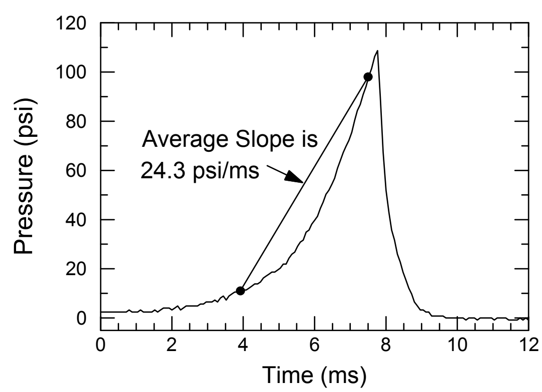

Figure 2. An example of a quickness determination for a sample of Civil War Black Powder.

illustrates the simplified method used to determine its quickness value. The reported quickness values are the average slope of the pressure rise curve between the points equaling 10% and 90% of the peak pressure observed. A series of eight measurements were made, alternating between measurements for Goex and the Civil War powders. The results and averages are reported in Table 5.

Table 5. Results of Quickness Testing.

Trial	Goex (psi/ms)	Civil War (psi/ms)
1	35.5	24.0
2	36.1	24.2
3	33.3	19.4
4	35.8	22.8
Average	35.2	22.6
Std. Error	0.6	1.1

To convert psi per millisecond to kPa per millisecond, multiply by 6.89.

Note that the standard error is the standard deviation, using the *n*–1 method, divided by the square root of *n*, the number of measurements.

As a test of performance more nearly replicating the powder's use during the period of its production, test firings were made using a Black Powder rifle. Four test firings were made, using the 16- to 20-mesh fractions of samples of the Civil War and Goex powders. The rifle used was a Connecticut Valley Arms 50-caliber rifle with a 26-in. (0.66-m) barrel, firing a 360-grain (23-g) maxi ball using a powder charge of 50 grains (3.2 g). Projectile muzzle velocities were measured using a Prochrono Plus Chronometer (Model CEI–3200).[13] Test firing results are reported in Table 6, along with their averages and standard errors.

Discussion

The physical appearance of the Civil War Black Powder retrieved from the cannon balls is consistent with its still being of high quality. The grains are hard and show absolutely no sign of physical deterioration. The powder is free

Table 6. Black Powder Rifle Results.

Trial	Civil War (ft/s)	Goex (ft/s)
1	1028	1078
2	1034	1068
3	981	1123
4	1019	1071
Average	1016	1085
Std. Error	12	13

To convert feet per second to meters per second, divide by 3.28.

Note that the standard error is the standard deviation, using the *n*–1 method, divided by the square root of *n*, the number of measurements.

flowing with minimal dust present. There is possibly a very subtle difference in color, as compared with current production powder (Goex), with the Civil War powder being ever so slightly lighter in color. Based on its general physical appearance, it would not be possible to detect that the Civil War powder was not of current production.

The granulation of the Civil War powder fits well with the range reported for Musket powder of that era, especially if it is recognized that, in 1860, the holes in military sieves were round and not square as they are today. Further, it would seem that the granulation is still consistent with today's US military specification for Musket powder. (See Tables 1 and 2.)

The grain density for the Civil War powder (1.67 g/cc) is close to that of current production powder and to the current US military specification. The grain density of the Civil War powder is a little lower than the reported standard of that time. It is uncertain whether there has been a slight change in the powder's density over time or if the powder had been manufactured to a somewhat different standard. The moisture content of the powder (0.67%) is still within current military specification. (See Table 3.)

In terms of its performance under significant confinement, in the Eprouvette and Black Powder rifle tests, the Civil War powder produces results within 7 to 10% of that of current production Goex powder. (See Tables 4 and 6.)

(Note that even though the powder samples had both been sieved to 16–20 mesh, it is possible that relatively small particle-size differences within this mesh range could have contributed to the difference observed in this study.) To help put this 7 to 10% performance difference into perspective, it should be noted that past examinations of other current production Black Powder (non-Goex) performed significantly poorer than the Civil War powder examined in the present study.[14]

At this time, it is not possible to say whether the small difference between the Goex and Civil War powders under confinement represents a degradation of its performance, as opposed to being the result of performing a limited number of tests, or the powder having been less effective originally. Such lesser performance could easily have been the result of less pure potassium nitrate and sulfur, or charcoal having not been processed optimally. It is also possible (likely?) that processing methods have improved somewhat over the intervening 135 years. (Another phase of this study is planned to look into some questions of the purity of the materials and differences in processing in comparison with current materials and methods.)

The only significant difference observed in this study are from the relatively low pressure quickness tests, where the average rate of pressure rise for the Civil War powder was about 35% slower than Goex Black Powder. (See Table 5.) At this time, the authors have no explanation for why this difference is so large, or why it is so much greater than differences observed in the other performance tests. It is possible that particle-size differences, within the 60–100 mesh range used, had an effect. Another possibility is that crushing the powder grains affected the samples differently, perhaps introducing microfractures in the particles. Of course, a third possibility is that it reveals a fundamental difference between the Civil War and Goex powders that is only significant in a relatively low pressure regime.

Additional Historical Background

The method of entry into the shells called "32 pounders" was not by the easier (and less hazardous) drilling through their relatively soft fuse (a 50:50 lead / tin alloy). Rather it was by drilling through the iron casing of the shell. This was done because the Bormann fuses have great historical value. Many deactivated shells from the war have been preserved and are available for study. However, in most cases, their fuses had previously been removed or destroyed.

Figure 3. A photo of a Bormann fuse in place on a 6-pounder cannon ball.

The Bormann fuses were a type of time delay fuse wherein a compacted semi-circular ring of Black Powder meal was protected by a lead alloy covering. Access to the powder, for the purpose of its ignition, was gained by cutting a hole in the covering, thus exposing the powder to the burning gasses as the shell was fired from its cannon. Accordingly, various delay times could be selected on the battle field by selecting the point along the powder ring, where the lead was cut. Delays up to 5.5 seconds, in quarter-second increments, were possible. (See Figure 3.) Some of the fuses on the recovered shells had the delays marked in numbers, while others had them in Braille. (Most of the rifled shells had an inertia type of fuse designed to explode the shell on impact, and some of these still had their percussion caps in place.) It might be of interest to note that a variation of the Bormann fuse principle is still used on some military items today (e.g., some illuminating flare rounds[15]).

At the end of the Civil War, many of the unused shells were returned to the Allegheny Arsenal for deactivation. Apparently this deactivation was accomplished by inserting a spanner wrench into holes in the fuses, and unscrewing them to remove the powder contained in the shells. In the case of the recovered shells, all the spanner wrench holes showed severe rounding indicating a failure of the attempt to remove the fuses. Apparently this inability to easily deactivate these shells was the reason for burying them.

The Allegheny Arsenal was a major supplier of munitions for the North during the US Civil War and was operational until 1901. However, it is most remembered as the site of a horrific explosion during the war that took the lives of 78 children employed for assembly work.[1] The children ranged in age from 12 to 14 and were mostly girls. Children were employed for economic reasons and because their small fingers aided in assembly of some munitions. The explosion occurred early in the morning hours of September 17, 1862. (This is the same date as the battle of Antietam, the single bloodiest date in the war.) The children were buried in a mass grave in the Allegheny Cemetery, just outside the grounds of the arsenal.

Acknowledgements

The authors wish to thank Clean Shot Technologies for performing the Black Powder rifle muzzle velocity testing, Martinez Specialties for supplying the thermal igniters used in the quickness tests, and L. Weinman and E. Brown for providing comments on a draft of this article.

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CAUTION: Very Fast "Black Match"

K. L. and B. J. Kosanke

There is a new style of black match used to make the quick match leader fuse on some Chinese products. The fuse has recently been found on some Flower Basket aerial shells and Lidu display fireworks boxes and may also be used on other items as well. While this new black match seems to function well in quick match, it has one characteristic that is important to note for safety reasons. Where normal black match tends to burn rather slowly at about an inch per second, this new black match burns very much faster, perhaps as fast as quick match (roughly 10–20 feet per second). Because of this much faster burn rate, it is possible for someone to have a serious problem. For example, if the end of a shell leader fuse were damaged, someone might attempt a repair by cutting off some of the damaged shell leader and then exposing a few inches of this new black match. In this case, the person may have the expectation that lighting the tip of the newly exposed fuse would provide a few seconds before the item would function. However, instead, the fireworks could begin to function essentially immediately upon ignition of the tip of the leader fuse.

Before further discussion of the burning of this new black match, it is appropriate to first consider the manner of its construction. (For a discussion of typical black match and quick match construction and their manner of burning, see reference 1.) Figure 1 is a photograph of the end of a shell leader of this new type, with the safety cap removed. Figures 2A and 2B are the same piece of shell leader that has been progressively dissected to reveal the manner of its construction.

The end of the shell leader is composed of three lengths of thin visco fuse (each a little larger than 1/16 inch in diameter and about four inches long). In Figure 2B, the end of one of the pieces of visco fuse has been cut open for a short distance to expose the fuse powder con-

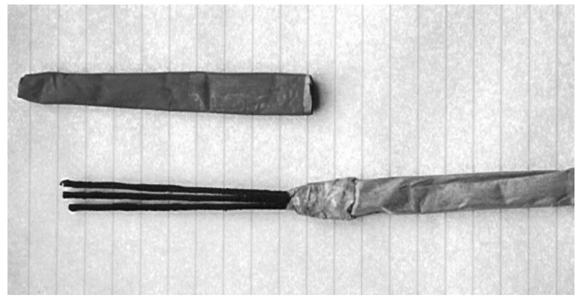

Figure 1. Photo of a shell leader containing the new fast burning black match. (Note that the three exposed fuses have been separated slightly for clarity.)

tained in it. Further, these three fuses have been surface coated with a slurry of powder. These fuses are attached to the length of shell leader with a thin wrap of tissue paper (not shown) over a string tie. Upon initial inspection, the shell leader appears similar to conventional quick match, with an outer wrap of Kraft paper (match pipe) over an internal fuse which is black in appearance. However, most importantly, this is not conventional black match. It is made using a wrap of approximately two and a half turns of a thin tissue paper around two cords of string heavily coated with a slurry of powder. Also in the tissue paper wrap is a substantial additional amount of a fine loose powder, some of which tightly adheres to the tissue paper (suggesting that the tissue paper was probably somewhat wet when wrapped up). Figure 3 is an attempt at a cross-sectional illustration of the construction of this central fuse.

Because the tissue paper of the central fuse is only loosely wrapped, abundant fire paths remain within it. Accordingly, when it is burned, even when not enclosed within the Kraft paper match pipe, it burns very quickly, much like it does when made into quick match. Thus for this fuse, the purpose of the Kraft paper match pipe

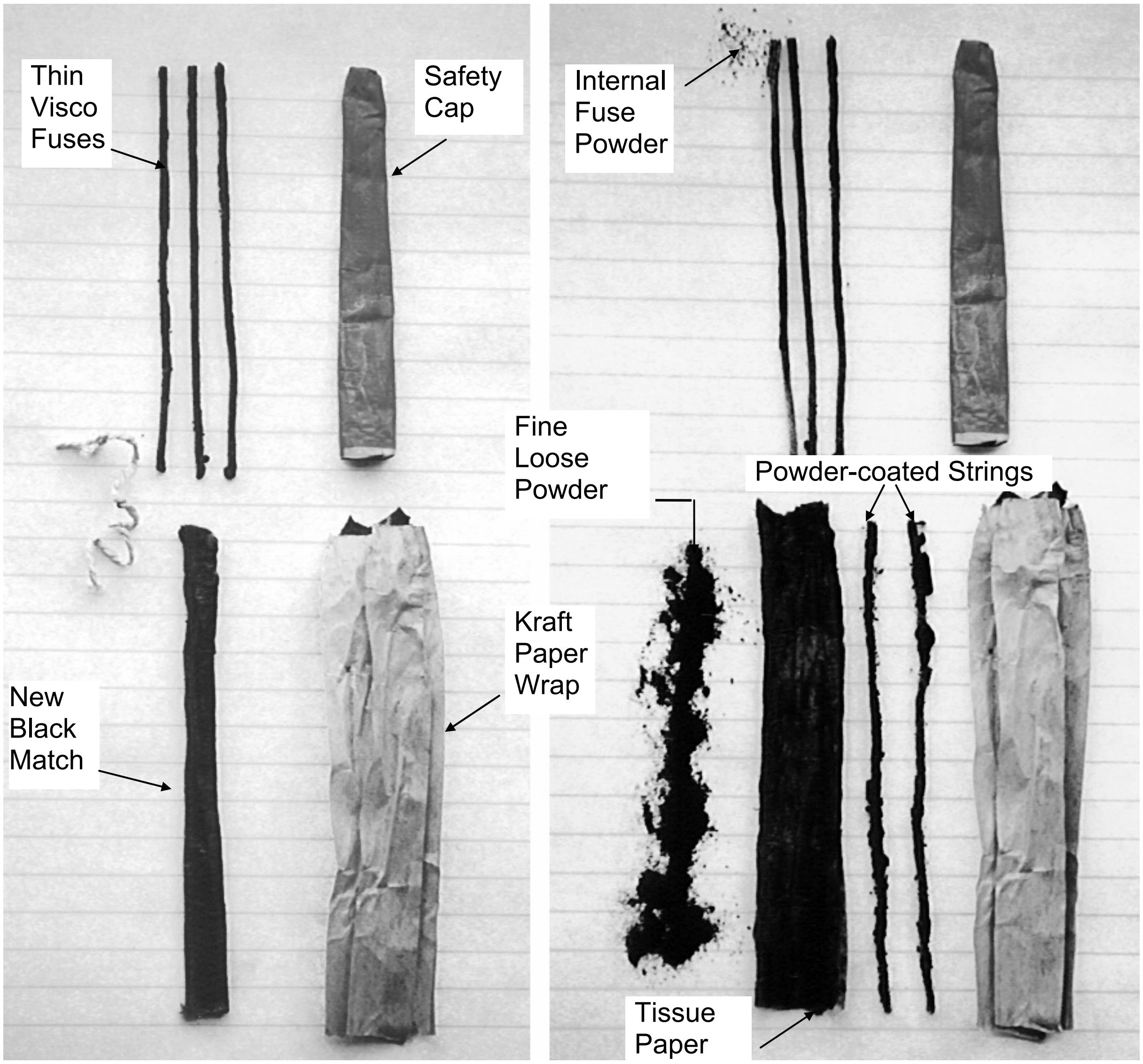

Figure 2. Photos of a dissected shell leader illustrating its construction.

seems to be mostly for additional strength and the protection of the central tissue wrapped fuse.

There is nothing intrinsically wrong with having a central fuse that burns essentially as fast as completed quick match. In fact, although it has not been extensively tested by the authors, it seems to perform quite well. Further, the abundant amount and distribution of the fuse powder probably makes this fuse less likely to fail as either a hangfire or misfire.[1] However, it can be important for users to know this new style fuse exists. For example, as suggested above, if a shell leader or the delay element is seriously damaged, or the delay elements are missing, one would normally make a repair in

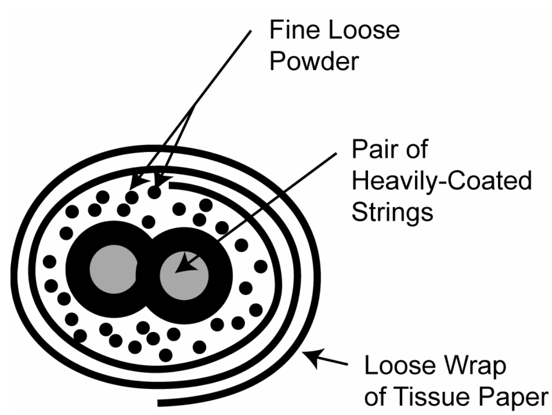

Figure 3. Cross sectional illustration of the new fast burning black match.

the field. This might be done by simply removing the damaged portion of the fuse and stripping back some of the Kraft paper match pipe to expose more of the central fuse. With a typical quick match shell leader this works well and is an appropriate repair. However, if this procedure is done using this new style of tissue fuse quick match, when it is ignited, instead of the expected few seconds delay, there would be essentially no delay at all. In most cases, that would merely startle the lighter. However, if the device being ignited seriously malfunctioned, or if the lighter was not properly positioned at the time, an injury could result. (Note: There has been at least one minor, but very nearly serious, accident caused by the unexpectedly fast burning of this fuse.)

It is not known how widely this new style of quick match is being used. The authors first saw it several years ago and have more recently seen it on Flower Basket aerial shells and on Lidu finale boxes. If you encounter it, there should be no problem, providing any delay elements are left in place or where no delay is intended when it is ignited. To reiterate, there seems to be nothing intrinsically wrong with this new style of tissue fuse core quick match. However, it is just important to be able to recognize it and to know what to expect when using it.

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1) K. L and B. J. Kosanke, "Quick Match: A Review and Study", *Proc. 4th Int'l. Symp. Fireworks* (1998). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)*, Journal of Pyrotechnics, 2002.

An earlier version appeared in *Journal of Pyrotechnics*, No. 10, 1999.

Peak In-Mortar Aerial Shell Accelerations

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ABSTRACT

Internal mortar pressures were measured for a range of somewhat typical fireworks aerial shell firing conditions. These data were used to determine the peak shell accelerations produced during firing. Under the conditions investigated, peak aerial shell acceleration ranged from approximately 4 to 16 km/s^2 (400 to 1600 times the acceleration due to gravity) and appeared to be mostly independent of nominal shell size.

As a check on the acceleration results, the same mortar pressure data were used to calculate aerial shell muzzle velocities. These were found to be in close agreement with measured velocities.

Keywords: fireworks, aerial shell, acceleration, muzzle velocity, mortar pressure, pressure impulse

Introduction

For safety reasons, a fireworks display operator needs to know that aerial shells leave the mortar at high speed. Further, it is important to know approximately how far the aerial shells can travel. However, it is not important for the operator to know the rate of acceleration of aerial shells within mortars as they are fired. Similarly, except to know that the acceleration is great and the resulting inertial forces on the shells are large, the shell manufacturer does not need detailed knowledge of the magnitude of aerial shell acceleration. Nonetheless, it is sometimes a topic of discussion, and knowledge of these accelerations would satisfy the curiosity of a number of individuals. This short article is intended to help satisfy that curiosity.

Several years ago data was collected, albeit for another purpose, that can be used to calculate the acceleration of aerial shells while being fired from mortars. These data are internal mortar pressures as a function of time for various shell parameters (e.g., size and shape, lift type and mass, and shell mass). At the same time, the muzzle velocity of the shells was measured and can be used as a check on the calculated shell accelerations. Some examples of the basic data and the results produced are presented in this article.

Background

If the forces acting on a body are known, it is a simple matter to calculate the acceleration produced. Pressure has the units of force per area; for example, Newtons per square meter (also termed Pascals and abbreviated Pa). Accordingly, the force (F) acting on an aerial shell with a known cross-sectional area (A) perpendicular to the pressure gradient, when experiencing a pressure difference (P) between one side and the other is[1]

$$F = P \cdot A \tag{1}$$

Then simply by rearranging Newton's second law of motion, and knowing the mass (m) of the aerial shell, the acceleration (a) it experiences can be calculated as

$$a = \frac{F}{m} \quad \text{or by substitution} \tag{2}$$

$$a = \frac{P \cdot A}{m} \tag{3}$$

Figure 1 is an example of the pressure measured inside a mortar as a shell is being fired. Because the pressure is not constant during the firing, neither is the acceleration of the shell. Nonetheless, equation 3 accurately predicts the

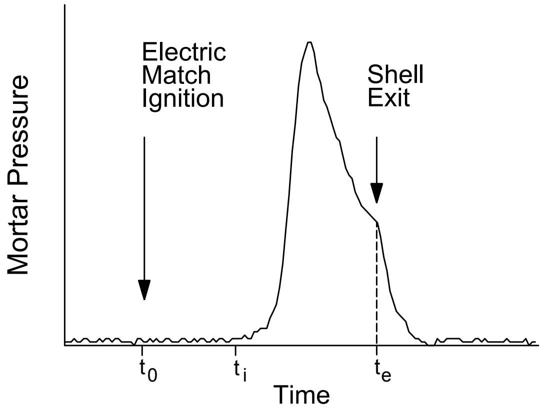

Figure 1. Typical internal mortar pressure during the firing of an aerial shell.

acceleration at every instant, providing the mortar pressure at the same instant is used. Thus, the shell's acceleration reaches a maximum when the mortar pressure peaks, and this peak acceleration can be calculated using equation 3.

