Pyrotechnic Literature Series No. 7

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

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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. Bonnie is also the publisher of 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 draft appeared in *American Fireworks News*, No. 160, 1995.

Stars Blown Blind

K. L. and B. J. Kosanke

When an aerial shell bursts, stars that fail to burn are often said to be "blind stars", or more descriptively as having been "blown blind". This detracts from the beauty of the shell and contributes to debris fallout. The problem can be caused by any of a combination of factors; the most important of these are the degree of violence of the shell burst and the burn characteristics of the stars.

In simplest terms, a star will ignite when its surface has been raised to its ignition temperature. The star will continue to burn only so long as the burning surface feeds sufficient energy to the next deeper layer of the star, to raise that unignited composition to its ignition temperature. (See Figure 1.) (For a more complete discussion of pyrotechnic ignition and propagation, see reference 1.)

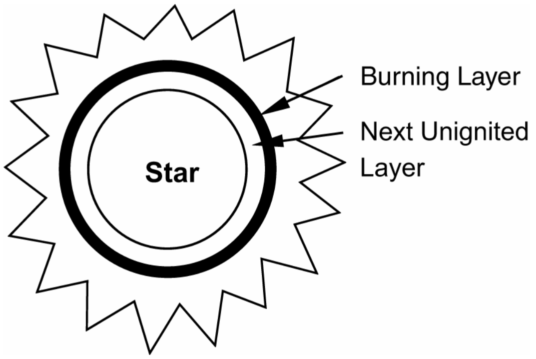

Figure 1. Illustration of a burning fireworks star.

One way in which thermal energy is fed to the next (unignited) layer is for radiant energy from the flame to be absorbed by the surface of the star and then conducted more deeply into the star. When a burning star is moving through the air, the flame will be deflected down wind. (See Figure 2.) Thus, in this case, the feedback of thermal energy to unignited composition is impeded. Also, the up wind side of the star will be exposed to relatively cold air. This acts to further cool the burning surface.

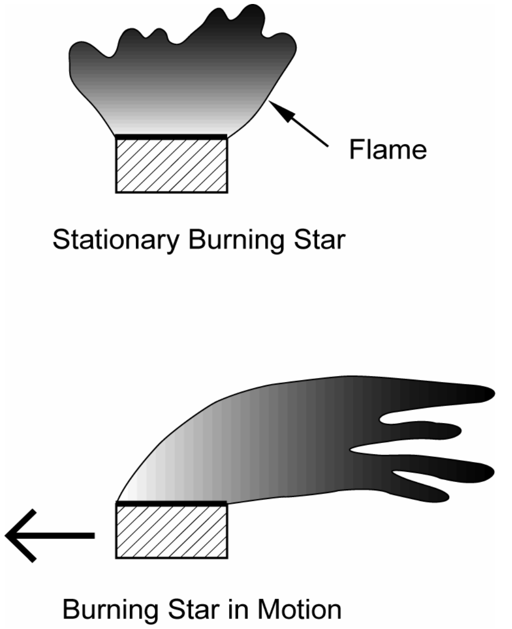

Figure 2. Illustration of the effect of air movement past a burning star.

During some recent tests, this effect was captured on film. Figure 3 shows the explosion of an 8-inch aerial shell that had been suspended in a test stand. (The purpose of this test was to determine its time to explosion and the blast pressure produced.) Figure 4 is an enlargement of a portion of Figure 3, showing stars (dark spots) with their flames (light areas) trailing behind.

If the amount of energy being fed back is no longer sufficient to raise the next layer of the star to its ignition temperature, the burning star will be extinguished. Among those factors of importance in determining whether this will happen is the speed of the star as it moves through the air. The faster the star is moving, the more its flame trails behind it, thus feeding

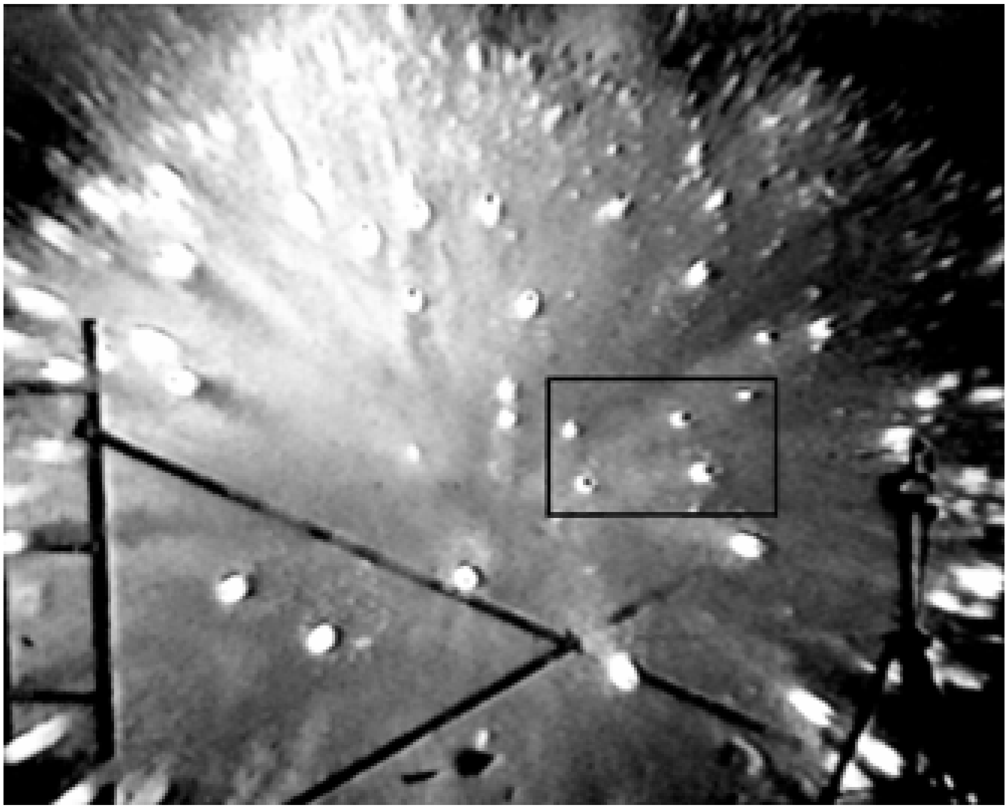

Figure 3. Explosion of an aerial shell in a test stand.

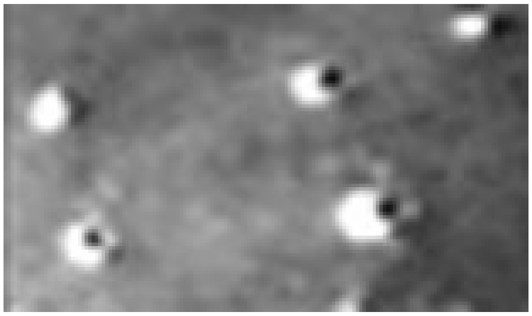

Figure 4. Enlargement of Figure 3 showing the flames trailing the burning stars.

back less radiant energy. Also there is a greater cooling of the star's surface from the air impinging on it. For a given star size and mass, its initial speed is determined by the violence of the shell burst. Thereafter the star slows due to aerodynamic drag forces. Thus, if a star manages to stay ignited during the first brief moments after the shell bursts, it will generally burn completely.

Other important factors determining whether a star will be extinguished upon shell burst are associated with the chemical nature of the star. For example, one factor is the amount of heat being produced by the burning composition; another is the amount of energy needed to raise a composition to its ignition temperature.

Often star priming is only thought of in terms of aiding star ignition. However, it is also an important aid in the continuation of burning during and just after shell burst. (For a more complete discussion of this phenomenon, see reference 2.) When the authors manufactured spherical stars commercially, they concluded that the optimal amount of rough meal prime was to use as much as possible without noticeably delaying the visual appearance of the star after the shell burst. Generally this was 10–15% of prime (by weight) for stars larger than 3/8 inch, and 15–25% for stars smaller than 3/8 inch. This was felt to be optimum for two reasons. First, with this amount of prime, perchlorate color stars and even strobe stars would stay ignited even after emerging from hard-breaking shells.

Second, rough meal prime (75% potassium nitrate, 15% charcoal, 10% sulfur and +5% dextrin) is the least expensive composition used in making stars. The more of it that could be used without detracting from the star's performance, the less expensive the stars could be made.

Blind stars are often thought of as failing to ignite before the shell bursts. However, as discussed above, the stars may have ignited, only to be blown blind by the violence of the explosion of the shell. Two easy solutions to the problem are to break the shells more softly or to prime the stars more heavily.

References

1) K. L. and B. J. Kosanke, "Pyrotechnic Ignition and Propagation: A Review", *Journal of Pyrotechnics*, Issue 6 (1997). Also appeared in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1999).

2) K. L. and B. J. Kosanke, "Pyrotechnic Primes and Priming", *Proc. 4th International Symposium on Fireworks* (1998).

An earlier draft appeared in *Fire Engineering*, June 1995.

Fireworks and their Hazards

Thomas J. Poulton, M.D. and Kenneth L. Kosanke, Ph.D.

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"What are fireworks like?" she had asked.

"They are like the Aurora Borealis," said the King, "only much more natural. I prefer them to stars myself, as you always know when they are going to appear...."

Oscar Wilde, *The Remarkable Rocket*

Although appreciative audiences may value the predictability of fireworks, firefighters, unlike the king in *The Remarkable Rocket,* know that on occasion they may not be so reliable. When the first-due company finds it is dealing with fireworks, it is in an unusual situation that requires specific technical knowledge to ensure the safest possible outcome.

Scope of the Challenge

During the past 15 years, the quantity of fireworks used in the United States has more than doubled to approximately 100 million pounds annually. Although fireworks remain most popular over the Fourth of July holiday, their use is now common throughout the year at theme parks, fairs, and public events. Performing artists have greatly expanded the use of pyrotechnic displays to enhance the entertainment value of concerts, plays, and other stage productions. In a recent year, the U.S. Fire Administration reported that approximately 6,000 (less than one percent) of the almost one million fires occurring in the United States involved fireworks. The average loss per incident was less than $2,000.

Pyrotechnics is part of the field of 'high energy chemistry'.[1] Pyrotechnics and explosives differ largely in the rate at which energy (in the form of heat, light, sound, and motion) is released. Pyrotechnic burning and explosion, like all burning, involve oxidation-reduction reactions. The degree of *confinement* of highly reactive compounds and compositions has considerable impact on the behavior of the material. A mixture that simply burns in the open may explode when contained within the hard covering of a fireworks aerial shell.

The local fire authority usually has at least one company standing by at major fireworks displays. Although the transportation safety experience with fireworks has been exemplary, motor vehicle accidents involving trucks carrying pyrotechnic devices can occur at any time without warning. Thus, firefighters and company officers must be aware of the hazards of pyrotechnic devices, understand the differences between the various classes of legal and illegal fireworks, and have basic strategies in mind for dealing with pyrotechnic-related incidents.

The firefighter and company officer may be familiar in a general way with the many guidelines and regulations under which consumer fireworks (DOT Explosives 1.4G, formerly referred to as common fireworks or Class C explosives) sales and display fireworks (DOT explosives 1.3G, formerly referred to as special fireworks or Class B explosives) performances are organized and conducted.

This article focuses on company operations and incident command decisions in dealing with the rare fire, explosion, or hazmat incident involving these devices after they are manufactured. We assume that departments having fireworks manufacturing facilities within their jurisdictions already have conducted extensive preplanning and training to deal with the potential problems they present.

Conflicting Information

Misinformation with respect to fire suppression when fireworks are involved has been promulgated. For example, it is frequently stated that applying water to fireworks or fires involving them is dangerous because of the presence of magnesium, titanium, and other metallic-reducing agents that can have adverse reactions with water. What is the bottom line? When faced with a fire involving display fireworks, does suppression truly present unusual risks and hazards? Can conventional fire suppression techniques implied by the fire tetrahedron be applied? What about the content of metals in pyrotechnic compositions? Will applying water produce more intense burning?

Clearly, the answers to these questions are loaded with potential mishaps. As always, basic principles of fire science and behavior must be applied to ensure reasonable safety, avoid the assumption of unnecessary risk, and maximize the likelihood of limiting property damage, protecting others' lives, and getting home in one piece.

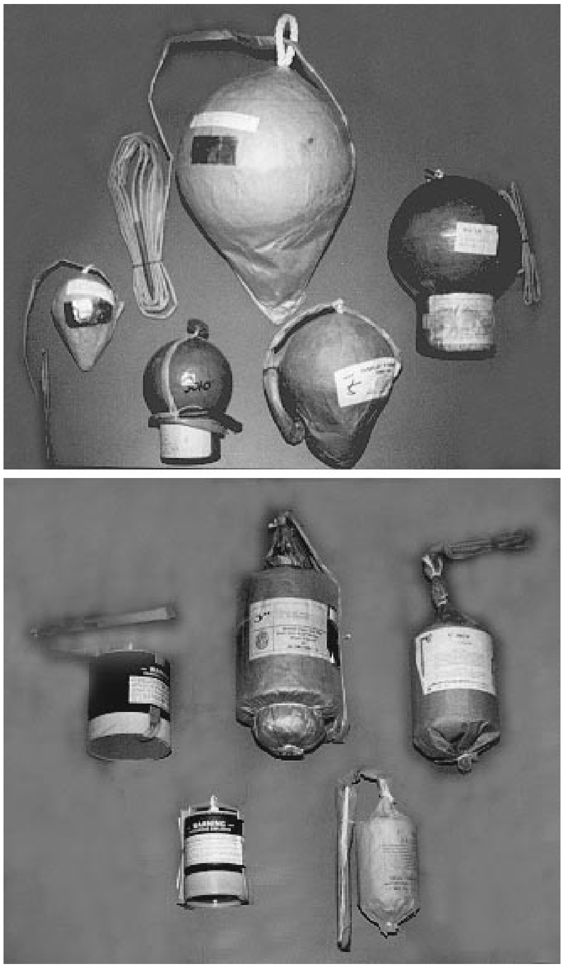

Figure 1. Photos illustrating typical shapes and sizes of display fireworks aerial shells (top—spherical 3–8 inch; bottom—cylindrical 3–5 inch).

Fireworks Composition

In chemical terms, fireworks are a mixture of an oxidizing agent and fuel. Ironically, care is often taken to ensure that color-producing pyrotechnic compositions burn and do not explode per se. An explosion would consume all the pyrotechnic material instantaneously, depriving the viewers of the glitter, glow, and attractive color combinations that characterize modern fireworks. Commonly used oxidizers include potassium nitrate, potassium perchlorate, ammonium perchlorate, and barium nitrate. Fuels (reducing agents) for the oxidizers include aluminum, magnesium, sulfur, charcoal, and carbohydrates (including lactose and natural res-

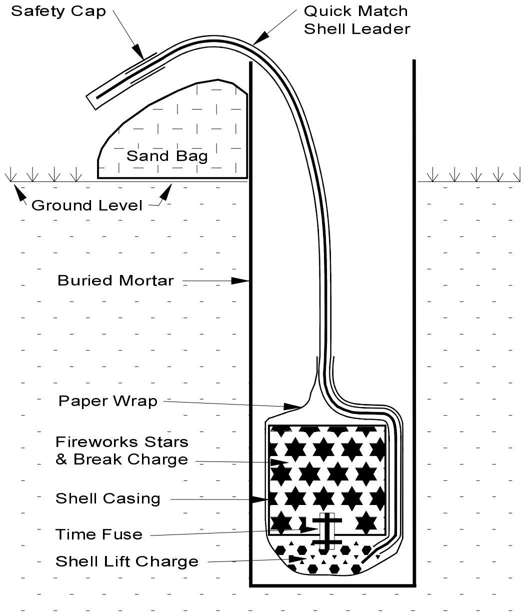

Figure 2. Drawing identifying the components of a typical aerial shell in a buried mortar.

ins). Modern compositions also typically include any of several types of binder and chemical additives to produce specific pyrotechnic effects, such as strontium salts for red color or titanium metal for white sparks.

The Devices

Although skyrockets occasionally are used to deliver display fireworks into the sky, they are relatively inefficient at lifting large payloads and are less predictable in flight than aerial shells. Accordingly, aerial shells are by far the most common display fireworks device. Cylindrical or spherical in shape (Figure 1), shells have a rapidly burning "quick match" fuse that also is used to lower smaller shells into a mortar—a tube, sealed at the bottom end, from which aerial shells are fired (Figure 2). Most commonly, mortars are made of spirally or cylindrically wrapped paper, high-density polyethylene plastic, or steel. Manually fired (hand-lit) shows use a relatively small number of mortars (several appropriate for each shell size being fired), which are repeatedly loaded and fired throughout the performance. Electrically fired performances require preloading every shell into its own mortar; often thousands of mortars are used. See Figure 3. In manually fired shows, a shell typically is launched every five to 20 seconds. Electrical firing makes it possible to launch more than one shell per second and to accomplish the precise timing and choreography typical of the finest shows. Regardless of the type of firing, the mortars are protected from tipping either by partially burying them or securing them in racks aboveground.

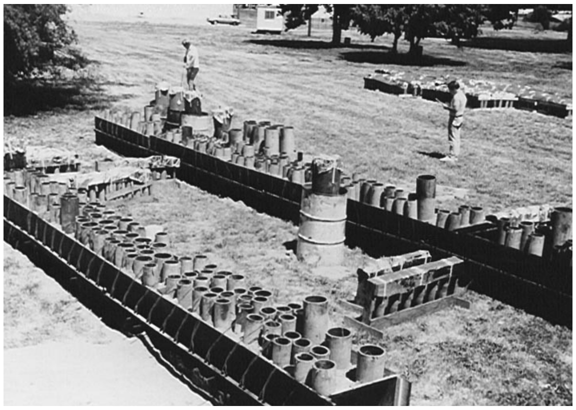

Figure 3. Photo of a typical setup for an electrically fired display where there is one mortar for every shell to be fired.

Although the shell leader (the length of quick match attached to an aerial display shell) may be used to lower the shell into the mortar, it serves primarily as the ignition device. (See Figure 4.) Underneath the shell is a lift charge of Black Powder (also called "gun powder," a mixture of potassium nitrate, charcoal, and sulfur). Ignition of the fuse (by an electric match,[2] a fusee, or similar device) proceeds to ignite the lift charge, which propels the shell up the tube and into the air. Aerial shells range in diameter from less than three inches to more than 12 inches; however, most shells used are between three and six inches. While the shell is hurtling upward, the time fuse between the lift charge and the main shell casing burns for a time calculated to ignite the break charge so the shell will explode just before it reaches its highest point.

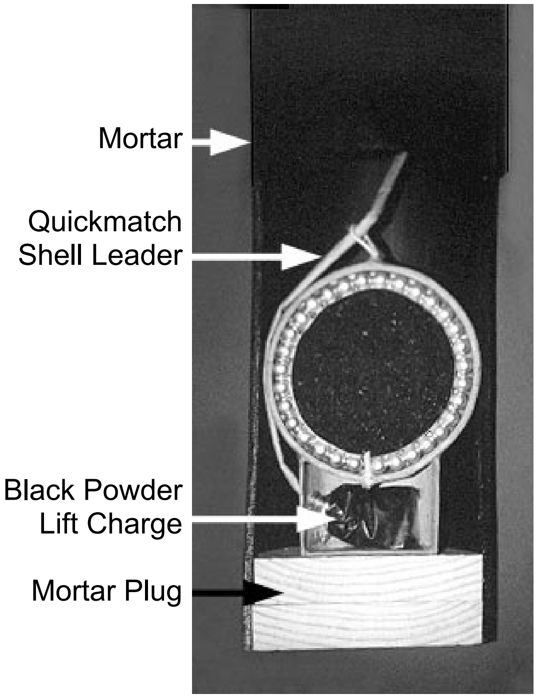

Figure 4. Photo of a cut-away model of an aerial shell in its mortar.

Lift charges (black powder positioned beneath an aerial shell) are of such a size that they typically produce a shell muzzle velocity of approximately 225 miles per hour regardless of the shell's size. The time fuse burns for approximately three to six seconds, depending on the size of the shell, which achieves a height of roughly 120 feet per inch of shell diameter. Thus, a six-inch shell will burst at an elevation of approximately 700 feet above the ground. The burst spread also depends on the size of the shell and may reach approximately 90 feet in diameter per inch of spherical shell diameter. The six-inch shell mentioned above may have a spread of roughly 500 feet; an 8-inch shell has a dramatic spread of about 700 feet (See Figure 5). Design also plays a role; some shells burst broadly while others may be designed to burst in a tight or narrow pattern. See Table 1 for typical fireworks aerial shell performance characteristics.

Figure 5. Photo of an 8-inch aerial shell exploding. Note that inside the small oval area (lower left) is a 1-ton cargo truck.

Table 1. Typical Spherical Display Fireworks Shell Characteristics.

Shell Size	Weight[a]	Burst Height[b]	Burst Radius[c]	Burst Delay[d]
(in.)	(lbs.)	(ft.)	(ft.)	Time (sec.)
3	0.3	400	125	3.0
4	0.8	550	175	3.5
5	1.5	700	210	4.0
6	2.5	775	250	5.0
8	5.5	950	400	6.0
10	11.0	1075	425	6.5
12	18.0	1175	450	7.0

a. The net weight of pyrotechnic materials in aerial fireworks shells is typically about one-half their gross weight. The weights reported here are gross weights for fairly typical spherical fireworks shells.[1]

b. These data, to the nearest 25 feet, are from reference 2 below. There are no published data on the burst height for cylindrical fireworks shells. It is felt they are generally about the same as for spherical shells.

c. These burst radii, to the nearest 25 feet, are for typical high-quality spherical shells.[3] The values were recalculated from data provided by T. Shimizu. Lower quality spherical shells and typical cylindrical shells may have burst radii only 40 to 80 percent of those reported here.

d. These are typical elapsed times, to the nearest half second, between the firing of a fairly typical fireworks aerial shell from its mortar and when it explodes.[4] The delay is provided by a pyrotechnic time fuse. The time fuse is ignited during the firing of the shell, and the shell bursts (explodes) when the time fuse burns through to the interior of the shell.

References for this table.

1) K. L. and B. J. Kosanke, “Shimizu Aerial Shell Ballistic Predictions—Part 1”, *Pyrotechnics Guild International Bulletin,* No 7 (1990). Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1995).
2) K. L. Kosanke, L. A. Schwertly, B. J. Kosanke, “Report of Aerial Shell Burst Height Measurements”, *Pyrotechnics Guild International Bulletin,* No. 65 (1991). Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1990 through 1992)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1995).
3) K. L. and B. J. Kosanke, “Japanese Shell Break Radii”, *Pyrotechnics Guild International Bulletin,* No. 59 (1988). Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 1 (1981 through 1989)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1995)
4) K. L. and B. J. Kosanke, *Lecture Notes for Display Fireworks Practices*, Journal of Pyrotechnics, Inc., Whitewater, CO (1995).

Set- or ground-piece devices produce showers of colored sparks, glowing letters or figures, or spinning fireworks near ground level. (See Figures 6 and 7.) Although they often burn at very high temperatures, they have little explosive potential. These devices, however, are commonly used and may be found near materials with explosive potential.

In addition to the commercially manufactured consumer and professional display fireworks, illegal explosive devices remain surprisingly common. These federally prohibited explosive devices are commonly known as “M-80s”, “blockbusters” or other names denoting powerful explosive capabilities. The U.S. Consumer Product Safety Commission restricts the content of ground firecracker-like devices to a maximum of 50 mg of explosive composition. The old commercially available “cherry bomb” typically contained up to one gram (1,000 mg) of explosive composition. The illegal M-80-type devices typically contain anywhere from 2 to 10 grams (2,000 to 10,000 mg) of explosive

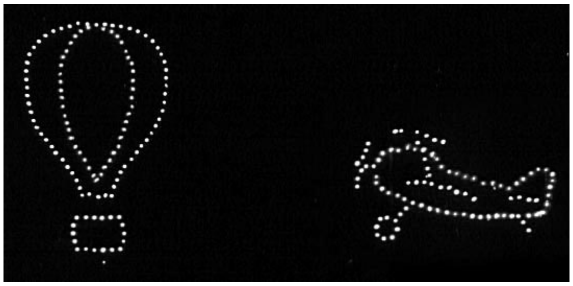

Figure 6. Burning lancework depicting a hot air balloon and an airplane.

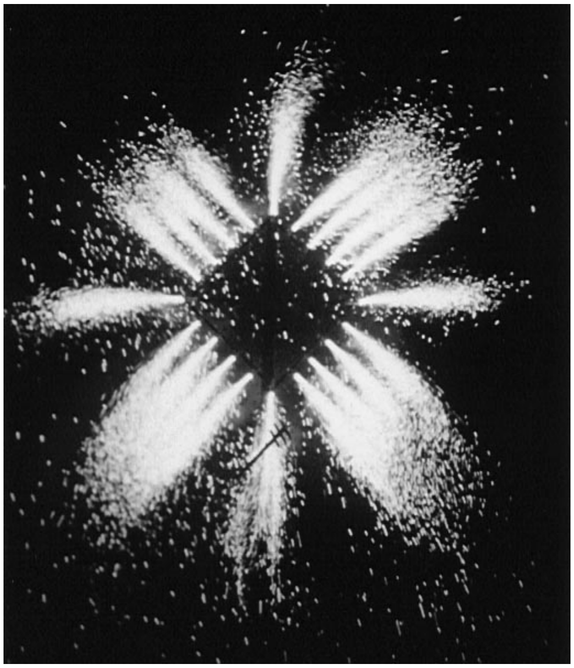

Figure 7. Fountain set piece producing multiple sprays of sparks.

composition. Note that such illegal fireworks cause many of the serious fireworks-related injuries.

Explosive Potential

The net weight of pyrotechnic materials in an aerial fireworks shell (Class B) is typically about half the total weight. Typical consumer fireworks (Class C) generally contain approximately 25 percent pyrotechnic material.[3] The remaining matter is usually a mixture of paper, plastic, and inert substances such as clay. Large quantities (approximately 15,000 pounds) of a mixture of consumer fireworks of various types (See Figure 8.) were tested in a fire situation when moderately confined (in large metal cargo containers).[4] In the two tests conducted, the time required for most of the pyrotechnic content of the fireworks devices to be consumed was more than 20 minutes and the burning of pyrotechnic material continued for about an hour. In neither of the tests was there a mass explosion. As a part of public displays conducted by the Pyrotechnic Guild International, huge quantities of firecrackers (more than three million individual firecrackers) have been ignited en masse. Doing this has never produced a mass explosion.

Figure 8. Photos of typical consumer fireworks items.

Figure 9. Photo of a box of 3-inch display fireworks shells.

We know of no situation where the burning of even massive amounts of consumer fireworks has produced what could accurately be described as a mass explosion. Large quantities of consumer fireworks (typical of those that might be encountered in a transportation vehicle on fire or a consumer fireworks stand on fire) will be expected initially to burn faster and hotter than the same mass of ordinary combustible material, especially when in an oxygen-limited environment. The reason for this, of course, is that the pyrotechnic material contains its own oxidizers. However, the total fuel load of consumer fireworks will be somewhat less than an equal weight of other combustible materials, since most of the pyrotechnic composition (typically about 70 percent) is actually oxidizer and not fuel.

The spread of fire will be more rapid for large quantities of consumer fireworks than for an equal weight of simple combustible material such as cotton and wood, because of the faster and hotter burning. In many cases, firebrands are propelled a distance away from the burning materials. Firebrands can significantly increase the rate of fire spread especially where many fireworks items are exposed, such as at a large retail sales outlet. Such rapid spread by firebrands, however, will occur to a much lesser extent in a location where the fireworks are stored in shipping cases, such as in a wholesale storage building or vehicle.

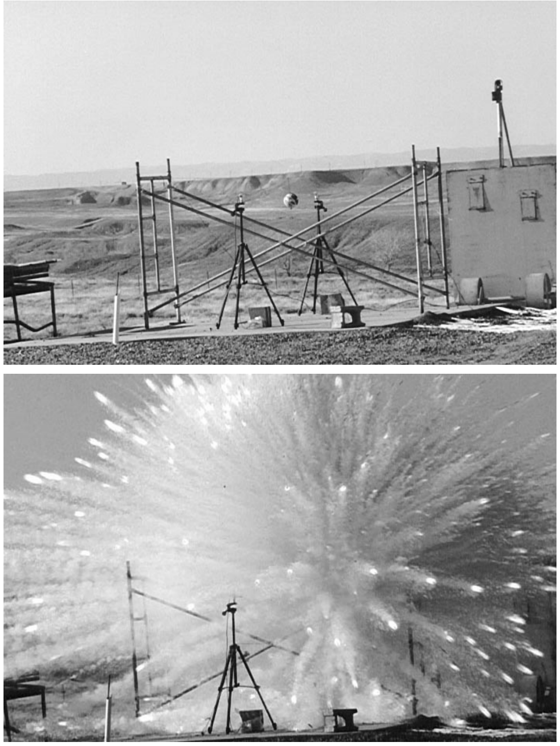

Figure 10. (Upper) Setup for measuring the explosive pressure produced by a display fireworks shell, seen suspended in the middle of the photo. (Lower) Explosion produced by the exploding aerial shell.

Exploding Display Fireworks Shells

While all display fireworks aerial shells (see Figure 9) have significant explosive potential (see Figure 10), the damage potential differs greatly between two primary groups: star shells and salutes. Star shells (those intended primarily to have colored visual effects) are spherical and cylindrical. Their performance in a fire situation will depend on size, but will be largely independent of shape. Salutes are shells that are usually cylindrical and generally less than five inches in diameter. They contain flash powder and are designed to produce an extremely loud explosive noise associated with a white flash of light. The explosive output of salutes and fireworks shells containing reports (functionally small salutes within a star shell) also depends on their size but is substantially greater than star shells of the same size.

The output of various explosives is sometimes compared with the explosive output of TNT (trinitrotoluene), the so-called TNT equivalent. The TNT equivalent determined for an explosive will depend on the method of comparison. Accordingly, the same explosive will have several different TNT equivalent values, one for each method of comparison. Depending on the test method, widely varying TNT equivalent values can be obtained. For example, the air blast pressure of two devices may be similar, but the shattering ability could be very different. What is the hazard posed by being adjacent to an exploding consumer fireworks device or a display shell? Obviously, there is no simple answer, since the explosive output certainly depends on the size and type of the shell, and both the air blast and projection hazards will vary with the distance from the explosion. A three-inch salute with a net pyrotechnic weight of approximately 2.5 ounces produces an air blast roughly equivalent to 1.5 ounces of TNT—clearly enough to produce injury.