In the same tests where mortar pressures were measured, aerial shell muzzle velocities were also measured. This provided an opportunity to indirectly confirm the accuracy of the peak acceleration determinations by using the mortar pressure data also to predict the measured muzzle velocities.

In general, for any body, its change in velocity (v) in response to a time dependent acceleration can be represented by

$$v_f - v_i = \int_{t_i}^{t_f} a(t)\ \mathrm{dt} \qquad (4)$$

where the subscripts i and f are for initial and final values. For an aerial shell initially at rest (stationary), substituting for acceleration using equation 3, and integrating over the time of exposure to the pressure in the mortar equation 4 becomes

$$v_m = \frac{A}{m} \int_{t_i}^{t_e} P(t)\ \mathrm{dt} \qquad (5)$$

where v_f is now muzzle velocity (v_m) and t_f is now the time of exiting (t_e), see Figure 1.

The integral in equation 5 is usually referred to as pressure impulse (I_p). In these tests, values for the pressure impulse were determined and used to calculate the aerial shell muzzle velocities from equation 6.

$$v_m = \frac{A}{m} I_p \qquad (6)$$

Experimental

For uniformity, all of the test shells for this project were assembled using molded plastic shell casings. Nominal shell size ranged from 3 to 8 inches. Most shells were spherical in shape, but some 3- and 4-inch shells were cylindrical. In an attempt to have the spherical shells perform in a similar manner to typical oriental shells, the lift powder used was a fairly homogeneous blend of powder harvested from a collection of shells manufactured in China. The lift powder for the cylindrical shells was 2FA fireworks Black Powder manufactured by Goex.[2] The air temperature at the time of firing ranged from 21 to 27 ºC (70 to 80 ºF). The tests were conducted at about 1400 m (4600 ft) above sea level, resulting in air pressure of approximately 850 mbar. Additional mortar and shell test information is provided in Table 1.

All mortars were steel with piezoelectric pressure gauges installed in the mortar plug. In this way the internal mortar pressures were measured as the shells were fired.[3] The mortars were also fitted with a series of trip wire sensors to detect the passage of the shell after exiting the mortar. Signals from the trip wires controlled a series of time counters to produce the data used to calculate velocities of the shells as they exited the mortar.[4]

The test results are reported in Table 2. In each case, the peak mortar pressure reported was the highest value from the digital pressure data. Pressure impulse is the integral of the pressure data, starting from the first sign of pressure rise (t_i) and ending at the point of shell exit (t_e) (such as identified in Figure 1). The measured velocity of the exiting shell was determined by noting the time taken for the shell to travel a known distance after exiting the mortar. The calculated shell velocity was determined by substituting the measured pressure impulse and the known cross-sectional area and mass for the aerial shell into equation 6. The peak shell ac-

Table 1. General Test Shell and Mortar Information.

Nominal Shell Size (in.)	Mortar Diameter (mm)	Mortar Length (m)	Shell Shape	Shell Diameter (mm)	Shell Mass (g)
3	79	0.51	Spher.	66	135
			Cylin.	67	180
4	103	0.61	Spher.	95	350
			Cylin.	92	500
5	129	0.76	Spher.	119	620
6	154	0.76	Spher.	144	1140
8	203	0.91	Spher.	193	2700

To convert inches to millimeters, multiply by 25.4.
To convert millimeters to inches, divide by 25.4.
To convert meters to inches, multiply by 39.4.
To convert grams to pounds, divide by 454.

celeration was determined from equation 3, using the measured peak mortar pressure.

To be consistent with the general reliability of the data, in Table 2 peak pressures were reported to the nearest 10 kPa, pressure impulses were reported to the nearest 0.1 kPa·s, measured and calculated muzzle velocities were reported to the nearest 5 m/s, and peak accelerations were reported to the nearest 1 km/s^2.

Discussion

The aerial shells had been assembled such that their mass, the type and amount of lift powder, and the mortar specifications were fairly representative of typical aerial shells. However, caution is warranted in applying the results of these tests in situations where any of the conditions are different.

An examination of the results for the series of 4-inch cylindrical shells provides an indication of the general reliability of these data. Note that

Table 2. Test Shell Firing Results.

Nominal Shell Size (in.)	Shell Shape	Lift Mass (g)	Peak Pressure (kPa)	Pressure Impulse (kPa·s)	Measured Velocity (m/s)	Calculated Velocity (m/s)	Peak Acceleration (km/s^2)
3	Spher.	28	430	4.5	80	85	8
	Cylin.	28	500	5.0	90	95	10
4	Spher.	28	210	3.2	65	65	4
		46	660	5.9	125	125	14
	Cylin.	50	880	7.9	110	105	12
			1200	8.0	110	105	16
			970	7.9	100	105	13
			770	7.5	100	100	10
5	Spher.	50	610	5.9	100	105	11
6	Spher.	85	680	7.4	110	110	10
8	Spher.	155	830	11.2	120	125	9

To convert inches to millimeters, multiply by 25.4.
To convert grams to ounces, divide by 28.3.
To convert kilopascals to pounds per square inch, divide by 6.89.
To convert meters per second to feet per second, multiply by 3.28.

while the peak pressures (and peak accelerations) for these firings varied considerably, the pressure impulses (and thus muzzle velocities) were in relatively close agreement. The authors have seen this same type of large variability in peak mortar pressure, yet reasonably consistent overall performance, in numerous other confined-combustion measurements. The reason for this effect is not clear but is suspected to be the result of small dynamic differences in the ignition and initial flame spread within the pyrotechnic charge (an interesting subject, but beyond the scope of this article.)

There was relatively close agreement between measured and calculated shell muzzle velocities, not only for the 4-inch cylindrical shells, but all others as well. Further, the muzzle velocities were reasonably close to 100 m/s (330 ft/s), regardless of shell size. This is consistent with the results reported by Shimizu,[5] Contestabile,[6,7] and in unpublished results of the authors. Thus there is a reasonably high degree of confidence in the reported results.

The maximum shell accelerations typically ranged from 8 to 12 km/s^2 and appear to be mostly independent of nominal shell size. In part, the 4 km/s^2 value reported in Table 2 was a result of using a smaller than normal amount of shell lift powder. However, it may also be a reflection of the widely varying peak pressures thought to result from the differences in ignition and flame spread mentioned above. Similarly, the 14 and 16 km/s^2 values may again be the result of these same differences.

These peak acceleration results can be put into perspective, recalling that the acceleration due to gravity is 9.8 m/s^2. Accordingly, at their maximum acceleration, these somewhat typical aerial shells were experiencing approximately 400 to 1600 times the acceleration due to gravity. Obviously, this produces powerful forces on the contents of the shell (so-called set-back forces) that communicate to the shell's casing as well. For example, in the relatively new "Lampare" style aerial salutes (maroons), a container is generally filled with liquid fuel, combined in some fashion with a charge of flash powder. Consider a liquid fuel with a density of 0.85 g/cc that is placed in a container with a height of 150 mm (about 6 inches). If that shell is propelled such that it receives the peak acceleration seen in the tests reported above, the liquid pressure at the bottom of the container would range from 0.5 to 2.0 MPa (70 to 290 psi). Thus it is clear why some fuel containers fail catastrophically during such shell firings and why the fuel containers typically are strongly encased.

Acknowledgements

The authors wish to thank Scot Anderson, Wes Smith and Larry Weinman for their review of an earlier version of this article.

Notes and References

1) This is a simplification in that things such as drag forces produced by the combustion gases rushing past the exterior of the shell are not considered. However, this is not expected to introduce a significant error in the results being reported.

2) Goex, Inc., PO Box 659, Doyline, LA 71023, USA.

3) The pressure gauges were PCB Piezotronics 101A04, connected to PCB Piezotronics 480D06 amplifying power supplies. The data were recorded using Fluke Scopemeters model 95 or 97, and then transferred to a computer for processing.

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An earlier version of this article appeared in *Fireworks Business*, No. 194, 2000.

Firing Precision for Choreographed Displays

K. L. and B. J. Kosanke

For maximum effectiveness of tightly choreographed fireworks displays, it is important that shell bursts occur very near their intended times. Two main sources of variation combine to affect the overall precision of the shell bursts. First is the preciseness of the shell firings; second is the preciseness of the time fuse burning. Other than by purchasing high quality shells, a display company generally has little control over the precision provided by the shell's time fuse. However, the display company can do much to control the firing precision for those shells. For the most part accurate firings are only possible using electrical ignition. For the purposes of this article, it is assumed that a computer or other means of accurately applying the firing current to electric matches (e-matches) is being used. This leaves the question as to the degree of firing precision achieved using various methods of attaching e-matches to shells and is the subject of this article.

There are three common points of attachment for e-matches. These are illustrated in Figure 1. In terms of convenience, safety and effectiveness (firing time precision), each has its own set of advantages and disadvantages. While issues of safety and convenience are quite important considerations, they are beyond the scope of this article. In terms of firing precision, common knowledge has it that installation of the e-match directly into the lift charge (point 3 in Figure 1) provides the most precise timing; attachment at the end of the shell leader (point 1) provides the worst timing; and attachment to the shell leader just above the body of the shell (point 2) is somewhere in between in terms of effectiveness. However, the authors are unaware of any reported test of this common knowledge. Further, there are those that claim that the precision achieved using attachment point 2 is just as good as using point 3. Accordingly, (and because it made an interesting short project) a series of instrumented shell firings were conducted as a test of these two schools of thought.

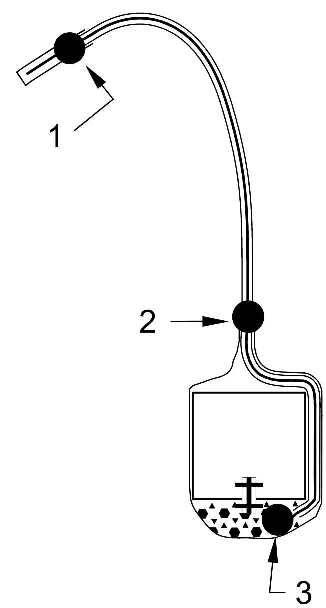

Figure 1. Illustration of the three common points of attachment of e-matches to aerial shells.

All tests were conducted using identical inert 3-inch (75-mm) spherical plastic aerial shells fired from mortars fitted with trip wires at their mouth. Firing times were measured using an instrument that provided the e-match firing current, and at the same instant started a precision timer, which stopped when the trip wire was broken. A series of eight tests were performed for each shell configuration, with the average and standard deviation of the firing times then calculated. To simulate actual field conditions, all test shells were assembled and fitted with e-matches, then placed in an environmental chamber [72 °F (22 °C) and 78% relative humidity] for three days.

In the first series of tests, e-matches were installed at the ends of 24-inch long shell leaders (point 1). Twenty-four tests were performed: eight with shell leaders made using a high quality quick match (from Precocious Pyrotechnics); eight with shell leaders taken from Horse brand shells; and two each with shell leaders taken from Yung Feng, Angel, Flower Basket, and Flying Dragon brand shells. The results are reported in the first three rows of Table 1. The firing times and their standard deviations for the third group of test firings are both rather excessive, due to the occurrence of two short duration hangfires (lasting approximately 2.5 and 1.2 seconds). In an attempt to give this method of e-match attachment the benefit of the doubt, the results were recalculated, this time omitting the two hangfire results. Finally, to approximate what would be expected in a typical display using a variety of different shell brands, all 24 (or 22) firings were considered as a single set, reported in Table 1 as "Combined".

Table 1. Firing Time Results for Various E-Match Attachment Points.

Test Conditions	No.[a]	F. Time[b] (sec.)	Std. Dev.[c] (sec.)
Precocious - long	8	0.26	0.15
Horse - long	8	0.32	0.12
Variety - long	8	0.76	0.76
	6[d]	0.41[d]	0.15[d]
Combined - long	24	0.45	0.49
	22[d]	0.32[d]	0.14[d]
Precocious - short	8	0.11	0.025
No Match® in lift	8	0.08	0.020
E-Match in lift	8	0.04	0.005

a) Number of individual test firings.

b) Firing time is the average of the eight elapsed times between applying current to the electric matches and the shells exiting from the mortars, rounded to the nearest 10 ms.

c) The one sigma standard deviations of the average firing times were determined using the *n*–1 method.

d) These data are for the same tests but do not include the two short duration hangfires that had occurred.

While the average firing times for the various groups differ somewhat, the precision for each individual group and the collection as a whole are not all that bad, if the two hangfires are not included. (Note that an average firing time of 0.32 second, with a precision of 0.14 second, means that about 70% of the firings will occur between 0.18 and 0.46 second, a range of approximately 0.3 second.) As a point of comparison, humans can fairly easily discern timing differences of 0.1 second, or about 1/3 that seen in these test firings. Accordingly, these tests produced a wider range than would be preferred, even if the time fuses and shell bursts had performed with absolute precision (no variation at all).

For the next group of eight test firings, again Precocious Pyrotechnics' quick match was used; however, this time the length of leader was only about four inches, just enough to reach to near the top of the shells. Another group of shells was fired using e-matches installed on the ends of B & C Products' 24-inch No Match® API shell leaders. (These were shock tube shell leaders.) Finally, there was a group of firings with the e-matches installed directly into the shell's lift charge. These additional results are included as the last three rows in Table 1.

These last three firing methods produced average firing times less than those using the full-length shell leaders. However, more importantly, the timing precision is greatly improved, with each method producing a firing-time precision better than would be perceived by spectators. Thus, although the precision achieved with e-matches installed directly in the lift charges was observed to be better than the short shell leaders (attachment point 2), the improvement would not be detectable by spectators.

In conclusion, it must be considered that this was a single brief series of tests. While the results are probably valid, it is possible that significantly different results would be found for other conditions and materials. Nonetheless, it would seem that both schools of thought about e-match attachment are generally correct. Attachment at the ends of long shell leaders produced the worst firing-time precision, but not terrible—providing actual hangfires were not considered. Installation of e-matches directly into lift charges produced the best precision (lowest standard deviation). However, the firing-time precision for short shell leaders was equally satisfactory, because it is better than could be detected by spectators. No Match® also performed well in these tests but only marginally better than the short quick match.

The authors gratefully acknowledge the assistance of D. Kark for upgrading the firing and timing instrument, B. Ofca for providing the No Match® components, and A. Broca for providing the Daveyfire e-matches used in these tests.

An earlier version appeared in *Proceedings of the 4th International Symposium on Fireworks*, 1998.

Sticky Match® and Quick Match: Temperature Dependent Burn Times

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ABSTRACT

Sticky Match® is an expedient and reportedly effective type of fuse, especially useful in fusing lance set pieces. However, some users have mentioned an apparent tendency for the fuse to burn noticeably slower at low temperatures. The authors conducted a brief investigation of Sticky Match burn rate as a function of temperature. The study was conducted over a temperature range from approximately –30 to +40 °C (–20 to 100 °F).

In what is likely to be its normal method of application, it was found that at the lowest temperature Sticky Match burn rate fell to as little at 1/3 that at the highest temperature. Using a slightly different method of application, it was found that its burn rate was even more strongly affected at both extremes of temperature. In a third and substantially different method of application, it was found that Sticky Match was essentially unaffected by temperature, but always burned rather slowly.

As a comparison to Sticky Match's temperature performance, the study also characterized the effect of temperature on the burn rate of conventional quick match. In two configurations, similar to those used for Sticky Match, it was found that the burn rate of quick match was virtually unaffected by temperature.

Introduction

Sticky Match®[1] is an expedient and reportedly effective type of fuse, especially useful in fusing lance set pieces. The fuse is made by confining a trail of granular Black Powder between two strips of thin plastic tape that face each other, with one tape being significantly wider than the other. Accordingly, the exposed adhesive on the wider tape is available to secure the fuse in place. (See Figure 1.) Sticky Match has gained considerable acceptance in the USA during the relatively short time it has been available. However, there have been reports of its burn rate being quite temperature dependent. While, even if true, this would generally not be a serious problem, it could produce unexpected results and would be something a user should be aware of. This article reports on an investigation of the temperature dependence of Sticky Match used in three configurations and compares those results with results for quick match. (For results of a more complete study of quick match performance, see reference 2.)

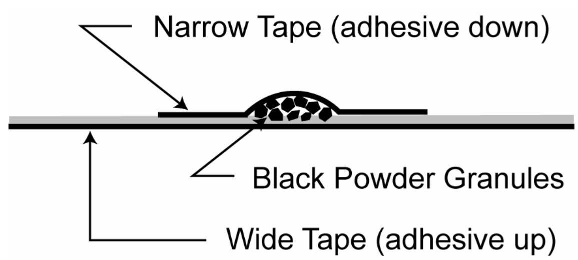

Figure 1. Cross section of Sticky Match.

Measurements

The first configuration studied is illustrated in Figure 2 and, in the test results, is designated "normal", as it represents the way Sticky Match would be used to fuse a lance set piece. For these tests a length of Sticky Match was used to span a row of four wooden dowel pins, spaced 0.15 m (6 in.) apart. The dowel pins were in-

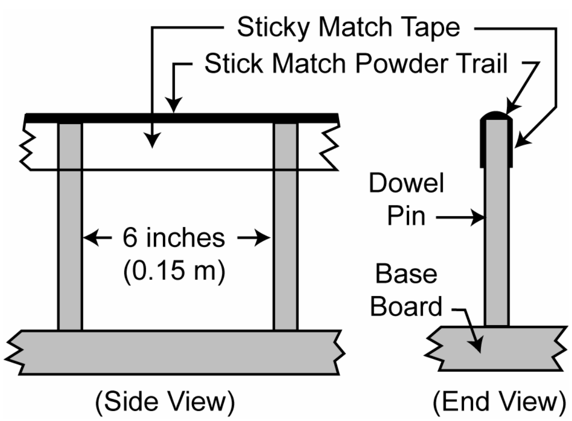

Figure 2. Sticky Match test configuration—"normal" (not to scale).

tended to represent lance tubes on a set piece. The Sticky Match was placed tightly over the top of the dowel pins and held in place by the adhesive of the wider tape. Between the dowel pins, the edges of the Sticky Match tape, with the exposed adhesive were pressed together to help hold it in place on the dowel pins and to produce a potential fire path below the Black Powder trail. It was thought that closing the space below the powder trail in this manner would help retain the heat of burning, passing more thermal energy along to unburned powder, and potentially making its burn rate less temperature sensitive.

For each burn-time test, a 0.46 m (18 in.) length of Sticky Match was used. In each case it was ignited with an electric match[3] installed against the powder trail at the first dowel pin. The progress of the burning was video recorded, and burn times were subsequently determined by playing the videotape field by field. Prior to each test, the assembly was held in a temperature-controlled chamber for at least two hours. The actual measurement was made in the temperature-controlled chamber. Then the door to the chamber was briefly opened, and the Sticky Match quickly ignited before its temperature could change significantly. In this manner, a set of three measurements were made at each of a series of temperatures ranging from about –30 to +40 °C ±1 °C (–20 to +100 °F). The results of these measurements are reported in Table 1; however, discussion of the results is deferred until later in this paper.

Table 1. Sticky Match Burn-Time Test Results.

Test Condition	Temperature (°C)	(°F)	Burn Time for 18 in. (0.46 m) (1/60 second) Test 1	Test 2	Test 3	Average	Average Burn Time (s)
Normal	–28	–18	75	52	46	58	0.97
	–11	12	44	54	36	45	0.75
	1	34	20	27	24	24	0.40
	14	58	21	23	22	22	0.37
	29	84	21	16	18	18	0.30
	38	100	20	18	22	20	0.33
Side Mounted	–31	–24	149	218	182	183	3.00
	–13	0	74	24	31	43	0.72
	2	35	38	31	41	37	0.62
	13	55	10	15	9	11	0.18
	30	86	18	12	26	17	0.28
	38	100	11	9	9	10	0.17
Pipe Mounted	–31	–24	115	135	174	141	2.35
	–13	0	61	131	65	86	1.43
	2	35	122	208	165	165	2.75
	13	55	64	128	187	126	2.10
	30	86	156	106	163	142	2.37
	38	100	43	168	86	99	1.65

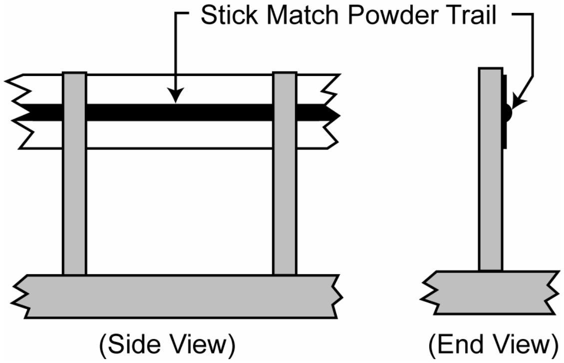

Figure 3. Sticky Match test configuration— "side mounted" (not to scale).