In general, standard firefighting personal protective equipment will afford more than adequate protection for fire suppression activities when dealing with consumer fireworks. On the other hand, being in close proximity to an exploding salute several inches in diameter—or even a medium-sized star shell—could seriously injure or possibly kill a firefighter in standard personal protective equipment. Being in close proximity to multiple exploding shells is quite likely to seriously injure or kill a firefighter in standard personal protective equipment.

Explosions of display fireworks produce blast waves, supersonic air shock waves, which, depending on their strength, may have the potential to break windows, perforate eardrums, knock down walls, etc. The strength of blast waves decreases rapidly with increasing distance from the explosion. For display fireworks, the blast wave from an individual aerial display shell will dissipate enough within 30 to 50 feet to be below what can cause serious injury.

Projectiles from explosions may be produced by the exploding device itself or by the blast wave as it mobilizes materials in the area of the explosion. In the case of star shells, some of the projectiles will be burning pellets of pyrotechnic composition (the stars), which will have the ranges indicated in Table 1. For salute shells, the explosive force generally is sufficient to mobilize materials from the environment in the immediate area of the explosion. Both the stars and environmental debris have the potential to produce serious penetrating injuries to those nearby.

With display fireworks, the nature and force of the explosion will depend on a number of factors, including the type of shells (star shells, salutes, or a mixture), the size and number of the shells, the type of shell construction, and the manner of packaging. Accordingly, there will be a range of possible explosive effects. At one extreme, consider a situation in which a large number of large and weakly constructed salutes are in close proximity to each other. In this scenario, it is quite likely that there will be a single mass explosion in which the entire explosive contents of all the shells are consumed in less than a few hundredths of a second after the first salute explodes. In such a scenario, when the first shell's lift charge ignites, the flash of fire ignites its time fuse and likely will cause many more shells and their lift charges to ignite. However, this would not in itself produce an explosion, since the lift charges are in small discrete units and are not tightly confined. Nonetheless, it would definitely produce a fireball and result in the ignition of the time delay fuses on many of the neighboring salute shells. After the delay expected for the size of the shell, the fuse of the first shell will ignite the explosive contents of that shell, producing an explosion. As that shell explodes, it immediately will destroy and explode adjacent salutes, which will continue the process by destroying and exploding additional adjacent shells in a nearly instantaneous chain reaction. The power of such a mass explosion almost certainly will destroy the structure housing the shells, potentially seriously damage nearby structures and even damage distant structures.

Although this is definitely an example of an extremely rapid exothermic chemical reaction, the explosion will not have the same intense shattering ability as most commercial high explosives. For example, while the scenario described above could certainly bend a steel plate and hurl it a large distance, it would not be able to shred the plate into shards of shrapnel. At the other end of the spectrum, consider a situation where there are relatively strongly constructed star shells. In this case, although a powerful explosion still would be produced, the blast pressures would be much lower; but the total duration of the explosive chain reaction likely would be much longer. In this scenario, when the first shell's lift charge ignites, the flash of fire would likely ignite many more shells and their respective lift charges. As with the salutes, ignition of the lift charges would not produce an explosion by itself but would result in a fireball and the ignition of the time fuses on adjacent star shells. When the first shell explodes, the force of the explosion will be much less than that of the salute and probably would be insufficient to cause the immediate destruction and explosion of adjacent shells. However, the force of the explosion is certainly sufficient to propel some of the shells, with their time fuses now ignited, some distance. The burning contents of the first shells are likely to cause the lift charges of other nearby shells to ignite. Within seconds, the fuses of other shells will burn through, and those shells in turn will explode at various closely spaced times. This sequence will create a chain reaction somewhat like that described for salutes above, but with the following two significant differences. First, instead of one massive explosion in much less than one second, a rapid series of smaller explosions spread out over several seconds would occur. Second, there is a much greater chance that the closely spaced but non-mass destructive explosions will propel other ignited aerial display shells up to hundreds of feet from the site of the initial explosion. After a few seconds, those shells will explode, creating additional risk.

In summary, when multiple display shells are involved in a fire, one or more explosions will almost certainly occur. When consumer fireworks alone are involved in a fire, there virtually never will be a significant explosion.

Transport Vehicle Fires

Based on the available research,[4] a semi-trailer fully loaded with consumer fireworks may produce an impressive fire, but it would be much smaller than that caused by a similar-sized trailer of flammable liquid. There is virtually no possibility of a mass explosion. In a warehouse or trailer fire only involving consumer fireworks, responders might scarcely be aware of the presence of fireworks unless the firecrackers popped or special devices whistled.

A fire involving a similar load of display fireworks has essentially the same potential for a powerful explosion as a stationary magazine loaded with a similar type and amount of display fireworks. They present a very dangerous situation.

Ground Fires at Display Sites

Burning debris commonly falls to the ground during fireworks displays. Display operators will take steps to avoid having the potentially hot debris directly contact unexploded fireworks. Fire personnel responsible for site safety should encourage the removal of combustibles from the fallout area before the display begins. When this proves impractical, an alternative would be to water down combustible materials immediately prior to the display. When the combustible material in the fallout zone is dry ground cover, a controlled burn of the ground cover a few days in advance of the display should be considered as an alternative to watering down the site.

Occasionally during a display, a ground fire may occur within the fallout zone. You should not be present in the fallout zone during the display, in part because this is the area in which dud shells are intended to fall. These aerial display shells leave the mortar but fail to burst in the air and subsequently fall to the ground, where they occasionally ignite from the impact. Some of them weigh 10 pounds or more and return to the ground at speeds in excess of 100 miles per hour. In addition, low-breaking shells, which produce an air blast and high-velocity burning material, may explode immediately above the fallout area. Finally, although unlikely, it is possible that dud shells or components from incompletely consumed shells already may have fallen into the area and could explode as a result of the ground fire. Generally, if the ground fire seems unlikely to grow to dangerous proportions during the time remaining for the display to be completed, consider delaying control measures until the display has been concluded. If it is not possible for the display to be completed first, the display should be halted. Careful preplanning and communication immediately before the show is fired will enable intelligent decisions to be made about the placement of water on a ground fire from a relatively safe distance.

Disposal Considerations

Just about the only way to render fireworks completely safe from their fire and explosion hazards is to release their chemical energy. This can be accomplished by either functioning individual items or, when safe, by burning. *Burial is never an acceptable method of disposal.* First, there is unacceptable environmental contamination. More importantly, even in wet ground, the relatively waterproof casing will preserve the explosive potential of the device for surprisingly long periods of time. The disposal of illegal explosives, such as M-80s, cherry bombs, and similar larger devices, should be under the control of bomb-disposal personnel.

Damaged, incompletely burned, or contraband consumer fireworks can be burned safely in large screened containers. One method, developed by the Chicago Police Department, uses large trash dumpsters that have been modified by cutting large holes in the sides and bottom and welding expanded metal screen over the holes. About 500 pounds of consumer fireworks, still in their cases, are loaded loosely into each modified dumpster and ignited by tossing a lighted fusee into the dumpster. Loose loading of the cartons is necessary for good air circulation, which aids in the relatively fast and complete burning (typically about 20 minutes per dumpster). Screened burning in a pit using an accelerant and remote ignition may be acceptable if the ignition of ground cover is not a problem.

Disposing of display fireworks is much more difficult because of the potential for dangerous explosions. When possible, the most desirable method for disposing of small numbers of display fireworks is to have the display operator remove the items from the site and transport them back to the facility of origin for salvaging or disposal there. When a small number of display fireworks must be disposed of at the site of a fire or performance, soaking in water (especially the fuse), then burning the devices individually in a small pit is probably the safest procedure overall. This process requires careful supervision by persons knowledgeable in pyrotechnics or bomb disposal, since the items may function normally with their full explosive potential. However, more often, the item does not ignite until the casing has been burned through, in which case it generally burns safely without explosion.

Fire Suppression

To summarize, fire suppression at incidents involving only consumer fireworks will present few surprises or unusual challenges or dangers if standard operating procedures are followed. Fires involving, or with a potential to involve, display fireworks or illegal explosives present an immediate life threat to fire suppression personnel. When fires involving display fireworks are encountered, a defensive perimeter should be established, and personnel must not be put at risk with direct fire suppression, unless the incident commander believes the potential benefit of a probable rescue outweighs the high risk. Remember that display fireworks are explosives, and in general, fires involving explosives should not be fought.

Since pyrotechnic materials contain their own oxidizers, methods that simply separate the fire from oxygen in the air will not be successful. Using large amounts of water will be successful, however, since the water removes enough heat to keep the materials below their ignition temperatures.

Pyrotechnic devices routinely contain metallic fuels, such as aluminum, that can react with water to produce ignition or even explosion. However, the likelihood of this being a practical problem is greatly overstated in most writings about fireworks materials—that is to say, the conditions under which this could be a problem are quite unlikely and fairly easily controlled. Consider first that most pyrotechnic materials do not become sensitized in any way by the addition of water, especially if that is a large quantity of water. In fact, the vast majority of fireworks compositions are made wet with water during their manufacture. The misconception regarding water comes from accidents that have occurred at manufacturing sites, where relatively large amounts of pyrotechnic composition have become hot and damp for extended periods of time.

Those metals that do have the potential for water reactivity generally produce their effects by burning so hot (greater than 7,000 °F for magnesium) that exposed water dissociates into oxygen and hydrogen. The quantities of reactive metals in pyrotechnic compositions are simply too small to create a threat from the addition of water. This reassurance clearly does not apply if drums of metallic powders such as those likely to be found at a fireworks manufacturing site are involved.

In addition to the reasons suggested above for not engaging in suppression of fires involving fireworks, there is another generally applicable reason. Any items containing pyrotechnic materials remaining after the fire will probably be hazardous waste needing to be disposed of, probably by burning. Accordingly, if it is safe to do so, why not just let the material burn completely in the first place?

Fireworks Stand Fires

In fireworks stands, or even large retail outlet stores with retail consumer fireworks, the rate of fire spread is likely to be such that full involvement will occur by the time the first-due engine company arrives. Note that for a properly configured sales location, the rate of fire spread should not be so great that people should have much difficulty fleeing. On arrival, it probably is prudent not to mount an interior attack. Even though there is virtually no potential for mass explosion and the fire probably will be significantly less intense than commonly imagined, there is still some potential danger to firefighters from rockets and small aerial shells igniting in the fire. Standard personal protective equipment will provide substantial protection from serious injury; however, there still may be significant physical discomfort from being struck by such projectiles. Although the range of such projectiles will be less than 300 feet, they may function where they land and ignite other materials.

Fireworks Manufacturing Site (Consumer or Display)

National Fire Protection Association (NFPA) and Bureau of Alcohol, Tobacco and Firearms (ATF) regulation changes over the past 10 years have resulted in safer designs and requirements for manufacturing sites. Nonetheless, by ATF regulation and NFPA 1124, *Code for the Manufacture, Transport and Storage of Fireworks*, 1998, as much as 500 pounds of pyrotechnic materials of all kinds or 10 pounds of flash powder may be in any one structure or area—a quantity certainly sufficient to produce a dangerously powerful explosion. In addition, although it is beyond the scope of this article, suffice it to say that fireworks manufacturing facilities are designed with separation distances and barricades that should ensure only a modest danger of fire spreading from one structure to another. Accordingly, attempting to fight a fire at a manufacturing site is quite dangerous, and there generally is very little reason even to attempt it.

Epilogue

The information presented in this article is based on the most current data regarding fireworks, their composition, and manner of functioning, as well as on our opinions. Realize, however, that many aspects of fireworks and their behavior have not been well studied scientifically, particularly in fire situations. Accordingly, while the recommendations made herein are thought to be correct and generally applicable, they cannot be absolutely guaranteed. As always, the incident commander must exercise his best judgment based on available background information as well as on the scene situation.

Acknowledgement

We acknowledge the contributions of Dr. John A. Conkling, executive director of the American Pyrotechnics Association and adjunct professor of chemistry at Washington College at Chestertown, Maryland, who provided valuable technical information and editorial advice, and Michael Poulton, who critiqued the manuscript.

Endnotes

1) J. A. Conking, *Chemistry of Pyrotechnics*, Dekker, New York, N.Y (l985). An outstanding text for background information.

2) Electric match, or fireworks igniter, consists of wire terminating at a relatively high resistance bridgewire surrounded with a small quantity of heat-sensitive pyrotechnic composition. When sufficient electric current is passed through the wire, the heat generated ignites the pyrotechnic composition, producing a small burst of flame. That flame typically ignites a fuse connected to one or more fireworks aerial shells.

3) K. L. Kosanke, "Net weight of explosives", *Fireworks Business*, No. 132 (1995).

4) J. A. Conkling, "American Fireworks Manufacturing and an Industry in Transition", NFPA *Fire Journal*, Vol. 80, No. 5 (1986) p 50–52.

An earlier draft appeared in *Journal of Pyrotechnics*, No. 1, 1995.

Concussion Mortar Internal Pressure, Recoil and Air Blast as Functions of Powder Mass

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ABSTRACT

A concussion mortar is a device used to produce jarring explosive sounds at events such as concerts and other theatrical productions. It consists of a heavy steel bar, drilled out to produce an explosion chamber. A type of pyrotechnic flash powder is loaded into the explosion chamber and fired with an electric match. Although concussion mortars are used quite frequently, for the most part, detailed measurements of their manner of functioning have not been reported in the literature. In the present study of concussion mortars, internal mortar pressure, recoil force and air blast were measured as functions of concussion powder load. It was determined that a full load (1 oz. or 28 g) of a strontium nitrate and magnesium concussion powder produced peak internal pressures averaging approximately 3100 psi (21 MPa). It was also observed that the width of the pressure peak ranged from approximately 7 ms for light loads, down to less than 2 ms for heavy loads. The recoil produced for a full load averaged approximately 5.9 lbf·s (26 N·s). The air blast for a full load, at a point 5 feet from and 3 feet above the mortar (1.52 m and 0.91 m, respectively), averaged approximately 1.5 psi (10 kPa). In addition, there were a number of unexpected observations, some of which have not been fully explained at the time of this writing.

Introduction

The present study is an extension of an earlier work by one of the authors,[1] and was undertaken to more completely characterize and understand the functioning of concussion mortars. (Concussion mortars are used to produce jarring explosive sounds at events such as concerts and other theatrical productions.) It was felt that a more thorough study of concussion mortars was appropriate for two reasons. The first reason is that, because of the likelihood of persons being located relatively near concussion mortars when they are fired, safety may be better assured through a more complete understanding of their operating characteristics. The second reason is simply that the study was expected to yield intrinsically interesting results that have not been reported elsewhere in the literature.

Typically, a concussion mortar consists of a massive steel bar approximately 2 inches (50 mm) in diameter, which has been welded to a heavy steel base plate. The steel bar contains an explosion chamber, produced by drilling an approximately 1-inch (25-cm) diameter hole—on axis—into one end of the bar, to a depth of 4 to 5 inches (100 to 120 mm). The construction of a concussion mortar is illustrated in Figure 1, which also demonstrates its loading with a charge of concussion flash powder and one method of installing an electric match. Upon firing the electric match, and because of the partial confinement, the concussion powder burns explosively (see Figure 2). The high pressure created in the

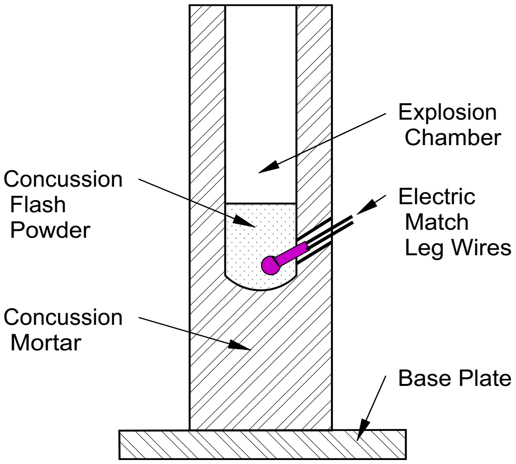

Figure 1. An illustration of the construction and setup of a concussion mortar.

explosion chamber results in the combustion gases being forced rapidly upward and out of the concussion mortar's explosion chamber. This necessarily produces a downward reactive force, the recoil of the mortar. As the high velocity gases exit the mortar, they expand as a shock wave, producing the air blast that is heard and felt by the audience. With a concussion flash powder that is fuel rich, such as the one used in this study, there will be additional burning of the exiting gases as they mix with oxygen from the air.

In this study, internal mortar pressure, recoil force, and air blast pressure—as functions of concussion powder load—were investigated. Internal mortar pressure is of interest to assure that in designing concussion mortars there is an adequate safety margin in the strength of its explosion chamber. Mortar recoil force is of interest to assure that the placement of concussion mortars can be such that their recoil will not damage other equipment. Air blast pressure is of interest to assure that the placement of concussion mortars is such that the hearing of persons will not be impaired as a result of its use. (Note that the present study only provides limited air blast data, and that additional studies are anticipated by the authors.)

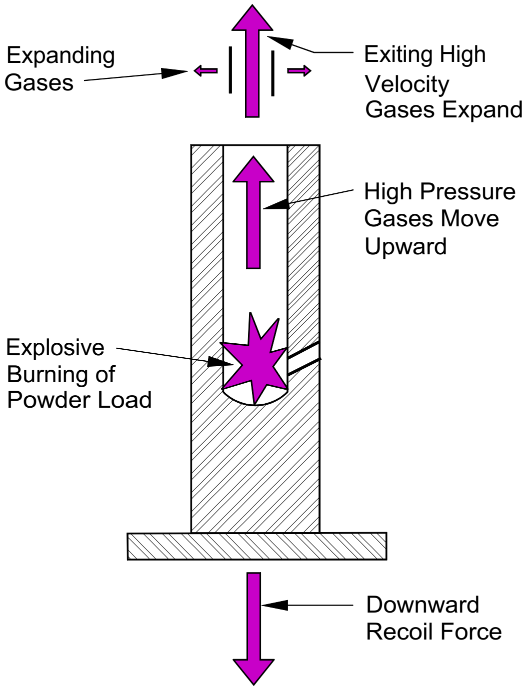

Figure 2. An illustration of the firing of a concussion mortar.

Experimental Method

A concussion mortar was modified as illustrated in Figure 3. A hole was drilled into the bottom of the explosion chamber, which, after threading, allowed the mounting of a pressure transducer to measure the high internal pressures produced upon firing the mortar. In addition, a hinge assembly was attached to one end of the base plate of the mortar, and the mortar was positioned such that the bore of the explosion chamber was located directly over a force transducer. The pressure transducer was a quartz piezoelectric gauge with a 0 to 75,000 psi (0 to 520 MPa) range, manufactured by Kistler Instrument Corp. (model 617C). The Kistler gauge produces a current output pulse, which was converted to a voltage pulse using a PCB Piezotronics voltage amplifier (model 401A03). The force transducer was also a quartz gauge, with a 0 to 5000 lbf (0 to 22 kN) range, manufactured by PCB Piezotronics (model 208A05).

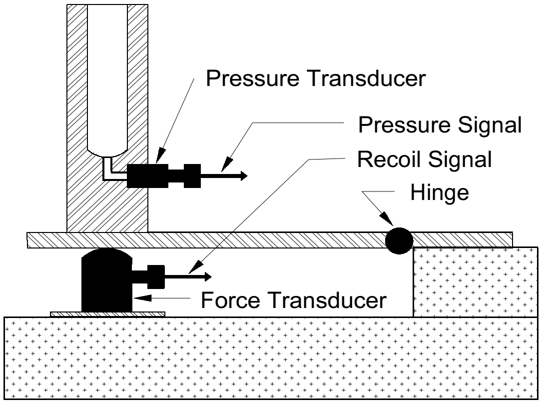

Figure 3. An illustration of the modified concussion mortar used to collect internal mortar pressure and recoil force data.

Air blast measurements were taken with the equipment setup as illustrated in Figure 4. The data was generated using a free-field blast probe aimed at the muzzle of the concussion mortar from a point 5 feet (1.52 m) distant and 3 feet (0.91 m) above. The pressure transducer has a ceramic sensing element with a blast pressure range of 0 to 50 psi (0 to 340 kPa) and was manufactured by PCB Piezotronics (model 137A12). This particular type of pressure transducer is somewhat temperature sensitive. Because the concussion powder used was quite metal fuel rich (see below), upon firing, a significant thermal pulse was generated. To eliminate the effect of the thermal pulse on the pressure measurements, the pressure transducer was covered with a thin film of silicon grease; then a 0.001 inch (0.025 mm) thick film of aluminized mylar was used to tightly cover the grease. While it is possible these measures had an effect on the pressure data recorded, it is felt any effect was small enough to be ignored in this study.

In each case, the power source for the gauges was an amplifying battery power unit manufactured by PCB Piezotronics (model 480D09). The results were recorded and temporarily stored using a digital oscilloscope and a digital storage unit. Permanent storage and plotting of the data was accomplished through the use of a personal computer.

The pyrotechnic powder used in the measurements was Luna Tech's Pyropak Concussion Flash Powder, supplied as a two-component (binary) system in packaging of 1.0-ounce (28 g) units. This is a fuel rich (approximately 1.5 times the stoichiometric amount of magnesium) combination of strontium nitrate and magnesium. The mixed powder was weighed and loaded loosely into the top of the concussion mortar. The powder was ignited using a Pyropak "BN" type electric match, which was inserted through a small hole near the bottom of the explosion chamber of the mortar (shown slightly enlarged in Figure 1). An attempt was made to be consistent in the placement of the electric match; this was accomplished each time by inserting the match as far as possible and then withdrawing it about 1/8 inch (0.3 cm) to raise it slightly off the bottom of the explosion chamber.

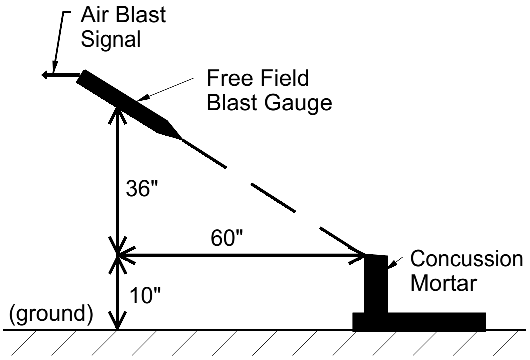

Figure 4. An illustration of the physical setup used to collect concussion mortar air blast data.

Between each mortar firing, the bore of the mortar (explosion chamber) was cleaned and to some extent cooled. This was accomplished using compressed air and a large test-tube brush. In part this was done for consistency in the results; however, it was also done for safety. Large numbers of measurements were being made, often with only a few minutes between mortar firings. In more than one case, even several minutes after a firing, live (incandescent) sparks were blown from the mortar upon cleaning. It was feared that there could possibly have been a premature ignition of the concussion powder while loading, had the mortar not been well cleaned between firings.

Concussion Mortar Internal Pressure

Substantially different internal pressure profiles (pressure versus time) were obtained for light and heavy concussion flash powder loads. Figure 5 presents somewhat typical pressure profiles for light (<12 g) and heavy (>12 g) powder loads. It was common for light loads to exhibit broad and undulating pressure peaks, while heavy loads essentially always produced fairly narrow single peaks. There was also considerable variation between pressure profiles from shot to shot even for the same powder load. This was especially true for intermediate concussion powder loads (8 to 14 g) when either broad undulating or single peaks occurred intermittently; see Figure 6. The full set of internal mortar pressure data is presented in Table 1.

Table 1. Internal Concussion Mortar Pressure Data

Load (g)	Peak Pressure (psi)	FWHM (ms)	Impulse (psi·s)
2	41	6.7	0.22
2	46	6.3	0.22
3	95	5.9	0.48
4	131	8.3	0.63
5	163	7.2	0.91
6	189	5.2	1.16
7	211	7.8	1.32
7	184	7.3	1.31
8	268	5.7	1.70
8	226	6.6	1.44
9	194	11.4	1.70
9	295	6.2	1.91
10	395	5.2	2.08
11	353	6.2	2.19
11	874	2.4	2.42
12	1050	2.0	2.72
12.5	647	4.1	2.82
13	1190	2.3	3.07
13	1540	1.6	2.93
14	1450	1.8	3.12
14	1580	1.7	3.01
14	1470	1.8	3.13
14	1710	1.6	3.03
14	1290	2.2	3.14
14	1180	2.1	2.72
14	1890	1.4	3.14
14	1630	1.5	2.55
14	1660	1.4	2.59
16	2210	1.3	2.32
17	2260	1.6	3.70
18	1890	1.6	3.12
19	2470	1.5	3.57
20	2390	1.8	4.02
21	2050	1.8	3.92
21	1820	1.8	3.30
21	2050	2.0	4.27
21	2790	1.4	3.79
21	1970	2.0	4.18
21	2710	1.9	5.28
21	1970	1.3	2.68
22	1870	1.6	2.97
23	2580	1.6	4.43
24	2890	1.7	4.14
25	2500	1.5	3.77
26	2870	1.8	4.65
27	2890	1.9	5.23
28	2870	2.1	5.74
28	2710	1.9	4.86
28	3160	2.1	6.13
28	3680	2.1	5.05
28	3420	1.8	6.06
28	2710	1.8	4.88
28	3470	1.8	6.12
28	2710	1.9	5.34
28	2930	1.8	5.43

(For conversion to SI units, 1 psi = 6.89 kPa.)

FWHM = Full-width at half maximum.

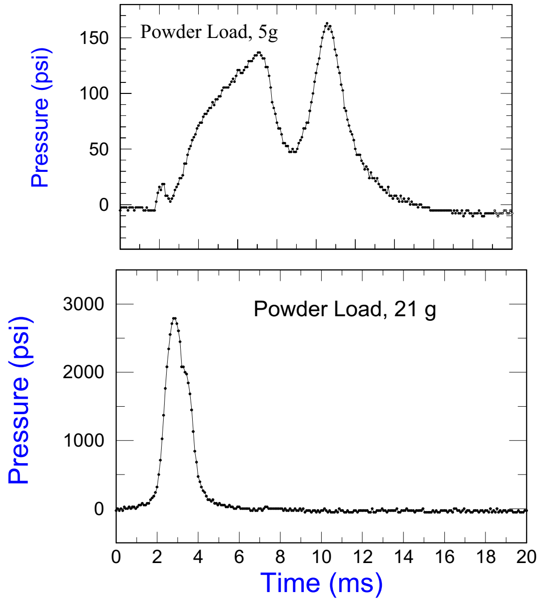

Figure 5. A comparison of typical concussion mortar internal pressure profiles for light and heavy powder load masses. (For conversion to SI units, 1 psi = 6.89 kPa.)

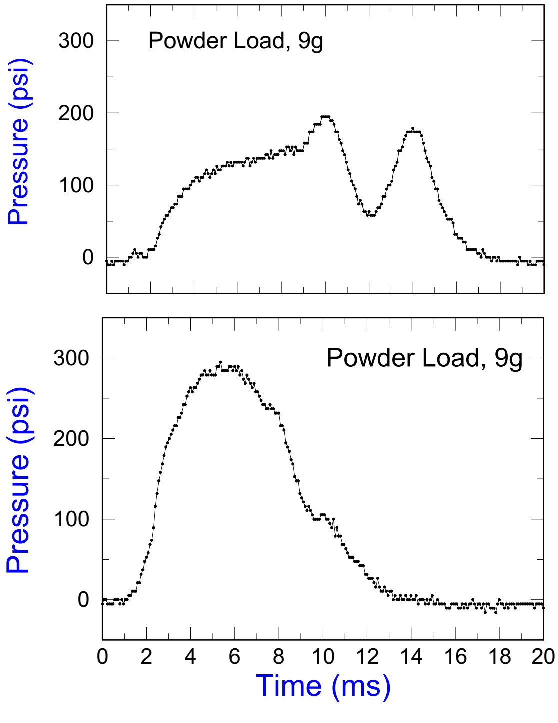

Figure 6. A comparison of two internal, pressure profiles for the same medium concussion powder load mass. (For conversion to SI units, 1 psi = 6.89 kPa.)

Peak width information, expressed as the full-width-at-half-maximum (FWHM), for the pressure peaks, is also included in Table 1. This method was chosen as the indicator of peak width, because of the ease of determination and the subjectiveness of otherwise establishing precisely where these peaks begin and end. Figure 7 is a graph of FWHM for pressure peaks as a function of concussion powder load mass. Note the transition from relatively broad to narrow pressure peaks that occurs around 11 g loads.

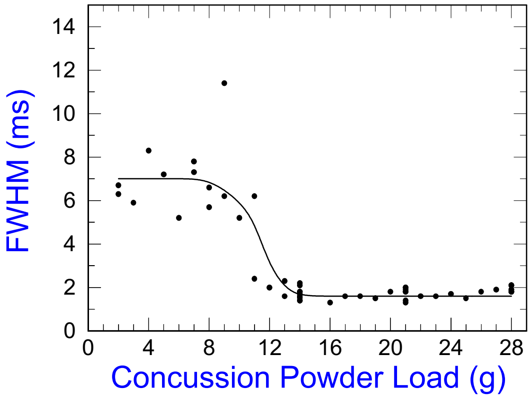

Figure 7. A graph of full-width-at-half-maximum (FWHM) for internal pressure peaks as a function of concussion powder load mass.

Peak internal mortar pressure as a function of powder load is presented as a graph in Figure 8. Because of the varying width of the peaks seen in the pressure profiles with increasing powder load, time integrated data (pressure impulse) was generated as a better estimator of the total energy released per mortar firing, see Figure 9.

In one brief set of measurements, internal mortar pressures were taken with a second pressure transducer installed in the side of the mortar, 1.5 inches (3.8 cm) below the muzzle. In these tests, because the high velocity gases were moving parallel to the bore of the mortar, significantly reduced pressures were recorded for the upper location. These results are presented in Table 2.

Table 2. Comparative Internal Pressure Data.

Load (g)	Peak Pressure Bottom (psi)	Peak Pressure Top/Side (psi)	Pressure Ratio
14	1710	950	0.56
14	1290	720	0.56
14	1180	820	0.69

(For conversion to SI units, 1 psi = 6.89 kPa.)

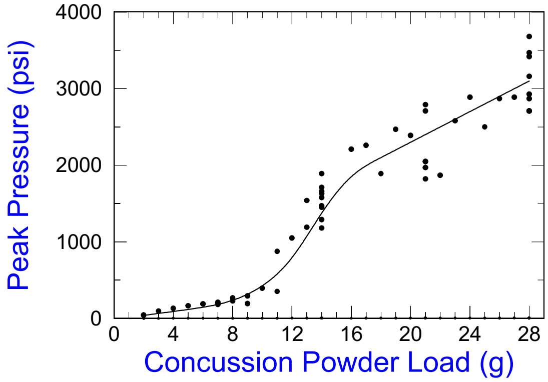

Figure 8. A graph of peak internal pressure as a function of concussion powder load mass (For conversion to SI units, 1 psi = 6.89 kPa).

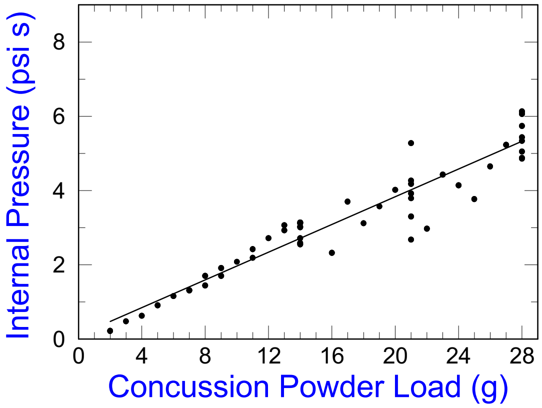

Figure 9. A graph of time integrated internal pressure (Pressure Impulse) as a function of concussion powder load mass. (For conversion to SI units, 1 psi·s = 6.89 kPa s.)

Concussion Mortar Recoil

For concussion mortar firings, the recoil force profile has the same approximate shape as the internal pressure profile; for an example, see Figure 10. The similarity of the two profiles is fairly obvious, particularly if the last doublet peak is mentally smoothed into a lower resolution singlet. However, there is a systematic shift in the timing of the peaks, with the recoil force peaks falling progressively farther behind the internal pressure peaks. In Figure 10 note that the first peaks (labeled as "1") occur at essentially the same time; there is nearly a 1 ms shift between the second peaks ("2"); and there is approximately a 2 ms shift in the timing of the third peaks ("3"). Similar time shifting of the peaks occurred whenever there were clearly defined multiple peaks. Somewhat similarly, when only single peaks were produced, every time the pressure peak always preceded the recoil peak by about 0.5 ms.

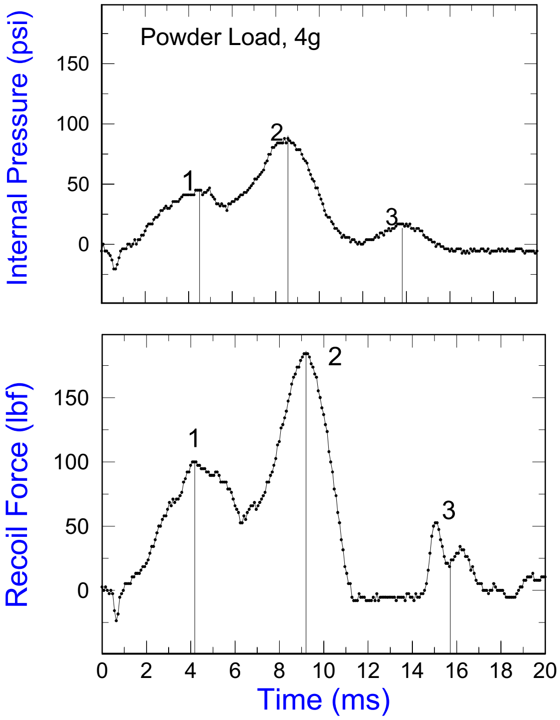

Figure 10. A comparison of an internal pressure profile and the recoil force profile for the same concussion mortar firing. (For conversion to SI Units, 1 psi = 6.89 kPa, and 1 lbf = 4.45 N.)

The full set of recoil force measurements is presented in Table 3. The width of recoil force profiles varied much like they did for internal pressure. However, there was an additional factor that affected the widths of the recoil force peaks; that is, the nature of the surface upon which the concussion mortar was placed. When the surface is very firm and hard, such as a concrete slab, the recoil force peaks are relatively narrow. When the mortar is placed on a more yielding surface, such as the ground or on thick carpet, wider peaks are produced. For example, consider the recoil force data reported in Table 3 for full powder loads (1.0 ounce, 28 g). The first four measurements (28-a) were made with the concussion mortar placed firmly on a concrete slab, the next five measurements (28-b) were made with the mortar on the ground, and the last three measurements (28-c) were made with the mortar placed on thick carpet. A summary of these results is given in Table 4. Note that there is a substantial increase in average peak width (46% and 410% when on the ground and carpet, respectively), accompanied by a significant decrease in peak force (27% and 66%, respectively). Note however, that the time integrated recoil force is much less affected (5% and 22% reductions, respectively). During the course of taking the recoil force data in this study, because of operational constraints, the location of the equipment was changed several times. Accordingly, it is felt that only the time integrated -

Table 3. Concussion Mortar Recoil Force Data.

Load (g)	Force (lbf)	FWHM (ms)	Impulse (lbf s)
2	52	7.7	0.27
2	56	6.9	0.26
3	91	6.3	0.46
4	131	6.0	0.61
5	150	8.6	0.90
6	175	4.4	1.10
7	211	7.4	1.26
8	269	6.9	1.48
8	277	5.2	1.50
9	213	12.5	1.58
9	303	6.0	1.69
10	366	5.7	1.92
11	299	6.7	2.06
12	1090	2.2	2.48
12.5	538	4.1	2.39
13	1400	1.8	2.68
14	1980	1.4	3.07
14	2110	1.3	3.10
14	1940	1.4	3.04
14	1910	1.4	3.01
14	1910	1.4	3.05
16	2540	1.3	3.68
17	2840	1.3	3.96
18	2370	1.4	3.44
19	3010	1.4	4.32
20	3210	1.3	4.44
21	2970	1.3	4.03
21	2490	1.3	3.44
21	2920	1.4	4.19
21	3100	1.6	4.93
21	3070	1.6	4.88
21	2470	1.7	4.52
21	3140	1.6	5.23
21	2360	1.6	3.92
22	3850	1.1	4.76
23	4190	1.2	5.27
24	4410	1.1	5.15
25	3960	1.2	5.02
26	4600	1.1	5.65
27	4710	1.1	5.65
28-a	4640	1.2	5.92
28-a	4450	1.2	5.66
28-a	5050	1.1	6.22
28-a	5500	1.1	6.50
28-b	4110	1.6	6.43
28-b	3140	1.8	5.23
28-b	4070	1.6	6.46
28-b	2950	1.8	5.06
28-b	3550	1.6	5.62
28-c	1380	6.3	4.49
28-c	2170	5.0	5.28
28-c	1350	6.2	4.43

(For conversion to SI units, 1 lbf = 4.45 N.)

Notes: a- Mortar on concrete.
b- Mortar on ground.
c- Mortar on carpet.

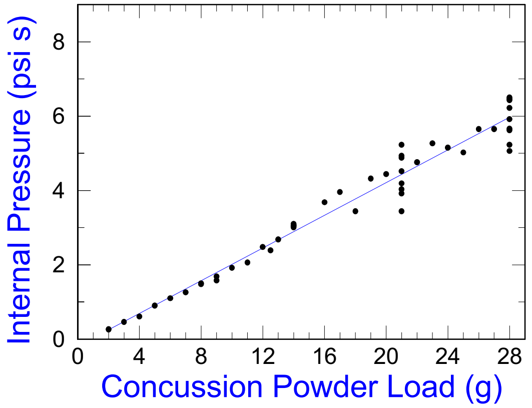

Figure 11. A graph of time integrated mortar recoil force (Impulse) as a function of concussion powder load mass. (For conversion to SI units, 1 lbf = 4.45 N.)

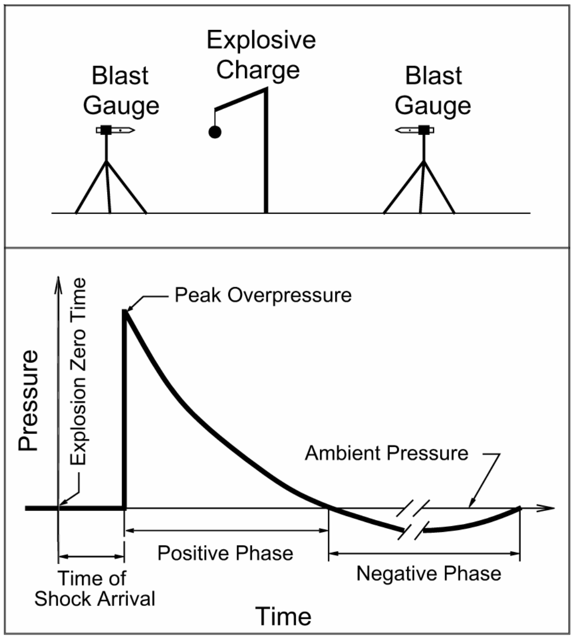

Figure 12. An illustration of a typical setup and blast profile from an explosive charge.

recoil force data (impulse) rather than the peak force results is sufficiently consistent to be relied upon. Recoil impulse data is presented in Figure 11.

Table 4. Average Results of Changing the Support Surface for the Concussion Mortar Fired with 28 g (1.0 ounce) Loads.

Parameter Averages	Concrete	Ground	Carpet
Peak Pressure (psi)	4910	3560	1630
FWHM (ms)	1.15	1.68	4.73
Impulse (psi·s)	6.08	5.76	4.73

(For conversion to SI Units, 1 psi = 6.89 kPa.)

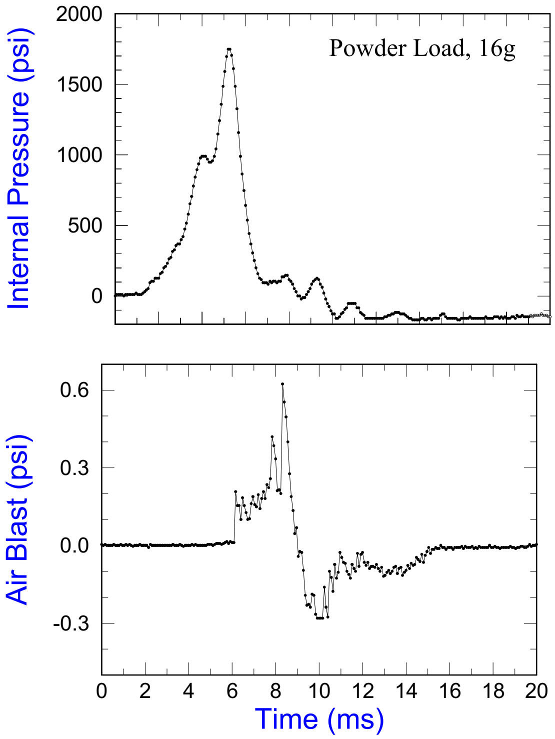

Figure 13. A comparison between an internal mortar pressure profile and an air blast profile for the same mortar firing. (For conversion to SI Units, 1 psi = 6.89 kPa.)

Concussion Mortar Air Blast

The air blast profiles (blast pressure versus time) do not have the same appearance as those from the explosion of individual charges such as illustrated in Figure 12. During the course of taking data, a few firings were accomplished in which internal mortar pressure and air blast data were recorded simultaneously. A comparison of the results suggests that when taken near the concussion mortar, approximately 5.8 feet (1.8 m),

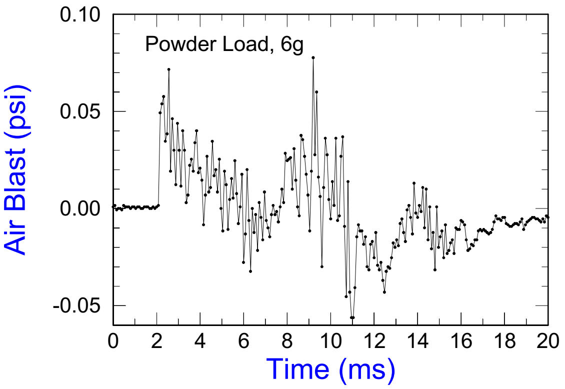

Figure 14. An example of the random oscillatory fluctuations typically seen in air blast profiles from light powder loads. (For conversion to SI Units, 1 psi = 6.89 kPa.)

the air blast profile still retains some general features of the shape of the internal pressure profile, see Figure 13. (Note that the time delay before the onset of the blast pressure event is due to the time taken for the blast wave to reach the detector. Also, the air blast profile has a negative phase, not seen in the internal pressure profile.) This similarity between the two profiles can only be possible if the so called "shocking up" process, which acts to produce the standard air blast wave shape, has not been completed by the time the blast wave arrives at the detector.

In addition to the air blast profiles tending to reproduce the internal pressure profiles, there is another cause of concussion mortar blast profiles appearing different from that of an explosion. For light powder loads (<12 g), there tends to be random oscillatory fluctuations in the air blast profile, see Figure 14. From the many other measurements made during this and previous studies, it is certain that the fluctuations are not the result of instrument or electrical noise. Further, these random oscillations essentially disappear for heavy powder loads (>20 g). The frequency of the fluctuations is high enough that it may possibly be the result of pressure oscillations occurring within the bore of the explosion chamber, perhaps combined with aliasing because of the fairly low data sampling rate (12,500 samples per second). The combination of internal pressure peak narrowing and the reduction of the oscillatory fluctuations for heavier powder loads, results in pressure profiles that appear much like those of typical explosions, see Figure 15 (compare with Figure 12).

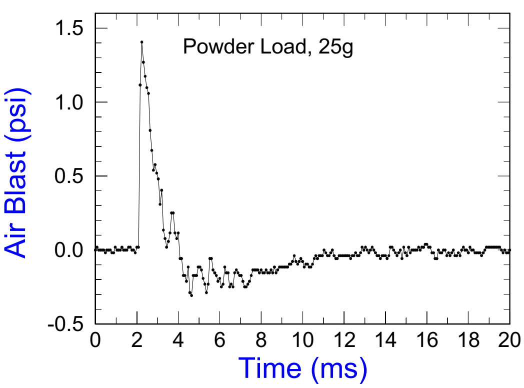

Figure 15. An example of an air blast profile for a heavy powder load. More closely resembling that of a typical explosion (see Figure 12). (For Conversion to SI units, 1 psi = 6.89 kPa.)

The full set of air blast results is presented in Table 5. Because of the presence of significant random oscillatory fluctuations in many of the air blast profiles, the rapid rise of many others, and because it is the duration of the positive phase of the blast wave that is of interest, it was felt that attempts to determine the FWHM would be difficult and of little value. Accordingly, for each profile, only an estimate of the duration of the positive phase was made. However, in some cases it was necessary first to mentally smooth the profiles to be able to pick the end point of the positive phase of the blast wave. Figure 16 is a graphical presentation of air blast impulse as a function of concussion powder load mass.

Discussion

Internal pressure

Based on fundamental principles, much of what was observed in these measurements might have been predicted, at least in a general way. For example, over the range of concussion powder loads, internal mortar pressure increases with load mass, but it is not strictly proportional to load mass, particularly for light loads. That is to say, it would be expected from basic principles that internal mortar pressure would be greater for a 6 g load than for a 3 g load. It would also be expected that internal pressure for a 6 g load

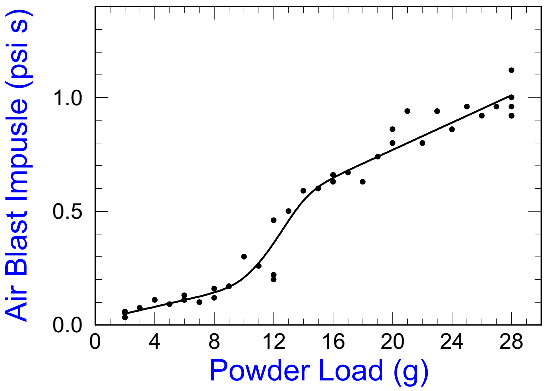

Figure 16. A graph of time integrated air blast (pressure impulse) as a function of concussion powder load mass. (For conversion to SI Units, 1 psi = 6.89 kPa.)

would be more than twice that for a 3 g load. Indeed, for some very small loads, it would be expected that the powder would burn without producing any detectable pressure event, particularly for a nitrate-based flash powder.

This study was particularly interesting for the authors, because there were a number of unexpected observations, for which the authors presently do not have satisfactory explanations. For example, while it might be expected that there would be a general narrowing (in time) of the internal mortar pressure profiles as powder loads are increased, it would not have been predicted that the narrowing would occur rather precipitously, over a relatively small range of loads (refer to Figure 7). Indeed, the data is fairly consistent with there being two essentially constant profile widths, one about 7 ms and one about 2 ms, with a fairly rapid transition between the two profile widths, occurring at loads of about 11 g of concussion powder. More unexpected was the observation that the wide internal mortar pressure profiles often consisted of a number of individual peaks (see again Figures 5 and 6). Presumably, this is an indication of some type of instability in the burning of light powder loads, but what would cause such instability? What is observed seems like multiple explosions; but would that even be possible, and if so, what is the mechanism that produces such a series of explosions within the concussion mortar?

Table 5. Concussion Mortar Air Blast Data.

Load (g)	Peak Pressure (psi)	Positive Phase (ms)	Impulse (psi·ms)
2	0.015	5.8	0.033
2	0.036	9.0	0.059
2	0.033	9.2	0.053
3	0.092	2.0	0.075
4	0.075	5.1	0.11
5	0.056	6.3	0.092
6	0.078	8.7	0.11
6	0.075	9.6	0.11
6	0.087	5.1	0.13
7	0.073	10.	0.10
8	0.11	4.7	0.16
8	0.096	5.4	0.12
9	0.20	3.4	0.17
10	0.20	4.2	0.30
11	0.23	4.0	0.26
12	0.13	4.6	0.20
12	0.30	4.2	0.46
12	0.13	5.4	0.22
13	0.54	2.2	0.50
14	0.57	2.6	0.59
15	0.75	1.9	0.60
16	0.58	2.9	0.66
16	0.62	3.0	0.63
17	1.12	1.8	0.67
18	0.92	1.6	0.63
19	1.06	1.8	0.74
20	1.17	2.5	0.86
20	0.83	2.3	0.80
21	1.21	1.7	0.94
22	1.13	1.6	0.80
23	1.32	2.1	0.94
24	1.00	1.6	0.86
25	1.40	2.0	0.96
26	1.38	2.4	0.92
27	1.34	2.0	0.96
28	1.40	2.1	0.96
28	1.38	2.1	0.92
28	1.60	2.2	1.00
28	1.63	1.2	0.92
28	1.62	2.0	1.12

(For conversion to SI Units, 1 psi = 6.89 kPa.)

Burst Strength Safety Margin

One reason for this study was to determine the safety margin in the strength of concussion mortars. Perhaps the simplest method to verify that the strength of a device like a cannon (or concussion mortar) provides an adequate safety margin, and a method that has been used for centuries, is to fire the device when intentionally overloaded with powder (a so-called "proof firing"). However, while adequate to the need, this does not give quantitative information on the pressures being developed internally. That is unfortunate, first, because it means that a proof firing cannot quantify the pressure safety margin, and second, because such pressure information is intrinsically interesting. Accordingly, internal pressure measurements were made as part of this study. Using Luna Tech's Concussion Flash Powder, it would appear that the internal mortar pressure for a maximum 28 g (1.0 ounce) load does not exceed 4000 psi (28 MPa) at the bottom of the explosion chamber and less near the muzzle of the mortar. It is important to note that the use of other, more brisant, flash powders would certainly produce much higher internal mortar pressures! Accordingly, the following discussion concerning the adequacy of the strength of concussion mortars only applies to their use with Luna Tech's Concussion Flash Powder.

To calculate the strength safety margin for a concussion mortar it is necessary to first determine its burst strength. For one way to do this, consider the following. Concussion mortars are generally made using a mild cold-rolled steel (such as AISI 1025), the yield strength of which is rated at 6.8×10^4 psi (4.6×10^8 N/m^2).[2] Clavarino's equation[3] can be used to estimate the maximum burst strength of a thick-walled, cylindrical pressure vessel with closed ends (the bottom of a concussion mortar's explosion chamber). Similarly, Birnie's equation[3] can be used for the calculation at the open end of the concussion mortar. When these calculations are performed, using a yield strength as the safe tensile strength of the steel, the result is a maximum burst strength of approximately 3.5×10^4 psi (2.4 MPa). Accordingly, there is a pressure safety margin of more than a factor of eight for the concussion mortar used in this study, when using Luna Tech's Concussion Flash Powder.

Recoil Forces

The recoil forces measured in this study during the firing of a concussion mortar with a full load of powder are in good agreement with the earlier study,[1] especially considering the significantly different test methods employed. In the earlier work, when using Luna Tech's Concussion Flash Powder, it was observed that the recoil, produced upon firing the mortar in a downward direction, was sufficient to raise a 25 pound (11.4 kg) mortar, 8 inches (0.20 m) into the air. This corresponds to an initial upward velocity of 6.6 feet/s (2.0 m/s). When using the impulse measured in this study for the concussion mortar fired on a concrete slab, an initial upward velocity of 7.9 feet/s (2.4 m/s) would be produced for the same mortar mass. This value is only 20% higher.

The recoil forces recorded in this study (as high as 5500 lbf), probably appear to some readers as being quite high. However, it is important to remember that these high forces are being applied for less than 2/1000 of a second. This is the same impulse and similar force that would be produced by dropping a hard 25-pound (11.4 kg) object from a height of one foot (0.3 m). Further, should it be necessary, the peak recoil force can be significantly reduced (e.g., by 66%) by simply placing the concussion mortar on a soft surface such as carpeting (refer to Table 4). Note that the use of carpeting under the mortar is also energy absorbing, as indicated by the 22% reduction in impulse.

Air Blast

The shape of the air blast pressure profile, under the conditions of these measurements, is not the same as those from typical explosions (refer to Figures 12, 13, and 14). As a result, the scaling equations used to predict blast pressures at various distances from an explosion may not be reliable. Accordingly, a more complete discussion of the expected effects of concussion mortar firing on human hearing should be delayed until more complete test data has been assembled. However, comments can be made regarding sound levels at the distance used in this study, 5.8 feet (1.8 m). For the full-recommended powder load (1.0 ounce or 28 g) of Luna Tech's Concussion Flash Powder, the maximum measured air blast pressure was approximately 1.6 psi (11 kPa). It is reported that upon exposure to a blast pressure of 15 psi approximately half the population will suffer rupture of the ear drum (tympanic membrane); at 3.2 psi, approximately 1% will experience rupture of their ear drums.[4] Further, the threshold for ear drum rupture is reported to be in the range of 2 to 4 psi.[4] Accordingly, there would seem to be no possibility of rupturing ear drums under the conditions of this study.

Ruptured eardrums are not the only concern relating to noise induced hearing loss. There can also be temporary and permanent loss in hearing acuity (referred to as baseline shifts). The government and various researchers have set different criteria for what degree of hearing loss is acceptable. For example, in the work place, US OSHA has established a maximum impulsive noise limit (explosive-like sounds) of 140 dB fast response.[5] The military has established that it is acceptable for exposure to 100 impulsive noise events (weapon firings) per day, where the maximum acceptable sound level is roughly150 dB.[6] At the distance used in this study, a sound level of 150 dB should be observed for loads exceeding approximately 6 grams.

Graphing internal mortar pressure and recoil force as impulse (time-integrated pressure and force) produced straight lines, effectively eliminating the effect of varying peak width. However, when this was done for air blast pressure, there is an obvious break in the curve at about 12 g loading mass (refer to Figure 16). In effect, powder loads greater than about 12 g are disproportionately more effective at producing an air blast than are loads less than about 12 g. This might possibly be the result of some type of increased efficiency in the explosive burning of the concussion powder inside the mortar. However, if that were the case, a similar break would also have to be present in the impulse curve for internal pressure, and no such break occurs (refer to Figure 9). A more likely explanation is that the added blast is being produced outside the mortar. Recall that the concussion flash powder used in these measurements is quite fuel rich (approximately 1.5 times the stoichiometric amount of magnesium). Most of this excess fuel must surely burn as it mixes with oxygen from the air. If the mixing is thorough and fast, it is possible (likely?) that the burning will be explosive, contributing to the production of air blast. To account for the near step-wise increase in air blast observed in the present study, two things would have to be the case. First, only medium and heavy powder loads must meet the requirements for explosive air burning; and second, there must be a rapid onset of conditions leading to explosive air burning. Although the authors do not have a satisfactory physical explanation for the observed near step-wise increase in time integrated air blast, based on the vast experience of one of the authors using this type of concussion flash powder, it is felt that explosive air burning is the most likely explanation.

Acknowledgments

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Hazardous Chemical Combinations: A Discussion

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ABSTRACT

All pyrotechnic compositions present some hazard due to their ability to produce energy. However, some compositions pose an added hazard because of the combination of incompatible materials. The use of such compositions may result in more frequent accidental ignitions during processing or spontaneous ignitions during storage. Other compositions pose an added hazard because of their ability to produce especially large amounts of energy with rapid reaction rates. The use of such compositions is likely to result in especially powerful explosions in the event of an accidental ignition.

This article attempts an organized examination of some combinations of commonly used pyrotechnic chemicals that are believed to have significantly increased hazard potentials.

Keywords: accidental ignition, spontaneous ignition, hazardous combinations, chemicals, compatibility, incompatibility

Introduction

By their very nature, all pyrotechnic compositions could be considered hazardous because of their potential for producing energy (occasionally at inopportune times). However, some combinations of materials present a special hazard, either because of an added potential for unintentional ignition or because of the potential for producing a powerful explosion upon ignition. Note that there are other hazards, such as health hazards, which may be associated with certain chemical combinations; however, that is beyond the scope of the present article.

A pyrotechnic chemical reaction characteristically produces heat energy. This so called “Heat of Reaction” may be useful directly as thermal energy, or more usually as light, sound, or kinetic energy to achieve the desired effect. However, a pyrochemical reaction must not begin to proceed as soon as the pyrotechnic composition is mixed, for then the composition could not be safely prepared. Such spontaneity is prevented by another characteristic of pyrotechnic compositions, a so-called “Activation Energy” barrier.

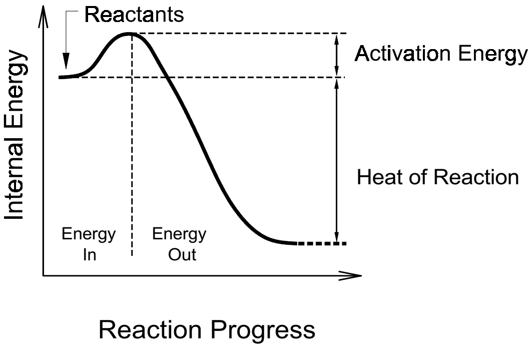

Figure 1. An illustration of the internal energy relationships in a pyrochemical reaction.

The internal energy associated with a pyrochemical reaction is depicted in Figure 1. Note that initially as the reaction begins, the internal energy of the system increases. This corresponds to the ignition process, when the composition is being supplied energy, such as by an externally applied flame. This requirement, to first input

Table 1. Some Hazardous Chemical Combinations Encountered in Pyrotechnics.

Species		Chlorates	Perchlorates	Aluminum	Magnesium	Zinc
Chlorate	ClO_3^-	0	—	X	X	X
Perchlorate	ClO_4^-	—	0	?	?	—
Aluminum	Al	X	?	0	—	—
Magnesium	Mg	X	?	—	0	—
Zinc	Zn	X	—	—	—	0
Acids	H^+	X	—	—	X	X
Ammonium	NH_4^+	X	—	—	X	X
Water	H_2O	—	—	?	X	?
Copper(II)	Cu^{2+}	?	—	?	X	X
Sulfur	S	X	X	—	X	X
Sulfide	S^{2-}	X	X	—	—	—

X = Generally a significantly hazardous combination.
? = Can be significantly hazardous depending on circumstances.
— = Ordinarily, little if any added hazard.
0 = Place filler.

activation energy to the composition, is what prevents its spontaneous ignition. If the activation energy barrier is high, much energy is required for ignition and accidental ignitions will be unlikely. If the activation energy barrier is low, less energy is required for ignition. When this is the case, accidental ignition will be more likely because a relatively small amount of mechanical, thermal or electrostatic energy can cause ignition of the composition. After ignition has been accomplished, internal energy falls as energy is released from the composition. (See reference 1 for a somewhat more complete discussion of activation energy and heat of reaction.)

Over the years, pyrotechnists have tested many substances that seemed promising for use in fireworks. It turned out that some of these, such as potassium permanganate and phosphorus, have such low activation energies in pyrotechnic compositions that they invariably create a significant hazard. Because their unsafe nature in compositions is ubiquitous, it is easy to eliminate such substances from use. A much more difficult problem is the particular combinations of materials that lead to a low activation energy, even though the same materials in other combinations do not pose that hazard. Many of these hazardous chemical combinations are mentioned in the pyrotechnic literature (e.g., reference 2) but usually without complete explanatory comments. This paper attempts to present somewhat more complete information and explanations. However, this task is often complicated by the lack of solid experimental data reported in the literature. As a result, in some cases the authors will only be able to offer conjecture and anecdotal evidence. While this is not ideal, until more studies are conducted and reported, it is the best that can be done, and it is preferable to not providing any information for these combinations.

Some chemical combinations in pyrotechnic mixtures that can be particularly hazardous are listed in Table 1. However, it is important to note that the list is not all-inclusive. Further, on occasion, because of mitigating factors, some listed combinations may not present a high degree of hazard. To better understand why particular combinations of materials can present an increased hazard, each column in Table 1 will be discussed in turn.

Table 2. A Comparison of Ignition Temperatures for Some Common Oxidizers in Stoichiometric Combination with Various Fuels.[3a]

Oxidizer	Ignition Temperature (°C)				
	Sulfur	Lactose	Charcoal	Magnesium	Aluminum
Potassium chlorate	220	195	335	540	785
Potassium perchlorate	560	315	460	460	765
Potassium nitrate	440	390	415	565	890

[Note that °F = 32 + (9/5) °C.]

Chlorates

Chlorates have the lowest activation energy towards decomposition of any class of oxidizers commonly used in fireworks. Consequently, mixtures containing chlorates tend to be sensitive to all types of accidental ignition. This is evidenced by the especially low ignition temperatures of binary mixtures of potassium chlorate and fuels with low melting point or low decomposition temperature (e.g., see sulfur and lactose in Table 2). One should pay close attention to the materials a chlorate is being mixed with, to be sure that the hazard is not thereby exacerbated. However, by no means is it intended to imply that all chlorate compositions are dangerously unsafe.