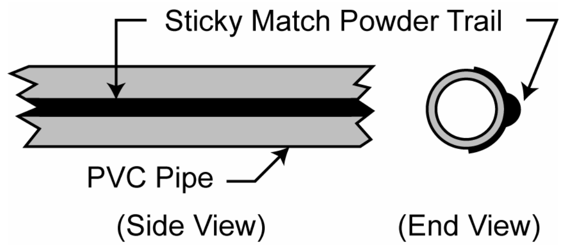

Figure 4. Sticky Match test configuration— "pipe mounted" (not to scale).

In a similar fashion, two other Sticky Match configurations were tested; these are shown in Figures 3 and 4. One is described as "side mounted", where the Sticky Match was just placed against the side of the dowel pins. In this configuration no fire path is formed below the powder trail as in the "normal" configuration (produced when the edges of the tape were pressed together). The other configuration is described as "pipe mounted", where the length of Sticky Match was tightly attached to a length of nominal 1-inch (25.4-mm) schedule 40 PVC pipe. It was thought that the close proximity of the pipe would be fairly effective in absorbing heat from the burning powder and might tend to slow the burning of Sticky Match. The burn-time results as a function of temperature, using these two configurations, are also presented in Table 1.

As a comparison, standard quick match[4] was tested in the "normal" and "pipe mounted" configurations. In the normal configuration, the quick match was held in place using masking tape, as is often the case when it is used to fuse lance set pieces. In the pipe mounted configuration, the quick match was held as tightly as possible to the surface of the pipe using 51 mm (2-in.) wide clear plastic packaging tape. Temperature conditioning of the assemblies and burn-time measurements were conducted just as they were for Sticky Match. The results from these measurements are presented in Table 2.

By comparing the results from the three individual measurements at each temperature in Tables 1 and 2, it is clear that large variations in burn times were often observed. Occasionally the range of burn times exceeded a factor of two. Accordingly, the statistical precision of the average burn times reported in Tables 1 and 2

Table 2. Quick Match Burn-Time Results.

Test Condition	Temperature (°C)	(°F)	Burn Times for 18 in. (0.46 m) (1/60 second) Test 1	Test 2	Test 3	Average	Average Burn Time (s)
Normal	–29	–21	11	9	15	11	0.18
	–16	4	9	7	15	9	0.15
	0	32	16	9	11	12	0.20
	15	59	9	6	11	10	0.17
	28	82	9	6	16	10	0.17
	38	100	10	10	8	9	0.15
Pipe Mounted	–30	–22	9	5	4	6	0.10
	0	32	7	7	4	6	0.10
	28	82	10	6	8	8	0.13
	38	100	5	6	6	6	0.10

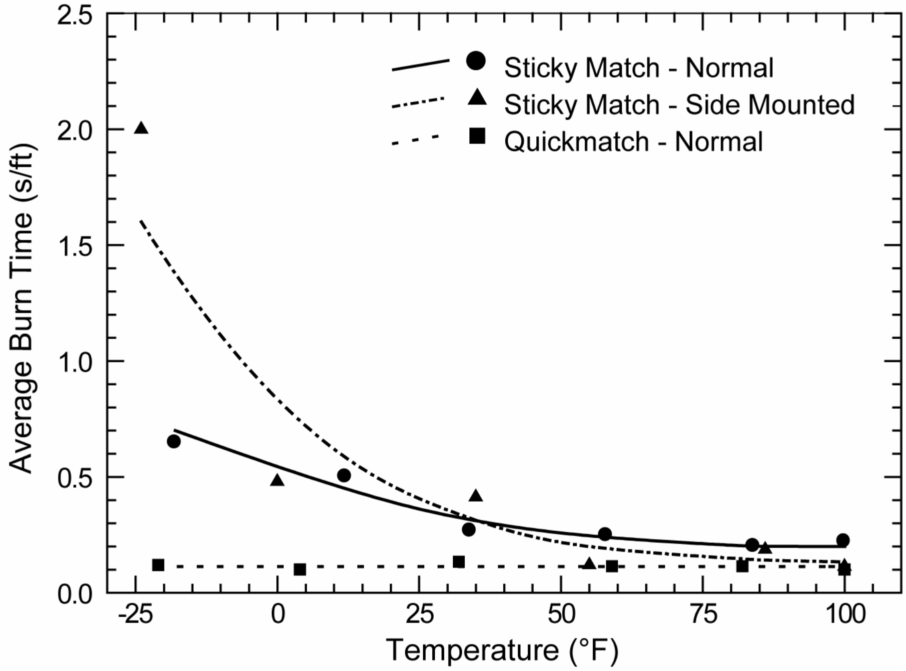

Figure 5. Burn-time results as a function of temperature for the "normal" and "side mounted" test configurations. [To convert s/ft to s/m, divide by 3.28. To convert °F to °C, °C = (°F – 32) × (5/9).]

are not high, and some caution is appropriate in attempting to interpret those results. Average burn-time results for the "normal" and "side mounted" configurations are presented graphically in Figure 5. Note that burn times for quick match seem to be mostly unaffected over the temperature range studied. On the other hand, while the burn times of Sticky Match are not strongly temperature dependent at higher temperatures, at low temperatures Sticky Match was observed to become increasingly slow burning. For the normal configuration, Sticky Match burn times increase by about a factor of three for the lowest temperatures. Note further that the burn times for the side-mounted configuration are even more sensitive to temperature, perhaps increasing by a factor of more than ten at the lowest temperatures studied.

Average burn-time results for the "pipe mounted" configuration are presented graphically in Figure 6. Note that the burn times for Sticky Match are quite variable, but seem to be mostly independent of temperature in this configuration. Again, burn times for quick match are quite constant and independent of temperature in the range studied.

Conclusions

A number of conclusions can be drawn from the reported data regarding the use of Sticky Match:

1) Over the range of temperatures normally expected for fireworks displays in the summer, 21 to 38 °C (70 to 100 °F), Sticky Match burns at a rate of about one half that of the quick match used in this study. This should not be a problem for use on lance set pieces and may allow for a more aesthetically pleasing ignition, along the lines described in reference 5.

2) Over the range of temperatures normally expected for fireworks displays in the summer, 21 to 38 °C (70 to 100 °F), the burn rate of Sticky Match is not noticeably temperature dependent.

3) When Sticky Match is to be used at low temperatures, $\lesssim$ 0 °C (32 °F), it must be anticipated that its burn rate will depend on temperature, and it may burn significantly slower than might be expected. However, its burn rate will be less temperature dependent if an attempt is made to enclose the space

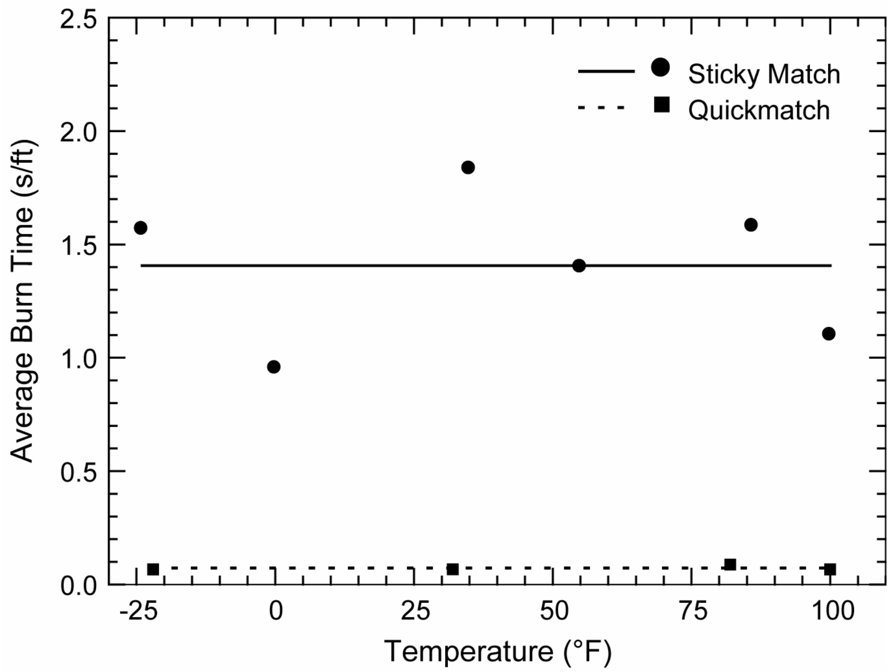

Figure 6. Burn-time results as a function of temperature for the "pipe mounted" test configuration. [To convert s/ft to s/m, divide by 3.28. To convert ºF to ºC, ºC = (ºF – 32) × (5/9).]

under it by pressing the edges of the tape tightly against itself over the span between the individual lance tubes.

4) At any temperature, the burn rate of Sticky Match can be retarded by taping it tightly against a surface. While it would seem that precise time delays might not be possible using this method, it is a method that may occasionally prove to be useful.

Sticky Match is an interesting and useful fusing material. However, for some applications, a better understanding of its properties may be important to use it successfully to accomplish one's purpose.

Acknowledgements

The authors are grateful for the suggestions made by L. Weinman and M. Williams on an early draft of this paper.

References

1) Sticky Match® is a Registered Trademark of Four-D Enterprises, Inc., 10510 El Comal Drive, San Diego, CA 92124 USA. Patent Number 5,662,719. The samples used in this study were supplied in early 1998, courtesy of Ron Dixon, Four-D Enterprises.

2) K. L. & B. J. Kosanke, "Quick Match: A Review and Study", *Proc. 4th Int'l. Symposium on Fireworks* (1998). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)*, Journal of Pyrotechnics, 2002.

3) The electric matches used were Daveyfire SA-2000, provided courtesy of Alan Broca, Daveyfire, Inc., 2121 N California Blvd. Ste. 290, Walnut Creek, CA 94596, USA.

4) Supplied in 1997 by Precocious Pyrotechnics, Inc., 4420 27th Ave. NW, Belgrade, MN 56312, USA.

5) B. J. and K. L. Kosanke, "Lancework - Pictures in Fire"; *Pyrotechnica* XV (1993); Also in *Selected Publications of K.L. and B.J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996, p 28.

An earlier version appeared in *Proceedings of the 5th International Symposium on Fireworks*, 2000.

Mortar Separations in Troughs and Drums

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ABSTRACT

Rarely is there only one mitigation strategy to reduce the level of hazard posed by a problem. This concept is explored in the context of alternate strategies for limiting the potential problem posed by fireworks mortar bursts within troughs and drums. This begins with a discussion of the nature of the mortar burst problem and the current National Fire Protection Association (NFPA) requirements for using mortar troughs. This is followed by a discussion of a series of alternate mitigation strategies that are thought to provide equivalent spectator protection.

Prolog

Since drafting this article, the referenced National Fire Protection Association (NFPA) code has been modified. One of the stated requirements has been dropped for electrically fired displays, and one of the mitigating strategies has been substituted. Since the hazard analysis presented in this article is generally relevant (and hopefully instructive), the article is preserved in its original form. However an epilog has been added to clarify the current code requirement.

Introduction

The 1995 edition of the National Fire Protection Association's *Code for Fireworks Display* (NFPA-1123) provided some requirements for the placement of mortars in troughs or drums for electrically discharged displays. One requirement was that there must be at least a 50-mm (2-in.) separation between individual mortars and between any mortar and the wall of the trough or drum[2,3] (see Figure 1). However, in a general recognition that alternate methods might be employed that provide an equivalent (or even superior) level of protection, the NFPA code includes an equivalency statement.[4] This allows consideration of alternate methods and

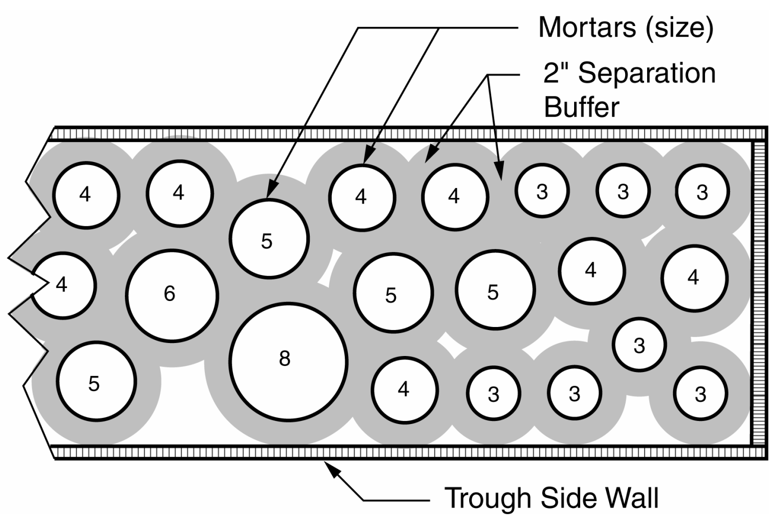

Figure 1. Illustration of mortar placement in a trough using the NFPA 50-mm (2-in.) separation. (Overhead view.)

equipment that provide equivalent levels of protection. This article presents a limited discussion of the rationale for the 50-mm (2-in.) separation and suggests some ways in which equivalent levels of spectator protection might be accomplished.

For electrically discharged displays, when mortars are in close proximity to one another, one area of major concern involves a possible aerial shell malfunction within its mortar, wherein the mortar is violently destroyed (a so-called "aerial shell detonation"). For star shells, this type of malfunction is quite rare. On those occasions when a star shell functions within its mortar, usually the result is a milder explosion. One where the mortar survives undamaged and the contents of the aerial shell are projected upward, out of the mortar in a mostly harmless display (a so-called "flowerpot").

A violent in mortar explosion (VIME) can be powerful enough to damage an adjacent mortar still containing an aerial shell. This could render the adjacent damaged mortar incapable of properly launching its shell. However, a greater potential problem is that adjacent mortars, still containing aerial shells, will become dangerously misaligned by the mortar explosion. Serious misalignment is of greater concern than mortar damage because the probability of this happening is greater, and the possible consequences are more severe.[5] (Why this is the case is discussed in the next few sections of this article and is followed by a discussion of some strategies to mitigate this hazard.)

There are a large number of ways in which a mortar explosion accident might proceed, as well as a large array of possible mitigation strategies. Thus, as a matter of practicality, only some of the most likely and consequential scenarios will be discussed in this article. For example, the discussion will be limited almost entirely to a discussion of mortar troughs, when many of the same points apply equally to mortars buried in the ground or in drums and even to mortars in racks. Also, it must be acknowledged that very little direct research has been done on mortar explosions and their consequences. Thus, for the most part, the information presented in this article is based on accident investigations and general scientific principles.

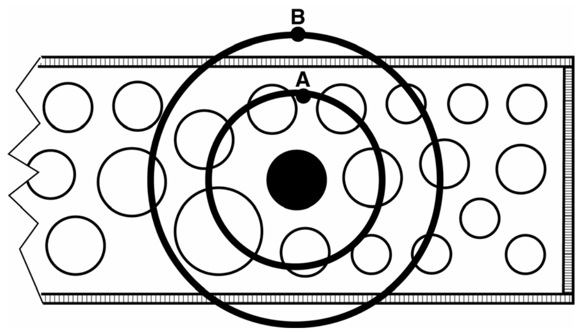

Figure 2. Zones of decreasing blast effect around a mortar explosion (overhead view).

Consideration of the Hazards from a Mortar Explosion

The energy transferred from an explosion to nearby objects decreases with distance. In large part, this is a manifestation of blast pressures dropping roughly in proportion to the area over which they are acting.[6] For example, in Figure 2, if there were a powerful explosion of the "black" mortar, and if there were no intervening materials, the blast pressure at point B would be approximately 1/4 that at point A. However, there is also a loss of energy to materials in the area of the explosion. In this case, some energy may be consumed in damaging adjacent mortars and in ejecting sand from the trough (sometimes called a "sandbox").

Generally much more force is required to dent or crush a mortar than is required to reposition it. Accordingly, for mortars to be damaged they must be relatively close to the exploding mortar. Because relatively few mortars will be close enough to be damaged, as compared with the number of mortars that are close enough to be repositioned, mortar repositioning is more likely to occur than is mortar damage.

For spectators, the potential consequences of a mortar explosion damaging or repositioning surrounding mortars is zero, unless one of those mortars contains an aerial shell that is subsequently discharged.[7] There are two ways in which such a post-mortar-explosion shell firing might occur. One is a direct result of the initial mortar exploding; such as the fire and firebrands produced in the initial explosion causing an ignition of another shell. The other way in which a shell might be discharged is that a firing signal might be sent to the electric match of that shell.

For spectators, an aerial shell firing after a mortar explosion is only a problem if the shell is discharged from a misaligned mortar that propels it into or over a spectator area. Given the speed and mass of aerial shells, a collision with a spectator could prove fatal. There is also a potential for serious injury from the pyrotechnic output of the shell, should it burst among or immediately over spectators. In this case there is actually a little less potential hazard from a damaged mortar (dented or crushed), than from an undamaged mortar. This is because, if the mortar were seriously damaged, the likely course of events would be that the discharging aerial shell would also explode in the mortar. In that event, the aerial shell would never reach the spectator area to threaten their safety.

Accordingly the major spectator hazard from a violent in mortar explosion (wherein a shell fires from an adjacent mortar) is from repositioned mortars, not from damaged mortars. As discussed above, this is because: (1) there will be many more repositioned mortars than damaged mortars; (2) the severity of consequences will tend to be less for damaged mortars because they are less likely to allow an intact shell to exit; and (3) a damaged mortar that is not also repositioned, presents relatively little spectator hazard.

Ballistic Considerations for Repositioned Mortars

To better evaluate various hazard mitigation strategies for mortar explosions, it is useful to consider what degree of mortar repositioning poses a problem. Figure 3 illustrates the trajectory of aerial shells fired from tilted mortars. These are computer-modeled data[8] for 150-mm (6-in.) spherical shells. (Note that the general accuracy of the computer model has been confirmed experimentally.) In this analysis, it has been assumed that the aerial shell bursts 5 seconds after leaving the mortar, and that it disperses its contents with a spread typical of a hard breaking spherical shell.[9]

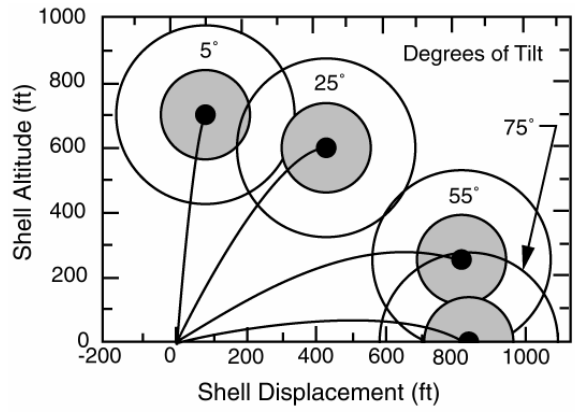

Figure 3. An illustration of the trajectory and functioning diameter of 150-mm (6-in.) aerial shells fired from tilted mortars. [To convert from ft to m divide by 3.28.]

In Figure 3, the location of the shell at the time of its functioning is shown as a large solid dot. At the scale of the drawing, the diameter of the dot is 15 m (50 ft) and is intended to correspond roughly to the zone of maximum injury potential. In each case the dot is surrounded by a shaded area, corresponding to a diameter of 76 m (250 ft), through which there is a much less, but still significant, potential for injury. The still larger circle, corresponding to the diameter of 152 m (500 ft), is the approximate maximum extent of burning material from the shell burst. It is intended to represent the approximate extent of even minimal injury potential.[10]

For normally functioning aerial shells, it is apparent from Figure 3 that it is not minor repositioning of mortars that poses a hazard to spectators. Of course this is because the aerial shells fired from those mortars will function far enough above the ground. It is only when the tilt angle (measured from vertical) exceeds approximately 60 degrees that much burning debris is expected to reach the ground.[11]

Mortar Explosion Hazard Mitigation

Before considering alternate hazard mitigation strategies, it is appropriate to first consider the level of protection provided by the NFPA's 50-mm (2-in.) separation requirement. Because the forces associated with an explosion fall off with distance, the 50-mm (2-in.) separation does provide a certain level of protection in the event of a mortar explosion. It is true that, as a consequence of the 50-mm (2-in.) separation, there will be slightly less blast pressure on adjacent mortars. However, this 50-mm (2-in.) clearance is very much less than is necessary to significantly reduce the chance of the adjacent mortars being repositioned. The greater benefit from the 50-mm (2-in.) separation is that potentially fewer mortars are affected. This is illustrated in Figure 4, in which the same number and sizes of mortars as in Figure 2 have been grouped more closely. Note that the mortars now occupy only about half the space as in Figure 2. This increased concentration of mortars means that a greater number of mortars could be dangerously repositioned in the event of a violent in mortar explosion. Accordingly, while the 50-mm (2-in.) separations do not eliminate the potential for spectator injury, they are of benefit in reducing the level of hazard.