With Aluminum:

Aluminum has a highly cohesive and nonporous oxide coating that must be disrupted in order for a reaction with oxidizers to take place. This feature tends to raise the activation energy for ignition, compared with many other pyrotechnic fuels, see again Table 2. However, when assessing degree of hazard, it is necessary to consider both the probability and the consequence of a potential accident.[4] In this case, the binary mixture of potassium chlorate with a fine particle size aluminum is a classic flash powder, and it has a relatively small critical mass for an unconfined explosion. Therefore, the consequences of such a mixture undergoing accidental ignition are likely to be significantly more severe than for an equivalently small amount of a standard chlorate colored star composition. The mixture is more dangerous because of the consequence, rather than a greater probability of an accident. Indeed, the probability of accidental ignition is probably less for aluminum than with common chlorate star compositions (except perhaps when the metal powder is so fine that the mixture becomes especially electrostatically sensitive).

The common solution to a hazard of this type, where the consequence is particularly severe, is to attempt to reduce the probability of an accidental ignition by raising the activation energy barrier. Usually this is accomplished by using potassium perchlorate in place of potassium chlorate. One can go further in this direction and raise the activation energy more by using barium nitrate as the oxidizer. However, one should beware of thinking that higher activation energy automatically means “safer”. It also means more difficult ignition and a greater potential for ignition failure (i.e., duds are more likely). Obviously, duds are a safety hazard just as is accidental ignition. In addition, the use of nitrate with aluminum can lead to other problems in the presence of water, as discussed below.

Conventional wisdom for flash powders would suggest using the above approach (i.e., substituting potassium perchlorate or barium nitrate for potassium chlorate). It is certainly possible that such a substitution will indeed make the resulting flash powder more resistant to accidental ignition. Unfortunately, published sensitiveness data does not fully support that. Look again at Table 2; the ignition temperature for potassium nitrate (presumably similar for barium nitrate) and aluminum is the highest of the three oxidizers. However, it is the mixture with potassium perchlorate, and not that with potassium chlorate, that has the lowest ignition temperature.

Table 3. A Comparison of Impact Sensitiveness for Some Common Oxidizers in Stoichiometric Combination with Various Fuels.[3b]

Oxidizer	Impact Sensitiveness ($kg\cdot m/cm^2$)				
	Sulfur	Lactose	Charcoal	Magnesium	Aluminum
Potassium chlorate	1.1	1.8	3.2	4.5	4.5
Potassium perchlorate	1.2	2.9	4.2	4.4	5.0
Potassium nitrate	3.6	5.0	5.0	4.6	5.0

Since these ignition temperature data are inconsistent with conventional wisdom, it is worth considering whether ignition temperature is the best indicator of the sensitiveness of mixtures, or even that the published data may be in error. Table 3 presents impact sensitiveness data for the same three oxidizers. Of the mixtures with aluminum, potassium chlorate is most sensitive; however, it is roughly equivalent to that for mixtures with either potassium perchlorate or potassium nitrate. Based on the data in Tables 2 and 3, it is not clear that improved safety results from substituting potassium perchlorate for potassium chlorate in two-component mixes with aluminum.

If it is true, that substituting potassium perchlorate for potassium chlorate does not significantly decrease the sensitiveness of binary mixes with aluminum, then one is left to ponder why conventional wisdom suggests that it does. Could it be a result of experience with flash powders that are not simple binary mixtures, but rather with mixtures including sulfur or antimony sulfide? Tables 2 and 3 do not include data for antimony sulfide but do have data for mixtures with sulfur. The impact sensitiveness data suggests that a sulfur-containing chlorate flash powder would be a little (but not much) more impact sensitive than that with potassium perchlorate. However, the ignition temperature data suggests that the chlorate flash powder would be considerably more sensitive.

The foregoing discussion is far from definitive in answering the question of relative flash powder sensitiveness. However, it is obvious, for safety, that sulfur (and almost certainly antimony sulfide) should not be present in flash powder using either potassium chlorate or perchlorate. In addition, in the absence of more data (e.g., friction and electrostatic sensitiveness), it would be prudent to abide with conventional wisdom regarding the preference for choosing potassium perchlorate or barium nitrate over potassium chlorate.

With Magnesium and Zinc:

Like aluminum, magnesium and zinc form energetic mixtures with chlorates, and similar considerations apply. However, because of the lack of a cohesive oxide coating on these metals, the activation energy for their ignition is significantly lower than it is for aluminum. The combination of both the fuel and oxidizer contributing to low activation energy provides these mixtures the potential to be particularly dangerous.

With Acids:

The predecessor of the modern match was a wooden splint tipped with a chlorate pyrotechnic composition. This was ignited by allowing the composition to come in contact with concentrated sulfuric acid[5] (which was sometimes absorbed on asbestos wool for relative safety). Use outside the home obliged one to carry a vial of sulfuric acid in one's pocket! Also, Alfred Nobel apparently invented a mine for use in naval warfare based on this principle. A ship hitting the mine would break a glass tube of sulfuric acid, which then triggered the potassium chlorate and sugar igniter.

The high ignition sensitiveness of chlorate compositions in the presence of acids is thought to involve the formation of chloric acid.[6,7]

$$KClO_3 + H^+ \rightarrow HClO_3 + K^+ \qquad (1)$$

Ignition may occur because chloric acid is capable of spontaneous ignition of organic fuels, or through its decomposition into highly reactive and unstable chlorine dioxide.[8–10]

One can therefore appreciate the necessity for keeping acidic materials away from chlorate compositions. However, if the acid is sufficiently weak, such as stearic acid, it is probably incapable of displacing sufficient chloric acid from the chlorate to induce spontaneous ignition. Moreover, the greasy nature of stearic acid helps lubricate the composition, thereby reducing its friction sensitiveness.

With Ammonium Salts:

Ammonium ions are capable of acting as an acid (proton donor).

$$NH_4^+ \rightarrow NH_3 + H^+ \qquad (2)$$

Accordingly, most ammonium salts, such as ammonium perchlorate, are acidic in aqueous solution and potentially lead to the problems discussed above.

In addition, a mixture of a chlorate oxidizer and an ammonium salt may form ammonium chlorate through a double decomposition reaction.[11]

$$NH_4^+ + ClO_3^- \rightarrow NH_4ClO_3 \qquad (3)$$

This is problematic because ammonium chlorate is a substance that explosively decomposes at 102 °C and is probably capable of undergoing a true detonation.[9,12a]

With Copper(II) [Cupric] Salts:

Like the ammonium ion, the cupric ion (Cu^{2+}) has an acidic reaction in aqueous solution. In addition, in common with other transition metals, copper ions catalyze the decomposition of some oxidizers by lowering their activation energy. For these reasons soluble copper(II) salts with an acidic reaction, such as the sulfate, should not be used with chlorates. In practice, experience has shown that such potential problems can be overcome by using a copper(II) compound that is insoluble and/or has a counter anion with a basic reaction (e.g., carbonate, oxide, etc.). Note also that copper(I) [cuprous] salts (Cu^+) do not have an acidic reaction and therefore engender a relatively minor increase in sensitiveness, unless they contain sulfur, such as copper(I) thiocyanate (CuCNS).

With Sulfur:

The combination of sulfur with chlorates is historically the most famous cause of accidental ignitions in pyrotechnics due to “incompatible” chemicals.[13,14] Such mixtures have long since been banned in some countries (e.g., England). One possible mechanism for the high sensitiveness of such mixtures may begin with the formation of polythionic acids on the surface of sulfur grains, and ultimately producing sulfuric acid[6,7] (see comments above about acids). To some extent, during mechanical action sulfur reacts with oxygen in the air to form sulfur dioxide.[13] It is thought that a chain reaction involving the gases sulfur dioxide and chlorine dioxide may be implicated in cases of spontaneous ignition of potassium chlorate and sulfur mixtures.[6,7]

$$2\ KClO_3 + SO_2 \rightarrow K_2SO_4 + 2\ ClO_2 \qquad (4)$$

$$4\ S + 2\ ClO_2 \rightarrow 2\ SO_2 + S_2Cl_2 \qquad (5)$$

It can be seen from the equations that one molecule of sulfur dioxide ends up generating two molecules of sulfur dioxide, and the cycle potentially repeats at twice the rate; and so forth until the ignition temperature may be reached. Further, sunlight is thought to exacerbate this problem as well as the use of sublimed sulfur (flowers of sulfur) rather than sulfur flour.[7,16]

It is probable that the bad reputation this mixture acquired in the past was due, in part, to impurities in the materials formerly available.[17] For example, the presence of chlorite in the chlorate, or various sulfur acids in the sulfur, could serve to initiate the chain reaction. Notwithstanding this proviso, it is clear that even with pure materials the sensitiveness of a chlorate and sulfur mixture to friction and impact is too high to justify its use.[18]

With Sulfides:

Similar considerations apply to mixtures of chlorates with sulfides as for mixtures with sulfur described above. For example, the mixture of arsenic sulfide with potassium chlorate is even more impact sensitive than the mixture of sulfur with potassium chlorate.[3c] However, different sulfides may vary in the degree and type of hazard involved. While the sulfides of antimony and copper were those most commonly

Table 4. Decomposition Energies for Some Common Oxidizers.[3d]

Oxidizer	Product	Decomposition Energy (kcal/mole)
Fe_3O_4	Fe	+266
KNO_3	K_2O	+151
$Ba(NO_3)_2$	BaO	+104
$Sr(NO_3)_2$	SrO	+89
$KClO_4$	KCl	–1.2
$KClO_3$	KCl	–10

Note that the sign convention is that negative values correspond to exothermic decompositions.

used with chlorates in the past, it would be wise to assume that any sulfide so used represents a significant hazard.

Perchlorates

Perchlorates produce substantially less energy upon decomposition than chlorates, see Table 4. Therefore, it can be inferred that any given material is likely to form a "safer" mixture with a perchlorate than with a chlorate. (However, note that ammonium perchlorate is incompatible with many materials because of the ammonium ion.) Perhaps equally important is the observation that, in perchlorate compositions, additives are sometimes specifically used to restore the favorable burning properties present in the corresponding chlorate composition. While it has not been well researched, there is the potential for these additives to increase the hazard, possibly approaching that of the chlorate composition. Thus, one can by no means make a valid generalization, "perchlorate compositions are safer than chlorate compositions". Much of the advantage of perchlorates lies with less stringent compatibility considerations, rather than its inherent safety.

With Aluminum:

The combination of potassium perchlorate with aluminum has quite a large activation energy and generally causes no problem. However, when the aluminum is a very fine powder, such as in the context of a flash powder, the consequence of accidental ignition is so devastating that such mixtures should be handled with extreme caution and avoided when possible. Mixtures containing relatively small percentages of potassium perchlorate or fine aluminum tend not to be a problem.

With Magnesium:

As with aluminum, there is generally no direct problem with the combination of potassium perchlorate and magnesium. However, as will be discussed below, the presence of water with this mixture is problematic. Further, with fine magnesium powder, the combination of lower activation energy and high energy output do make for a substantial hazard. Small percentages of either potassium perchlorate or fine magnesium in these mixtures do not seem to pose a problem.

Substances Hazardous with Chlorates but not with Perchlorates:

Zinc is not a particular hazard with perchlorates because, despite zinc having a lower activation energy than aluminum, it is not a sufficiently high energy fuel to form a dangerous flash powder with these oxidizers (see Table 5). It is important to note, however, the combination of zinc with ammonium perchlorate is exceptionally hazardous because of its incompatibility with the ammonium ion (discussed below).

Acids (typically encountered in pyrotechnics), ammonium salts, or copper(II) salts present little or no problem with perchlorates for two reasons. First, perchloric acid is a significantly stronger acid than chloric acid and so is less susceptible to displacement from its salts. Second, perchloric acid is a stable acid, in marked contrast with chloric acid, which spontaneously decomposes at 40 °C (104 °F).[12b]

Table 5. Heats of Reaction for the Complete Combustion of Various Fuels.[19,20]

Fuel	Heat of Reaction (kcal/mole) [a,b]
Aluminum	–200
Titanium	–225
Silicon	–216
Magnesium	–144
Shellac	–131[c]
Stearic Acid	–151[c]
Lactose	–113[c]
Carbon[d]	–94
Zinc	–84
Sulfur	–71

(a) Unless otherwise noted, this is per mole of fuel.

(b) Note that negative values correspond to exothermic reactions.

(c) This value is per mole of carbon in the compound.

(d) Carbon is in the form of graphite.

With Sulfur:

The combination of sulfur with a perchlorate is generally believed to be substantially less hazardous than the combination with a chlorate. However, with respect to impact sensitiveness (see Table 3), the difference is barely worth mentioning. It has been speculated that to some extent the bad reputation of sulfur and chlorate mixes came about because earlier supplies of materials were contaminated.[17] If this was the case, that might explain the wisdom about perchlorate and sulfur mixtures being substantially less hazardous. That may have been true at one time but not for high purity materials.

Nonetheless, potassium perchlorate and sulfur mixes do have a low activation energy barrier, are quite sensitive to accidental ignition, and must be avoided if possible.

With Sulfides:

Similar considerations apply to mixtures of perchlorates with sulfides as for mixtures with sulfur.

Aluminum

The burning of aluminum metal produces the greatest amount of energy of the fuels in common use in fireworks, see Table 5. Nonetheless, aluminum can be one of the safest high energy metal fuels because of the cohesive and nonporous oxide coating, which engenders a high activation energy barrier for both combustion (see Tables 2 and 3) and corrosion. However, there are certain circumstances in which the oxide coating may be disrupted, potentially creating a hazard.

With Water:

Water is widely used to activate binders of pyrotechnic compositions and must therefore be considered a temporary ingredient of such compositions. Any active metal has the capability for a reaction with water to produce hydrogen gas. One example is the simple mixture of aluminum metal powder and pure water.

$$2\,Al + 6\,H_2O \rightarrow 2\,Al(OH)_3 + 3\,H_2 \qquad (6)$$

Because this is an exothermic reaction, there is the potential for generating sufficient heat to reach the ignition temperature of a pyrotechnic composition. (Even if the ignition temperature is not reached, the metal can corrode and the pyrotechnic composition can become useless.) In Figure 2, note the relatively sudden onset of the exothermic reaction after a prolonged latency (see Table 6 for experiment conditions).

The water reactivity of aluminum rises in particular with nitrate compositions, wherein the following exothermic decomposition can take place:

$$6\,KNO_3 + 16\,Al + 9\,H_2O \rightarrow 6\,KAlO_2 + 6\,NH_3 + 5\,Al_2O_3 \qquad (7)$$

Aluminum oxide is amphoteric, meaning that not only can it dissolve in acids to form aluminum salts, but it can also dissolve in alkalis to form aluminates (such as the potassium aluminate formed in the reaction above). Consequently, the alkaline nature of the ammonia produced in this reaction (equation 7) can enable it to dissolve not only some of the aluminum oxide produced in the reaction, but also some of the oxide coating of the aluminum. The

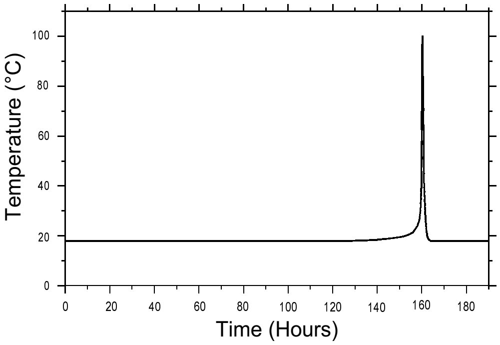

Figure 2. An example of an aluminum and water exothermic reaction.[21] *[See Table 6 for Experiment Conditions.]*

aluminum so activated can then go on to react directly with water, generating more heat. Another series of tests similar to that shown in Figure 2 was performed; however, half of the aluminum was replaced with potassium nitrate (see Table 6). In this case, a slightly higher temperature was reached as the water was consumed, and the reaction peaked after only 10 hours. At least one plant explosion, is believed to have been caused by such an aluminum, nitrate, and water reaction, when it occurred in 12 kg (26 lb) of a pyrotechnic mixture left partially submerged in water.[22]

In practice, many of these water and aluminum reactions do not appear to be a serious problem when atomized or coarse flake aluminum is used. Presumably, this is because the wetted compositions are cut or rolled into relatively small stars, from which heat readily escapes. Also the amount of water present is relatively small and drying is fairly fast.

If for some reason it is desired to use fine aluminum with a nitrate present, or if the anticipated drying time will be prolonged, a small amount of boric acid can be added to counteract the incipient alkalinity and prevent decomposition. This is partly because the protective oxide coating of aluminum is much more resistant to mild acids than it is to alkali. Moreover, aluminum borate, formed[23] on the surface of the aluminum, is very insoluble and therefore improves the protection offered by the oxide coating. For example, when as little as 0.2% boric acid was added to an aluminum and potassium nitrate mixture, no detectable reaction with water occurred even after 500 hours, see Table 6. (Note that using 0.5% boric acid would provide a more reliable safety margin.)

Table 6. Aluminum and Water Reactivity Data at 18 °C (64 °F) unless otherwise stated. [21]

Conditions for Test[a]	Exotherm Time(b) (hours)
Aluminum, 2 g Distilled water, 2 g	159
Aluminum, 1 g Potassium nitrate, 1 g Distilled water, 2 g	10
Aluminum, 1 g Potassium nitrate, 1 g Boric Acid, 0.04 g Distilled water, 2 g	>500
Aluminum, 1 g Copper(II) oxide, 1 g Distilled water, 2 g	15
Aluminum, 2 g Distilled water, 2 g Temperature 43 °C (109 °F)	1

(a) Aluminum was always Alcoa S-10, 12µ atomized.

(b) (b) Average time to exotherm for three tests. (See Figure 2.)

With Copper(II) [Cupric] Salts:

A metal will react with the salt of a more electronegative (less reactive) metal in what is called a displacement reaction. Such a reaction is exothermic and has the potential of producing enough heat to raise a pyrotechnic composition to its ignition temperature. A classic example of this is the silver nitrate and magnesium flash powder that is initiated by a mist of water droplets:[8]

$$\mathrm{Mg} + 2\,\mathrm{AgNO_3} \rightarrow \mathrm{Mg(NO_3)_2} + 2\,\mathrm{Ag}$$

Displacement Reaction (8)

$$6\,\mathrm{Mg} + 2\,\mathrm{AgNO_3} \rightarrow 6\,\mathrm{MgO} + 2\,\mathrm{Ag} + \mathrm{N_2}$$

Flash Reaction (9)

The activation energy of the displacement reaction is lowered so much by the presence of water that the reaction proceeds at ambient temperature, generating sufficient heat to initiate the pyrotechnic flash reaction.

Displacement reactions can occur with copper salts and aluminum, but in practice, this is seldom a problem because of the large activation energy engendered by the oxide layer on aluminum. However, problems can arise when the copper salt is significantly soluble. Although most copper salts used in pyrotechnics are not very soluble, it should be borne in mind that the presence of ammonia substantially enhances the solubility of the copper salts.[24] Consequently, situations with the potential for generating ammonia, such as described in the previous section (equation 7), can be exacerbated by the presence of a copper compound.

As part of the testing of aluminum's reactivity with water (Table 6), a series of tests were conducted wherein a mixture of atomized aluminum and copper(II) oxide were used. Despite the low solubility of copper(II) oxide, a reaction similar to that shown in Figure 2 occurred. The time interval before the peak (exotherm) was 15 hours, nearly as fast as it occurred when testing aluminum with potassium nitrate.

Magnesium

The activation energy for the reaction of magnesium is substantially less than for aluminum. As a result, the associated chemical reactivity problems are generally similar in kind but much greater in degree.

With Acids:

Magnesium is extraordinarily reactive toward acids, thus even mild acids, such as boric acid, must be avoided.

$$Mg + 2\,H^+ \rightarrow Mg^{2+} + H_2 \qquad (10)$$

With Ammonium Salts:

The ammonium ion is sufficiently acidic to react with magnesium:

$$Mg + 2\,NH_4^+ \rightarrow Mg^{2+} + 2\,NH_3 + H_2 \qquad (11)$$

The only effective way of preventing this reaction is by conversion coating the metal. Traditionally, the only effective coating was obtained by treatment with a dichromate.[25,26] This, however, may be considered an extreme solution because of the carcinogenicity of dichromates. Recently, a conversion coating that may be superior to that of dichromate was reported.[27] That coating is based on treatment with a low toxicity ammonium metamolybdate and ammonium dihydrogen phosphate solution.

With Water:

The reactivity of magnesium with water is so great that aqueous binding is generally considered to be incompatible with the presence of magnesium. In fact, reactions occur with unprotected magnesium and many (most?) salts in the wet state. For example, Shimizu[25] reports that active or violent reactions occur between magnesium and the wet salts listed in Table 7.

Table 7. Some Wet Salts Invoking Active or Violent Reactions with Magnesium.[25]

Barium nitrate	Potassium chlorate
Potassium nitrate	Potassium perchlorate
Sodium oxalate	Sodium chloride
Sodium bicarbonate	Sodium carbonate
Strontium nitrate	

With Copper Salts:

The reactivity of magnesium with copper salts (both cupric and cuprous) is so great that such mixtures are generally considered to be incompatible. This is because of an exothermic displacement reaction.

$$Mg + Cu^{2+} \rightarrow Mg^{2+} + Cu \qquad (12)$$

Copper metal or copper(II) oxide should be used when combinations with magnesium are desired. Copper metal works because both it and magnesium metal are in the same oxidation state, zero or neutral, thus displacement is not possible. However, because of magnesium's intrinsic water reactivity and because copper and magnesium metals form an electrochemical couple, non-aqueous binding is essential. When drying times are fairly short, copper(II) oxide seems to be acceptable because of its low solubility. However, there may be problems similar to that when mixed with aluminum (see above and Table 6).

With Sulfur:

Sulfur can act as an oxidizer for active metal fuels. A metal associated with low activation energies, such as magnesium, can react spontaneously with sulfur leading at least to corrosion, and perhaps to ignition under some circumstances. Even aluminum and sulfur mixtures can present a problem under rare circumstances. For example, it has been reported that when a mixture of aluminum and sulfur was ball milled, an explosion resulted.[28] Presumably this was partly the result of physical abrasion removing enough of the protective aluminum oxide layer to lower the activation energy to unsafe levels for ball milling.

Zinc

Despite being a substantially less energetic fuel than magnesium (see again Table 5), zinc also has a somewhat low activation energy barrier, and so generally shares similar compatibility concerns.

With Acids:

Zinc reacts readily with acids, and the combination is best avoided.

$$Zn + 2\,H^+ \rightarrow Zn^{2+} + H_2 \qquad (13)$$

With Ammonium Salts:

Like magnesium, zinc is incompatible with ammonium salts. The reaction is exacerbated in this case because zinc oxide is dissolved by aqueous ammonia.

$$Zn + 2\,NH_2^+ \rightarrow Zn^{2+} + 2\,NH_3 + H_2 \qquad (14)$$

$$ZnO + H_2O + 4\,NH_3 \rightarrow [Zn(NH_3)_4]^{2+} + 2\,OH^- \qquad (15)$$

Thus, the ammonia formed in the first reaction is able to solubilize the partly protective zinc oxide layer on the zinc particles, thereby accelerating its decomposition. A classic demonstration of spontaneous combustion is a mixture of zinc and ammonium nitrate that is initiated with a drop of water. Under conditions of high humidity, the presence of hygroscopic ammonium nitrate will cause the mixture to spontaneously heat up.

With Water:

In its behavior with water, zinc more closely resembles aluminum than magnesium. Usually there is no problem, even with nitrates present. However, on occasion, such mixtures have been known to heat up. Ammonia, the water reaction product of nitrates and zinc (see equation 7 for a similar reaction) dissolves the protective zinc oxide layer, leading to a self-accelerating reaction.

With zinc metal, because of its acid sensitiveness, anything but a neutral pH composition must be avoided. Thus, in practice, nitrate and zinc mixtures can generally be used with aqueous binding only if there are no acidic or alkaline ingredients present to initiate its decomposition. However, it is well to be aware of this potential problem.

With Copper Salts:

Like magnesium, zinc is incompatible with copper salts due to exothermic displacement reactions as discussed above.

$$Zn + Cu^{2+} \rightarrow Zn^{2+} + Cu \qquad (16)$$

With Sulfur:

The mixture of zinc and sulfur is a traditional model rocket fuel.

$$Zn + S \rightarrow ZnS \qquad (17)$$

However, it is not generally recognized that this mixture has a quite low activation energy for ignition and is significantly sensitive to both friction and impact. According to Partington[29] "... the mixture may detonate on percussion." As with magnesium, this combination is best avoided, even though it probably is not capable of a true detonation.[30]

Addendum for Magnalium

In general, the properties of an alloy are somewhat intermediate between those of its constituent metals. However, this is not necessarily the case. For example, the hardness of magnalium (magnesium/aluminum alloy) is significantly greater than that of either of its constituent metals. Nevertheless, its chemical sensitiveness is more often intermediate than resembling a mixture containing particles of the individual metals.[25] Of particular interest are hazardous combinations that are not exactly predictable from the properties of the constituent metals. (For the purpose of this discussion, magnalium refers specifically to the 50:50 alloy. Other magnalium alloys may be expected to have properties more or less intermediate between this alloy and the major constituent metal.)

With Chlorates and Perchlorates:

It is not expected for there to be a significant deviation from intermediate properties here; namely significantly hazardous with chlorates, less so with perchlorates. (See below for ammonium perchlorate.)

With Acids:

Here again the properties are intermediate. Magnalium is more acid sensitive than aluminum, but less so than magnesium. However, it is still sufficiently acid sensitive so as to preclude its use even with mild acids such as boric acid.[25,31] There are a number of published formulations that combine boric acid with magnalium, or even with magnesium. However, such compositions are almost always used with non-aqueous binding, which minimizes the danger. If similar formulations are developed for use with aqueous binding, the boric acid content should be deleted in the interest of safety.

With Ammonium Salts:

Magnalium is more reactive than aluminum, but less reactive than magnesium, towards moist ammonium perchlorate.[25] Boric acid does not prevent this reactivity and should not be used because of magnalium's reaction with acids. In practice, the problem can be avoided with the use of non-aqueous binding.

With Water:

Magnalium does not usually present any problem with aqueous binding. However, the potential for decomposition exists and it is well to be aware of this possibility when developing formulations. Certain substances seem able to trigger the reactivity of magnalium towards water. Examples are lampblack and alkali metal oxalates.[25,32] The reasons are not obvious and do not necessarily depend on any acidic or alkaline reaction. For example, aqueous lithium oxalate has a pH of 7 (neutral), yet is able to trigger such exothermic decomposition of magnalium.

In general, magnalium is more stable in an alkaline rather than an acidic environment, in contrast with aluminum. Thus, lithium carbonate, with an alkaline reaction, presents no problem with magnalium, although it is incompatible with aluminum.[32]

With Copper Salts:

Copper salts, both copper(I) and copper(II), should be avoided with magnalium unless the counter anion has a basic reaction. Fortunately many of the copper salts used in pyrotechnics, such as the carbonate or benzoate, fall into the latter category and normally present no problem. A danger can arise when conditions allow the production of ammonia, which has the ability to solubilize otherwise poorly soluble copper compounds.[24] Ammonium perchlorate in combination with alkaline materials, such as hexamine, can produce sufficient ammonia to cause a solubilization effect with certain copper salts.[33] Thus, the fourfold combination of ammonium perchlorate, hexamine, copper(II) carbonate, and magnalium is incompatible despite the fact that any of the binary combinations cause no problem.[34] Certain copper compounds, such as copper(II) benzoate, seem to be less problematic for unknown reasons.[34,35]

With Sulfur:

Magnalium does not cause any particular problems with sulfur and resembles aluminum in this respect.

Exercise for the Reader

As a self test, the reader is invited to consider all of the combination hazards associated with the hypothetical blue star formulation in Table 8. Any experimentation with this composition is definitely not advised.

Table 8. Hypothetical Blue Star Formulation.

(Consider what is wrong with this blue star formulation!)	
Ammonium perchlorate	30
Potassium chlorate	30
Sulfur	20
Copper(II) sulfate	10
Zinc	10
(Dampen with water)	

Closing Remarks

The discussion of some particularly hazardous combinations and the listings in Table 1 should not be interpreted too rigidly. They should serve only as guidelines. Some combinations listed as generally hazardous can be used by knowledgeable and skilled pyrotechnists in certain circumstances with reasonable safety, provided appropriate precautions are taken. Conversely, the list is not all inclusive, with other hazardous combinations existing.

Knowledge of hazardous combinations has been acquired through more than a century of observations by pyrotechnists. The explanations given in this article should be seen as post facto rationalizations rather than as theoretical predictions. Consequently, formulation development should be guided by cautious experimentation. For example, it is not obvious that titanium is compatible with ammonium salts whereas manganese is not, despite the two metals having almost identical electronegativities.

New star compositions containing active metal fuels should be dampened with water (if at all) only as a small sample. Such stars should be checked periodically for the occurrence of an exothermic reaction or other indication of an adverse reaction (e.g., an ammonia or a hydrogen sulfide odor).

Great care must be taken when working with new formulations, especially if there is any known potential for an adverse reaction. It is always appropriate to start working with very small quantities and to store these materials separate from other pyrotechnic materials and in a manner such that an accidental ignition would be less than disastrous.

Only after small batches have been successfully prepared, should larger batches be attempted. However, it must be recognized that since small batches did not experience adverse reactions, is not a guarantee that problems will not appear when batch sizes are scaled up. Mostly this is because increasing temperature generally has a powerful effect on the rate of chemical reactions. As an example, consider the two experiments with aluminum and water reactions in Table 6. Note that while at 18 °C the reaction peaked only after 159 hours, the same reaction at 43 °C peaked in only 1 hour. When large batches are prepared, any heat produced will generally escape more slowly (i.e., the temperature will rise to higher levels). This in turn accelerates chemical reaction rates and the rate of heat production. Such a thermal run-away may well lead to a catastrophe for a large batch while a small batch may show no signs of a problem.

In the event an adverse reaction is detected, it may be necessary to take more or less immediate safety measures. If the reaction is mild, the amount of material is small and it is in an isolated location, it may be possible to monitor the situation and hopefully wait it out. Actual ignitions of compositions undergoing adverse reactions are not common; nonetheless, disposal is probably the best way to terminate the potential problem.