The present NFPA code provides essentially no minimum requirements for the construction, orientation, barricading or operating procedures for troughs. All of this is left to the good judgment of the fireworks display company, along with that of the local enforcing authority. Obviously, not all methods of construction, orientation, barricading, and operating procedures are equivalent in terms of spectator safety. Accordingly, it may be possible to achieve equal (or even superior) levels of spectator safety without using the 50-mm (2-in.) separation. For example, consider the following two scenarios. In one case, the 50-mm (2-in.) mortar separations are used, along with equipment and procedures that are typical of those in the industry. In another case, mortars are placed with less than the 50-mm (2-in.) separations, but superior equipment and procedures are used. It is possible that the use of superior equipment and procedures will fully compensate for the lack of the 50-mm (2-in.) mortar separations. (It may even provide an increased level of spectator safety.)

When there is a violent in mortar explosion in a trough, it is likely that at least one wall of the trough will be broken. This generally allows many of the mortars contained in that section of trough to tip, with some reaching potentially dangerous orientations. Obviously, details of the construction of the trough can be an important mitigating factor, with heavy construction and numerous securing cross members being a benefit. Heavy construction [e.g., 19-mm (¾-in.) plywood walls reinforced with nominal 2 × 4-in. (37 × 87 mm) lumber] makes it less likely that a trough wall will fail. In turn this makes it less likely that mortars will be repositioned. Numerous securing cross members (e.g., threaded rods between the trough side walls), in addition to strengthening the trough walls, also act to shorten the length of sidewall that may fail. The added strength again makes it less likely that mortars will be repositioned because a trough wall breaks. However, when a trough wall does fail, it tends to fail between pairs of securing cross members. Thus, if there are numerous sidewall-securing cross members, the number of mortars within the length of trough between cross members will be less, and the hazard is reduced because the number of mortars that might be repositioned will be less.

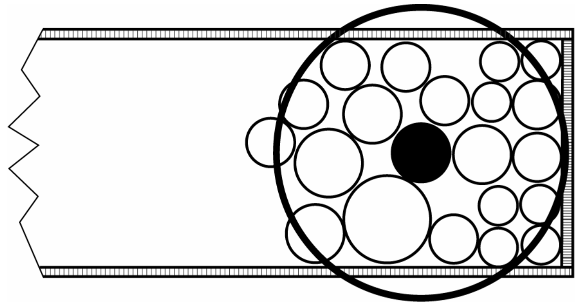

Figure 4. Mortars placed without the NFPA 50-mm (2-in.) separation.

The orientation of the trough is also important. When a mortar explosion breaches the walls of the trough, mortars will be repositioned, and that repositioning will tend to be in directions away from the exploding mortar. This is illustrated in Figure 5, in which the large arrows are pointing in the approximate directions in which repositioned mortars would tend to be aimed. However, it is only those mortars that still contain aerial shells that have any potential for launching a shell. In Figure 5, it is assumed that the firing of the display is from the bottom of the drawing to the top. Thus those mortars toward the bottom of the drawing are likely to be empty, those mortars aimed toward the sides might have a 50% chance of still containing an aerial shell, and those mortars aimed towards

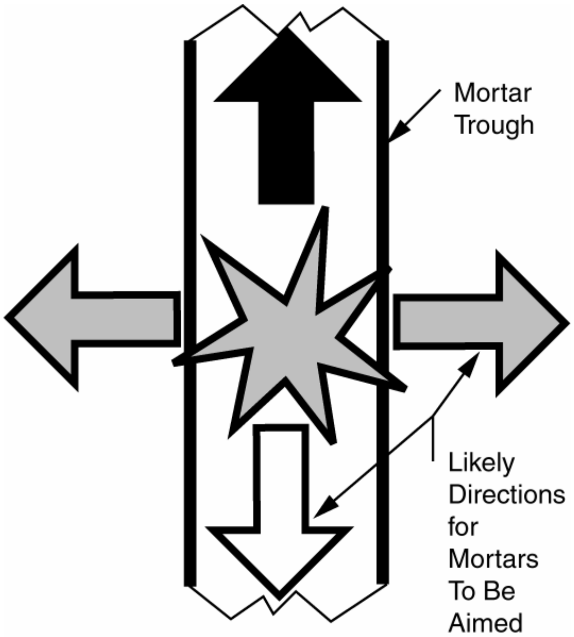

Figure 5. Illustration of likely mortar orientations after a mortar explosion in a trough. (Overhead view.)

the top (black arrow) most likely will contain live shells. An important conclusion can be drawn from this: the preferred orientation of a trough is in a line away from the main spectator area, with the firing beginning on the end nearest the main spectator area and proceeding away from the main spectator area.

A strong barricade of some sort between the trough and spectators, extending several feet above and to the sides of a trough, can be effective in helping to stop or destroy any fireworks shells that are propelled toward spectators. These barricades could be specifically erected for this purpose, but this is likely to be expensive and time consuming. Thus this strategy is most practical when natural features, (like dense woods) or man-made features (like a structure or retaining wall) can be used as a barricade.

Prudent operating procedures can also help mitigate the hazard of mortar explosions leading to shells firing into spectator areas during electrically discharged fireworks displays. One such practice (sometimes called "short wiring") is to secure the electric match wires to the mortar, leaving only the minimum length needed to reach the point of attachment to the firing system (sometimes called a "rail" or "slat"). In this way, if there is a mortar explosion that seriously repositions mortars still containing aerial shells, it is likely that the electric match wires will be torn apart or will be pulled loose from the firing system. When this happens, there is no possibility of the firing current reaching one of these shells. (However, they might still fire from sparks or firebrands igniting the shells.)

Another critically important mitigation strategy is to formally train the firing crew members to be alert to the possibility of mortar explosions and to carefully and explicitly instruct the crew how to deal with them. One example of an effective procedure, whenever there is any possibility that a mortar explosion has occurred, is to insist that the firing crew automatically cease firing from the potentially affected mortars, until an inspection determines that it is safe to proceed with the display. (With advance planning for this possibility, this inspection could be accomplished in as little as 15 or 20 seconds.) Another useful procedure, in the event of a possible mortar explosion, is to have the firing crew automatically skip all firing cues for mortars that could have been repositioned, at least until it can be confirmed that it is safe to fire those mortars. (To be most effective, training needs to be very specific as to the actual procedures to be followed, and that needs to be explicit company policy.)

Trough status indicators might be used to report on the condition of the troughs. This could be something as simple as a wire looped tightly around then zigzagging across a trough. With this properly installed, a mortar explosion that seriously damages the trough will cause this sensing wire to be severed. Then, if this wire were used to power a safe status light at the firing console, that light would serve to indicate whether the trough had been seriously damaged.

The other way that an aerial shell in a repositioned mortar can be discharged is from flame or burning debris from the mortar explosion itself. In this case, the use of tight fitting mortar coverings, such as the polyethylene pipe covers manufactured by Cap Plug®, can help reduce the possibility of such aerial shell ignitions. Further, if the electric match has been installed into the lift charge and the shell leader removed, there is less chance of fire or firebrands causing an ignition.

Another procedure to limit the potential hazard to spectators is to control where and how salutes are discharged during a fireworks display. The potential for a salute producing a mortar explosion is much greater than that for a typical star shell. This is because salutes function by exploding powerfully. If they function within a mortar, there is a much greater chance that the mortar will be destroyed than if it had contained a star shell. (For HDPE and paper mortars it is essentially certain that an exploding salute will burst the mortar.) Examples of mitigation—regarding the firing of salutes—are to use relatively few salutes, limit their size to 75 mm (3 in.), and to fire them from individual mortars each placed in their own widely separated small containers (e.g., 5 gal. pails).

There are also situations when no possible malfunction at the discharge site will present a hazard to spectators. Specifically, this would be when there is a great distance [at least 1 km (1/2 mile)] separating the nearest spectator and the firing site, such as with some barge displays. In that case, no other spectator hazard mitigation is needed.

Conclusion

All human activities involve some risk; everyday people slip in the shower to receive serious injuries, while others choke to death eating food. Yet showering and eating are generally considered safe. This is because the risks associated with those activities are low enough that we readily accept them as part of life. Similarly, there will always be some risk associated with the entertainment provided by fireworks displays. The NFPA code states that its purpose "is to provide requirements for the reasonably safe conduct of outdoor fireworks displays"[12]. Accordingly, the code sets this "reasonable" level of safety as the standard for judging the acceptability of alternate procedures and equipment.

Recall that, for electrically fired displays with the mortars buried in the ground, drums or troughs, the use of a 50-mm (2-in.) buffer space, by itself, does not provide complete spectator safety in the event of a violent in mortar explosion. By the same token, using less than the 50-mm (2-in.) separation does not preclude achieving the same level (or even a greater level) of protection, providing that some additional mitigation strategies such as suggested above are utilized.

Acknowledgement

The authors gratefully acknowledge that Royce Trout of Atlas Enterprises provided financial support for the drafting of this article.

Epilog

In the 2000 edition of the NFPA code, the requirement for a 50-mm (2-in.) separation between the mortars in a trough and the wall of the trough when firing electrically remains.[13] However, while it remains a good practice to do so, for mortars no larger than 150 mm (6 in.) in diameter and providing the shells are not chain fused, the requirement for a 50-mm (2-in.) separation between individual mortars was dropped.[14] Instead, the code adopted two of the other possible mitigating factors suggested in this article. Specifically, there is now a requirement to orient the trough such that its narrow side is toward the area with the greatest number of spectators.[15] Further, there is now a requirement that the sides of the troughs be braced or reinforced in two places at least every 1.2 m (4 ft).[16]

Notes and References

1) While the authors are members of the National Fire Protection Association (NFPA) Technical Committee on Pyrotechnics, the thoughts and opinions expressed in this article are only those of the authors.

2) NFPA-1123 (1995) "2-3.3.3* Mortars that are buried in the ground, in troughs, or in drums shall be separated from adjacent mortars by a distance at least equal to the diameter of the mortar. Exception: Where electrical firing is used, all mortars buried in earth or placed in drums or troughs shall

be spaced at least 2 in. (50 mm) nominally apart."

3) NFPA-1123 (1995) "2-3.3.3.2 There shall be a separation distance of at least 2 in. (50 mm) or 1/2 the diameter of the mortar, whichever is greater, between the mortar and the trough or drum. Exception: When electrical ignition is used, all mortars placed in drums or troughs shall be spaced at least 2 in. (50 mm) from the wall of the drum or trough."

4) NFPA-1123 (1995) "1-3 Equivalency. This code is not intended to prevent the use of systems, methods, or devices that provide protection equivalent to the provisions of this code, provided equivalency can be demonstrated to the authority having jurisdiction."

5) For more information on performing hazard assessments, see
(a) K. L. and B. J. Kosanke and C. Jennings-White, "Basics of Hazard Management", *Fireworks Business*, No. 129 (1994). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 2002.
(b) K. L. and B. J. Kosanke, "Dud Shell Hazard Assessment: NFPA Distances", *Fireworks Business*, No. 178 (1998). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)*, Journal of Pyrotechnics, 2002.
(c) K. L. and B. J. Kosanke, "Dud Shell Hazard Assessment: Mortar Angling", *Fireworks Business*, No. 179 (1999). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)*, Journal of Pyrotechnics, 2002.

6) For more information on the general subject of attenuation of blast waves, see G. F. Kinney and K. J. Graham, *Explosive Shocks in Air*, Springer-Verlag, 1985.

7) For the purposes of this article, no consideration is given to the possibility of debris from a mortar explosion reaching spectator areas. For the most part, when using the NFPA distances, this can only occur for steel mortars, and then the 50-mm (2-in.) separation will make essentially no difference in limiting the range of those fragments.

8) K. L. and B. J. Kosanke, "Computer Modeling of Aerial Shell Ballistics", *Pyrotechnica XIV* (1992). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 2 (1990 to 1992)*, Journal of Pyrotechnics, 1995.

9) K. L. and B. J. Kosanke, "Japanese Shell Break Radii," *Pyrotechnics Guild International Bulletin*, No. 59 (1988). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 1 (1981 to 1989)*, Journal of Pyrotechnics, 1995.

10) The burst spreads of the aerial shells in Figure 3 are shown as being spherical, where actually those fired from the more angled mortars would be distorted somewhat because of the motion of the shell at the time of its explosion.

11) When mortars are tilted nearly horizontal, often they will be free to recoil along the ground if a shell fires from it. This has the potential for reducing the distance to which the shell can be propelled; however, that has not been considered in Figure 3.

12) NFPA-1123 *Code Fireworks Display* (1995) 1-2.1.

13) NFPA-1123 *Code Fireworks Display* (2000) 2.4.4.1.

14) NFPA-1123 *Code Fireworks Display* (2000) 2.4.4.0.

15) NFPA-1123 *Code Fireworks Display* (2000) 2.4.5.2.

16) NFPA-1123 *Code Fireworks Display* (2000) 2.4.5.1.

An earlier version appeared in *Proceedings of the 5th International Symposium on Fireworks*, 2000.

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

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ABSTRACT

Based on the experience of a small fireworks display company with several low-breaking aerial shells, it was speculated that the cause might be related to having modified the aerial shell ignition system. To evaluate this possibility the effect of various levels of ignition stimuli on the performance of aerial shell Black Powder lift charges was briefly investigated. The purpose of the study was to scope the nature and magnitude of any resulting effects. Armed with that information it would then be possible to better design a more extensive study if needed.

Three levels of ignition stimuli were used: hot-wire igniters, electric matches, and fireworks quick match. Using identical test shells, upon firing, no statistically significant differences were found in their times of flight and mortar pressure impulses. Thus, either the low breaks were the result of something unrelated to ignition stimulus, or the statistically small number of trials was not sufficient to identify the effect.

Introduction

A few years ago, the owner of a small fireworks display company was experiencing what he felt was an abnormally large number of significantly low breaking shells (a few percent). These appeared to be the result of those shells being weakly propelled from the mortars. These were aerial shells of Chinese manufacture that had been modified by the display company for their use in electrically fired displays. The quick match shell leaders were removed and replaced with electric matches inserted directly into the lift charge. Obviously, one possible explanation for the low breaks was a deficiency associated with the lift charge of some of the shells. The deficiency could be simply an insufficient amount of Black Powder, or that the powder was of poor quality and thus burned too slowly to be fully effective. However, a few displays had also been performed where the quick match had not been removed, and during which there seemed to be many fewer low breaks. Accordingly, speculation about potential causes was expanded to include the possible effect of a relatively weaker ignition stimulus level being provided by an electric match in comparison to that provided by a jet of burning gas from a vigorously burning quick match shell leader.

Background

McLain has reported[1] that varying levels of ignition stimulus can produce differences in pyrotechnic output. To some extent, Shimizu also documents[2] the effect of varying the level of ignition stimulus. He reports that the velocity of propagation for flash powders can be substantially greater when initiated using a detonator (blasting cap) in comparison to that produced by thermal ignition. For example, a potassium perchlorate, aluminum, and sulfur flash powder (in a ratio of 70:27:3, respectively) propagated at approximately 870 m/s when an electric igniter was used, as compared with a rate of 1420 m/s when initiated using a number 8 detonator.

In addition to McLain's and Shimizu's reports, the authors' found indirect evidence suggesting that the internal ballistics of aerial shells

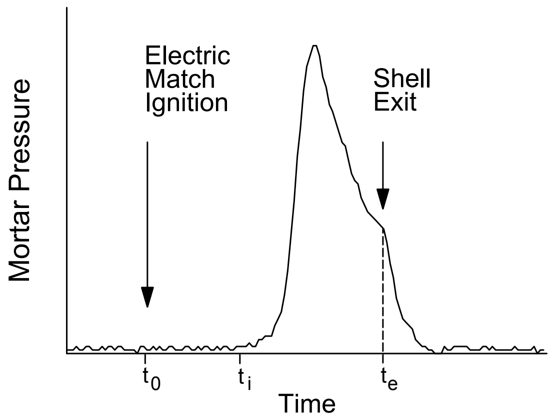

Figure 1. A typical mortar pressure profile during the firing of an aerial shell.

are quite sensitive to relatively minor changes in ignition stimulus. During laboratory measurements, it was found that surprisingly large variations in peak mortar pressure and muzzle velocity occur for apparently identical shell and lift powder configurations.[3–6] One possible explanation for this is that small differences occurring in the earliest stages of lift charge burning are responsible for relatively large differences in the propulsion of the aerial shells. Limited support for this theory can be seen in the lift pressure profile in a mortar as a shell is fired (lift pressure as a function of time). (See Figure 1.) For approximately half of the time (t_0 to t_i) between igniting the lift powder and the expulsion of the aerial shell (t_0 to t_e), there is no significant pressure rise. Presumably this apparently quiescent period is the time taken for the fire to spread through the grains of Black Powder before the burning becomes vigorous enough to cause a measurable rise in pressure. If that is the case, it is certainly possible that changing the manner of ignition of the lift powder could change the dynamics of the early fire spread and thus produce a significant difference in the propulsion of aerial shells. More support for this theory was found when it was discovered that lift performance can be significantly affected by relatively small changes in the point of ignition with all else being constant.[4]

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

However, to the contrary, if a weak ignition stimulus was the cause of the low break problem, then why did the problem not occur in many more of the Chinese shells being fired using an electric match? Further, why had other display companies, that also used electric matches installed directly into the lift charges, not been reporting similar problems? Despite these possible contrary indications, it seemed that the ignition stimulus hypothesis was worth further consideration; not only because it might be related to the low break problem, but also because it might help to explain the large variations in lift performance observed experimentally during the firing of what seemed to be identical aerial shells. Accordingly, a brief study was undertaken to investigate the effect of various levels of ignition stimulus on lift powder performance.

Experimental

In this scoping study, 3-inch (75-mm) aerial shells were used. This was for reasons of cost and because the display company felt that most of the low breaks occurred with small diameter shells. In the first part of this investigation the lift charges were harvested from three shells of each of the brands to be studied—Thunderbird, Sunny and Jumping Jack. In physical appearance, the Thunderbird and Jumping Jack powders were indistinguishable. Sieve analyses of the powers were performed, with the results shown in Table 1 and discussed below.

The general performance of lift powder for each shell brand was then evaluated using an apparatus designed to simulate the conditions during the firing of small aerial shells.[4] In this apparatus, a loose fitting projectile is fired from

Table 1. Sieve Analysis for Test Shell Lift Powders.

Powder Type	Percent in Mesh Fraction			
	+12	12–20	20–30	–30
Jumping Jack	33.8	66.0	0.2	0.0
Thunderbird	31.3	68.1	0.6	0.0
Sunny	0.0	46.8	46.9	6.3

(Mesh numbers are for US Standard Sieves.)

a test mortar fitted with a series of trip wires. Upon firing, the timing of the breaking of the trip wires was used to determine the speed of the projectile. In addition, the mortar pressure profiles were measured and digitally recorded. To accomplish a reliable comparison between the three powder types, in these tests, only their 12–20 mesh fractions were used. For each firing the charge mass was 5.0 g (0.18 oz), the temperature of the powder and combustion chamber was maintained at 80 ºF (27 ºC), the apparatus was in its normal configuration, and three test firings were conducted for each powder type. Averages for each set of three firings are presented in Table 2. In the reported results, "Delay Time" is the interval of time between the application of current to the electric match (t_0) and the first detectable rise in pressure in the mortar (t_i). (The firing time of the electric match under these conditions was previously measured to be less than 1 ms.) In Table 2, "Impulse Time" is the interval of time between the first detectable pressure rise (t_i) and when the projectile exits the mortar portion of the apparatus (t_e). Exit times were determined by the change in slope of the pressure curves (See Figure 1.) and verified by the trip-wire data. (These results are discussed below.)

The main portion of this study was the investigation the effect of varying levels of ignition stimulus on the actual firing of aerial shells. For these tests, the three methods of ignition were used. It is believed that the weakest ignition stimulus was that produced using a simple hot wire igniter. This was hand made using a short length of 26 gauge (American Wire Gauge) nichrome wire attached to 22 gauge copper leg wires. The next greater stimulus is thought to be that produced using an electric match (Daveyfire SA-2000). The third level of ignition stimulus, thought to be the highest level, was that produced by a length of quick match. In each case, the end of the igniter was introduced into the approximate middle of a small plastic bag of lift powder. To provide fairly constant geometry and dead volume, the bag of lift powder was placed in a small paper cup that was then taped to the bottom of the test shell.