The only certain way to eliminate a pyrotechnic hazard is to consume the material, generally by burning. While such disposal may constitute unlicensed hazardous waste disposal, it may also be a safety imperative. Great care must be taken when materials under going adverse reactions are handled or moved, such as in preparation for disposal by burning. Consideration must always be given to the possibility that the material may enflame at any time. If the temperature of the composition has risen (as will almost always be the case), combustion of the material will probably be especially violent and could be explosive. When burning pyrotechnic materials, always be extremely careful. Even under the best of conditions, unexpectedly large or violent output is possible. Some limited guidance on the subject that may be useful can be found in references 36 and 37. In cases where immediate disposal by burning is not possible and when the amount of material is relatively small, it will generally be possible to limit the buildup of heat in the materials by their immersion in a large amount of water. This will preclude the ignition of the material, but often will not terminate the adverse reactions such as the production of flammable (potentially explosive) hydrogen gas. If such treatment is necessary, as soon as possible the pyrotechnic composition should be separated from the water and disposed of by burning. Obviously, the best course of action is studiously to avoid those potentially hazardous combinations that might lead to adverse chemical reactions!

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Explosive Limit of Armstrong's Mixture

K. L. and B. J. Kosanke

When investigating the cause of an accident, it was necessary to learn something about the lower explosive limit with regard to phosphorus content in Armstrong's Mixture. A short literature search did not produce the needed information; thus a brief laboratory study was undertaken. Because the results of the study may be useful regarding safety and because they may be intrinsically interesting, this short article was prepared.

Armstrong's Mixture is both a very sensitive and very explosive pyrotechnic composition, potentially making it extremely dangerous.[1–3] Its practical use is limited to manufacturers of toy caps, although from time to time hobbyist experimenters are reckless enough to experiment with it. Davis[4] reports the formula for Armstrong's Mixture as given in Table 1. However, hobbyist experimenters often do not include the lesser two ingredients. There is little hope of mixing the ingredients in the dry state without their exploding, and dangerous reactions may occur even in the wet state.[3]

Table 1. Formula for Armstrong's Mixture.

Ingredient	Percent by Weight
Potassium chlorate	67
Phosphorus (red)	27
Sulfur	3
Calcium carbonate	3

In this study, to duplicate conditions of the accident, mixtures containing only potassium chlorate and red phosphorus were examined. Mixtures, containing from 2 to 30% red phosphorus, were prepared wet, using an additional 40% water. One-gram quantities of the mixes (dry weight of ingredients) were applied wet over the tips of electric matches in sample holders, see Figures 1 and 2. For each composition, three test samples were prepared. After drying for two days, the test samples were placed between two free-field blast gauges, one at a distance of one foot and the other at two feet, see Figure 3. Upon activating the electric match, the explosive output (as a blast wave) was recorded digitally for later analysis.

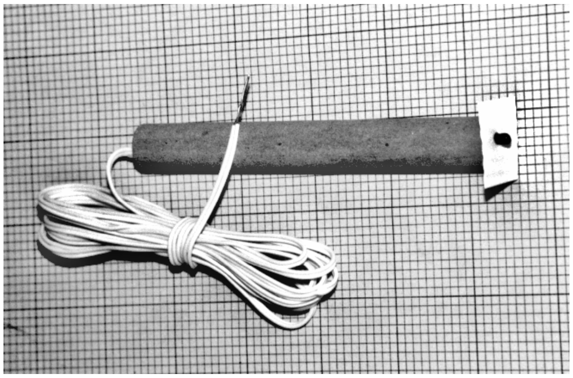

Figure 1. Test sample holder, made using a 5/16-inch ID paper tube with an electric match glued in place and protruding through a square of heavy filter paper.

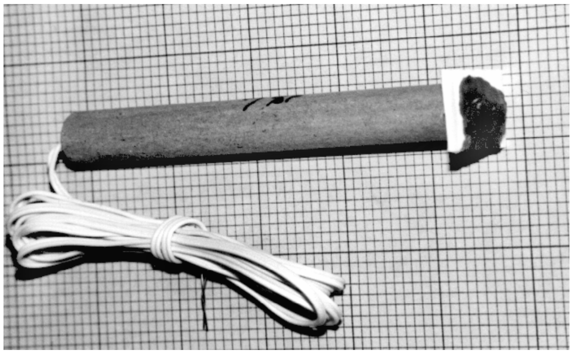

Figure 2. Test sample holder with a 1-gram sample applied over the electric match tip.

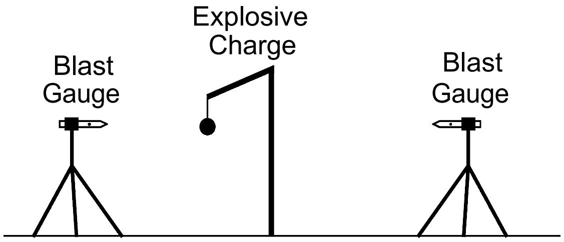

Figure 3. Drawing illustrating the set-up of blast gauges to measure the explosive output of the test samples (not to scale).

One method of reporting explosive output is in terms of TNT equivalent under specific conditions. For example, in these measurements, the maximum output for a sample was found to produce a TNT equivalent of 27%. For this sample, the explosive output (air blast wave) of 1 gram was found to be equivalent to that expected to be produced by 0.27 gram of TNT. The average results from the series of test mixtures are graphed in Figure 4 and demonstrated in Figure 5.

Note that in the case of 10 and 20% red phosphorus test mixtures, nearly one inch of the end of the support tube was blown off by just one gram (0.04 ounce) of material. For an unconfined pyrotechnic in such a small quantity this is impressive. (Considering the extreme sensitivity of these mixtures, this is just plain scary.) Note also that even small percentages of red phosphorus produce explosive results and would certainly be disproportionately more explosive in larger amounts.

Acknowledgments

The authors are grateful to Don Haarmann for supplying some of the important reference material needed for this study.

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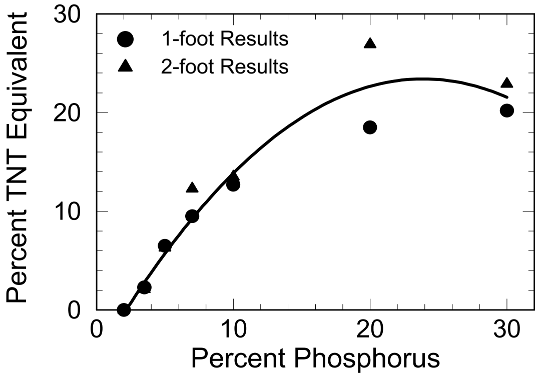

Figure 4. A graph of the TNT equivalent as a function of red phosphorus content. Air blasts were measured at 1 and 2 feet from 1 gram, unconfined test samples.

2) D. Haarmann, "Tell the Wiz, Armstrong's Mixture", *American Fireworks News*, No. 54 (1986) p 4.

3) D. Haarmann, "Tell the Wiz, Armstrong's Mixture", *American Fireworks News*, No. 51 (1985) p 3.

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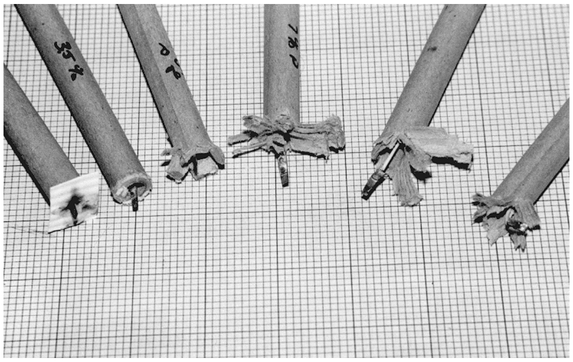

Figure 5. Representative examples of damage to the test sample holders for 2, 3.5, 5, 7, 10, and 20% red phosphorus mixtures, shown from left to right.

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Aerial Shell Drift Effects:
(A) The Effect of Long Mortars

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(B) The Effect of Capsule-Shaped Shells

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ABSTRACT

Aerial shell drift is defined as the difference between the ballistically predicted trajectory of a shell and its actual trajectory. It had been speculated that longer length mortars and capsule-shaped shells might experience significantly different drift than normal length mortars and spherical shells. While longer mortars propelled 6-inch (155-mm) aerial shells to greater heights, the average shell drift was unaffected. Further, it was found that 6-inch (155-mm) capsule-shaped shells probably drifted slightly more than spherical shells.

Key Words: aerial shell drift, mortar length, shell shape.

Introduction

Knowing the initial conditions (mortar tilt and azimuth, wind speed and direction, and shell parameters), the flight path of aerial shells can be calculated using ballistics models.[1] While such calculations are fairly good at predicting the average path taken by a large number of identical shells, they are rather poor at predicting the actual path of an individual aerial shell. In large measure this is because of additional aerodynamic forces acting on the shells along their trajectory that are difficult or impossible to characterize prior to firing a shell. One example is the magnus force resulting from the shell tumbling along its path.[2] This force can not be determined without first knowing the rate and orientation of tumbling. Because this information is generally unknowable before a shell is fired, the resulting magnus force and drift cannot be predicted. (For a dud aerial shell, shell drift is defined as the difference between the ballistically predicted and actual points of fall of the aerial shell.)

Aerial shell drift was originally studied for to help determine the adequacy of spectator separation distances during fireworks displays. Based on initial tests, the average drift distance for dud spherical aerial shells was established to be approximately 32 feet per inch of shell size (0.38 m/mm).[2] If there are conditions that produce significantly different average drift distances, that could be justification for suggesting different spectator separation distances for those conditions.

During various discussions of the initial reports of shell drift, it was speculated that mortar length might affect the results. For example, using longer mortars might result in increased average aerial shell drift, because the shell would have a higher initial velocity. A greater shell velocity will result in a greater magnus force and because the flight time will be greater, there will be more time for the force to act on the shell. On the other hand, a longer mortar might result in reduced average shell drift, because the longer mortar might allow less divergence of the shell as it exits the mortar (a consequence of the shell being smaller than the mortar ID). This possibility is supported by some observations that the use of long mortars facilitates the precise placement of shell bursts during choreographed displays. Assuming this is true, reduced shell drift may be part of the explanation.

Some results discussed in reference 2 for an unusual shell shape (a cylinder with one concave and one convex end) apparently had a drift distance less than that for spheres. Accordingly, it seemed possible that capsule-shaped shells (roughly a cylinder with two convex ends) might also have a drift distance less than spheres. The two brief studies reported in this article were conducted to determine whether either mortar length or the modified shell shape significantly affected drift distance of dud shells.

(A) The Effect of Long Mortars

Nine pairs of identical aerial shells were fired to determine whether there was an effect of mortar length on shell drift. The shell pairs were nominally 6-inch (155-mm) Sunny International shells. The lift charges were temporarily removed from the shells and water was injected into the time fuses to prevent them from burning. The mortars used were 6.08-inch (154-mm) internal diameter steel pipe with internal lengths of 29 and 65 inches (0.75 and 1.65 m). Both mortars were placed vertically in a field at approximately 600 feet (180 m) above sea level.

For these tests, essentially calm wind conditions would have been preferred. However, the tests were conducted as part of another project that had a serious time constraint that resulted in having to perform the tests on a day when surface winds averaged 25 mph (40 km/h). The test protocol followed for these tests was the same as used in all previous tests, which approximately corrects for the effects of wind (and minor mortar orientation errors), and is described in reference 2. In essence, the shells are fired into the air, and their points of fall determined in a coordinate system with the mortars at a known location. (In this case, the mortars were located at North 0 and East –200 feet). A new coordinate system is established at the point of average displacement (center of gravity) of the collection of points of fall from the mortar. Then shell drift is measured within this new coordinate system. The shift of the coordinate system is believed to approximately correct for wind effects and mortar positioning errors (in the case of these measurements, care was taken to assure that the mortars were vertical to within less than 0.5 degree). In these tests, to minimize the effect of any changes in wind speed or direction between the firing of shells from the long and normal length mortars, each pair of shells were fired within seconds of each other. The data from these tests are presented in Tables 1a and 1b, and in Figure 1. Also shown in Figure 1 are the average displacements of the points of fall of the shells from the long and normal length mortars, and the average drift distances about these average displacements.

As expected, the average time of flight for the shells from the long mortar are greater (by 2.5 seconds), indicating that these shells were propelled to a greater height before falling back to earth. This allowed the wind to act for a longer time on those shells, causing their average point of fall to be shifted further down wind. That the average displacements of the two sets of points of fall do not lie on the same line from the mortars, must be partly due to statistical effects, but may also be due in part to different wind direction as a function of altitude.

Table 1a. Data from Normal Length Mortar Shell Drift Tests.

Shell Number	Time of Flight (s)	Point of Fall (Orig. Coord. Sys.)		Point of Fall (Shifted Coord. Sys.)		Drift Distance (ft)
		North (ft)	East (ft)	North (ft)	East (ft)	
1	12.2	5	–43	167	–69	181
2	14.3	–225	189	–63	163	175
3	(a)	–339	75	–177	49	184
4	13.7	–66	262	96	236	255
5	12.1	–78	100	84	74	112
6	(a)	–104	–104	58	–130	142
7	14.5	–241	15	–78	–11	79
8	(a)	–208	–229	–46	–255	259
9	(a)	–207	–29	–45	–55	71
Average	13.4	–162	26	≅ 0	≅ 0	162
Std. Dev.	1.1					68

(a) Time of flight not determined, usually because sight of shell was lost.

For conversion to SI units, 1 foot = 0.30 m.

Table 1b. Data from Long Mortar Shell Drift Tests.

Shell Number	Time of Flight (s)	Point of Fall (Orig. Coord. Sys.)		Point of Fall (Shifted Coord. Sys.)		Drift Distance (ft)
		North (ft)	East (ft)	North (ft)	East (ft)	
1	16.1	76	92	166	–74	182
2	15.6	–80	31	10	–135	135
3	17.9	44	–12	134	–178	223
4	15.4	–156	321	–66	155	168
5	14.7	–267	162	–177	–4	177
6	(b)	(b)	(b)	(b)	(b)	(b)
7	15.9	6	235	96	69	118
8	(a)	–114	192	–24	26	35
9	(a)	–225	309	–135	143	197
Average	15.9	–90	166	≅ 0	≅ 0	154
Std. Dev.	1.1					58

(a) Time of flight not determined, usually because sight of shell was lost.

(b) This shell burst in the air, because one of its time fuses functioned even after having been wetted.

For conversion to SI units, 1 foot = 0.30 m.

The average shell drifts for the paired sets of shells were found to be 162 feet (49 m) and 154 feet (47 m) for the normal and long mortars, respectively. The one-sigma standard errors are ±23 feet (7.0 m) and ±19 feet (5.8 m). Thus the two drift distances are the same, to within the limits of statistical certainty.

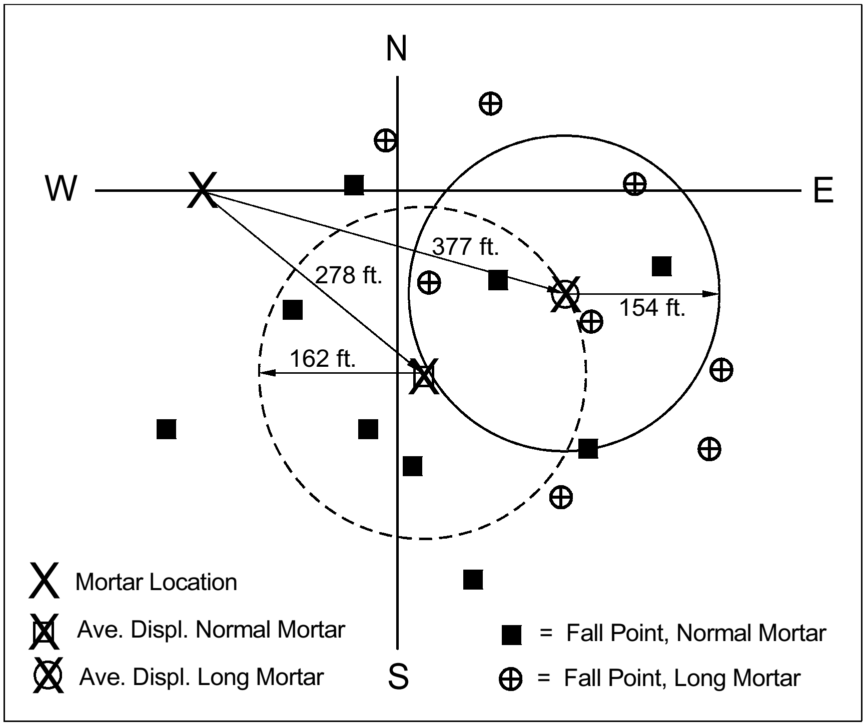

Figure 1. The location of the points of fall for the shells fired from long and normal length mortars.

(B) The Effect of Capsule-Shaped Shells

Ten 6-inch (155-mm) capsule-shaped aerial shells were fired to determine whether this shell configuration resulted in shell drifts that were noticeably different from typical spherical shells of the same size. A cross sectional view of a capsule-shaped shell casing is illustrated in Figure 2. The shells had a maximum diameter of 5.88 inches (149 mm), a length of 7.31 inches (186 mm), and were filled to a weight of 2.5 pounds (mass of 1.13 kg) using a mixture of dry dog food and small pebbles. The shells were fired from a steel mortar with an internal diameter of 6.05 inches (154 mm) and a length of 29 inches (0.75 m). The mortar was positioned vertically. In each case, the propelling charge was 1.75 ounce (50 g) of 4FA Black Powder. This is about one ounce (28 g) less than typical for a 6-inch (155-mm) spherical shell, and was done in an attempt to correct for the fact that these shells fit more tightly in the mortar. They were about ¼ inch (6 mm) larger in diameter than typical spherical shells. (The success of this adjustment can be judged by comparing the average flight times reported in Tables 1a and 2, which are virtually identical.)

These tests were conducted at an elevation of approximately 4600 feet (1400 m) above sea level and with a surface wind of less than 2 mph (3.2 km/h). Again, the standard test protocol was used.[2] The test results are presented

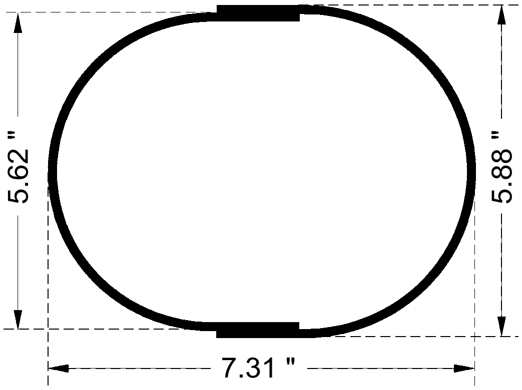

Figure 2. Illustration of a capsule-shaped aerial shell casing.

Table 2. Data from Capsule-Shaped Shell Tests.

Shell Number	Time of Flight (s)	Point of Fall (Orig. Coord. Sys.)		Point of Fall (Shifted Coord. Sys.)		Drift Distance (ft)
		North (ft)	East (ft)	North (ft)	East (ft)	
1	12.3	–13	–240	31	–189	192
2	13.4	–229	61	–185	112	216
3	13.3	–241	–66	–197	–15	197
4	13.6	–147	–237	–102	–186	213
5	13.4	287	–10	331	41	334
6	13.3	202	–220	246	–169	299
7	14.5	–114	–90	–70	–39	80
8	14.6	–167	299	–123	350	371
9	13.9	87	212	131	263	294
10	12.3	–106	–219	–62	–168	179
Average	13.5	–44	–51	≅ 0	≅ 0	237
Std. Dev.	0.7					82

For conversion to SI units, 1 foot = 0.30 m.

in Table 2.

The average drift distance for the 6-inch (155-mm) capsule-shaped, pulp-molded shells was 237 feet (72 m) with a 1-sigma standard error of ±26 feet (7.9 m). Past measurements of 6-inch (155-mm) shells under similar conditions gave a drift distance of 145 feet with a 1-sigma standard error of 31 feet (9.5 m). Based on a linear fit to drift data for various sized shells, a drift distance of approximately 192 feet (59 m) would be expected.[2] Accordingly, it seems that the capsule-shaped shells do not drift less than spherical shells, and it is likely they drift somewhat more.

Conclusion

Based on these brief studies, it seems clear that mortar length does not have a major effect on spherical aerial shell drift. Further, it seems clear that capsule-shaped shells do not drift significantly less than spherical shells and probably drift slightly more. Accordingly, for either case, there seems to be no reason to consider modified spectator separation distances at fireworks displays.

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Pyrotechnic Spark Generation

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ABSTRACT

Pyrotechnically generated sparks are probably the earliest augmentation of pyrotechnic burning for entertainment. While much is known about spark production both scientifically and as a craft, new effects and enhancements continue to be made. This review article presents a summary of the basic science of incandescent bodies, which establishes the range and limitations of possibilities for sparks. This is followed by a discussion of the pyrotechnic production of carbon and metal sparks, including control of spark duration and color. Finally, there are limited discussions of the control of corrosion of metal spark materials and control of spark branching.

Introduction

The intentional production of pyrotechnic sparks contributes significantly to the beauty and spectacle of fireworks and was developed very early in the history of pyrotechnics. An early example of the use of sparks is the "fire-club" carried by the "green-man" (originally also called the "wild-man") shown on the title page of the second volume of John Bate's Book *Mysteries of Nature and Art*.[1] [See Figure 1.]

Upon first consideration, the production of attractive spark effects may seem trivial; simply add an amount of some spark producing material to a basic pyrotechnic composition. For example, when titanium is added to rough Black Powder and pressed into comets, attractive white sparks can be produced (see Figure 2). However, upon closer examination, not all spark production is that simple. For example, consider effects such as Senko Hanabi,[2a] "fire-fly" spark effects,[3a] and even the duration of simple carbon sparks,[4a] all have complexities beyond the simple model suggested above.

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Figure 1. Illustration of "green-man" holding a "fire club" from reference 1.

This review article presents the basic chemistry and physics of spark incandescence; however, some questions will remain unanswered.

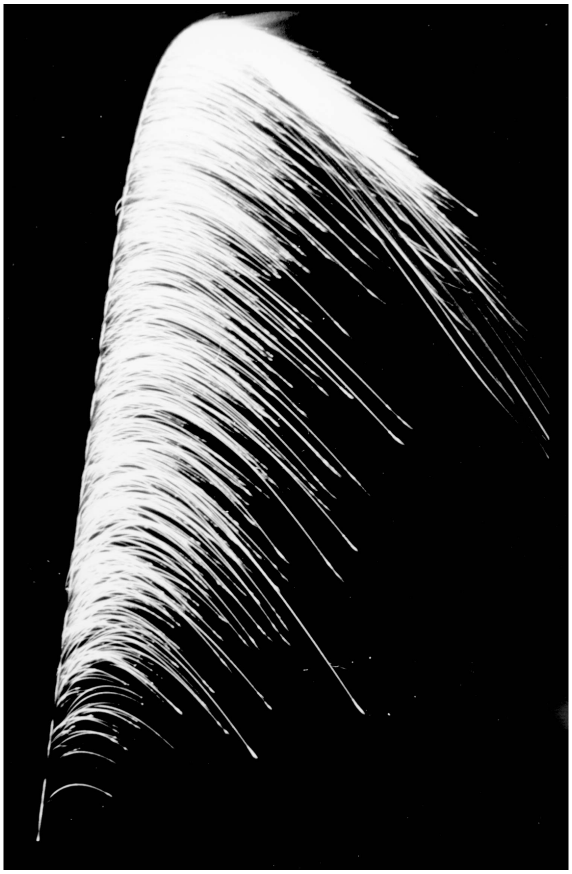

Figure 2. A Black Powder comet with 10% flake titanium (10–20 mesh).

This is because many interesting aspects of spark production are still unknown; for example, the mechanism causing spark branching.

Spark attributes generally considered attractive are high spark density and long spark duration. To some extent, these are interrelated because when individual sparks last a long time, the appearance will be that of greater spark density. Another most attractive attribute, when the viewer is close enough to observe it, is spark branching, such as produced by cast iron sparks.

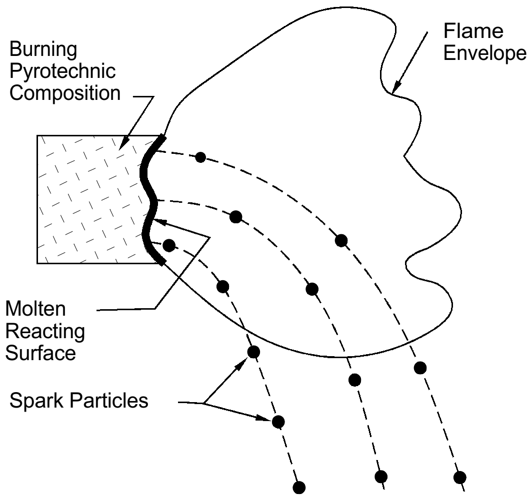

Figure 3. Illustration of the generation of pyrotechnic sparks.

Incandescence

In the simplest terms, pyrotechnic sparks are tiny pieces of glowing material emitted from the burning surface of a pyrotechnic composition. (See Figure 3.) Any liquid or solid particle will emit light (incandesce) when it is heated to a sufficiently high temperature. The brightness and color of the emitted light are both functions

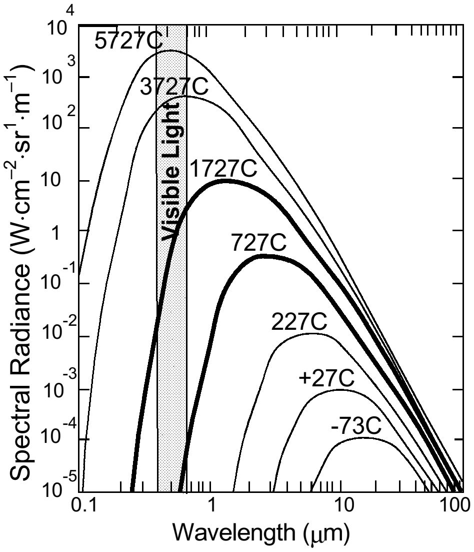

Figure 4. Spectral radiance of a black body at various temperatures.[5]

of temperature. This is demonstrated in Figure 3 for black bodies (ideal absorbers and emitters of thermal radiation).

Note in Figure 4 that an increase in temperature from 727 to 1727 °C results in an increase in peak emission by a factor of approximately 30. Note further that, in the range of visible emissions, there is an increase by a factor of approximately 100,000. At 727 °C, the visible emissions predominate at the extreme long wavelength (red) end of the spectrum. Accordingly, such an incandescent body will appear red to an observer. Whereas, at 3727 °C, the emissions are more evenly distributed across the entire visible range, producing nearly white light. The possibilities for color and relative brightness of black body sparks are summarized in Table 1.

Some pyrotechnic spark particles are probably quite close to being black bodies (e.g., some carbon sparks); others (e.g., aluminum sparks) deviate noticeably from ideal[4b] black bodies and may be referred to as “gray bodies”. Shimizu illustrates the perceived colors of black and gray bodies as a function of temperature in Figure 5. Note that, unlike black bodies, gray bodies have the ability to produce yellow sparks.

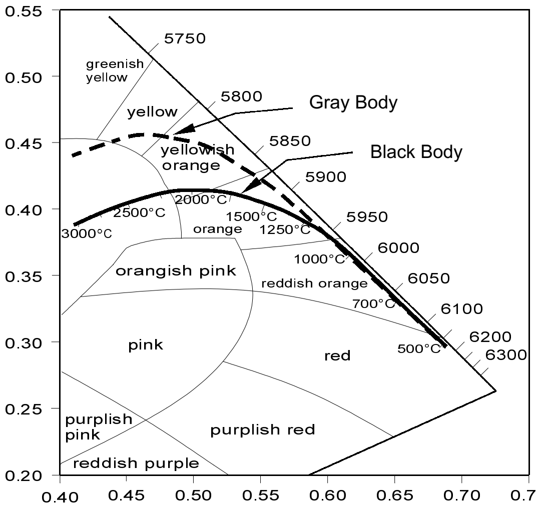

Figure 5. A portion of the chromaticity diagram illustrating the color of light emitted by black and gray bodies.[4c]

Based on the above discussion, it should be apparent that the color and brightness of pyrotechnic sparks are linked, and that the range of possibilities is rather limited. Red sparks will always be dim and white sparks must be bright. For the most part, it is not possible to produce bright red or dim white sparks. However, when points of light are viewed at a distance such that their size is less than the observer’s visual acuity, size and brightness of the point of light are linked to some extent. That is to say, brighter objects appear somewhat larger, and larger objects appear somewhat brighter.[7] This presents an opportunity to make small adjustments in a spark’s perceived brightness without affecting its color. For example, consider two sparks at the same temperature (color), one that is twice the diameter of the other. The larger spark will have 400% more surface area emitting light, and thus emits 400% more light. If these light sources are small enough and are seen in the dark there will be an approximate logarithmic relationship between intensity and perceived brightness.[6] Accordingly, the larger spark should be perceived as being about 60% brighter, but with the same color as the smaller spark. If this is correct, while spark color and brightness are linked, there is the possibility to make some independent adjustments. However, note that changing a spark’s size will change its surface to mass ratio, which is likely to change its chemistry to some extent (discussed further below).

Table 1. Color and Relative Brightness of Black Body Sparks.

Temperature (°C)	Descriptive Color[4b]	Relative Brightness(a)
500	Red	1
850	Reddish-Orange	4
1500	Orange	7
2200	Yellowish-White	9
3000	White	10

(a) Relative brightness is an estimate based on the Planck radiation formula and the assertion that human eyes have an approximate logarithmic response to light intensity when viewing points of light in a void.[6]

Pyrotechnic Spark Duration

Based on the discussion of incandescence, it would seem that merely merely introducing inert particles into a flame could produce useful pyrotechnic sparks. There the particle would be heated to high temperature and would leave the flame glowing brightly. In practice this does not work at all well; see Figure 6, which is of two essentially identical fountains (gerbs). Both fountains were made using the same compressed handmade Black Powder, the added spark producing materials were of the same size, were essentially the same material (mostly iron), and both fountains had a choke of 1/3 the tube diameter. Nonetheless, there is a stark difference in the performance of the two fountains. The difference is that the fountain on the left was made using stainless steel grains, while the one on the right was made using cast iron grains.

In each case the spark particles were heated to high temperature and left the flame incandescing. However, the stainless steel grains quickly became invisible after leaving the flame. Not only are such sparks not aesthetically pleasing, they burn out so quickly that they actually seem depressing to the viewer. Such performance is not unique for stainless steel; it is common for all relatively inert spark particles. This is the result of the low mass of spark particles, which causes them to loose their thermal energy (become invisible) quickly after they leave the high temperature environment of the flame. This will always be true unless there is some mechanism for the spark particle to produce additional energy. For the cast iron sparks, which persisted a long time (and then produce attractive branching sparks), the mechanism for producing this additional energy is air oxidation.

$$4\ \text{Fe}_{(\text{High Temp.})} + 3\ \text{O}_2 \rightarrow 2\ \text{Fe}_2\text{O}_3 + \text{Heat} \qquad (1)$$

The difference for the stainless steel spark grains is that stainless steel, while mostly iron, is formulated such that air oxidation (rusting) is essentially precluded. Without the ability to produce additional thermal energy, these sparks quickly cool to below the temperature of significant visible light emission.

Common Spark Producing Elements

For the reason discussed above, all common spark producing materials are capable of self sustained air oxidation after being heated to a high temperature, for example:

$$\text{C}_{(\text{High Temperature})} + \text{O}_2 \rightarrow \text{CO}_2 + \text{Heat} \qquad (2)$$

$$\text{Ti}_{(\text{High Temperature})} + \text{O}_2 \rightarrow \text{TiO}_2 + \text{Heat} \qquad (3)$$

Table 2 lists the most common chemical elements used for the production of pyrotechnic sparks. Also included are zinc, zirconium, and magnesium, which are occasionally used as spark producers.[8–10]

The color and brightness of a spark particle depend on the temperature that is maintained during its air oxidization. To some extent, the spark particle's temperature depends on the amount of heat released in the oxidation reaction (heat of combustion). Unfortunately, while it is easy to calculate the heat of combustion (see Table 2), there are other complicating factors. It is obvious from the data in Table 2 that, by itself, the amount of energy produced is not a completely successful predictor of spark color (temperature). For example, the heats of com-

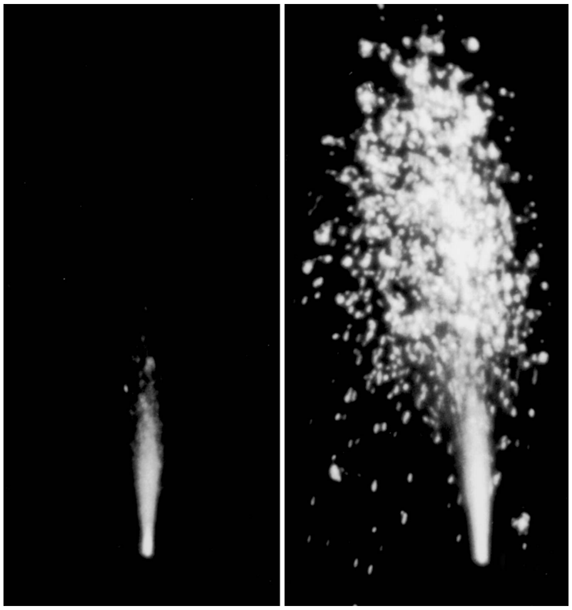

Figure 6. Pictures of two essentially identical fountains, both producing incandescent sparks; however, only the fountain on the right produced sparks that were bright enough and had long enough duration to be attractive.

Table 2a. Properties of Spark Producing Elements.

Element	Spark Color	Heat of Combustion(a)	Combustion Product(b)	Electronegativity[11]
Carbon(c)	Orange	–94	CO_2	2.55
Iron	Yellow	–98	Fe_2O_3	1.83
Zinc	Yellow(d) (green/blue/white)	–84	ZnO	1.65
Aluminum	Yellowish White to White	–200	Al_2O_3	1.61
Titanium	Yellowish White to White	–225	TiO_2	1.54
Zirconium	White	–263	ZrO_2	1.33
Magnesium	White	–144	MgO	1.31

Table 2b. Properties of Spark Producing Elements (Continued).

Element	Melting Point °C(e)	Boiling Point °C(e)	Combustion Product(b)	Melting Point °C(e)	Boiling Point °C(e)
Carbon(c)	~3550	3825(g)	CO_2	–57(f)	–78(g)
Iron	1535	2750	Fe_2O_3	1565	—
Zinc	420	907	ZnO	1975	—
Aluminum	660	2467	Al_2O_3	2072	2980
Titanium	1660	3287	TiO_2	~1840	~2800
Zirconium	1852	4377	ZrO_2	~2700	~5000
Magnesium	649	1100	MgO	2852	3600

(a) The Heat of Combustion at 25 °C (more correctly termed Enthalpy of Combustion) is derived from reference 12, and the units are kilocalorie per mole of fuel. Note further that Heat of Combustion is temperature dependent.

(b) Assumed principal product.

(c) Note that charcoal commonly used in pyrotechnics is not pure carbon. Charcoal is typically only about 82% carbon,[4d] and it has in an amorphous structure.[2b] The listed heat of combustion is for carbon as graphite.

(d) Sparks produced in a gas flame (Bunsen burner) eventually appear yellow, but while burning in the flame, they appear greenish–bluish white.

(e) Values are from reference 12.

(f) Melting point at a pressure of 5.2 atmospheres.

(g) Temperature of sublimation.

bustion for carbon and iron are essentially the same, and yet there is a significant difference in typical spark color. Also, it would not be predicted that magnesium would produce white sparks. Table 2 includes each material's electronegativity, which is an indicator of the element's relative tendency to acquire additional electrons. Electronegativities are known for all elements and seem to be a good predictor of spark color.

Other important factors in determining spark color are the melting and boiling points of the spark material and their air oxidation products (also presented in Table 2). The reason the spark material's melting and boiling points are important is that they will determine the physical state in which most of the air oxidation reaction takes place. For example, carbon will be a solid at its expected spark reaction temperature, while most other materials will be liquid. This is not of overwhelming importance, but it affects our understanding of the nature of carbon sparks (discussed below). Of more importance is the fact that zinc and magnesium will be vaporizing as they react and that only solids and liquids incandesce. This is an important part of the reason why these potentially useful materials are only infrequently used as spark materials.

The melting and boiling points of air oxidation products are important because they can affect the degree of protection afforded the spark particle (discussed below) and generally set a limit on the maximum temperature (color and brightness) reached by a spark particle. The reason for this is that thermal energy is consumed or released in the processes of vaporizing and solidifying, respectively.

$$\text{Liquid} + \text{Heat of Vaporization} \rightarrow \text{Gas} \qquad (4)$$

$$\text{Liquid} \rightarrow \text{Solid} + \text{Heat of Fusion} \qquad (5)$$

For example, the amount of energy produced by a typical spark particle will be sufficient to cause it and its oxidation product to be molten. However, because of their high heat of vaporization, sufficient energy is not produced to allow the spark particle to completely vaporize. This acts to prevent the temperature reached by a spark particle from exceeding its boiling point. On the other hand, once air oxidation is complete and the spark particle cools, the liberation of the heat of fusion can help maintain the spark's temperature a little longer.

Control of Carbon Sparks

For spark particles ignited in the flame of a gas burner (e.g., Bunsen burner), equations of the type 1 through 3 apply. The control of spark duration is straightforward; large particles take longer to burn than small particles. Thus, if one wished to produce longer duration spark particles, simply use larger particles of the spark material (providing they are not so large that the flame fails to ignite them). Control of spark color is even less complicated; it is not possible. The color produced is exclusively a function of the material being used.

For pyrotechnically generated sparks, the combustion products of the primary fuel(s) and oxidizer(s) complicate spark chemistry. As it turns out, this is a good thing, because it provides the basis for some control over spark duration and color. Combustion products can be gases, liquids or solids, depending on temperature and the chemicals used. For example, consider equation 6, a chemical equation for the confined burning of potassium nitrate, charcoal and sulfur. (Note that while this example is based on information from references 2, 4, 13, and 14, for this illustration it has been idealized and simplified.)

$$8\ KNO_3 + 11\ C + 2\ S \rightarrow 2\ K_2CO_3 + 2\ K_2S + 4\ N_2 + 9\ CO_2 + \text{Heat} \qquad (6)$$

In the presence of oxygen, such as when burning the composition in air, there is a further exothermic reaction of potassium sulfide to form potassium sulfate, equation 7.

$$K_2S + 2O_2 \rightarrow K_2SO_4 + \text{Heat} \qquad (7)$$

The nitrogen and carbon dioxide produced are gases. The melting points of potassium carbonate, potassium sulfide and potassium sulfate are 891, 840 and 1069 °C, respectively.[12] Based on the expected temperature of most pyrotechnic sparks, these three combustion products will be liquid.

The liquid (molten) combustion products are of primary consequence for sparks. Gases play a role in helping to eject droplets of molten combustion products from the burning surface, but for the most part, the gases must then be lost to the atmosphere. Solid combustion products, if any, seem to be relatively inert at typical spark temperatures. If the ratios of reactants in equation 6 are altered by the addition of more charcoal, some will not react in the flame and will come to reside within the molten droplets of combustion products, as suggested in Figure 7, to form a composite spark particle.

One function of some of the liquid components in the charcoal spark particle is to produce additional thermal energy by their reaction with atmospheric oxygen (equation 7). However, probably the more important function is the protection of the charcoal particles from too rapid oxidation by the air. The importance of this can be appreciated if one ignites even large charcoal particles (20 mesh) in a gas flame. These sparks are totally consumed in approximately one second. Whereas the duration of pyrotechnic charcoal sparks can easily be many

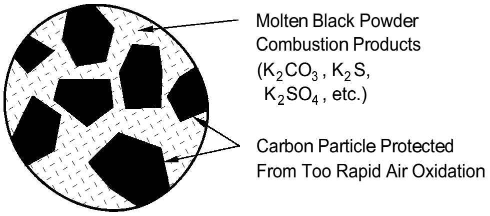

Figure 7. Illustration of a composite carbon spark droplet, consisting of solid charcoal particles residing in droplets of molten combustion products.

seconds, even when the charcoal particles are smaller than 100 mesh. The increase in spark duration is thought to be the result of greatly reducing the direct exposure of the carbon particles to atmospheric oxygen. However, since oxygen from the air can be expected to dissolve into the molten spark droplet, oxygen can still reach carbon particles that are buried within a molten spark droplet, although at a slower rate. The molten combustion products help achieve both of the most desirable spark attributes, long duration and high visual density. (In part, this is because more and smaller particles of the spark material can be used, but it is mostly because each spark particle lasts so long that more sparks are visible at any one time).

The ability to alter the type and amount of molten combustion products provides the opportunity to control carbon spark duration, and, to some extent, spark color. If the formulation is adjusted to produce a relatively high percentage of liquid products, the charcoal particles will have greater duration (because they are better protected from air oxidation), and their color should tend to be more red (because they are reacting more slowly and thus maintain a lower temperature). If the formulation is adjusted to increase the ratio of reactive to inert products (i.e., potassium sulfide to potassium carbonate), the sparks may be more orange (because the additional energy production will raise their temperature).

As an example of control of spark duration, consider the two gold charcoal spark formulations in Table 3. These formulations have been written to list handmade meal powder as the primary ingredient. This helps to explain the reason for the difference in the spark durations. If it is assumed that in air, meal powder reacts fairly completely, then it produces mostly inert combustion products. The formulation producing short duration sparks has only charcoal added to the meal powder (and binder). The long duration formulation has about the same amount of charcoal, but it also has a significant additional amount of sulfur. The extra sulfur produces more molten combustion products, which provides additional protection for the carbon particles. The long duration formulation also produces more sulfides, and thus has an additional source of spark energy while competing with the residual charcoal for air oxygen.

The size of the individual carbon particles within the composite spark particle does play a role in determining the duration of carbon sparks, but it is not of paramount importance. This is because the charcoal particles are contained within these larger spark droplets. For example, consider that some sparks produced using lampblack are among the longest lasting carbon sparks, yet lampblack has much smaller particles than common charcoals.

While it has not been reported, the relative size of the composite carbon spark droplets must also have an effect on spark duration. That is because both the relative reaction rate with atmospheric oxygen and the rate of energy loss must be functions of the droplet's surface area (proportional to particle diameter squared), while the amount of reacting material within the droplet is a function of its volume (proportional

Table 3. Gold Charcoal Spark Formulations.

Ingredient[(a)]	Short Duration[2c]	Long Duration[15]
Handmade Meal [(b)]	73	65
Charcoal (Air Float)	22	20
Sulfur	—	10
Binder[(c)]	5	5

(a) Ingredients are given in mass percent.

(b) This is a mixture of 75% potassium nitrate, 15% air float charcoal, and 10% sulfur.

(c) The binder is glutinous rice starch and dextrin, for the short and long duration formulations, respectively.

to particle diameter cubed). Accordingly, all else being equal, larger droplets should have longer durations. This is because the rate of oxygen absorption is proportional to the spark particle's surface area and not its mass.

There are a number of factors that must affect the size of composite carbon spark droplets, among these are: the fraction and rate of production of gaseous combustion products; the viscosity of the liquid combustion products; for a comet star, the velocity of the star through the air, or for a gerb, the diameter of the choke. Accordingly, rapidly burning comets with much gas production, that generate low viscosity liquid combustion products, and that are rapidly moving through the air, must tend to produce relatively smaller composite spark particles.

Control of Metal Sparks

In an earlier section it was suggested that the control of sparks produced in a gas flame was rather straightforward. Spark duration is controlled by particle size, with larger spark particles burning longer, provided they are not too large to be successfully ignited while they remain in the flame. In this case, spark color is controlled only by the choice of spark material. The control of pyrotechnically generated metal sparks is often treated as simply as if they were produced using gas flames. While this simple treatment has been sufficient to explain some aspects of pyrotechnic metal sparks, there are complexities that deserve discussion.

For the metals listed in Table 2, considering their expected spark temperatures (based on their colors and the temperature information in Table 1), most of these spark particles and their oxides will be liquid[2d] (see Table 4). Thus, for iron, aluminum, titanium and zirconium, the oxides can be expected to collect on the metal particle surfaces and act to retard their air oxidation in somewhat the same way as discussed for carbon sparks.

Beyond the protection afforded by the molten metal oxides, additional protection may be provided by the combustion products of the primary fuel(s) and oxidizer(s), in much the same way as discussed for charcoal sparks. Consider the pairs of aluminum and titanium spark formulations given in Table 5. While the pairs of formulations differ in the flame temperatures produced, that is unlikely to be the primary reason for the different spark colors

Table 4. Observations Regarding Spark Producing Elements.

Element	Physical State(a)		Common Forms	Common Size Range (Mesh)	Other Use References
	Element	Oxide			
Carbon	solid	gas	Charcoal Lamp Black	10 to 325 –325	2e
Iron	liquid	liquid	Iron Filings Steel Filings	20 to 60 ~100	16b 16c
Zinc(b)	gas	liquid (?)	Dust Filings	325 20 to 60	9
Aluminum	liquid	liquid	Flake Atomized	20 to 80 60 to 150	16b, 17
Titanium	liquid	liquid	Sponge Turnings	10 to 100 10 to 100	18 19
Zirconium(b)	liquid	liquid	Sponge Turnings	10 to 80 10 to 80	(b)
Magnesium(b)	gas	liquid	Atomized	10 to 50	10

(a) The most likely abundant physical state.

(b) Rarely used in fireworks for spark production.

produced. This is because the effect of high flame temperature will persist for only a short time after the spark particle leaves the flame; recall the example shown in Figure 6. For the aluminum and titanium formulations, it is believed that the difference is mostly the result of the protection provided to the metal by the reaction products. In both cases, the formulations producing yellow sparks contain a moderately large amount of sulfur, and thus are expected to produce a relatively high abundance of molten combustion products that are capable of retarding the air oxidation of the metal particles. If this is true, some of the same measures used for the control of carbon sparks should apply to metal sparks.

Another method that can sometimes be used to alter the color of white aluminum sparks is to add a source of sodium to the composition. In this case, it is believed that the strong atomic emissions from sodium can act to add a yellow component to the light emitted by the spark. Although not documented, this may also be the case for other metals.

Unlike the more common spark elements, the boiling points of magnesium and zinc are quite low, 1100 and 907 °C, respectively. Accordingly, the spark particles must be in the process of vaporization, with some of the oxidation occurring with metal vapor while still inside the flame. This can be confirmed by observing these sparks when ignited in a gas burner; both types of sparks appear to be propelled such as from gas production, and both leave a smoke trail from condensing combustion products. Their low boiling points make these materials somewhat less useful for the production of pyrotechnic sparks. For example, only quite large magnesium particles seem capable of surviving long enough to exit the pyrotechnic flame to produce sparks.[10] Also, when metals are partially consumed in the flame, they will tend to brighten it, which generally detracts from any sparks produced. However, to the contrary, zinc dust can be used to make quite attractive comets such as electric spreader stars. In this case, the star burns to produce a large number of fragments, each burning greenish-bluish-white. It seems likely that an important part of the mechanism for fragmenting the stars may be the production of zinc gas, which then burns to produce the attractive flame. The source of the greenish-bluish-white flame is most likely a combination of spectral emissions from gaseous zinc (blue[22]), high temperature incandescence of liquid zinc oxide particles in the flame, and possibly spectral emissions from gaseous zinc oxide (yellow green[23]).

Table 5. Aluminum and Titanium Spark Formulations.

Ingredient[(a)]	Aluminum Sparks		Titanium Sparks	
	White	Yellow	White	Yellow
Potassium Perchlorate	43	—	45	—
Potassium Nitrate	—	38	—	54
Aluminum Powder	52	48	—	—
Titanium (10 – 20 Mesh, Flake)	—	—	20	16
Sulfur	—	9	—	13
Charcoal (Air Float)	—	—	—	13
Zircalium (Al_2Zr, –100 Mesh)	—	—	20	—
Accroides Resin	—	—	10	—
Binder[(b)]	5	5	5	4
Reference	4e	4e	20	21

(a) Ingredients are given in mass percent.

(b) This is glutinous rice starch and dextrin, for the aluminum and titanium formulations, respectively.

Alloys and Corrosion

In addition to the elements listed in Table 4, alloys are often used for spark production. Among the most common are magnalium (magnesium-aluminum, typically 50% magnesium), ferro-titanium (typically 30% iron), and ferro-aluminum (typically 35% iron). In addition, cast iron and carbon steels are alloys of mostly iron with a small amount of carbon. Generally, the properties of these alloys are an average of their constituents' properties. Accordingly, both ferro-titanium and ferro-aluminum produce light yellow sparks. Ferro-titanium is easier to ignite than ferro-aluminum, which apparently acquires some ignition difficulty from its aluminum content.

Corrosion can be a problem for some spark materials, especially for iron and magnesium. The most common method for handling this corrosion for iron is to coat the particles with linseed oil, which air cures to form a protective film. Protection for iron can also be accomplished using alloys with either of the corrosion resistant metals—aluminum or titanium. Thus, ferro-titanium and ferro-aluminum typically need no treatment, providing the alloys contain no more than 30 to 40% iron.[24] Magnesium, typically, needs to be protected from corrosion. For magnesium, treatment with linseed oil is usually quite effective except when using ammonium perchlorate.[25] Protection can also be accomplished by formation of a conversion coating on the surface of the particles.[2g,25,26] Similar to iron, magnalium (magnesium-aluminum alloy) that contains at least 30 to 40% aluminum generally does not need protection. Aluminum generally requires no protection even in water dampened compositions; however, when protection is needed, the addition of a small amount of boric acid will generally be sufficient.[2f] Another approach to solving corrosion problems is the use of thoroughly dried materials with non-aqueous binding.

"Fire-Fly" or Transformation Effects[3]

In the "fire-fly" effect, also sometimes called transformation or transition effects, initially rather normal appearing long duration orange charcoal sparks are produced, which ultimately transform to produce yellow-white sparks. In some instances, a single orange spark may produce a series of short-lived yellow-white sparks, thus giving somewhat the appearance of a fire-fly. These spark formulations contain both charcoal particles and aluminum flakes.

In the initial several seconds of the spark's duration, the air oxidation reaction is limited to converting potassium sulfide to potassium sulfate, and consuming the excess carbon in the spark particle, with the aluminum remaining dormant. Then at some point, conditions allow the aluminum to ignite to produce the yellow-white spark effect. It has been suggested that the aluminum ignition process may be repeated more than once as suggested in Figure 8, to produce the fire-fly effect.[3] Proper functioning of the fire-fly effect requires that the burning composition produces flame temperature that is not sufficiently high to cause the immediate ignition of the aluminum. Also required is the use of a charcoal with the capability of engendering the correct conditions to produce a sustained low temperature spark and then cause the ignition of the aluminum flakes. If the late stage spark temperature is too low, the aluminum will fail to ignite and not produce the transition to bright yellow-white.

An excellent treatment of the subject of the fire-fly effect[3a] implies that the use of a coarse flake aluminum (flitters) is required. However, the temperature of the spark particle (during the carbon burning) is sufficiently high and sufficiently long in duration to melt the aluminum. This would seem to make the original shape of the aluminum irrelevant. That flake aluminum is not necessary for the fire-fly effect is con-

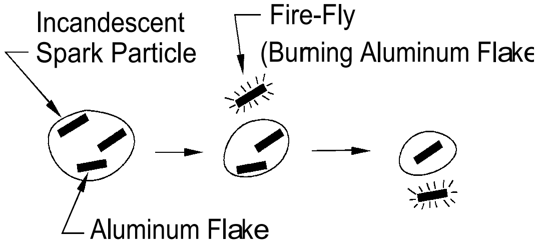

Figure 8. Shimizu's model of the mechanism for the production of Fire-Flies.[3b]

firmed by a report[27] of using coarse atomized aluminum to produce the effect. It is also reported[27] that magnesium, magnalium and titanium[28] can be used to produce somewhat similar delayed ignition metal sparks.

Branching Sparks and Senko Hanabi

Sparks that branch, such as illustrated in Figure 9, are extremely attractive when one is close enough to observe the effect. Most spark materials provide a limited degree of branching; however, none are close to rivaling those produced by cast iron and high carbon steels. While details of the mechanism resulting in branched sparks is not reported in the literature, it is known that the percentage of dissolved carbon in the iron is important. It is reported[2h] that 0.7 to 0.8% carbon is the most effective for producing finely branched sparks.

Attractive branching sparks are also produced by the traditional Japanese item, Senko Hanabi[2a] and the European spur-fire fountain, called flowerpots. Senko Hanabi is made in one of two forms, one is a thin straw coated with a wet composition (Figure 10-a1), and the other has dry composition twisted inside tissue paper. (Figure 10-a2). The effect is produced using a sulfur-rich Black Powder composition that burns rather slowly to produce a ball of molten combustion products suspended from the straw or twisted tissue paper. Initially, for a period of several seconds, not much appears to happen. Then branching sparks begin to be projected from the molten ball, increasing in intensity and producing a delicately beautiful display of branching orange sparks.

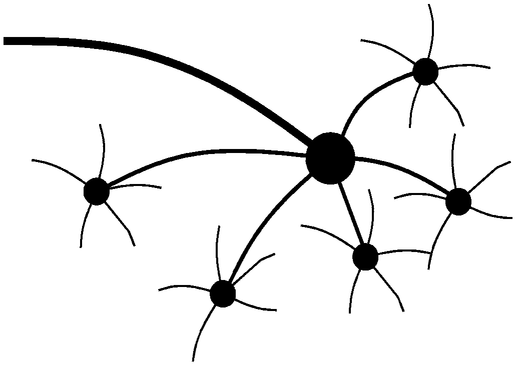

Figure 9. Illustration of the appearance of branching spark particles.

During the initial apparently quiescent period, there is continuing air oxidation of the reactive combustion products. One possible series of reactions, based on information from reference 2a are shown in equations 8–10.

$$2\ K_2CO_3 + 5\ S \rightarrow 2\ K_2S_2 + 2\ CO_2 + SO_2 \quad (8)$$

$$K_2S_2 + O_2 \rightarrow K_2S + SO_2 \quad (9)$$

$$K_2S + 2O_2 \rightarrow K_2SO_4 \quad (10)$$

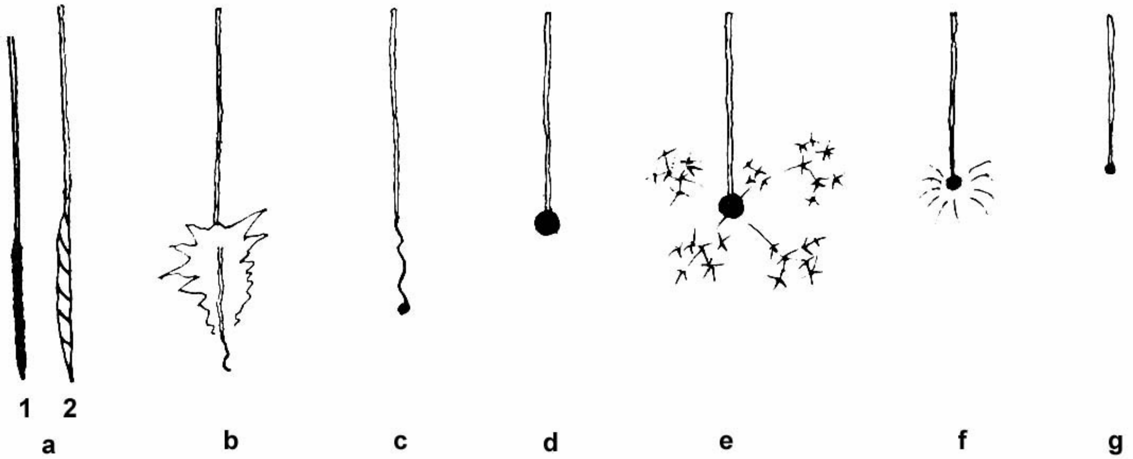

Figure 10. (a) Two typical forms of senko hanabi. (b–g) The typical senko hanabi process.[4f]

$$C + (?) \rightarrow \text{Sparks} \quad (11)$$

These reactions (equations 8–10) produce heat that maintains the temperature of the molten ball and alters the chemical components of the ball. In addition, a continuing amount of carbonized material from the straw or tissue paper is continually adding to the molten ball of combustion products. At some point minor explosive reactions of the carbon particles produce the branching sparks (equation 11). While details of the spark mechanism are unknown, the nature of the source of carbon (charcoal or soot) plays an important role in the character and abundance of the sparks produced.[2i]

Glitter and Microstars

The glitter effect can be thought of as a spark effect wherein initially orange sparks are generated, then after a brief time delay they proceed to produce a bright flash. That flash may range in color from yellowish-orange to white. Figure 11 illustrates the glitter effect, which should not be confused with the simple continuous aluminum spark effect, often referred to as flitter. The glitter effect and its chemistry have been fairly extensively treated in the literature,[29–36] although there is some disagreement about certain aspects of its chemistry. For this reason, and because the subject has recently been covered in a review article,[34] the discussion of glitter in this article will be rather limited in its scope. The initial chemistry is similar to that for carbon sparks. Equation 12 suggests a simplified chemical reaction for sulfur-rich Black Powder, which produces the yellowish-orange sparks (molten droplets). Equations 13 and 14 were seen above as equations 9 and 10 and provide thermal energy to maintain the temperature of the spark droplets sometimes referred to as the “spritzels”.[32] Equation 15 is the reaction producing the terminating glitter flash. In equation 15 the exact nature of the fuel is not specified, because there is some disagreement as to what it is: Fish[30] implies it is aluminum sulfide, Oglesby[32] suggests it is aluminum metal, and Stanbridge[31] suggests it is aluminum carbide.

$$2\,KNO_3 + 3\,C + 2\,S \rightarrow K_2S_2 + 3\,CO_2 + N_2 \quad (12)$$

$$K_2S_2 + O_2 \rightarrow K_2S + SO_2 \quad (13)$$

$$K_2S + 2\,O_2 \rightarrow K_2SO_4 \quad (14)$$

$$K_2SO_4 + (\text{Al fuel}) \rightarrow \text{Flash} \quad (15)$$

The attributes of attractive glitter effects are long delay and large bright flashes. Glitter delay is most commonly achieved using antimony sulfide, or an oxalate, carbonate or bicarbonate in the composition. Flash size and brightness can be increased using barium nitrate, a spherical atomized aluminum, or magnalium. If larger particle size aluminum is used, the glitter flashes will produce radiating yellowish-white sparks.

Microstars[37,38] are small pellets of composition, usually emitted by fountains that react invisibly (at low temperature) as they move through the air and eventually produce a bright flash of light. Microstars may be thought of as a strobe effect[39] where only a single flash is produced. Although there is some similarity between microstars, glitter and simple pyrotechnic sparks, microstars are not typically considered to be a spark effect, and they will not be discussed in this article. There is, however, the exception that conventional metal sparks can be produced in the microstar flash reaction. Presumably, this is accomplished using metal particles that are too large to be fully consumed by the flash reaction.

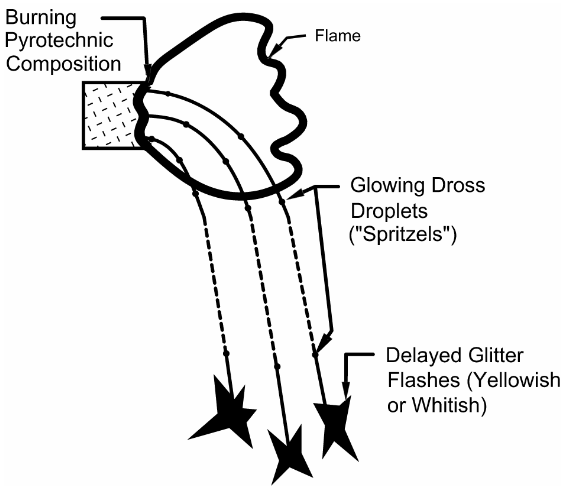

Figure 11. Illustration of the appearance of glitter sparks and flashes.

Conclusion

Spark effects have been used to augment firework effects for a very long time, and new and improved effects continue to be developed. In some cases, our understanding of spark effects is quite good, in others, much remains to be learned. Hopefully this review article has summarized much of what is known and identified some things deserving further study.

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An Instrument for the Evaluation of Black Powder as a Propellant for Aerial shells

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ABSTRACT

None of the standard laboratory tests for Black Powder provide a direct indication of its performance characteristics for propelling aerial fireworks shells. Typically such testing must be performed by firing dummy projectiles on a test range—with all the problems that can entail, including the use of fairly large amounts of Black Powder for each test sample. Accordingly, a small, inexpensive laboratory test apparatus was developed, which uses only a minimal amount of powder per firing. The performance of the instrument was quantified regarding the effect of operating temperature, sensitivity of output to variations in ignition point, the effects of combustion product accumulation in the bore of the apparatus, the effect of grain size distribution, and the statistical precision of the results. Following these characterizations, the instrument was used to evaluate the performance of a series of Black Powder samples.