To have a high degree of uniformity among the test aerial shells, the original shells were not used, rather nine inert shells were prepared for firing. Each test shell weighed 130 g (4.6 oz), was 2.62 in. (67 mm) in diameter, and was made of plastic. The amount and type of lift powder on the various test shells was the same as that used by the three shell manufacturers. There were 34 g (1.2 oz) of Thunderbird's lift used on three test shells, one each using the three ignition methods. Similarly, 25 g (0.9 oz) of Sunny's lift was used on three test shells, and 30 g (1.1 oz) of Jumping Jack's lift was used on three shells. (See Figure 2 for an illustration of the component parts of the test shells, including the three types of igniters.) The assembled test shells were fired at an ambient temperature of 55 ºF (13 ºC) from a steel mortar 3.10 in. (79 mm) ID, 24 in. (0.61 m) long, and instrumented with a piezoelectric pressure transducer.[7] The re-

Table 2. Average Performance Test Results for the Three Lift Powders.

Powder Type	Muzzle Velocity (ft/s)	Peak Pressure (psi)	Impulse Time (ms)	Delay Time (ms)
Jumping Jack	170	54	7.8	15
Thunderbird	170	52	7.7	17
Sunny	210	64	7.2	17

To convert feet per second (ft/s) to meters per second (m/s), divide by 3.29.
To convert pounds per square inch (psi) to kilopascals (kPa), multiply by 6.89.
Because of the limited number of trials, results are reported to only 2 significant figures.

sults from the three sets of three test firings are reported in Table 3. In each case, the time of flight (ToF) reported is the average of the times determined by two people using stop watches to determine the total flight times of the test shells. Peak pressure (P. Pres.) is the maximum pressure measured during each firing. Pressure impulse (Imp.) is the area under the pressure versus time curve for each firing up until the exit of the test shell.

Discussion

Based on their physical appearance, particle size distributions (Table 1) and performance data (Table 2), it seems fairly likely that Jumping Jack and Thunderbird lift powders are from the same source. It also appears that the Sunny lift powder is a little more effective than the others and is probably why a somewhat smaller amount was used on the Sunny shells [25 g (0.9 oz) versus 30 g (1.1 oz) and 34 g (1.2 oz) for the Jumping Jack and Thunderbird shells, respectively]. As essentially identical ballistic bodies, the times of flight of the test shells are a good (although not a linear) indication of the relative heights reached by the shells. Further, for essentially identical test shells, pressure impulse is a good measure of the shell's muzzle velocity[5] and thus the height reached by the shells. The results from this limited series of trials are reported in Table 3 and offer no support for the hypothesis that the cause of the low breaking shells was the result of substituting electric matches for quick match into the lift

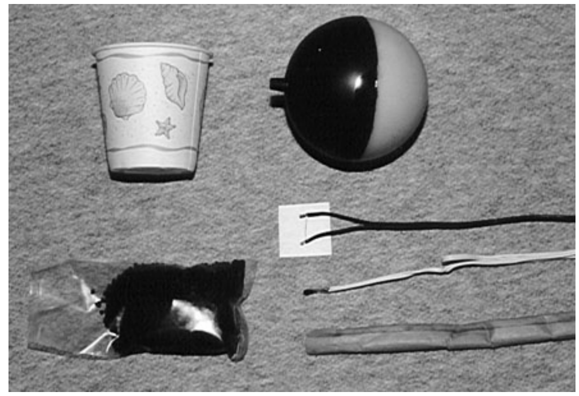

Figure 2. Photograph of the component parts of the test shells.

charges. That is to say, to within the limits of statistical uncertainty in the data, no difference was found in the propulsion of the test shells for the presumed three levels of ignition stimulus used.

A fairly wide range of ballistic performance is observed even for apparently identical aerial shells.[3–6] Thus it is not expected that making a change in ignition stimulus would necessarily cause all the test shells fired with electric matches to be significantly under propelled. Further, with only three test firings, it certainly is possible that none would be significantly under propelled. Thus, while it is possible there is essentially no effect from using the three lift powder ignition methods, these results cannot be interpreted as being conclusive. However, as a minimum, the results identify that a more extensive study is needed (using more shells and

Table 3. Results from the Firing of the Series of Test Shells.

Shell Mfg.	Hot-wire ToF (s)	Hot-wire P. Pres. (psi)	Hot-wire Imp. (psi s)	Electric Match ToF (s)	Electric Match P. Pres. (psi)	Electric Match Imp. (psi s)	Quick Match ToF (s)	Quick Match P. Pres. (psi)	Quick Match Imp. (psi s)
Thunderbird	7.6	26	1.2	7.8	23	1.2	7.9	26	1.3
Sunny	8.8	37	1.6	7.6	34	1.2	9.4	42	2.0
Jumping Jack	7.6	24	1.2	8.1	30	1.5	6.4	18	0.8
Average	8.0	29	1.3	7.8	29	1.3	7.9	29	1.4

Note that, "ToF" is aerial shell time of flight, "P. Pres." is peak internal mortar pressure, and "Imp." is pressure impulse acting on the aerial shell while it is in the mortar.

To convert pounds per square inch (psi) and psi-seconds (psi s) to kilopascals (kPa) and kPa-seconds (kPa s), multiply by 6.89.

Because of the limited number of trials, results are reported to only 2-significant figures.

possibly considering more potential explanations). It is hoped that a follow-on study will be undertaken in the future.

Acknowledgements

The authors wish to acknowledge Alan Broca of Daveyfire for providing the electric matches used in these tests. Further the authors wish to thank Scot Anderson and Charlie Wilson for their suggestions and assistance in preparing the shells for testing.

References / Notes

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3) K. L. and B. J. Kosanke, "Hypothesis Explaining Muzzle Breaks", *Proc. 2nd Int'l. Symp. Fireworks* (1994). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996.

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

6) K. L. and B. J. Kosanke, unpublished muzzle velocity measurements of fireworks aerial shells.

7) The pressure gauges were PCB Piezotronics 101A04, connected to PCB Piezotronics 480D06 amplifying power supplies. The data was recorded using Fluke Scopemeters model 95 or 97, then transferred to a computer for processing.

An earlier version appeared in *Journal of Pyrotechnics*, No. 11, 2000.

Pyrotechnic Particle Morphologies — Metal Fuels

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ABSTRACT

The morphology (size, shape and surface features) of the constituent particles in a pyrotechnic composition affects its performance. This is particularly true of metal fuel particles in the composition. Particle morphology can also constitute an important part of forensically establishing a match between materials of known origin and evidence. This article catalogs and briefly discusses some characteristic features commonly associated with metal fuels in pyrotechnic compositions.

Keywords: morphology, forensics, metal fuels, pyrotechnics

Introduction

Morphology is a term borrowed from biology for describing the appearance of organisms. In pyrotechnics and forensics the term is often used to denote information about the size, shape and surface features of particles, where knowledge of these attributes is frequently important. In pyrotechnics, particle morphology influences such things as the ease of ignition and burn rate of a composition.[1] While this is true in general, it is especially true for the fuel particles in those compositions. This is because the oxidizer(s) will usually have melted below the ignition temperature of the composition, whereas the fuel particles usually will not have. (See Table 1 for examples.) Large particle size, rounded shape, and smooth surface features all tend to make ignition more difficult and the burn rate slower. Accordingly, knowledge of a composition's particle morphology is important in any attempt to predict (or control) the ignition and propagation properties of a pyrotechnic composition.

Table 1. Examples of Melting Points (in °C) of Some Common Fuels and Oxidizers.

Fuel	T_m	Oxidizer	T_m
Aluminum	660	Ammonium perchlorate	d ~150
Boron	2300	Barium peroxide	450
Iron	1535	Potassium chlorate	356
Magnesium	649	Potassium nitrate	334
Silicon	1410	Potassium perchlorate	d ~400
Titanium	1660	Sodium nitrate	307

Notes:

T_m is melting point in degrees Celsius (°C); values are taken from references 2 and 3.

d is the decomposition temperature and means the oxidizer decomposes before melting.

An important aspect of forensic science is the recognition and identification of materials, often for the purpose of determining the source of the material. Typically this would be accomplished by attempting to physically and chemically compare items of evidence with materials from known sources. In attempting to determine whether two materials match, various attributes of the two are compared and contrasted. The degree of certainty of the match is a function of the number of attributes compared and the degree to which they are identical.[4] For pyrotechnic compositions, one important part of this matching process should be a comparison of the morphologies of the materials. Probably the best

Table 2. Information for Some Common US Sieve Mesh Sizes.

Mesh Number	Opening (in./1000)	Opening (micron)
10	79	2000
20	33	850
40	16	425
60	9.8	250
100	5.9	150
140	4.1	106
200	2.9	75
325	1.7	45
400	1.5	38

Note that particles smaller than about 400 mesh are typically only described in terms of their physical size, usually in microns.

Table 3. Metals Used in Pyrotechnics.

Commonly Used	Occasionally Used[(a)]
Aluminum	Chromium
Boron[(b)]	Copper
Iron	Manganese
Magnesium	Molybdenum
Silicon[(b)]	Nickel
Titanium	Selenium
	Tellurium
	Tungsten
	Zinc
	Zirconium

(a) Many of these are only used in military items, some of which are being phased out.

(b) A metalloid, not strictly a metal.

known and most complete work on this subject are the writings of McCrone and Delly.[5] This multi-volume treatise provides extensive overall information. However, of necessity, it tends to include only a few of the most common chemicals, and then only in one form. The emphasis is on identification of the nature of the chemical. This is valuable information but it falls short of what is needed to determine whether a firm match exists between materials.

This article presents general information about particle morphology of metal fuel particles used in pyrotechnics. This is augmented with a series of electron micrographs as illustrations.

Particle Size

As a rule, the size of metal fuel particles in a pyrotechnic composition is less than 100 mesh, and they are often less than 400 mesh (see Table 2 for a list of some common mesh sizes and their openings). Metal particles added to a composition for the purpose of producing spark effects are an exception. This often requires that the particles be large enough so as not to be completely consumed during their passage through the reaction zone and flame of a burning pyrotechnic composition.[6] Such particles may be as large as 10 mesh. Table 3 is a list of metals commonly present in pyrotechnic compositions. Some examples of aluminum particle types and sizes used in pyrotechnics and fireworks are presented in Table 4.

All metal powders used in pyrotechnics have a range of individual particle sizes; for some the range is narrow, for others it is quite broad. (Collectively, the figures in this article are examples of the typical range of particle size for metal powders commonly used in pyrotechnics.) Further, in the authors' experience, both the average particle size and the range of particle size can differ somewhat from lot to lot from the same manufacturer. In terms of consistent performance, this can be frustrating for the pyrotechnists. However, for a forensic analyst this can help determine the degree to which a match exists between two materials. (As a word of caution, it must be recognized that even between different points within a single drum, there can be some differences in average particle size and the range of size, although generally these would be rather subtle differences.)

In general, the most expeditious method for determining particle size of bulk powders is by performing a sieve analysis. In this process, a sample of powder is passed through a series of successively finer sieves (typically in a stack that is mechanically agitated). The fraction (by mass) of material that is retained on each sieve is then reported, along with the amount passing the finest sieve. However, for mixed materials such as a pyrotechnic composition, or when only very small amounts of material are avail-

Table 4. Information about Some of the Aluminum Powders Used in Pyrotechnics.[7]

Description — Common Name (Approximate Size Range)	Commonly Used in	Purpose — Effect Produced
Flake — Coarse Flitters (10–28 mesh / 700–2000 μ)	Fireworks comet stars, waterfalls, and fountains	Long duration white sparks
Flake — Fine Flitters (20–80 mesh / 200–850 μ)	Fireworks comet stars, waterfalls, and fountains	Medium duration white sparks
Flake — Bright (≈325 mesh / ≈35 μ)	Fireworks comet stars & fountains	Short duration white sparks
	Large fireworks salutes	Explosive sound or report
Flake — Dark (≈15 μ)	Medium fireworks salutes	Explosive sound or report
	Military simulators	Explosive sound or report
Flake — German Dark (≈5 μ)	Small fireworks salutes	Explosive sound or report
Atomized — Granular Blown (50–150 mesh / 100–350 μ)	Fireworks comet stars and fountains	Long duration white sparks
	Military thermite	Heat and molten iron
Atomized — Spherical (–400 mesh / ≈30 μ)	Fireworks glitter stars / fountains	Delayed trailing flashes
	Composite rocket propellant	Energy production
Atomized — Spheroidal (≈20 μ)	Fireworks color stars	Flame brightening
	Military photo-flash	Intense light production
Atomized — Spherical (≈10 μ)	Fireworks glitter stars / fountains	Delayed trailing flashes
	Military igniters	Thermal energy
Atomized — Spheroidal (≈5 μ)	Large fireworks Salutes	Explosive sound or report
	Fireworks color stars	Flame brightening

able, a sieve analysis to report such “mesh fractions” is often not possible. In that case a microscopic investigation is a common approach, whereby the physical dimensions of a large number of individual particles are measured and reported. For a light microscope this involves the use of a calibrated reticule in the eyepiece or associated with the slide mounting. For an electron microscope, the instrument provides scale information associated with the images produced. These procedures can be performed manually. However, in many cases, computer assisted image analysis can be used.

Particle Shape

A range of particle shapes are used in pyrotechnic compositions, and like particle size, shape also affects ignition and propagation characteristics.[1] Details of particle shape can also provide the basis for forensic comparison of metal powders. Normally it is the manner of production of the material that is the determining factor for particle shape. Atomization (spraying molten metal through an orifice and allowing it to solidify as it falls to a collection area) produces particles that are spheroids. Often, atomization produces nearly perfect spheres, see Figure 1. However, when the metal is quite reactive and when the atmosphere into which the metal is sprayed is not completely inert, much less perfect spheres are often produced.

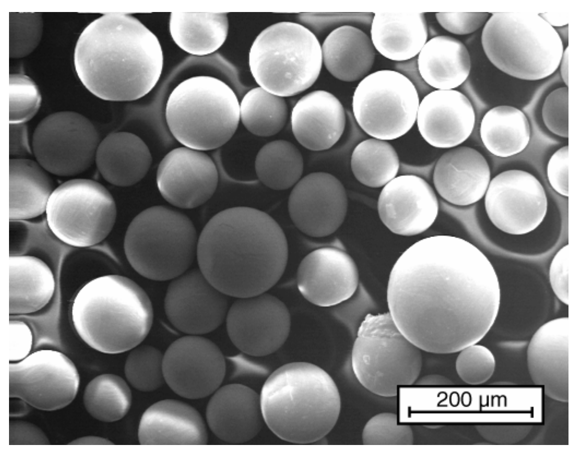

Figure 1. Example of nearly perfect spherical particles of titanium produced by atomization (100 ×).

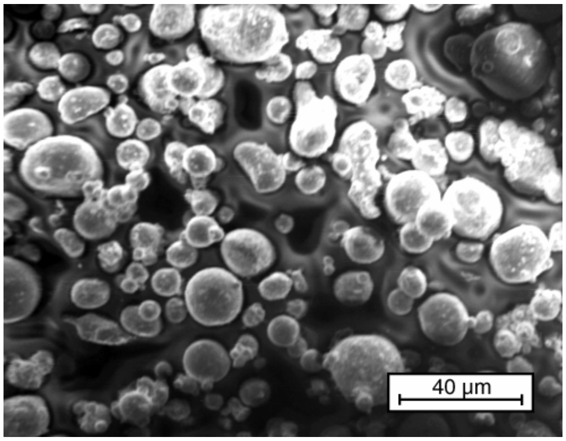

Figure 2. Example of so-called spherical atomized aluminum (500 ×).

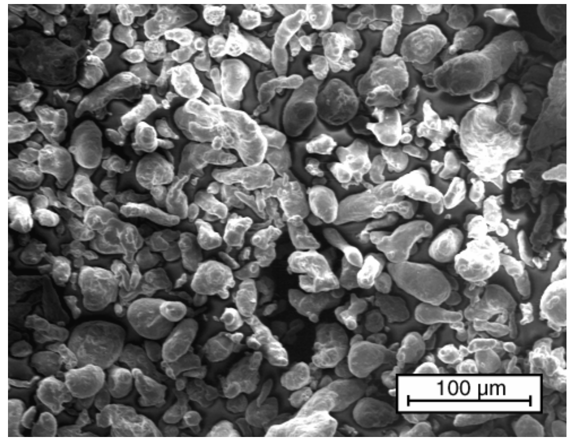

Figure 3. Example of so-called spheroidal atomized aluminum (200 ×).

Aluminum, because of its ability to quickly form a rigid oxide coating, produces a good example of this. Even when using relatively inert atmospheres, the so-called spherical atomized aluminum particles are less than perfect spheres, see Figure 2. Further, when the atmosphere used contains even a modest amount of oxygen, highly distorted spheroids are produced; see Figure 3.

Depending to some extent on the physical properties of the metal, mechanical diminution such as grinding is possible. This produces metal particles that tend to have sharp angular features like the example in Figure 4. While it is somewhat unusual to produce granular aluminum powders, it is common for some aluminum alloys, such as those with iron, titanium and magnesium, to be produced by grinding. Because of their sharp, angular features, particles that have been ground will be more reactive than those of the same size produced by atomization. Also, the sharp, angular features of the ground particles make them fairly easy to differentiate from atomized particles. However, one type of atomized aluminum, so-called "blown" aluminum, has surface features (coarse texturing) that may at first appear somewhat similar to ground particles, see Figure 5. This type of aluminum powder is generally atomized as fairly large particles (20 to 100 mesh / 150 to

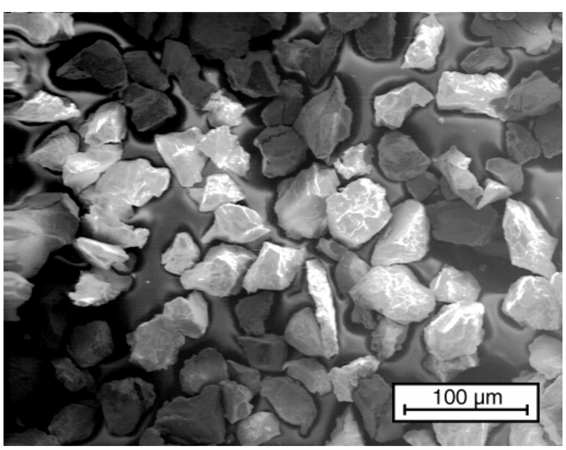

Figure 4. Example of ferro-aluminum alloy particles prepared by grinding (200 ×).

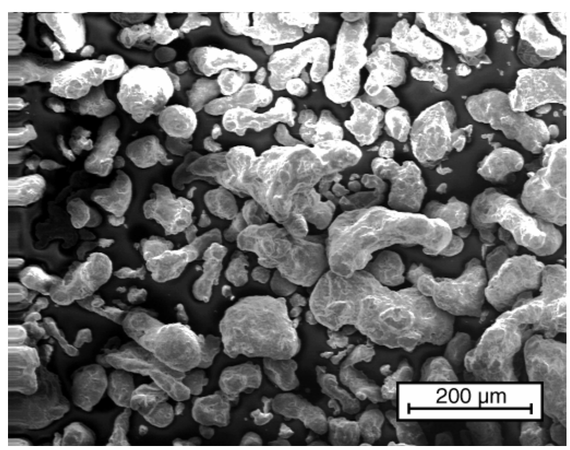

Figure 5. Example of "blown" atomized aluminum particles (100 ×).

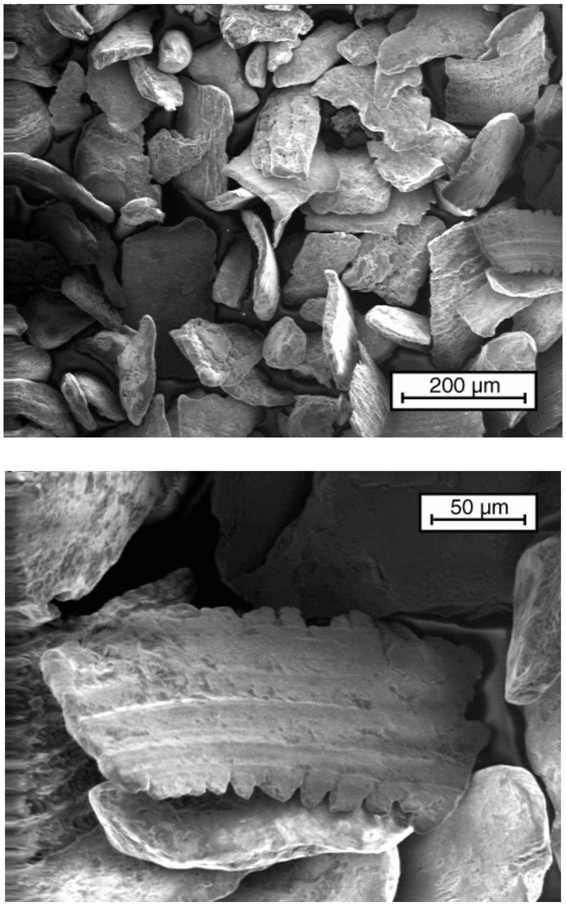

Figure 6. Example of titanium metal turnings at two magnifications (100 and 300 ×).