Introduction

There are standard tests used to determine the performance of Black Powder (e.g., strand, quickness, and flame spread tests). However, none generate results that directly indicate how the powder will perform when used as lift charge for aerial shells with their substantial clearance within their fireworks mortars. Typically, one must resort to test firing aerial shells to collect the desired information. This requires access to a test range and having to deal with problems such as weather. Accordingly, in preparation for studies[1–3] of the effects of varying materials and processing methods on the performance of Black Powder when used to fire aerial shells, a small-scale, simple, cost-effective, laboratory apparatus was constructed. This article describes the apparatus, presents data characterizing the device, and compares the performance of a few Black Powder samples. Figure 1, shows the instrument in operation, where combustion gases can be seen exiting the apparatus through a series of vents. Presumably, the sparks seen are pieces of still burning black powder exiting with the combustion gases.

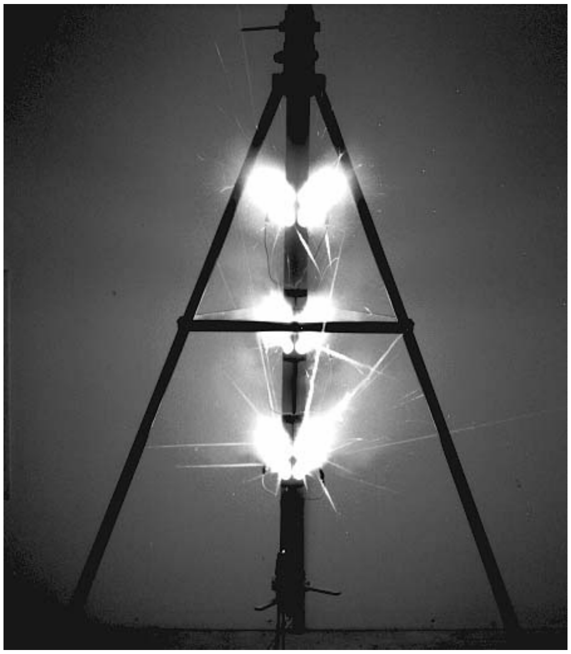

Figure 1. Test instrument shown during firing of a Black Powder test sample (time exposure).

Design and Construction

To keep cost to a minimum, whenever possible, off-the-shelf components and pre-existing hardware were used. Another important consideration was the size of the apparatus. Small size generally equates to less expensive, requiring smaller samples of powder, and being more suitable for indoor use. This apparatus was built around the use of golf balls as projectiles,[4] which are rugged (reusable) and cost less than one dollar each. With this size mortar, cylindrical projectiles could also be made using 1.75-inch (45-mm) nylon rods, see Figure 2. The material for the mortar and barrel of the apparatus was commercial drill stem tubing, which fit the golf ball fairly well and still allowed the use of standard 2-inch (51-mm) pipe fittings. Table 1 presents some information about the projectiles, the test apparatus mortar, and typical values for aerial shells.

The fit of the projectiles in the test mortar is an important parameter for the instrument to provide meaningful results. As shown in Table 1, the fit of the golf ball and nylon rod in the mortar, as indicated by cross sectional area ratios, is in close agreement with that for small aerial shells. The density of the test projectiles, however, is higher than that of typical small aerial shells. This is not a serious problem; however, if desired, the test projectiles could be drilled and capped to lower their densities.

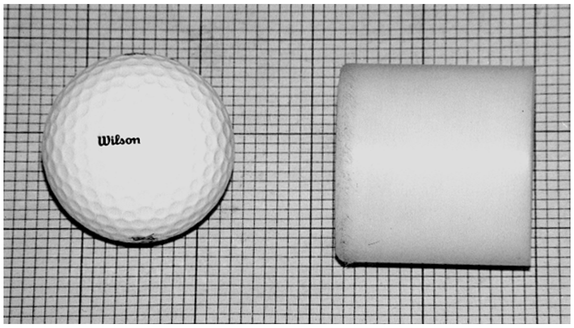

Figure 2. Typical projectiles, golf ball and short length of nylon rod, are reusable.

The instrument consists of a combination of a mortar, a time-of-flight velocity measurement section, and a projectile arrester. The apparatus and its supporting tripod are shown in Figure 3. The bottom-most portion of the vertical tube is the mortar. It is closed at the bottom with a breech plug (Figures 4 and 5) that is threaded into a standard 2-inch (51-mm) pipe union for attachment to the mortar.

Table 1. Specifications of Projectiles and Mortar.

	Projectile Type(a)		
Parameter, Units	Spherical	Cylindrical	Mortar
Diameter, inches (mm)	1.68 (43)	1.75 (44)	1.89 (48)
Cross Sectional Area, in^2 (cm^2)	2.22 (14.3)	2.41 (15.5)	2.81 (18.1)
Projectile to Mortar Area Ratio	0.79	0.86	n/a
Typical 3-in. (76-mm) Shell Area Ratio(b)	0.76 to 0.84	0.76 to 0.84	n/a
Weight, ounces (Mass, grams)	1.6 (46)	2.8 (78)	n/a
Density, g/cm^3	1.12	1.13	n/a
Typical 3-in. (76-mm) Shell Density	0.76(c)	0.75(d)	n/a

(a) Spherical projectiles were golf balls; cylindrical projectiles were nylon rods.

(b) These are values for 2.62- and 2.75-inch (67- and 70-mm) diameter shells, respectively, and a 3.00-inch (76-mm) mortar.

(c) Assuming a 2.75-inch (70-mm) diameter spherical projectile weighing 0.3 pound (mass of 0.14 kg).

(d) Assuming a 2.75-inch (70-mm) diameter by 2.5-inch (64-mm) long cylindrical projectile weighing 0.4 pound (0.18 kg).

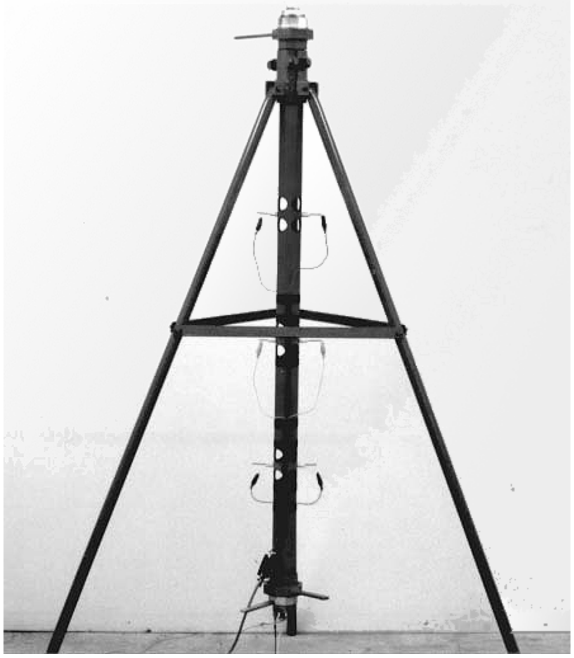

Figure 3. Black powder test instrument and tripod.

In an earlier study of aerial shell exit times[5a] the authors observed that even apparently identical aerial shells (using the same type of electric matches and firing set) typically demonstrated a wide range of mortar exit times. A likely explanation for this is that there are significant differences in the dynamics of flame spread and combustion. Among other things, this may be caused by relatively minor differences in the relative geometry of the lift powder charge, the point of ignition, and the shell position. For this reason the breech plug of this instrument was designed to provide an easily reproducible geometry for the powder, electric match and projectile (see Figure 4). Shown removed from the center of the plug in Figure 5, is the mechanism for inserting and securing an electric match. Also shown in Figure 5, on the bottom left side of the breech plug is a piezoelectric pressure sensor (PCB Piezotronics[6] 101A04). On the right side of the plug is the attachment of a thermocouple. The breech plug design has subsequently been modified to

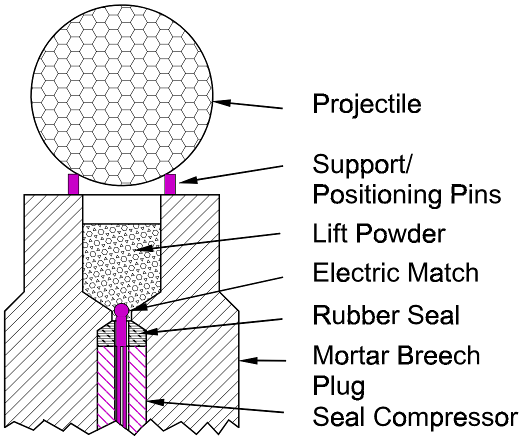

Figure 4. Cross sectional drawing of the breech plug for the mortar portion of the instrument.

Figure 5. Breech plug for mortar portion of test instrument.

mount the thermocouple approximately 1-inch (25-mm) deep inside the plug. This reduces ambient temperature effects allowing a more accurate reading of the plug and powder temperature. Another modification was the addition of two small electric cartridge heaters inserted into the breech plug. These are used to raise and hold constant the temperature of the plug and powder.

Figure 6 shows one of three sets of holes in the apparatus for the escape of the combustion gases. It also shows a trip-wire for measuring the time-of-flight of the projectile. The trip-wire is a short length of computer wirewrap that is held in place, after tensioning, with a pair of wedges inserted into 1/8-inch (3.1-mm) plastic tube fittings. Initially, graphite pencil leads were used as trip-wires; however, they sometimes failed prematurely. A series of three trip-wires spans a total distance of 2 feet (0.61 m) thus providing two one-foot (0.30 m) time-of-flight segments. Trip-wire break times are measured to 0.1 millisecond, using an existing instrument[7] that also fires the electric match.

Above the third set of exhaust holes and trip-wire, is the arrester portion of the instrument. This is simply a closed portion of pipe, in which a build up of gas pressure in front of the projectile is expected to begin reducing the velocity of the projectile. However, the primary arrester is a hard rubber disk mounted in the pipe using another pipe union. This keeps the projectile within the apparatus. After impacting the arrester disk, the projectile falls relatively slowly back to the bottom of the apparatus.

The apparatus is essentially symmetrical in its design; thus it can be inverted, with the breech plug and arrester disk switched from end to end. This symmetry, and because the distance to the first exhaust holes is different on opposite ends of the pipe, makes it possible to have two different mortar lengths with a single instrument. One end provides a mortar length of approximately 5 times the diameter of the mortar, and the other, approximately 8 times its diameter. These are approximate lengths because the mortar section does not end abruptly; rather the solid mortar section ends at the round exhaust holes.

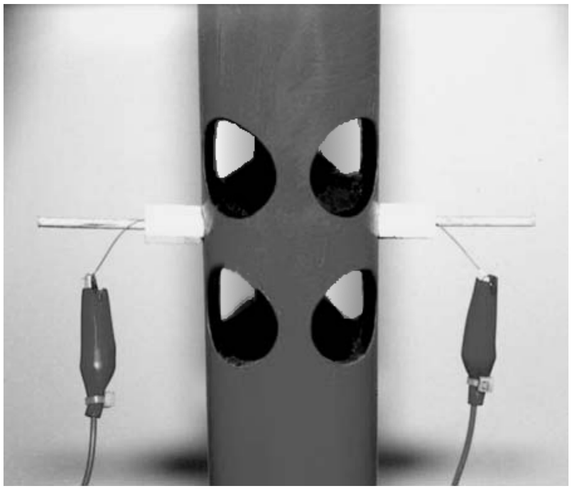

Figure 6. One set of combustion gas exhaust holes and one timing trip-wire.

In addition to the trip-wire data (providing exit times from the mortar and muzzle velocities), the instrument also generates mortar pressure data. This data is collected using a digital storage oscilloscope, triggered by the application of power to the electric match. Figure 7 presents an example of a typical mortar pressure profile. Using such data, peak pressure (determined by visually smoothing the data) and pressure impulse (area under the curve) are easily obtained. In addition, other interesting data are available: delay time (defined as the time between applying electric current to the electric match and when mortar pressure rises to 10% of maximum), rise time (defined as the time for the pressure to rise from 10 to 90% of

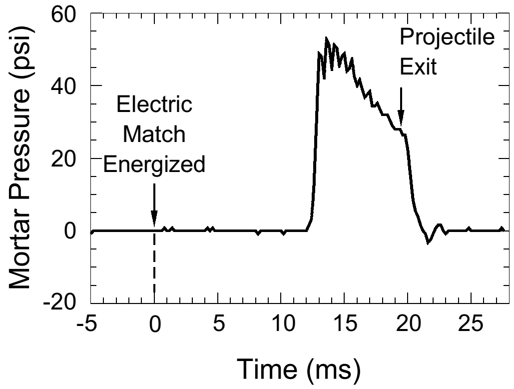

Figure 7. A typical mortar pressure profile for a golf ball (1 psi = 6.89 kPa).

maximum), projectile exit time (defined as the time from match firing to the break in the pressure curve indicating the exit of the projectile), exit pressure (defined as the pressure at time of projectile exit), and impulse time (defined as the time difference between start of the pressure pulse and projectile exit).

Characterization of the Instrument

Many factors affect the burn rate of pyrotechnic materials (e.g., temperature and grain size). Other factors affect the efficiency of propulsion (e.g., clearance around a projectile). To the extent that any of these factors may change during or between test runs, they need to be controlled or the data corrected. Accordingly, one needs to know how these factors affect the data, such that either the necessary level of control can be determined, or the necessary correction can be applied.

Point of Ignition

After a few initial test firings, the first characterization data collected was on the effect of varying the point of ignition of the lift powder. The normal location of the electric match is at the very bottom of the powder chamber in the breech plug. Figure 8 demonstrates the reproducibility of the pressure pulse achieved for three golf ball firings using 5.0 g (0.18 oz) loads of Goex[8] 4FA powder, with the instrument at a constant temperature. (It is interesting to note that the pressure pulse data seems to demonstrate damped ringing of a constant frequency of approximately 1.6 kHz. This same feature was seen in many pressure peaks. At the present time, the authors are not prepared to suggest an explanation.)

In addition to the data presented in Figure 8, with the electric match in its normal position, a pair of firings with the same powder load had the match raised 0.2 and 0.6 inch (5 and 15 mm) above its normal position, see Figure 9. The purpose of these firings was to help establish the degree of sensitivity of the instrument to varying electric match positions. Figure 10 and Table 2 show the results of these tests. Raising the ignition point 0.2 inch (5 mm) reduced muzzle velocity by approximately 10%; raising the ignition point 0.6 inch (15 mm) reduced muzzle velocity by approximately 50%. Obviously, closely controlling the location of the electric match is important. This observation supports the conclusion that maintaining a constant ignition point, and powder and projectile geometry are essential for consistent results. Toward this end, the operator visually verified the position of the electric match before each test reported herein; then after loading the powder, the plug was tapped several times to settle and even the powder level in the chamber.

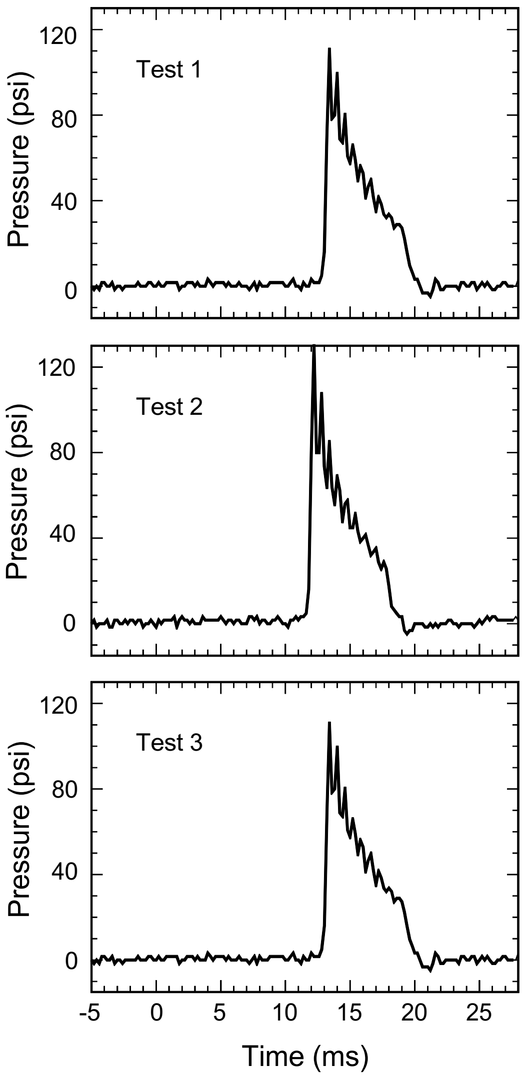

Figure 8. Illustration of reproducibility of test firings with electric match in its normal position (1 psi = 6.89 kPa.)

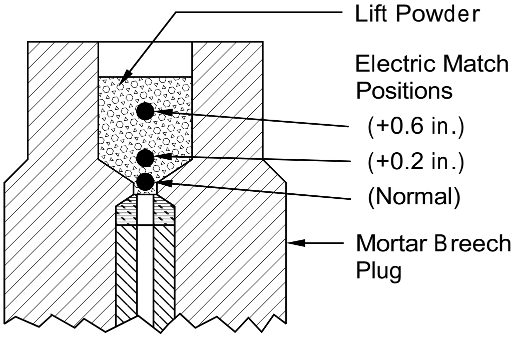

Figure 9. Illustration of electric match positions in breech plug.

Temperature

With each firing, the breech plug and mortar retain some of the thermal energy, which raises their temperature, and that of the next load of powder. This increases muzzle velocities and affects other results.[9,5b] Accordingly, to establish how elevated temperature affects results, a series of individual firings was conducted, each using 5.0 g (0.18 oz) of Goex 4FA powder, with breech plug temperatures ranging from 16 to 130 °F (–9 to 54 °C). The powder samples were conditioned to the approximate temperature of the instrument before loading. After loading the powder into the combustion chamber, the powder was allowed to thermally equilibrate for five minutes before firing. These results are presented in Table 3 and graphically in Figure 11.

As an alternative to running multiple tests at fewer temperatures, individual firings were run at a relatively large number of temperatures. This was done for several reasons. First, the primary interest was in the overall functional

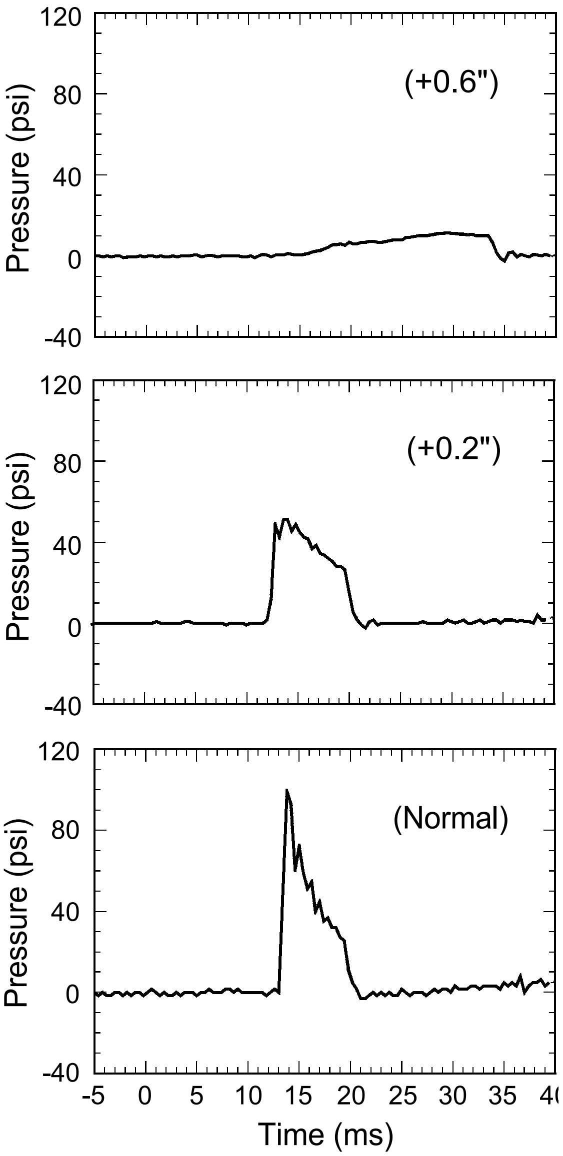

Figure 10. Typical mortar pressure profiles as a function of electric match position.

Table 2. Muzzle Velocity and Pressure Data as a Function of Electric Match Position.

Match Position in.	(mm)	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time (ms)	Delay Time (ms)
0.0	(0)	200	(61)	92	(630)	6.0	12.8
		220	(67)	108	(740)	6.0	13.0
		202	(62)	96	(660)	5.9	11.1
0.2	(5)	196	(60)	48	(330)	7.3	12.5
0.6	(15)	99	(30)	12	(83)	18.4	15.2

Table 3. Muzzle Velocity and Pressure Data as a Function of Temperature.

Temperature		Muzzle Velocity		Peak Pressure		Impulse Time	Pressure Impulse		Delay Time
°F	(°C)	ft/s	(m/s)	psi	(kPa)	ms	psi · ms	(MPa · ms)	ms
16	(–9)	187	(57)	84	(580)	6.8	244	(1.68)	12.2
21	(–6)	200	(61)	76	(520)	7.0	340	(2.34)	11.2
25	(–4)	206	(63)	86	(590)	6.9	298	(2.06)	11.2
30	(–1)	222	(68)	88	(610)	7.0	326	(2.25)	9.0
35	(2)	215	(66)	92	(630)	6.6	291	(2.01)	15.9
42	(6)	235	(72)	112	(770)	6.0	327	(2.25)	12.9
46	(8)	222	(68)	72	(500)	7.2	314	(2.16)	11.0
51	(11)	233	(71)	112	(770)	5.7	329	(2.26)	12.0
52	(11)	230	(70)	100	(690)	6.4	320	(2.20)	10.5
56	(13)	235	(72)	108	(740)	6.0	333	(2.29)	15.0
60	(16)	227	(69)	108	(740)	6.6	321	(2.21)	12.0
65	(18)	241	(74)	100	(690)	6.0	343	(2.36)	10.3
70	(21)	247	(75)	118	(810)	6.0	346	(2.39)	11.0
75	(24)	244	(74)	120	(830)	5.8	334	(2.30)	11.0
80	(27)	253	(77)	122	(840)	5.8	349	(2.41)	11.0
85	(29)	278	(85)	140	(960)	5.0	362	(2.49)	9.1
91	(33)	267	(81)	144	(990)	5.2	354	(2.44)	8.9
96	(56)	263	(80)	144	(990)	5.4	356	(2.45)	9.4
101	(38)	270	(82)	172	(1190)	5.0	375	(2.58)	10.6
106	(41)	286	(87)	168	(1160)	5.0	362	(2.49)	9.5
112	(44)	274	(84)	176	(1210)	5.2	372	(2.56)	8.8
116	(47)	278	(85)	184	(1270)	5.2	373	(2.57)	10.5
122	(50)	282	(86)	208	(1430)	5.0	376	(2.59)	8.7
130	(54)	290	(88)	200	(1380)	4.8	375	(2.58)	17.1

relationships with temperature, which could be established using regression analysis, where relatively large individual uncertainties would not distort the results. Second, it was easier to accurately measure the temperature than it was to hold temperatures constant for a set of several tests. Third, plotting the data points from individual tests allows an easy visual comparison of statistical precision of the data relative to the magnitude of change with temperature.

Over the temperature range studied, muzzle velocity increased linearly by approximately 50%, or about 0.9 ft/s per °F (0.5 m/s per °C). Over the same temperature range, peak mortar pressure increased exponentially by more than 100%, while the corresponding impulse time decreased approximately 30%. The net result is that pressure impulse increased linearly by approximately 30%.

Following these measurements, instead of correcting individual readings for variations in temperature, because it was more expeditious, the instrument and powder were held at a constant, slightly elevated temperature. To accomplish this, two small cartridge heaters were installed in the breech plug. Unless otherwise noted all of the data reported in the rest of this article was collected with an instrument temperature of 80 °F (27 °C). Based on the observed magnitude of the changes, temperature effects and the typical level of statistical precision of the data during operation, the instrument

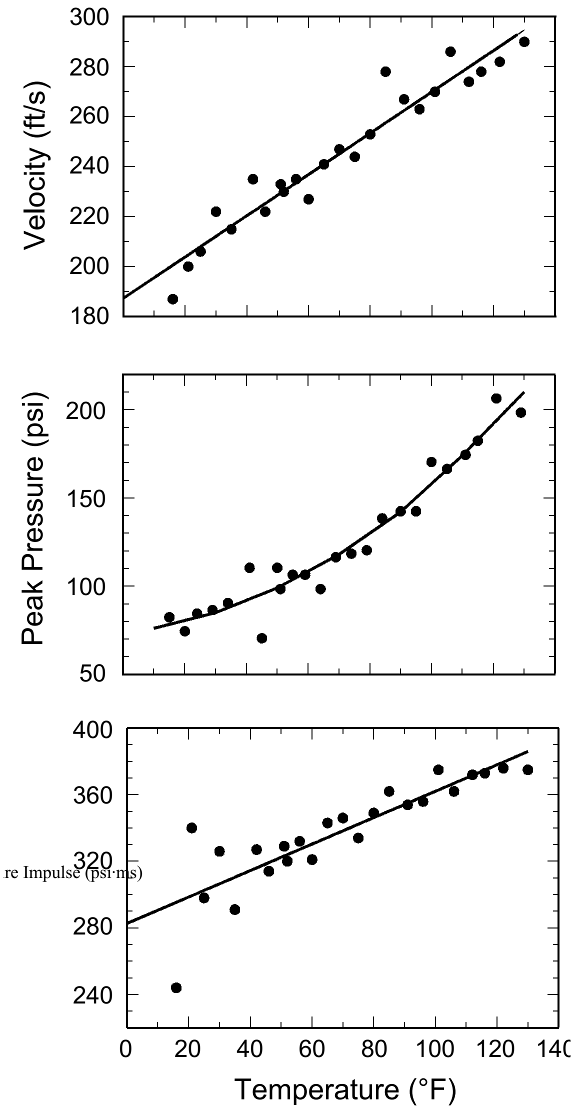

Figure 11. The effect of temperature on muzzle velocity, peak pressure, and impulse pressure.

was only held to within about 2 °F (1 °C) of the target temperature.

Cleaning

With each firing of the instrument, combustion products collect within the bore of the apparatus. This build-up acts to decrease the clearance around the projectile, which results in higher mortar pressures and greater muzzle velocities. One solution would have been to wash and dry the bore of the apparatus after each test firing. However, the time required for this would not have been practical. Another possible solution was to allow the accumulation of combustion products until a steady state was achieved, wherein each firing freed about as much combustion product as was deposited. This method was tried during the temperature characterization discussed above, and was minimally acceptable. The problem with this method is that if the instrument were cleaned, many firings would have been necessary to restore the instrument to its previous steady state condition. Another problem would occur if the instrument were used in a humid environment where the hygroscopic combustion products absorbed moisture and became partially liquefied. Accordingly, this steady state strategy was rejected.

The cleaning strategy, which achieved consistent results without taking excessive time, was to clean the bore of the instrument using a tight fitting set of wire brushes after every nine firings. (If for any reason one test firing in a series was unsuccessful, a tenth firing was allowed before cleaning the apparatus.) As part of the cleaning process, the breech plug was also washed and blown dry. Using this strategy, under the same test conditions, muzzle velocities and peak pressures for the tenth firing averaged approximately 10% higher than for the first firing. This large effect could not be ignored. One possibility was to correct each test result for its position in the sequence of firings between cleanings. However, this would require accurately determining and applying correction values for each measurement in the firing sequence. Accordingly as an alternative, the authors chose to use a firing order that essentially canceled (averaged) the mortar cleaning effect. For example, in most tests, a series of three measurements was made for each of three conditions being tested (three tests each for condition A, B, and C = nine firings). Typically the test firing order was {A, B, C, B, A, C, C, B, A}. This procedure virtually eliminates any systematic effect from accumulating combustion products within the instrument. This sampling scheme was applied to a series of nine identical test firings (data discussed below and presented in Table 7). Treating the data as three separate sets, the average deviations of the three muzzle velocities and pressure impulses from their collective means was less than 2% compared with their coefficients of variation of approximately 5%.

Particle Size

Most spherical fireworks shells and small cylindrical shells are typically fired using 4FA Black Powder; accordingly, this granulation was chosen as the standard grain size for this instrument. The US specification for 4FA powder is for no more than 3% to be +12 mesh, and no more than 12% to be –20 mesh.[10] This specification is sufficiently loose that significant variation in performance might occur because of differences in particle size distributions all well within the specification limits. For this reason, a series of tests was performed on various mesh fractions from the same can of Goex powder, where each mesh fraction would easily qualify as being 4FA. The powder was sieved, and the mesh fractions observed are reported in Table 4. The results from a series of three tests of each of the various fractions are reported in Table 5.

The observed muzzle velocities follow the expectation that the smaller particle size material produces the highest velocities. Similarly, the pressure impulse results also trend as expected, following the muzzle velocity results. Mortar pressure measurements in other portions of this study and other studies demonstrate that peak mortar pressures vary more widely than muzzle velocity and pressure impulse. Thus, while it is logical to expect that peak pressure would be greatest for the smaller particle size powder that was observed in this case. Apparently, the effect was not masked by the uncertainty in the pressure data.

This test was performed to determine the sensitivity of the data to small variations in powder particle size distribution. Note that there is an approximate 10% difference between the muzzle velocity and pressure impulse results for 12 to 16 mesh and 16 to 20 mesh. Accordingly, while grading test samples to the limits for the various commercial granulations may be satisfactory in many cases, it may not be sufficient. This is because minor variations in performance could be attributable to nothing more than slight differences in particle size distribution.

Table 4. Observed Mesh Fractions for Goex 4FA Black Powder.

Mesh Range[a]	Percent
+12	1.9
12–16	52.3
16–20	43.6
–20	2.2

(a) US Standard mesh size.

Free Flight Mode

A series of 21 test firings was performed outdoors with the projectile arrester removed; thus allowing the projectile to be propelled into the air. These tests were performed to determine “effective” (average) drag coefficients for golf balls in the velocity regime of interest for another project.[2] While interesting, those drag coefficient results will not be reported here except to note one thing. The average muzzle velocities recorded in the free flight mode were substantially higher than those for the same conditions in the captive mode, see Table 6. Presumably, this is the result of combustion gases escaping around the projectile and accumulating in the bore of the apparatus in front of the golf ball, and thus impeding its motion. Currently, this is the best explanation to be offered; however, the effect is significantly greater than might have been predicted. Accordingly, while

Table 5. Test Results for Goex 4FA Black Powder (Averages from Three Tests Each).