850 μ) and in an atmosphere that has a relatively large oxygen content. This causes the rapid formation of an aluminum oxide crust, and the resulting particles are far from being spherical. The diagnostic feature differentiating blown atomized aluminum from granular aluminum powders is the nature of their edges and surface features. For blown aluminum these appear rounded and not sharp, as is the case for ground aluminum alloy particles.

Another type of mechanical particle size reduction is by chipping. This may be the primary intent of the operation, or it may be that the material is a byproduct produced when machining metal parts (turning or milling). These particles tend to have two dimensions that are relatively large and a third that is less, either producing large flake-like particles, or long thin strips of material. The large flake-like particles are generally too large for use directly as a pyrotechnic fuel, but may be suitable for producing pyrotechnic spark effects. Chipped material is often further reduced in size by a secondary process such as hammer milling. Figure 6 is an example of titanium metal turnings that have been hammer milled to break the largest particles into smaller ones (hammer milling will not reduce the thin dimension of such particles). That these large flake-like particles were produced from machine turnings, is fairly obvious in the higher magnification micrograph where tool marks are obvious.

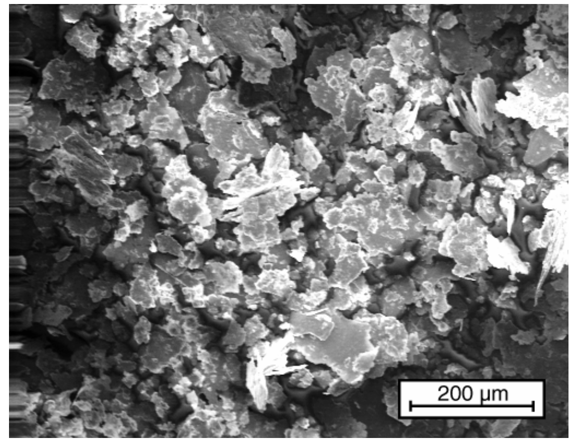

Figure 7. Example of flake aluminum powder (100 ×).

A third type of mechanical particle diminution is the stamping or milling of already tiny particles to produce thin flakes. For malleable metals, this method is quite common, and it is one of the most common methods for the production of aluminum metal powders, especially for those with the greatest surface area to mass ratios. For the same nominal mesh size materials, flakes tend to have the greatest reactivity as compared with the other powder forms. This is because, while one or two flake dimensions may be substantial, the third dimension is generally quite small in comparison. Accordingly flakes can be raised more quickly to their ignition temperature, tending to make pyrotechnic compositions containing them easier to ignite and faster to propagate. Flaked metal powders have a physical appearance that is fairly distinct and identifiable, see Figure 7.

Metal powders can be produced in other, less common ways. For example, flaked mate-

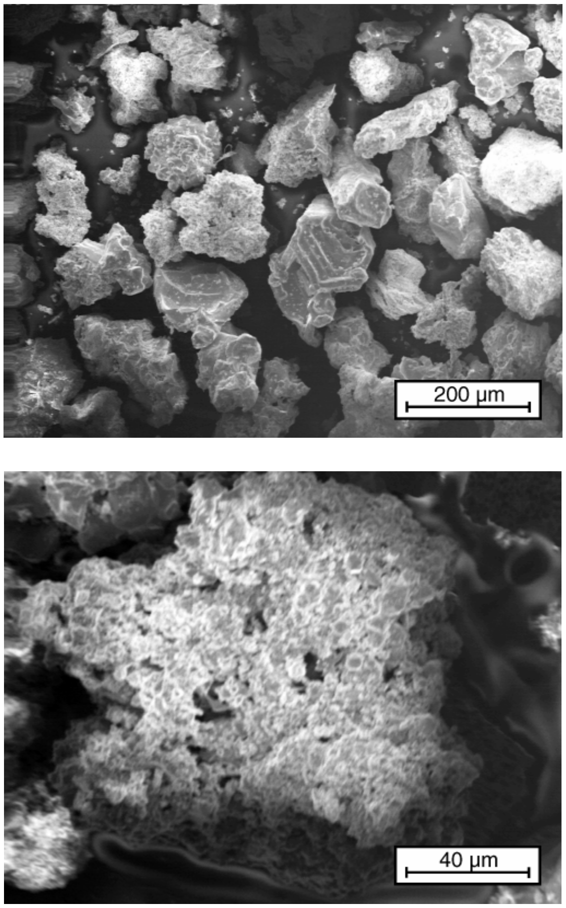

Figure 8. Example of titanium sponge, two magnifications, (100 and 500 ×).

rial can be made by stamping from foil; however, this tends to produce materials that are too large and too thick to be of much use in pyrotechnics.

Surface Features

Particle surface features can significantly affect the reactivity of metal fuel particles. Probably the best-known example of this in pyrotechnics is so-called titanium "sponge". This is the initial product of normal titanium production, wherein titanium tetrachloride is reacted with magnesium metal. Titanium sponge is quite porous, giving it the appearance vaguely like that of the biological organism for which it is named. While this may not be entirely obvious at low magnification, the structure and porosity becomes more apparent at higher magnifications (see Figure 8). These same features are also easily recognizable as a characteristic that

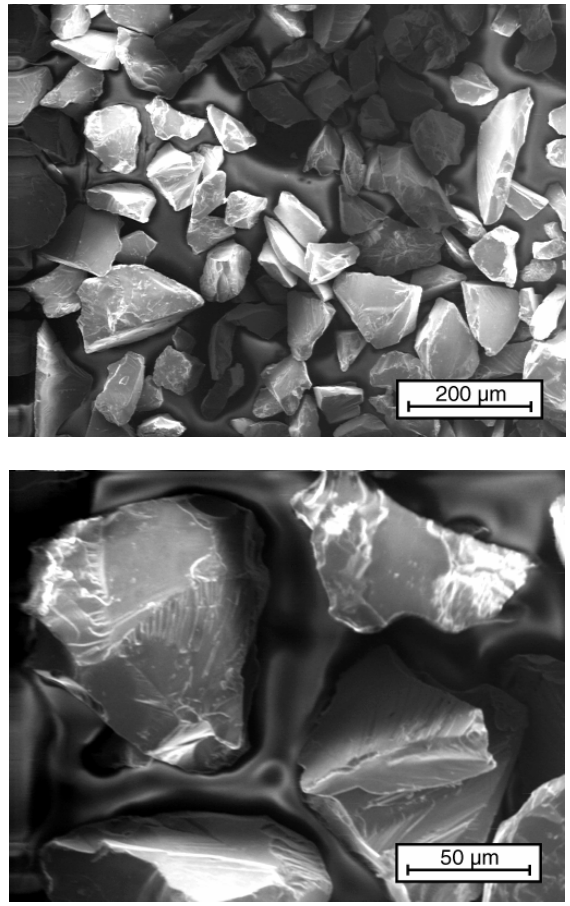

Figure 9. Example of surface features of magnalium, two magnifications (100 and 400 ×).

is useful in identifying the material. Pyrotechnically, it is because of the pores and fine surface structures that titanium sponge ignites easily and can be propelled at very high velocity through the air without being extinguished.

Particle size reduction of especially brittle metals can produce interesting and characteristic surface features. For example, fracture patterns and "whiskers" are seen in Figure 9 of the 50:50 alloy of aluminum and magnesium (often called "magnalium" in pyrotechnics). While these surface features are not thought to significantly affect pyrotechnic reactivity, they certainly help characterize the particles. Similarly, the two examples of surface features mentioned earlier in this article (coarse surface texturing on blown aluminum and tool marks on titanium turnings) are unlikely to have a noticeable affect on pyrotechnic reactivity, but can be diagnostic in terms of helping to establish a match between materials.

Conclusion

Experience has taught pyrotechnists that particle size, shape and surface features are important controlling factors for ease of ignition (both intentional and accidental) and for burn rate once ignited. Accordingly, knowledge of these attributes is an important first step in designing a pyrotechnic composition or altering the performance of a composition once formulated. From a forensic standard point, these same particle attributes constitute an important part of the basis for establishing a reliable identification of pyrotechnic materials or a match between known and suspect materials. Accordingly, for pyrotechnists it is hoped that this short article provided some information about the physical nature of some of the metal powders being used. For forensic analysts it is hoped that this article has suggested some additional points of comparison that might prove to be useful in their efforts to identify the components of pyrotechnic materials.

Acknowledgements

The authors are grateful for the suggestions of J. Bergman, J. Giacalone, F. Whitehurst, and W. Smith on an earlier draft of this paper.

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An earlier version appeared in *Fireworks Business*, No. 197, 2000.

Peak Mortar Pressures when Firing Spherical Aerial Shells

K. L. and B. J. Kosanke

The Pyrotechnics Committee of the National Fire Protection Association (NFPA) recently revised the *Code for Fireworks Displays,* NFPA 1123. The revised code included recommendations for wall thickness for fiberglass mortars and for larger sizes of high-density polyethylene mortars. In anticipation of the committee's discussions of the needed strength of mortars, the authors decided to assemble data on typical peak mortar pressure as a function of aerial shell size. Because of the limited amount of data located, one could not be overly selective (i.e., essentially all available data was used[1–4]). Obviously, it would have been preferred to have had an abundance of data for a wide range of typical shells fired under a wide range of known conditions. Nonetheless, the amount and type of data (136 measurements for spherical shells) is felt to be sufficient to establish approximate averages of peak mortar pressure for spherical aerial shells as a function of their size. This short article was prepared in the hope that some readers would find this data useful (or at least interesting).

Figure 1 is a mortar pressure profile that illustrates internal mortar pressure as a function of time during a typical shell firing. First there is an extended period of time (t_0 to t_i) during which there is effectively no pressure rise. This length of time is commonly 15 to 20 ms (thousandths of a second). This would seem to be 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. Then a rapidly accelerating increase in mortar pressure occurs up to some peak value, generally occurring over a period of 5 to 10 ms. Next, as the shell accelerates upward and the rate of gas production decreases, mortar pressure drops during the time before the shell exits the mortar. This pressure drop generally continues for 10 to 15 ms. Finally, the exiting of the shell (at time t_e) causes an even more precipitous drop in pressure back to ambient levels. The total time taken for shells to exit (t_0 to t_e) typically ranges from approximately 45 ms for small shells to less than 30 ms for large shells.[5]

Averages of peak internal mortar pressure data, as a function of spherical shell size, are presented in Table 1. (Also included in Table 1 are the numbers of individual measurements used for each size shell.) These data are also plotted in Figure 2. The curve in Figure 2 assumes the data is linear and passes through zero—an assumption that appears generally valid. Using this linear relationship, refined estimates for typical peak mortar pressures can be determined, and are included as the last column in Table 1.

For the most part, these data are presented without comment. It is left for the reader to decide what (if any) use they wish to make of this information. For example, these data might be used for such things as estimating the appropriate wall thickness of mortars to fire spherical aerial shells. However, if this is done, it must be understood that this data cannot be applied directly to mortar strength required for cylindrical

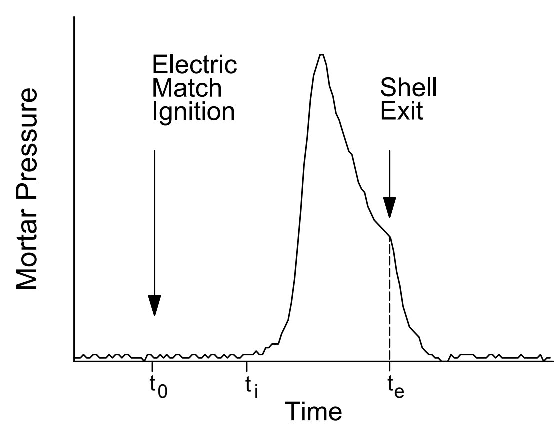

Figure 1. Typical internal mortar pressure profile during the firing of an aerial shell.

Table 1. Average Peak Internal Mortar Pressure Data.

Shell Size(a) (in.)	Num. of Meas.(b)	Meas. Pres.(c) (psi)	Fitted Pres.(d) (psi)
3	22	32	41
4	12	65	54
5	5	78	68
6	20	78	82
8	34	114	106
10	28	129	136
12	15	154	163

(a) Nominal spherical aerial shell size.

(b) The number of measurements used for this size shell.

(c) Average measured peak internal mortar pressure.

(d) Peak internal mortar pressure from the straight line visually fitted to the measured data.

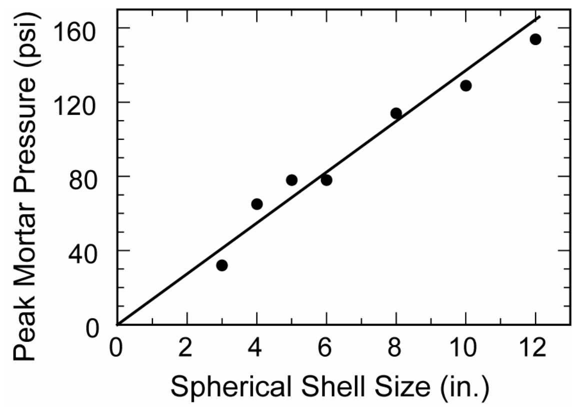

Figure 2. Graph of average peak internal mortar pressure as a function of spherical shell size.

aerial shells. The reason is that cylindrical shells produce considerably greater internal mortar pressures. This is the result of the combined effect of their greater shell mass, greater lift mass, and generally reduced dead volume under the shells.[6] (Limited testing by the authors suggests that the peak mortar pressures for typical cylindrical shells are roughly twice that for typical spherical shells of the same size.) Obviously, multibreak cylindrical shells produce even greater internal pressures, stressing their mortars to still higher levels and requiring even stronger mortars.

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An earlier version appeared in *American Fireworks News*, No. 229, 2000.

Indoor Pyrotechnic Electrostatic Discharge Hazard

K. L. Kosanke

An investigation of an unfortunate accident involving indoor pyrotechnics was completed a little while ago. This article was written in the hope that by suggesting a trivially simple step, similar accidents might be avoided in the future.

The accident occurred during the demonstration of indoor pyrotechnic effects in the course of obtaining a permit for their use. The particular effect being demonstrated was a concussion mortar. The mortars in question had not been fired for days; earlier on the day of the accident the concussion mortars had been put in place in a carpeted area; there were electric matches installed in the mortars; and firing control wiring had been attached to the electric matches, but that wiring was not connected to the firing controller. The pyrotechnic operator had previously mixed the concussion powder but had not yet loaded any of the mortars. With the one-ounce (28 g) supply of concussion powder in hand, the operator approached the first mortar. He opened the bottle of powder and poured out a cap-full of powder. As best as can be determined, as the powder was poured into the mortar, an explosion occurred involving the essentially full bottle of powder that he was holding in his other hand. The force of the explosion was sufficient to cause the traumatic amputation of some of his fingers.

One likely scenario for the cause and sequence of the accident is as follows. As the result of walking on the carpeting, the pyrotechnic operator had built-up a significant charge of static electricity on his body. As he began pouring the concussion powder, an electrostatic discharge occurred from the operator to the mortar. This might have been a result of a dielectric breakdown through the flowing powder or as the result of the pyrotechnic operator touching the metal mortar. As a result of the electrostatic discharge, the powder being poured into the mortar was ignited. (The discharge might have directly ignited the powder being poured; or the discharge might have ignited the electric match, which in turn ignited the powder.) Apparently an incendive spark produced by the burning concussion powder then entered the open bottle of powder in the pyrotechnic operator's other hand, causing the ignition and explosion of the bottle of powder, and in turn causing the severe damage to his hand.

Assuming the cause and course of the accident were as described, this accident could easily have been avoided by using a well established safety precaution. The pyrotechnic operator could simply have touched the metal concussion mortar for an instant before opening the bottle of powder. In this way the charge on the operator and that on the mortar would have been equalized by an electrostatic discharge safely occurring at that time. (Having such electrostatic discharges occur safely is the principle behind having grounded touch plates or other means of discharging personnel entering magazines and process buildings.) In the case of this accident, had the operator caused the discharge to occur by first touching the mortar, at worst the electric match installed in that mortar might have fired, or if another mortar had already been loaded with concussion powder, its electric match and powder might have fired. However, even if this had happened, assuming no one was in the proximity of the other concussion mortar, it is unlikely there would have been an injury.

Note that: as is often the case in investigating accidents, not all of the facts are clearly established or completely free of dispute; not all concussion powders and electric matches are equally sensitive to accidental ignition from electrostatic discharges; not all indoor venues are equally likely to produce electrostatic charges on people and / or equipment; and not all concussion powders produce equally powerful explosive effects. Nonetheless, while it is always appropriate to consider the hazards of each situation, it is prudent to take basic precautions as a matter of habit.

(An earlier draft of this article was reviewed by L. Weinman and G. Laib.)

An earlier version appeared in *Journal of Pyrotechnics*, No. 12, 2000.

Pyrotechnic Particle Morphology—Low Melting Point Oxidizers

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ABSTRACT

The morphology (size, shape and surface features) of the constituent particles in a pyrotechnic composition affects its performance. While this is particularly true for high melting point fuels and oxidizers in the composition, to a lesser extent it is also true for those with low melting points. Particle morphology also constitutes an important part of establishing the likelihood of a forensic match between evidence and materials of known origin. This article catalogs and briefly discusses some morphologic features often associated with some of the most commonly used low melting point oxidizers in pyrotechnic compositions.

Keywords: morphology, oxidizer, forensics, pyrotechnics, potassium nitrate

Introduction

The term morphology is one borrowed from biology, where it is used to describe the appearance of organisms. In pyrotechnics and forensics, the term is often used to denote information about the size, shape, and surface features of particles, where knowledge of these attributes is often important. In pyrotechnics, particle morphology generally influences such things as the ease of ignition and the burn rate of a composition.[1] Large particle size, rounded shape, and smooth surface features all tend to make ignition more difficult and burn rates lower. While this is especially true for those components with high melting points (e.g., metal fuels and high melting point oxidizers), to a lesser extent it is also true for those components with low melting points (e.g., organic fuels and low melting point oxidizers). It is less important for these particles because of their tendency to have begun to melt (or decompose) below the ignition temperature of the composition. See Table 1 for melting points of some common pyrotechnic oxidizers and metal fuels.

An important aspect of forensic science is the identification of materials, often for the purpose of determining their source. Typically this would be accomplished by attempting to "match" one material (or its components) with other material(s). In attempting to determine whether two materials match, various attributes of the two are compared. The degree of certainty of the match is a function of the number of attributes compared and the degree to which they are identical.[4] For pyrotechnic compositions, one important part of the matching process should be a comparison of the morphologies of the materials. Probably the best known and most complete work on this subject are the writings of McCrone and Delly.[5] This multi-volume treatise provides extensive overall information. However, of necessity for chemicals, it tends to only include a few of the most common chemicals, and then in only one form (e.g., individually grown crystals). Their atlas emphasizes the identification of the nature of the chemical. This is valuable information but it falls short of what is needed to determine whether a firm match exists between known and evidentiary materials.

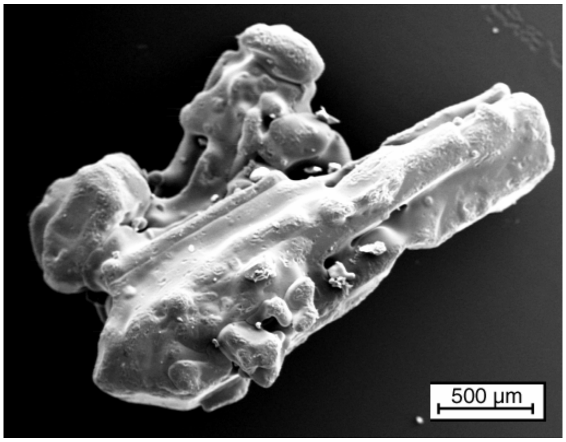


Figure 1. Micrograph of a somewhat typical initial particle of analytical reagent (AR) grade potassium nitrate (35 × magnification).

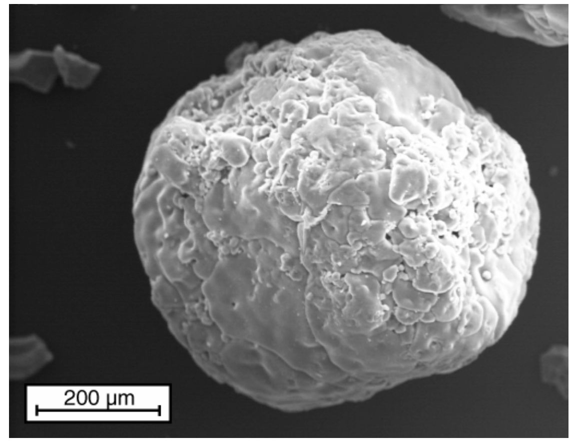


Figure 2. Micrograph of a somewhat typical initial prill of agricultural (AgP) grade potassium nitrate (100 × magnification).

This article is the second in a series on the subject of pyrotechnic particle morphology.[6] Whereas the initial article examined a number of different chemicals (metal particles), the current article considers only one. This was done for brevity and to emphasize the wide range of possible oxidizer particle morphologies for a single chemical. Potassium nitrate, the oxidizer in Black Powder (gun powder) and used extensively in fireworks, was chosen because it is probably the most frequently used pyrotechnic oxidizer. However, the information presented for potassium nitrate is generally applicable to other members of that much wider class of common oxidizers, alkali-metal and alkaline-earth nitrates, perchlorates and chlorates.

Two sources of potassium nitrate were used in this study. One source was analytical reagent (AR) grade[7] with an initial average particle size of approximately 6 to 60 mesh (3400 down to 250 microns), see Figure 1 for a somewhat typical example of its initial morphology. The other source was an agricultural prill[8] (AgP) with an initial average particle size ranging from approximately 18 to 150 mesh (1000 down to 100 microns), see Figure 2 for a somewhat typical example of its initial morphology.

Particle Size

For low-temperature oxidizers, ones that have melting points (or have begun to decompose) at

Table 1. Examples of Melting Points (in °C) for Some Common Pyrotechnic Components of Forensic Interest.

Metal Fuels	T_m (a)	High T_m Oxidizers	T_m (a)	Low T_m Oxidizers	T_m (a)
Aluminum	660	Barium sulfate	1580	Ammonium perchlorate	d ~ 150 (b)
Boron (c)	2300	Copper(II) oxide	1326	Barium peroxide	450
Iron	2535	Iron(II) oxide	1565	Potassium chlorate	356
Magnesium	649	Lead chromate	844	Potassium nitrate	334
Silicon (c)	1410	Lead(II) oxide	886	Potassium perchlorate	d ~ 400 (b)
Titanium	1660	Potassium sulfate	1069	Sodium nitrate	307

Notes: (a) The symbol T_m is the melting point in degrees Celsius (°C); values are taken from references 2 and 3.

(b) The symbol d indicates that the oxidizer decomposes before melting and is followed by the approximate decomposition temperature.

(c) These are metalloids and not strictly metals.

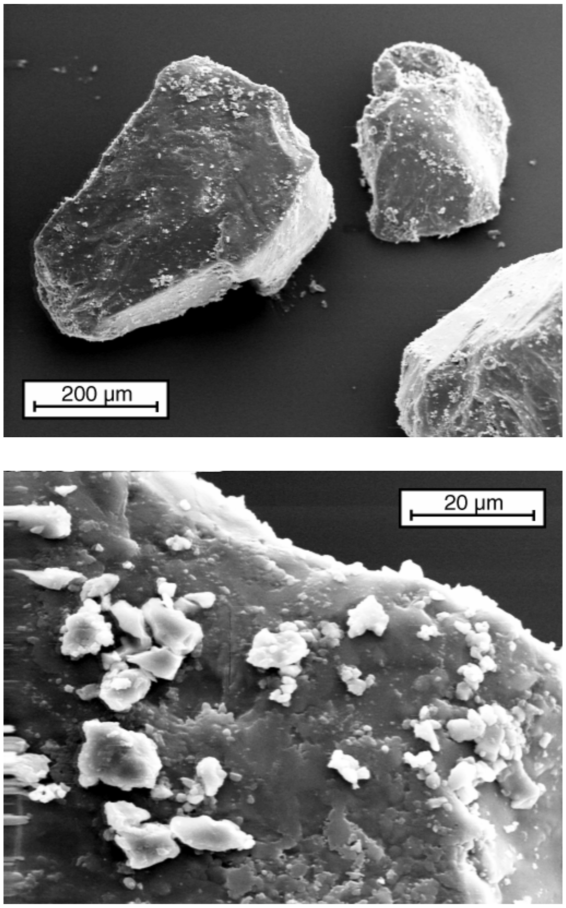


Figure 3. Two images of potassium nitrate, 60 to 100-mesh (150 to 250-micron) particles produced using a rotating disk mill. This documents the presence of many tiny particles adhering to the surface of larger particles. Upper, 100 × magnification; lower, 1000 × magnification.

temperatures below approximately 700 °C, particle size is of less importance than it is for higher melting point components. Nonetheless, relatively small particle size remains important to achieve an intimate mixing of the components of a pyrotechnic composition, and the degree of mixing plays an important role in determining burn rate and other properties of pyrotechnic compositions. Accordingly, even for low temperature oxidizers, it is common for their particle size to mostly fall in the range of 60 to 200 mesh, corresponding to particles ranging from about 250 down to 74 microns. (Of course, for high temperature oxidizers, such as some of those listed in Table 1, small particle size is even more important.[1])

Table 2. Mesh Fractions of AR Grade Potassium Nitrate Produced by Grinding.

Mesh Range(a)	Particle Size (microns)	Fraction (percent)
+60	> 250	1
–60 to +100	250 to 150	16
–100 to +200	150 to 74	31
–200 to +400	74 to 37	28
–400	< 37	24

(a) Mesh numbers are for US Standard sieves. Mesh number is the number of standard diameter wires per inch of wire mesh. A plus sign (+) means *larger than* or *fails to pass through* the specified sieve. A minus sign (–) means *smaller than* or *passes through* the sieve.

Two competing processes act to significantly widen the 60 to 200-mesh range of particle size. One is the diminution process, where most commonly some type of crushing or grinding is used to reduce the particle size to smaller than 60 mesh. In this process, as the large oxidizer crystals are broken, in addition to producing particles in the range of 60 to 200 mesh, many much smaller particles are also produced that range down to a few microns and below. For example, when a portion of AR grade potassium nitrate was processed to produce –60 mesh particles by grinding in a rotating disk mill, many particles in the 0 to 20 micron range were also produced, see Figure 3. (Note: The mill was a 4-inch (102-mm) diameter stone mill, similar to a flourmill.) The upper micrograph is at a magnification of 100 ×, and the lower micrograph is a portion of one of the same particles viewed at a magnification of 1000 ×. Notice that adhering to the surface of the larger particle are some of the very tiny particles that were produced. Table 2 presents the results of a sieve analysis of this ground material. Note that while 99 percent of the larger particles were reduced to smaller than 60 mesh (250 microns), 52 percent of those particles were reduced to smaller than 200 mesh (74 microns).

The other process affecting the range of particle size is agglomeration, the adhering of smaller particles to form larger particles. This process is aided by the presence of moisture and the passage of time. (In pyrotechnics this process is often referred to as “caking”.) An example of this was observed when a portion of AR grade potassium nitrate was ball milled for 12 hours, without first drying the material; eventually most of the smallest particles agglomerated into a few large masses inside the mill. (Note: the milling media consisted of ceramic cylinders, 0.5 inch (12 mm) diameter by 0.5 inch long, weighing 5.5 grams. Because of the relatively low density of this milling media, milling is described as being “mild”.) At that time, the particles had not yet clumped solidly together, and they still could be fairly easily broken apart when minimal finger pressure was applied to the lumps during sieving. See Figure 4 for examples of the appearance of the agglomerated particles (upper and middle micrographs) and the smaller particles from which they were formed (lower micrograph). When viewed with a visible light microscope, these large agglomerated particles have an opaque white appearance much like that of a snowball.

From a pyrotechnic performance standpoint, compositions prepared using solidly agglomerated particles of low melting point oxidizers are expected to behave somewhat differently than those made using individual solid particles. This is because the increased permeability and porosity of the agglomerated particles should affect their ignition and burning characteristics, as well as their physical properties, such as when being compacted (rammed).

Forensically, while oxidizer particle size distribution can provide potentially useful information, care must be exercised because of the possibility that agglomeration has occurred to differing extents for known and suspect materials. Accordingly, for materials such as low melting point oxidizers, a sieve analysis should be augmented with a microscopic inspection.

Particle Shape

Particle shapes tend to fall into two basic categories, rounded particles and sharp angular particles. Rounded particles may have been formed that way, such as the agricultural prill shown in Figure 2. (Prill is formed by spraying a hot concentrated solution of the chemical species into the top of a tower, where the droplets

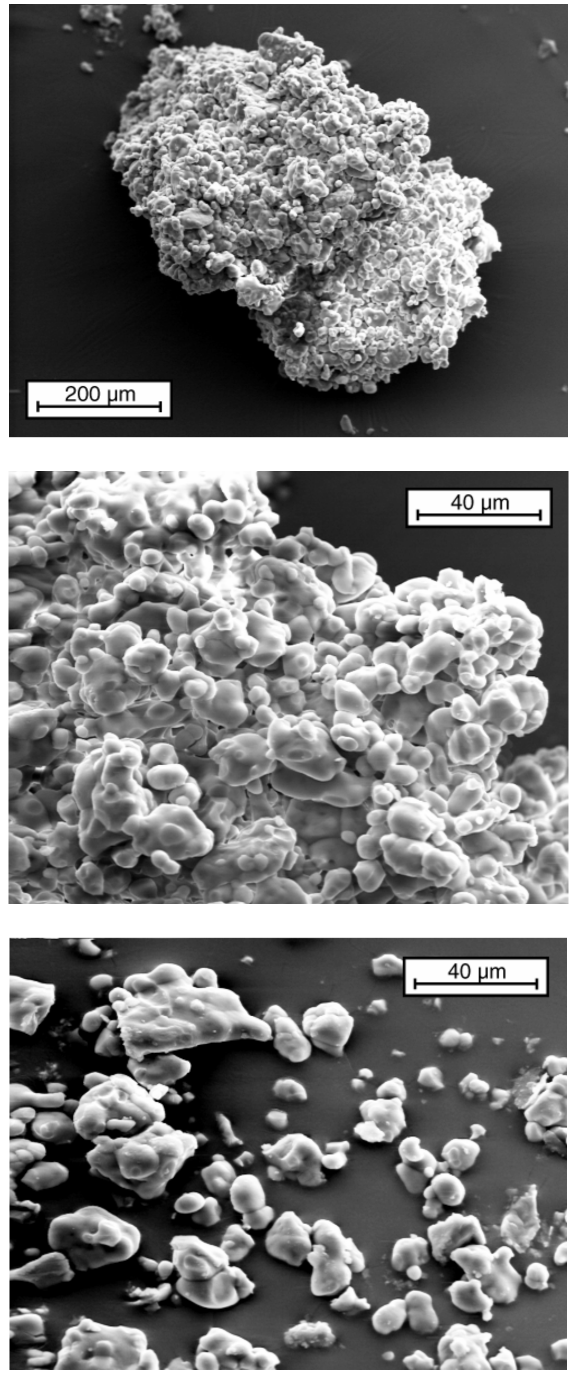


Figure 4. Two mesh fractions of undried AR grade potassium nitrate produced by mild ball milling for 12 hours. Upper, a particle in the range of 60 to 100 mesh (205 to 150 micron) at 100 × magnification; middle, the same particle at 500 × magnification; and lower, –400 mesh (< 37 micron) particles at 500 × magnification.

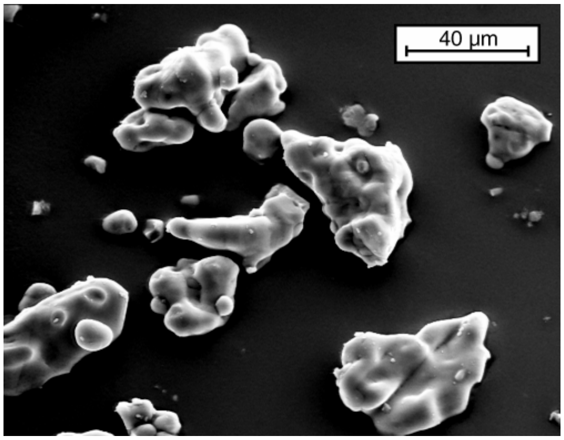


Figure 5. AR grade potassium nitrate particles from the –400 mesh (< 37 micron) fraction produced by mild ball milling for two hours (500 × magnification).

assume a fairly spherical shape when they cool and solidify as they fall.) Particles that are less spherical, but still quite rounded, can be produced during ball milling. In this case, even though the milling media chips-off and crushes particles that must initially be relatively sharp and angular, they quickly lose those features during the milling process as the particles abrade against each other. Figure 5 demonstrates the effect of even a fairly short duration (two hours) mild ball milling. Note that while these –400 mesh (< 37 micron) particles are not as small or rounded on average as those shown in the lower frame of Figure 4, where the milling continued for several more hours, they are already fairly small and quite rounded.

Particles reduced in size by grinding predominantly have sharp angular features. Whether the grinding was accomplished using a motorized disk grinder or by hand using a mortar and pestle, the result is essentially the same. The similarity in particle size distribution and angular features of the –400 mesh (< 37 micron) particles can be seen in Figure 6, in which the upper micrograph is of particles produced using the rotating disk grinder, and the lower micrograph is of particles produced using a mortar and pestle. These fairly sharp angular particles can be contrasted with those of the same size but with rounded features seen in Figures 4 and 5.

Another process that may be used for particle size reduction is coacervation. (This is purport-

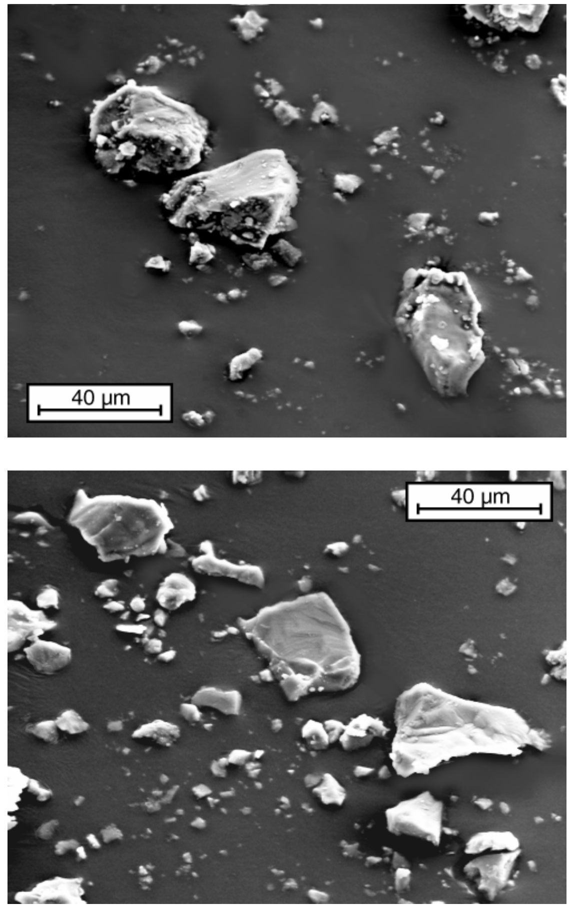


Figure 6. AR grade potassium nitrate particles from the –400 mesh (< 37 micron) fraction produced by grinding (500 × magnification). Upper fraction, produced using a rotating disk grinder; lower fraction, produced using a mortar and pestle.

edly used in the CIA's field expedient method for the manufacture of Black Powder.) In this process, large size particles are dissolved in water to make a nearly saturated solution, usually at an elevated temperature to increase the amount of material that can go into a solution. Then alcohol is added, usually quickly and while stirring vigorously. The alcohol acts to displace the dissolved material from the solution because the alcohol has a much greater solubility, and to some extent also by cooling the solution. In this process, tiny particles are formed, many of which fuse together to form larger particles, especially when not being vigorously stirred. Figure 7 documents the appearance of these particles, where the upper and middle micrographs are views of a particle, in the 60 to 100 mesh (250 to

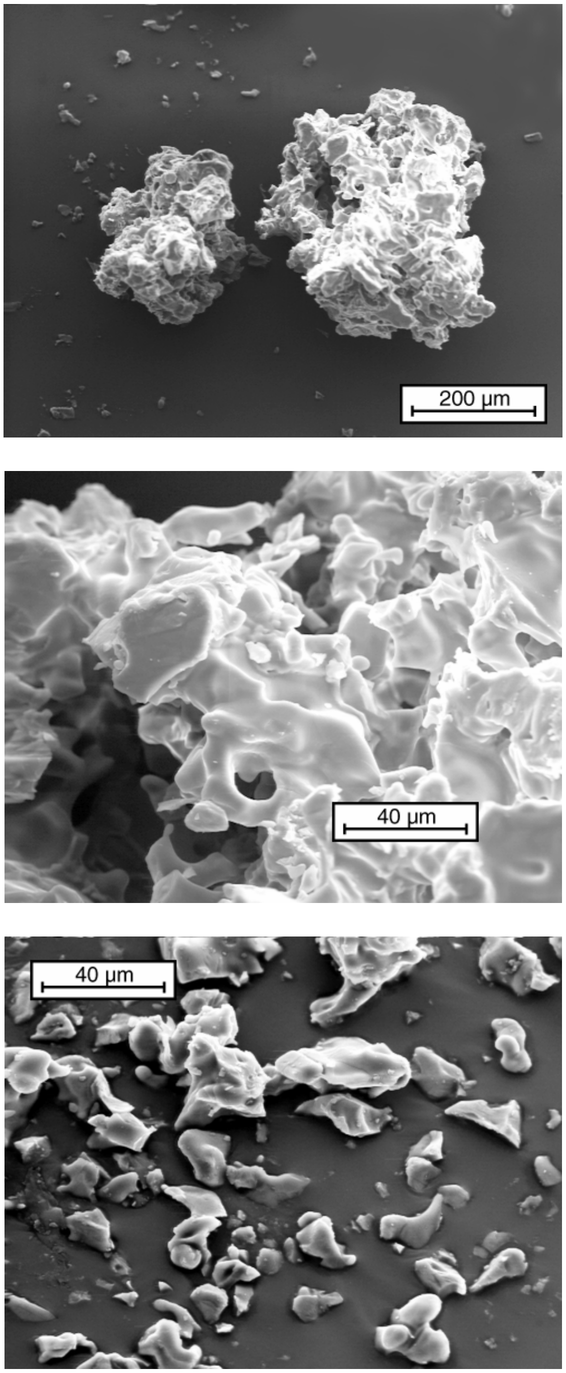


Figure 7. Particles from two mesh fractions of AR grade potassium nitrate produced by hot coacervation with rapid stirring. Upper, 60 to 100 mesh (250 to 150 micron) particles at 100 × magnification; middle, a portion of one particle at 500 × magnification; lower, –400 mesh (< 37 micron) particles at 500 × magnification.

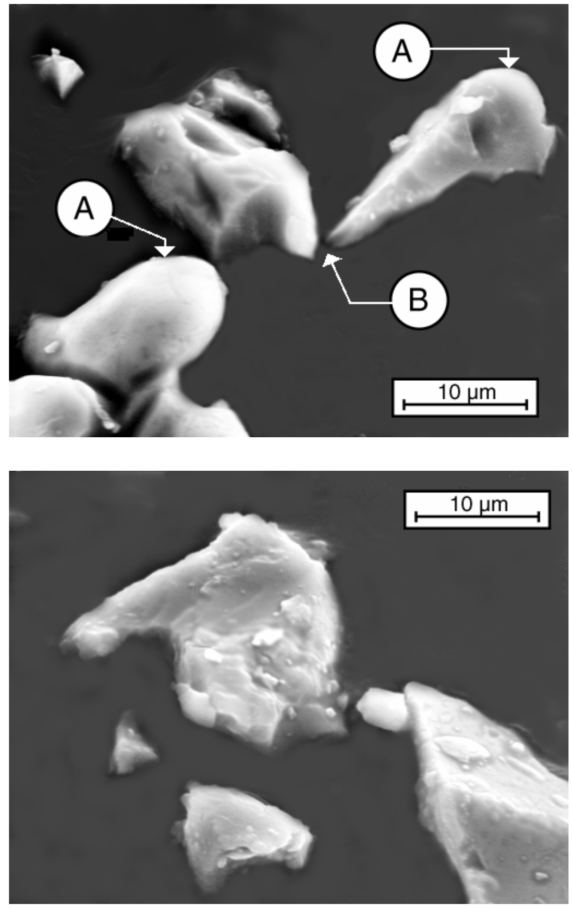


Figure 8. Comparing the sharpness of –400 mesh AR grade potassium nitrate particles. Upper, coacervated particles at 2000 × magnification illustrating features that are sometimes quite rounded (A) and other times fairly sharp and angular (B); lower, mortar and pestle produced particles at 2000 × magnification.

150 micron) fraction, at 100 and 500 × magnifications. The lower micrograph is of the –400 mesh (< 37 micron) particles at 500 × magnification. The larger particles are clearly agglomerations; however, their appearance is substantially different than that seen for the caked particles in Figure 4. The constituent particles are angular as opposed to being rounded and the agglomeration is fairly open as opposed to being relatively tightly packed. Many of the –400 mesh particles are as angular as the ground and crushed particles seen in Figure 6; however, many others are quite rounded. This can be seen more clearly in Figure 8, which compares –400 mesh coacervated particles with

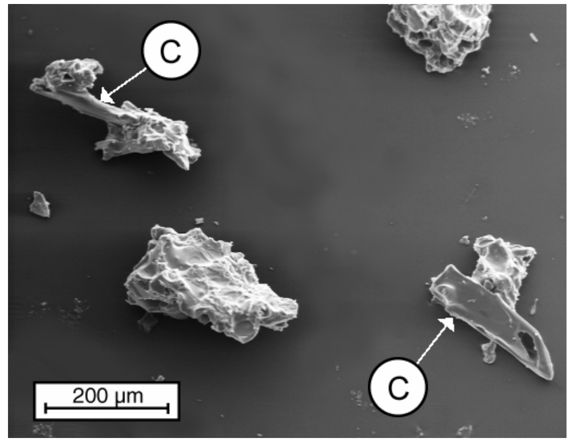
those produced with a mortar and pestle, both at 2000 × magnification.

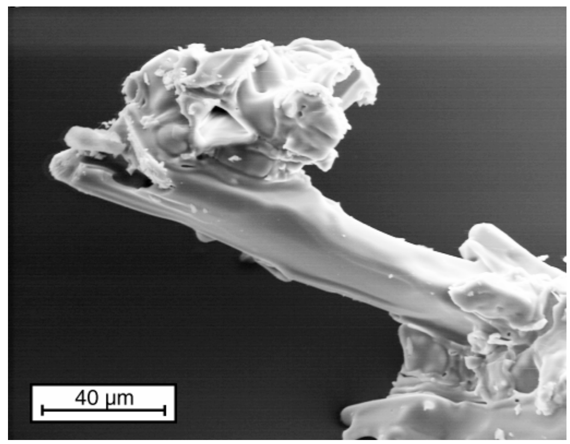
When coacervation is carried out with the rapid addition of the alcohol and vigorous stirring from a near saturated—but cool—solution, the appearance of the particles is substantially similar to those for a hot solution, like those particles seen in Figure 7. However, when the alcohol is added slowly and mostly without stirring, some of the particles produced have a somewhat rod-like shape that is characteristic of potassium nitrate crystals, see Figure 9.

Surface Features

Surface features and texture can significantly affect the reactivity of some pyrotechnic materials (e.g., so called titanium sponge ignites easier than solid titanium particles of the same size). However, for compositions made with low melting point oxidizers, except for particles that are agglomerations of a large number of much smaller particles, surface features are not expected to noticeably affect the ignitability and burn rate of pyrotechnic compositions. However, surface features are an important part of forensic materials comparison.

Some of the possible particle surface features have already been mentioned. For example, particles can be agglomerations of smaller particles that have characteristic shapes, and the agglomerations can be densely packed or have relatively open structures, see Figures 4 and 7. However, there are other characteristic surface features that should be mentioned. When particles are crushed, noticeable fracture patterns can be produced. These particles have concave particle surfaces and deflection fracture marks, sometimes called "whiskers". (Whiskers are somewhat parallel ridges on the fractured surface). When particle diminution is accomplished by hammer milling, where high speed rotating blades impact and shatter the particles, the number and degree of fracture patterns observed can be significantly greater than those patterns produced by crushing and grinding, see the upper and middle micrographs in Figure 10. The lower micrograph in Figure 10 is a rather extreme example of fracture features formed when this particle was smashed. The degree to





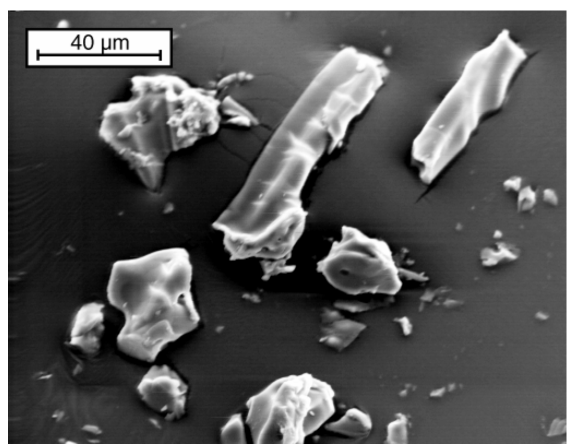


Figure 9. Particles with some rod-like characteristics (C) are produced by slow coacervation. Upper, 60 to 100 mesh (250 to 150 micron) particles at 100 × magnification; middle, a portion of one particle at 500 × magnification; lower, –400 mesh (< 37 micron) particles at 500 × magnification.

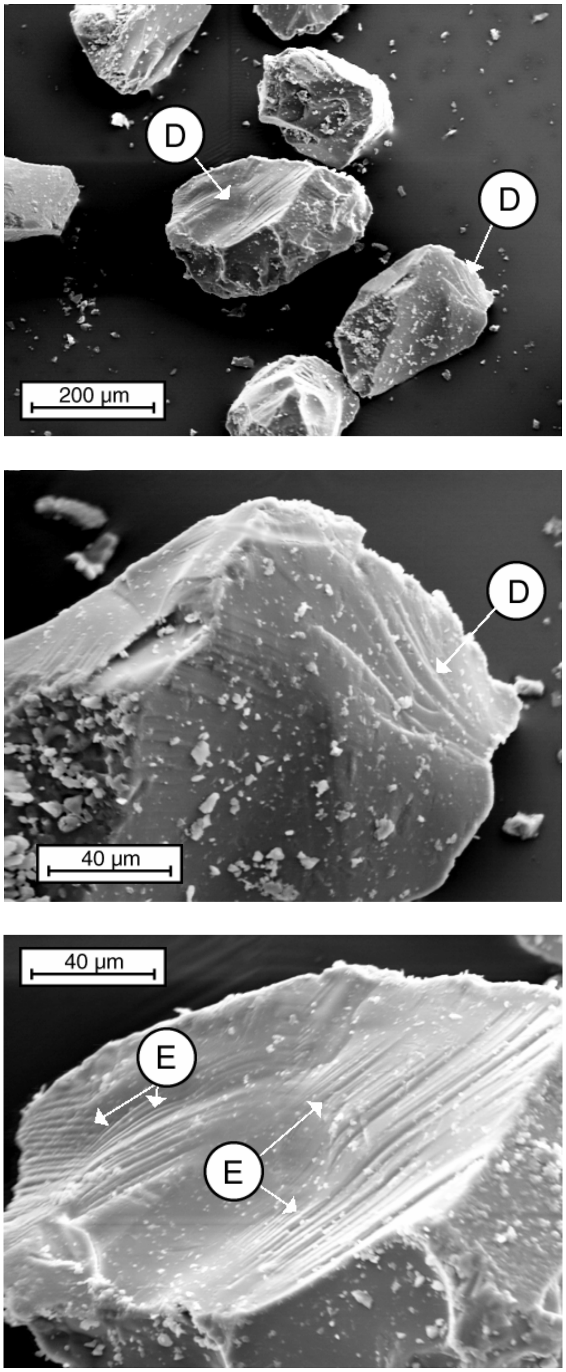


Figure 10. Particles of AR grade potassium nitrate produced by hammer milling. Upper and middle, demonstrating fracture patterns (D) (100 and 500 × magnification, respectively); lower, a rather extreme example of "whiskers" (E) (500 × magnification).

which fracture patterns are produced during milling seems to range from modest (for rotating disk mills) through moderate (for mortar

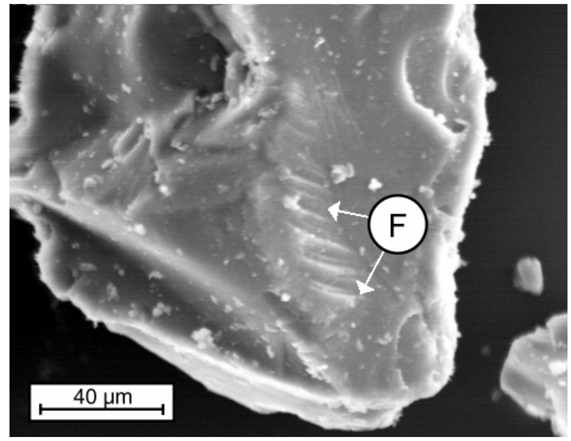


Figure 11. Possible example of tool marks (F) produced during hammer milling AR grade potassium nitrate (500 × magnification).

and pestle) to substantial for hammer milling. Also, on rare occasion, a hammer-milled particle may exhibit what appear to be tool marks (mostly straight parallel grooves) from a blade scraping across the particle, see Figure 11.

When particles have been ball milled, the large number of impacts can leave the larger particles with a pitted surface texture; see Figure 12. These micrographs illustrate the typical appearance of the 60 to 100 mesh (250 to 150 micron) particles of AR grade potassium nitrate after having been ball milled for 2 hours. At first glance and under minimum magnification, the particle may appear somewhat like the agglomerated particle in Figure 4. However, under higher magnification the difference is obvious. Using the visible light microscope, the difference in appearance between the agglomerated and pitted particles is even more readily apparent. Particles such as those in Figure 12 are translucent and are definitely single particles, appearing much like lightly frosted glass. To the contrary, particles such as those in Figure 4 are opaque white, appearing much like snowballs.

Occlusions or voids, though not uniquely surface features, are sometimes discernable on the surface of particles. This is especially the case for agglomerated particles (see Figure 4), coacervated particles (see Figure 7), and particles produced from prilled chemicals (see Figure 13). However, it should be noted that voids were also occasionally observed in particles

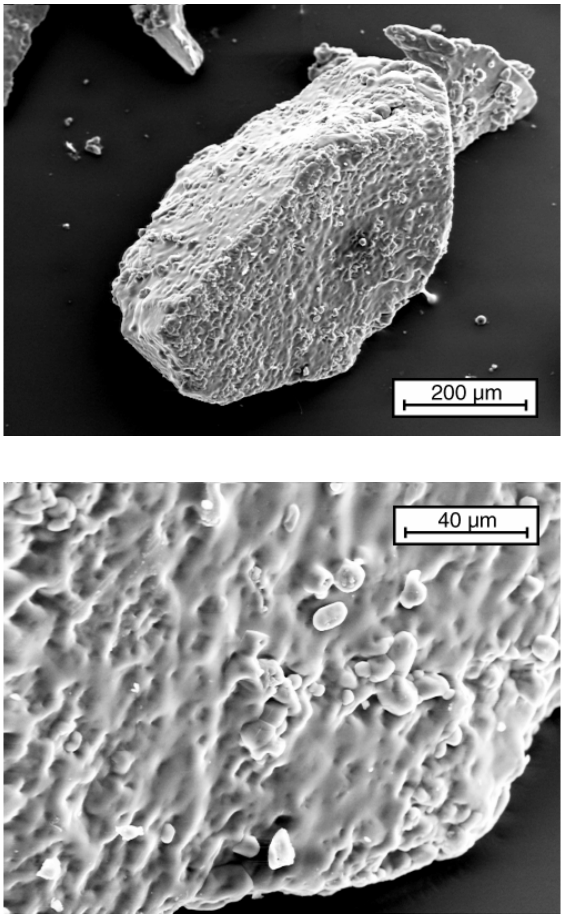


Figure 12. Particle of AR grade potassium nitrate produced by mild ball milling for 2 hours, illustrating the pitted surface of the 60 to 100 mesh particles. Upper, 100 × magnification; lower, 500 × magnification.

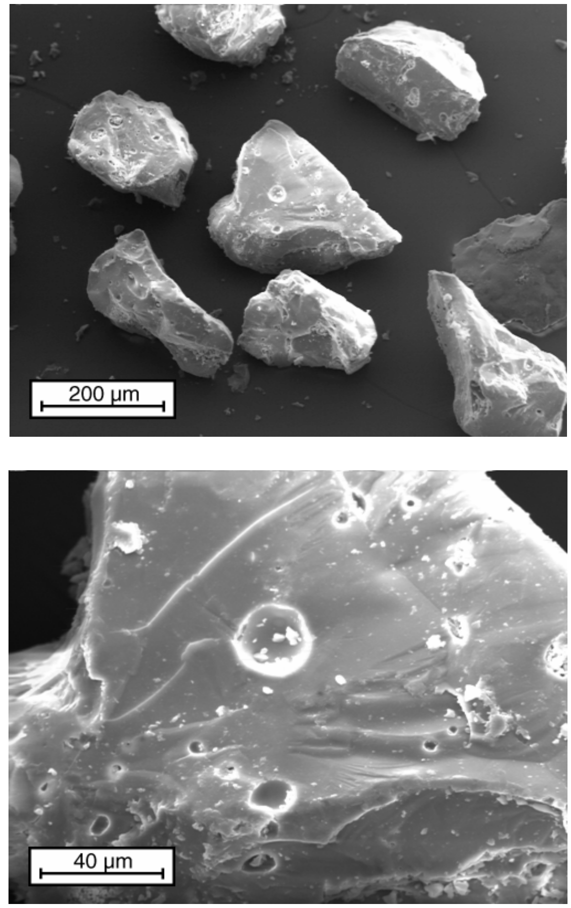


Figure 13. Particle of AgP grade potassium nitrate produced using a mortar and pestle, illustrating the presence of numerous occlusions (voids). Upper, 100 × magnification; lower, 500 × magnification.

produced from potassium nitrate that was slowly recrystallized from an aqueous solution and from potassium nitrate that solidified from high temperature melts.

A definite surface feature, but one that is not characteristic of unexamined potassium nitrate particles, is illustrated in the lower micrographs of Figure 14. The thermal expansion and fissuring of the particle's surface is an artifact introduced during the examination process itself. Specifically this is a result of particle heating when the specimen absorbs the energy of the electron beam of the scanning electron microscope (SEM). (For a more complete discussion of possible causes of thermal expansion and some steps to help limit the problem, see reference 9.) The possibility of causing beam-induced artifacts becomes a greater problem at higher magnifications, when the electron beam is more concentrated (the same beam current is spread over a smaller area). The upper micrograph of Figure 14 is the initial image of an uncoated AR grade potassium nitrate particle at 2000 × magnification. The middle and lower micrographs were recorded after approximately one and three minute exposures to the beam of the SEM, and they demonstrate the progressive expansion and development of the fissures in the particle's surface. For these AR grade potassium nitrate particles, essentially no further surface damage was observed after approximately three minutes.

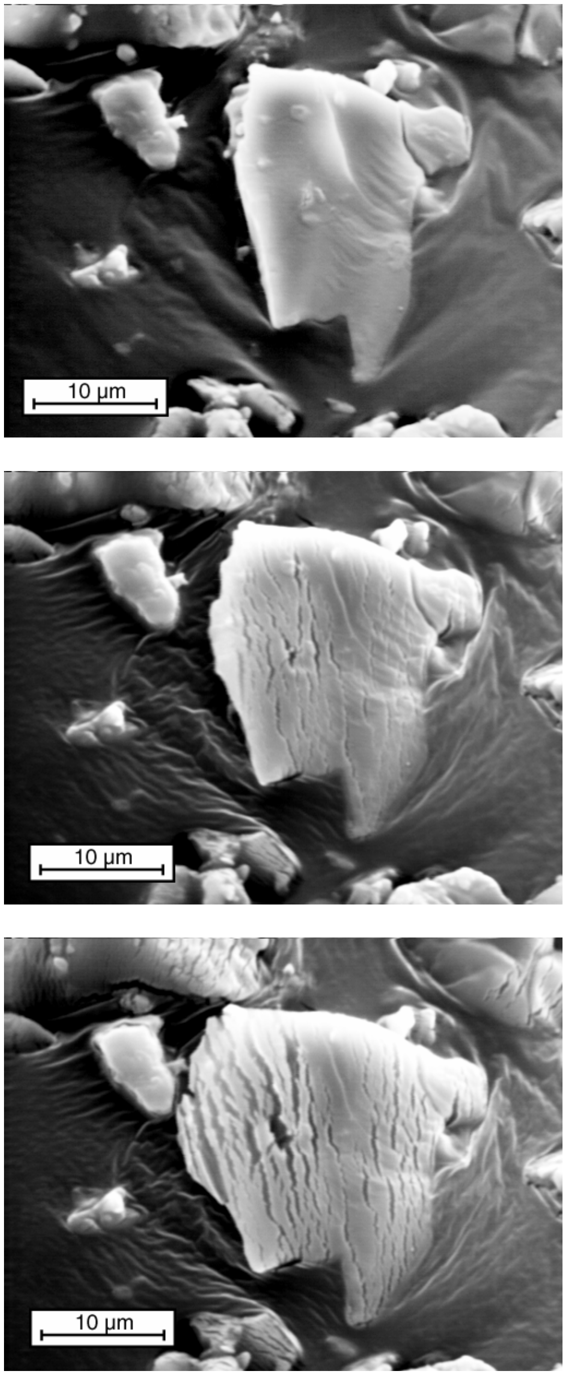


Figure 14. Illustration of SEM beam-induced surface damage (thermal expansion) to AR grade potassium nitrate particles under high magnification (2000 ×) as a function of time. Upper, initial image; middle, image recorded after approximately one minute; lower, image recorded after approximately three minutes.

Conclusion

Particle size, shape and surface features of low melting point oxidizers are not as critically important in determining the ease of ignition and burn rate of pyrotechnic compositions as they are for many other components in these mixtures. Nonetheless, knowledge and control of these attributes is necessary to maintain consistent performance of pyrotechnic devices. Further, from a forensic standpoint, an investigation of these attributes can be an important part of establishing reliable matches between known and evidentiary materials. [Unfortunately, the converse is also true (i.e., failing to consider detailed particle morphology makes any claim of a match less credible.)]

As a note of caution for the forensic analyst, it is important to avoid over-inferences based on a limited investigation of particle morphologies. Specifically, while it is true that the method of particle size reduction plays a major role in determining particle morphology, so do many other things. Accordingly, one should resist the temptation to use particle morphology as the sole basis to infer the method of production of the material. For example, consider the potassium nitrate particles shown in Figure 15. These particles definitely have sharp angular features. Based on the information presented in this article, one might be tempted to conclude that the method of their production was by crushing or grinding, see Figure 6. Similarly, one might be tempted to exclude the possibility that this material was produced by extended ball milling, see the lower micrograph of Figure 4. However, if either conclusion were reached, it would be erroneous. Figure 15 is the –400-mesh (< 37-micron) fraction of AgP potassium nitrate produced by 12 hours of ball milling. The rather extreme difference in particle morphology, when compared with that seen in Figure 4, is simply due to differences in the physical properties of the AR and AgP grades of potassium nitrate.

Acknowledgments

The authors are grateful for the suggestions of J. Bergman, J. Giacalone, F. Whitehurst, and D. Naedel on an earlier draft of this paper.

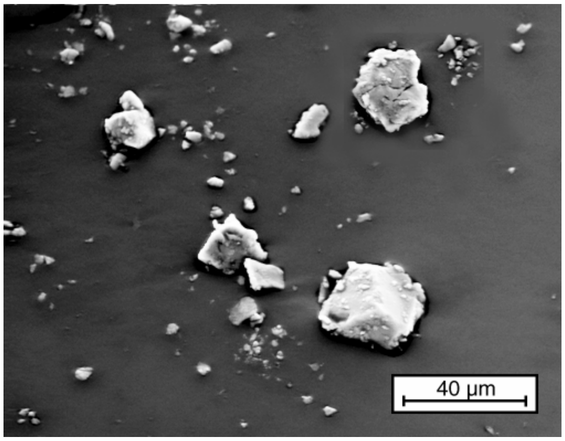


Figure 15. Micrograph of the –400 mesh (< 37 micron) fraction of AgP potassium nitrate produced by ball milling for 12 hours (500 × magnification).

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