Mesh Range[a]	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Pressure Impulse psi ms	(MPa ms)
16 – 20	295	(90)	183	(1260)	447	(3080)
12 – 20	278	(85)	196	(1350)	417	(2870)
12 – 16	267	(81)	186	(1280)	386	(2660)

(a) US Standard mesh size.

Table 6. Comparison of Muzzle Velocities for Free Flight and Captive Modes (Averages from Three Tests Each).

Powder Charge oz.	(g)	Free Flight Muzzle Velocity ft/s	(m/s)	Captive Muzzle Velocity ft/s	(m/s)
0.07	(2.0)	75	(23)	—	—
0.09	(2.5)	118	(36)	—	—
0.11	(3.0)	139	(42)	66	(20)
0.12	(3.5)	189	(58)	—	—
0.14	(4.0)	223	(68)	150	(46)
0.16	(4.5)	259	(79)	—	—
0.18	(5.0)	300	(91)	210	(64)
0.21	(6.0)	—	—	280	(85)
0.25	(7.0)	—	—	340	(104)

captive mode test results with the instrument are expected to be diagnostic and self-consistent, in some cases, care may need to be exercised when quantitatively applying captive flight results to free flight situations.

While speculating on the subject of gas flow in the apparatus, another unexpected occurrence should be noted. Even though combustion gas has apparently passed the projectile and is impeding its progress, and even though the projectile has passed vent holes with a total area of more than 8 times the pipe diameter, the projectile continues to accelerate as it passes through the time-of-flight portion of the instrument. It is typical for velocities 5 to 10% higher to be recorded for the second (upper) one-foot (0.31 m) flight section. The only explanation offered is that once the propulsive gases have established their upward momentum in the mortar, they tend to continue in that direction and provide additional acceleration to the projectile. While this effect might have been expected, its magnitude is greater than would have been predicted.

Precision

A series of 9 firings under the same conditions was performed to determine the statistical precision of the results. These conditions for the test were: a 5.0-g (0.18-oz) powder charge of Goex 4FA Black Powder; a temperature of 90 °F (32 °C); the bore of the instrument had just been cleaned; and firing a standard golf ball. The results of these measurements are presented in Table 7. Because of the limited number of tests of each condition, the reported standard deviations were computed using the (*n*–1) method.

In examining the results in Table 7, considering the full set of data, it is apparent that the muzzle velocities and pressure impulses have fairly low coefficients of variation, approximately 5%. This is even without attempting to correct the data for systematic effects from accumulating of combustion products in the instrument between cleanings. Considering the data as three separate sets of three consecutive measurements, the one-sigma standard error for muzzle velocity or pressure impulse measurements is over three percent. This is perhaps already sufficiently low; however, a sampling scheme designed to reduce such systematic effects offers further improvement. Using the {A, B, C, B, A, C, C, B, A} sampling scheme discussed earlier, the sets of three measurements now have no more than approximately a 2% standard error.

Some Powder Test Results

Based on the experience with the characterization tests, a standard set of conditions and procedures was established. Unless otherwise noted: the projectile was a golf ball weighing 1.7 ounces (mass of 46 g); the powder load was 5.0 g (0.18 oz) of 16 to 20 mesh; the powder

Table 7. Statistical Precision of Repeat Firings.

Firing Order	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Pressure Impulse psi·ms	(MPa·ms)	Delay Time ms
1	247	(75)	106	(730)	6.4	353	(2.43)	7.8
2	278	(85)	(a)		—	—	—	—
3	274	(84)	158	(1090)	5.2	392	(2.70)	9.4
4	278	(85)	155	(1070)	5.2	385	(2.65)	9.4
5	290	(88)	(a)		—	—	—	—
6	260	(79)	119	(820)	5.8	355	(2.44)	7.6
7	282	(86)	177	(1220)	5.2	384	(2.65)	8.4
8	299	(91)	162	(1120)	5.6	389	(2.68)	7.2
9	274	(84)	177	(1220)	5.4	391	(2.69)	8.6
Ave.	276	(84)	151	(1040)	5.5	378	(2.61)	8.3
Std. Dev.	15	(4.6)	28	(190)	0.4	17	(0.12)	0.9
Co. Var.(b)	5.4%		19%		8.1%	4.5%		10%

(a) Oscilloscope failed to trigger; no pressure data was recorded for this test.

(b) The Coefficient of Variation is the standard deviation expressed as a percent of the mean.

was ignited using a Daveyfire SA–2000 electric match at the bottom of the powder chamber; the temperature of the powder and instrument was 80 ± 2 °F (27 ± 1 °C); the short mortar end (5 times diameter) of the instrument was used; the apparatus was cleaned after every nine or ten firings; and a series of three measurements was made using the reported sampling scheme to average the effects of cleaning.

Muzzle velocity is easy to measure and must correlate quite well with pressure impulse, which is more difficult to calculate. Thus, pressure impulse was not determined for these tests. The observed standard deviation for peak pressure is quite a high (perhaps because of the apparent ringing or oscillations in the data, see Figure 3). Accordingly, the reported peak pressure results should only be used for approximating the range of forces being exerted on the mortar.

Table 8. The Effects of Various Black Powder Granulations (Averages from Three Tests Each).

Powder Type	Nominal Granulation mesh(a)	Glazing	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Delay Time ms
2FA	4 – 12	No	187	(57)	69	(480)	7.0	15
Cannon	6 – 12	Heavy(b)	149	(45)	33	(230)	9.9	18
3FA	10 – 16	Light(b)	273	(83)	149	(1030)	5.2	10
Fg	12 – 16	yes	268	(82)	142	(980)	4.9	9.7
4FA	12 – 20	unknown	278	(85)	159	(1100)	4.8	11
2Fg	16 – 30	yes	338	(103)	247	(1700)	4.2	9.0

(a) Values taken from reference 10, typically 3% may be coarser and 12% may be finer than the stated range.

(b) The relative thickness of the glazing was estimated visually.

Granulation

A series of 18 test firings (three each for six different powder samples) was performed to examine the effect of various Black Powder granulations. All powders were commercially manufactured by Goex, Inc. These data were collected during the time when a steady state approach was being tried with respect to the accumulation of combustion products. Thus the velocities and pressures are somewhat higher than if the instrument had been cleaned more frequently, nonetheless, the sequence of firings was such that the data should be internally consistent. These data are presented in Table 8. It would have been preferred for comparison purposes that the powders had all been glazed. However, the powders tested were the only samples available in the lab at the time. Glazing presumably reduces the rate of flame spread as compared with unglazed powders. This, in turn, would be expected to reduce muzzle velocity and peak pressure. However, at this time the extent of these effects is unknown to the authors. Also there probably were some performance variations between different production lots of the Goex powders. It is implicitly assumed in reporting these test results that the intrinsic burn characteristics of the powders were all identical and that the differences observed are solely the result of differences in granulation. Of course, this probably was not entirely correct.

In each of the test firings of Cannon powder (and at least once for 2FA), a precursor peak was observed, such as shown in Figures 12a and 12d. [Note that time axis values in Figure 12e apply to all graphs in the series.] This was not clearly seen for any of the faster burning Goex powder samples. These precursor peaks were observed again when examining some slower burning imported powders, see Figures 12b and 12c. In examining the full series of examples in Figure 12, it appears that as the time between the precursor peak and the main impulse peak decreases, the precursor peak narrows and becomes the leading edge of the main impulse peak.

Although it seemed extremely unlikely, tests confirmed that the precursor peaks were not related to the firing of the electric match. One series of tests determined the ignition times for Daveyfire SA–2000 matches using the same firing-set as in the Black Powder tests. Firing times were found to be less than 1 ms; thus, the match firings occurred 10 to 20 ms before the precursor peaks were observed. While the presence of precursor peaks is interesting, the authors have no explanation for their existence at the present time.

Table 9. The Effects of Varying Black Powder Load Mass (Averages from Three Tests Each).

Lift Mass g	Lift Mass (oz.)	Muzzle Velocity ft/s	Muzzle Velocity (m/s)	Peak Pressure psi	Peak Pressure (kPa)	Impulse Time ms	Delay Time ms
3.0	(0.11)	66	(20)	10	(70)	19	14
4.0	(0.14)	150	(46)	32	(220)	10	14
5.0	(0.18)	210	(64)	88	(610)	6.4	12
6.0	(0.21)	280	(85)	210	(1450)	4.8	11
7.0	(0.25)	340	(104)	360	(2480)	3.2	9.4

Powder Charge

A series of 15 test firings was performed to examine the effect of Black Powder load mass. All powders were 4FA from Goex, Inc. These data were recorded before the electric heaters had been installed in the breech plug. The powder and instrument temperatures were 58 ± 2 °F (14 ± 1 °C). Thus, while the data are internally consistent, the velocities and pressures are lower than would have been the case for a higher temperature. From the data presented in Table 9 and Figure 13, note that muzzle velocity increases linearly with lift mass, while peak pressure increases exponentially, and impulse time decreases exponentially with lift mass.

Powder Type

A series of 30 measurements was made using Black Powder from various sources that were available in the authors' lab. These data are presented in Table 10. For comparison, values observed from roughly equivalent granulations of Goex powder are also included. Some of the pressure pulse shapes for various brands and powder types were surprisingly different from what had been expected. See Figure 14. At this time, the authors are not prepared to suggest an explanation of the pressure pulse shapes, except to note the likely presence of precursor peaks.

Conclusion

The instrument for testing Black Powder, after only minor modifications, has met its design criteria. It is small and portable; it costs approximately US$500 (not including electronics already on hand); it works reliably and requires low maintenance (cleaning); it consumes only small amounts of powder and can be fired indoors; and it uses a variety of inexpensive reusable projectiles. The significant differences in the velocities observed in the captive vs. free flight modes is disappointing, although should not interfere with the studies being undertaken using this instrument.

It is not clear whether inferences drawn from this small caliber instrument will apply directly to large caliber mortars and aerial shells.

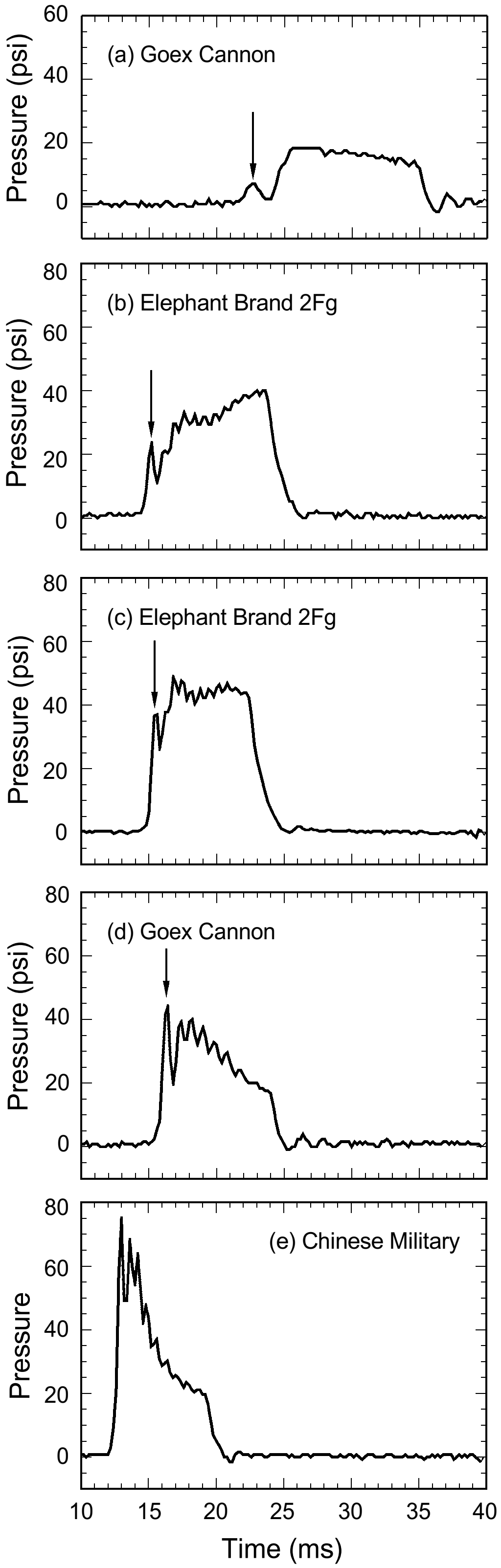

Figure 12. Examples of the precursor pressure peaks seen when firing slower burning powders.

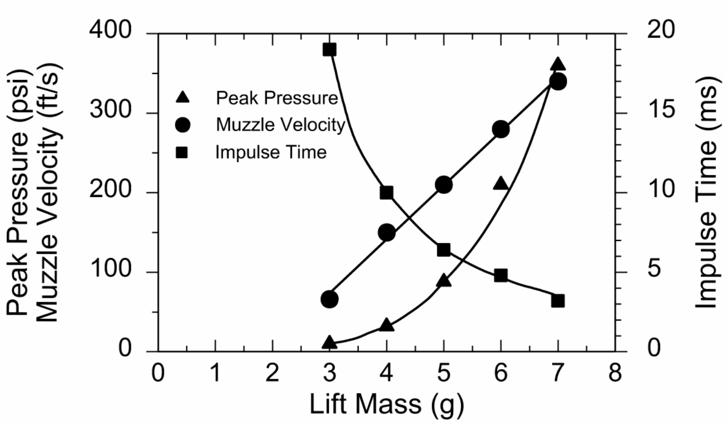

Figure 13. Graph of peak pressure, muzzle velocity and impulse time as functions of lift mass.

However, that was not an objective for the current instrument. Further, the success of this small-scale apparatus suggests that the design should be practical for a larger scale instrument, should that be needed.

It was not the principal purpose of this article to present Black Powder data from which significant conclusions could be drawn. Nonetheless, a few points are worth mentioning:

- The sensitivity of muzzle velocity to variations in ignition point geometry is surprisingly great. This suggests that, if preparing for a competition at the highest levels, where precise placement of shells is important, it may be worth carefully controlling the ignition and burning of the lift charge. Specifically, the ignition stimulus and geometry should be as consistent as possible, as well as the source, granulation, amount, and packaging of the lift charge.
- The muzzle velocities achieved by the Elephant brand and Chinese powders were significantly less than for the equivalent Goex granulations. This suggests that much (all?) of the potential cost advantage from using these less expensive powders may be nonexistent.

Table 10. Performance Values of Various Sources of Black Powder (Averages from 3 Tests Each).

Powder Source	Granulation[a]	Muzzle Velocity ft/s	(m/s)	Peak Pressure psi	(kPa)	Impulse Time ms	Delay Time ms
Elephant Brand	Cannon	69	(21)	11	(76)	18	30
Goex	Cannon	149	(45)	33	(230)	9.9	18
Elephant Brand	Fg	82	(25)	13	(90)	18	20
Temp. of Heaven	Fg	98	(30)	22	(150)	14	20
Chinese Military	Fg	179	(55)	63	(430)	7.6	13
Goex	Fg	268	(82)	142	(980)	4.9	9.7
Chinese Military	2Fg	172	(52)	31	(210)	9.7	15
Elephant Brand	2Fg (1996)	210	(64)	43	(300)	10	16
Elephant Brand	2Fg (1994)	247	(75)	79	(540)	6.2	11
Goex	2Fg	338	(103)	247	(1700)	4.2	9.0

(a) In the case of some of these powders, this is only an estimate based on its physical appearance.

- The difference in performance between the same grades of Elephant brand powder acquired two years apart suggests greater batch-to-batch variability than might have been anticipated. (It would be interesting to know what degree of variability occurs between batches of Goex powder.)
- Aerial shells fired in winter typically do not reach the same heights as in the summer. Were it desired, the temperature data in this article might be used to determine the adjustment needed to compensate for the reduction in muzzle velocity.

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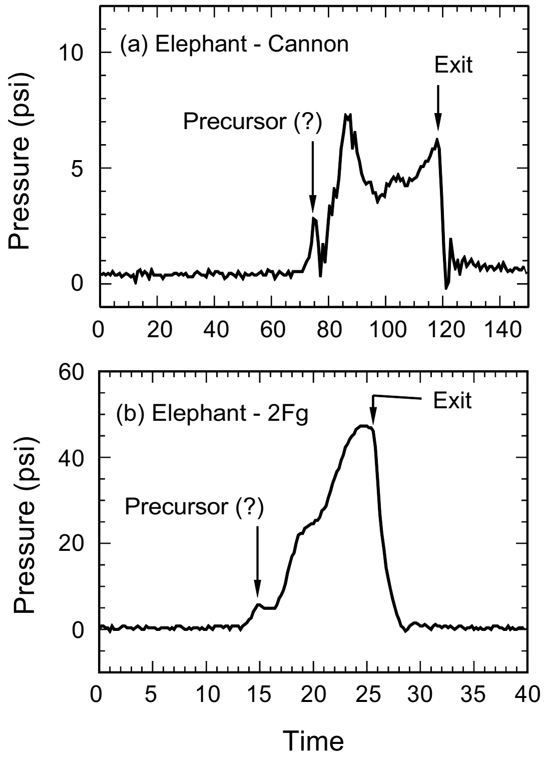

Figure 14. Examples of two unexpected pressure pulse shapes.

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Simple Measurements of Aerial Shell Performance

K. L. and B. J. Kosanke

In designing the most effective choreographed aerial fireworks displays, it is useful to know when, where, and how each shell burst will appear. To do this, in addition to aesthetic features like colors, etc., three aerial shell performance parameters are needed. These parameters are: time to shell burst after firing, burst height above the ground, and burst spread. It can be difficult and expensive to generate these. However, all three can be generated using a slightly modified video camera and videocassette recorder (VCR). Further, it will generally be possible to collect the raw information during the performance of actual displays; so there is no cost for the test fireworks. This article suggests a method to gather shell performance data.

The setup for making the video recording is illustrated in Figure 1. A video camera is mounted on a tripod, located in the general vicinity of the firing mortars[(a)] and aimed vertically to record the shell bursts. A typical camera, when set on its maximum wide-angle setting, has an approximately 40º field of view. The burst radius of hard breaking spherical shells is about 45 feet per shell inch[1,2] and burst heights are about 120 feet per shell inch.[3] This corresponds to an approximately 40º-spread angle. (See Figure 2.) Because of shell drift,[4] bursts will occur somewhat shifted from the point directly in line with the mortar. To be able to calculate a shell's performance characteristics, it is only necessary to capture the central point of the shell burst and its maximum spread in at least one direction (see Figure 3). However, to improve the chances of capturing a sufficient portion of the shell breaks in the video image, an inexpensive (≈\$20) wide-angle adapter can be added to the camera lens. This should increase the wide-angle field of view to about 50º.

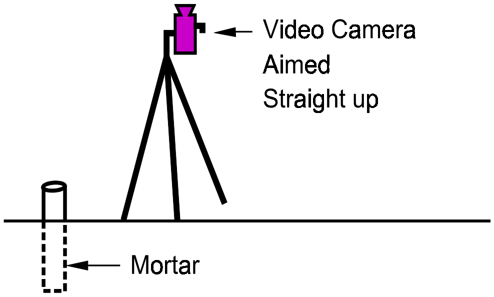

Figure 1. Illustration of basic setup for making shell performance measurements.

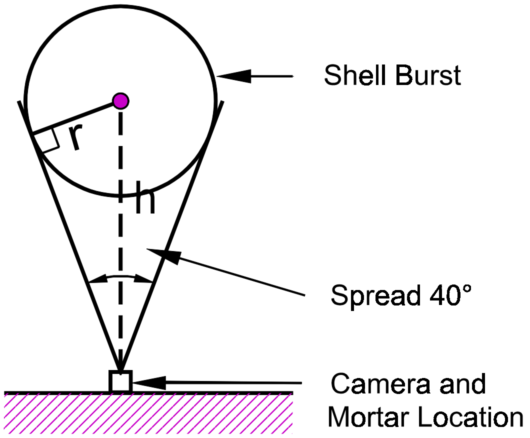

Figure 2. Geometry of a typical hard breaking spherical shell.

In the following discussion, it is assumed that the VCR has a time counter (in seconds), a counter reset button, and the ability to advance the tape by individual video fields.[(b)] It is possible to perform the operations described below without these features; however, that requires a stop watch, would be more difficult, and is less accurate.

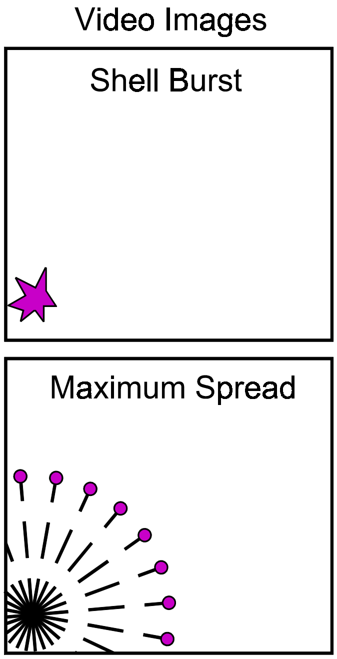

Figure 3. Illustration of the minimum video image requirement to be able to calculate shell performance characteristics.

Time to Shell Burst

Time to shell burst is the simplest performance characteristic to determine. Using the time counter on the VCR, start timing by pushing the reset button when the shell fires from the mortar. Use either the muzzle flash from the firing (if this can be seen) or the sound of the firing. (Because of the relative closeness of the camera to the mortar, the flash and sound will be essentially simultaneous.) Next, advance the videotape to the point where the shell bursts, and note the time (T_s) on the tape counter. This is the time to shell burst in seconds, rounded down to the next lowest integer. To determine the additional fraction of a second, advance the VCR field by field, counting the number of images (n) until the time counter increases to the next second. The shell burst delay time (T_b) is then

$$T_b = T_s + \left(1 - \frac{n}{60}\right) \text{seconds} \tag{1}$$

Shell Burst Height

One way to determine the height of the shell burst is to measure the time lapse between the appearance of the first light from the shell burst and the arrival of the sound of the burst. (Reference 6 presents a more complete description of the basis for this method.) To be able to make this determination using a video camera and VCR, a slight modification is necessary. Almost all VCR's block the sound when advancing the tape field by field; thus this feature needs to be defeated. (It cost the authors $60 to have a video repair shop add a switch to their VCR to accomplish this.)

To measure burst heights, the videotape is advanced to the first field with light appearing from the shell burst. At this point, the time counter reset button should be pushed. Next, listening to the sound produced with each advancing field, count the number of fields (m) until the sound of the shell burst is heard. This is not as easy as it might seem. Even when there is essentially no background sound, with each advance of the tape, a sound (something like "chuff") will be heard. The time of arrival of the shell burst sound will be when the chuff sound is suddenly noticeably louder. Identification of when this occurs is made easier if the listener knows about when to expect it. (For 3 or 4-inch shells the time of arrival will be after approximately 25 fields; for 5 or 6-inch shells it will be after approximately 35 fields; and for 8 to 12-inch shells, it will be after approximately 50 fields.) Shell burst height (H_b) is then

$$H_b = m \cdot D_s \tag{2}$$

where D_s is approximately 19 feet, the distance sound travels in 1/60 second.(c) Because these times are only determined to the nearest 1/60 second, there will be an uncertainly in burst height averaging about 20 feet.

Shell Burst Spread

To determine a shell's spread, it is necessary first to calibrate the video camera's field of view as presented on the TV monitor to be used. To do this, a video recording must be made of (at least) two objects approximately perpendicular to the view of the camera, at a known distance from the camera (D_c) and a known width (W_c) between the two objects. Preferably, the two objects will appear somewhere near the center of the TV monitor screen.(d) The use of two burning highway flares is often convenient for this. The camera must be set for the maximum wide-angle setting (just as when recording the shell bursts). When the calibration scene is played back, the distance between the two markers as seen on the TV screen—the screen calibration distance (S_c)—is measured. A thin transparent ruler may be convenient for this. The needed calibration constant (K) is

$$K = \frac{W_c}{S_c \cdot D_c} \qquad (3)$$

When the playback of a shell burst is observed, and the burst-spread distance on the screen is measured (S_b), the width of the burst spread in the air (W_b) is

$$W_b = S_b \cdot H_b \cdot K \qquad (4)$$

Recall that H_b is the previously determined shell burst height. Note that the measured, calibrated distances W_c and D_c must be in the same units (e.g., feet), as are the measurements from

Table 1. Five-Inch Aerial Shell Performance Values.

Shell Name	Brand	Burst Time(a) (s)	Time to Sound(b) (fields)	Burst Height(c) (feet)	Radial Spread(d) (inches)	Burst Radius(e) (feet)
Red Silk	Horse	4.4	36	680	n/a(f)	n/a(f)
White Rose	Horse	4.0	38	720	3.5	140
Green Peony	Horse	4.5	39	740	3.9	160
Red Peony	Horse	3.7	26	490	6.2	170
Red Peony	Horse	3.8	36	680	3.3	130
Average		4.1		660		150
Std. Dev.(g)		0.4		100		20
Double Ring	Sunny	3.8	34	650	3.5	130
Double Ring	Sunny	3.7	36	680	2.7	100
Double Ring	Sunny	3.9	39	740	2.8	120
Double Ring	Sunny	3.9	39	740	2.8	120
Average		3.8		700		120
Std. Dev.(g)		0.1		40		10

(a) This is the time in seconds between the shell firing from the mortar and its bursting, and was calculated using equation 1. Burst times are reported to the nearest 0.1 second.

(b) This is the time in video fields (in this case 1 field = 1/60 s) between the first light from the shell break and the arrival of the sound.

(c) This is the height of the shell burst, calculated using equation 2 using a speed of sound of 19 feet per 1/60 second. Burst heights are reported to the nearest 10 feet.

(d) This is the maximum radial spread of the stars, as measured in inches on the screen of the TV monitor.

(e) This is the maximum radial spread of the stars, calculated using equation 4. The calibration constant K was equal to 0.0056/inch, and was calculated using equation 3. Burst radii are reported to the nearest 10 feet.

(f) This was a very weak breaking (poka) shell dispersing sizzling red stars. The burst spread was too small to be included appropriately with the other hard breaking (warimono) shells.

(g) Because of the limited amount of data, the standard deviations were determined using the so-called *n*–1 method.

the TV monitor S_c and S_b (e.g., inches or centimeters), and that burst width W_b will have the same units as W_c and D_c.

The shell burst dimension determined using equation 4 is the "apparent" dimension as seen at the location of the camera. Because of a geometrical effect, which is described in reference 2, this over estimates the true burst dimension by approximately 6%. If desired, the true shell burst dimension (W_t) can be calculated using equation 5.

$$W_t = W_b \sin\left[\tan^{-1}\left(\frac{H_b}{W_b}\right)\right] \tag{5}$$

Performance Measurements

A collection of 5-inch aerial shells was fired for the purpose of measuring the performance parameters discussed above. The results are presented in Table 1. This testing was performed in western Colorado, at an elevation of approximately 4600 feet. (Note that because of the relatively high elevation, there is a little less aerodynamic drag acting on the shells after they leave the mortar. This allows the shells and stars to travel a little further than would be the case nearer sea level.) For each shell performance parameter, the Sunny brand shells behaved more consistently than the Horse brand shells. While this is not unexpected, given the reputation of the two shell brands, because of the limited number of test shells fired, it cannot be assumed that this will always be the case.

Conclusion

One could spend a considerable sum of money on the equipment and test shells to make the above measurements. However, using the method suggested, the cost for equipment is minimal (if you already have access to a camcorder and VCR), and there need be no cost for test shells (if data is collected during displays). Further, any hobbyist collecting and publishing such shell performance data would be doing a service to the industry.

Notes

a) It is not absolutely necessary that the video camera be relatively close to the mortar. However, some calculations will be easier to perform and some results will be more accurate if it is close.

b) The difference between a field by field VCR (sometimes called an AB VCR), which displays 60 video images per second, and a frame by frame VCR (sometimes called an AA VCR), which displays only 30 video images per second, is explained more fully in reference 5.

c) The speed of sound (i.e., D_s) depends on temperature. At 50 °F, D_s is 18.4 feet; at 68 °F, D_s is 18.8 feet; and at 86 °F, D_s is 19.1 feet. These values are derived from reference 7.

d) Color TV monitors can generally be relied upon to be approximately linear with respect to the horizontal and vertical scale of images. However, black and white monitors may not be sufficiently linear for reasonably accurate results. If desired, a simple test can be performed by video taping a piece of graph paper and measuring the linearity when viewed on the TV monitor.

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Flash Powder Output Testing: Weak Confinement

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ABSTRACT

A variety of flash powders were tested under weak confinement to determine the sound pressure levels and tonal characteristics produced. In these tests it was found that: the sound output from mixtures prepared with potassium perchlorate from four manufacturers are essentially equivalent; there are significant differences in the level of sound output as a result of using six different common aluminum powders; the addition of either of two common flow or bulking agents have essentially no effect on the sound produced; the substitution of potassium chlorate for potassium perchlorate in a common flash powder has essentially no effect on the sound produced; and the addition of antimony sulfide or sulfur reduces the duration of positive phase without increasing the level of the sound produced. In short, it was found that nothing surpassed the level of sound produced by a 70:30 mixture of reasonably high-quality potassium perchlorate and a high quality flake aluminum powder. This is significant because the use of potassium chlorate, antimony sulfide, and sulfur, can seriously increase the sensitiveness of flash powders to accidental ignition.

Keywords: flash powder, sound pressure level, blast pressure, weak confinement, positive phase

Introduction

The science of pyrotechnics as applied to fireworks frequently suffers from a lack of basic scientific data. Too often, conjecture serves as the basis for what eventually becomes “common knowledge”. The sound output from flash salutes is one area in which there is much common knowledge but little quantitative data reported in the literature. This study of the sound output from a collection of flash powders under weak confinement is an attempt to provide some of the needed measurements.

For most of this study, only flash powders using 70% potassium perchlorate and 30% aluminum were examined. With these flash powders, the relative effectiveness of four types of potassium perchlorate, six types of aluminum, and two bulking agents were examined. Following this, a series of seven flash powders using one or a combination of potassium chlorate, barium nitrate, antimony trisulfide and sulfur were tested for sound output under the same conditions.

Background

All blast waves, even those produced by radically different explosives have much the same basic shape,[1a] illustrated in Figure 1. The blast wave is a shock wave, traveling greater than the speed of sound in air. Prior to the arrival of the shock front, ambient (atmospheric) pressure is unaffected. With the arrival of the shock front, there is a near instantaneous rise in pressure (overpressure) to some peak value. Thereafter, overpressure falls, returning to ambient level. This excursion is termed the “positive phase” of the blast wave. The peak overpressure attained is a function of the magnitude of the explosion and, to a lesser extent, on ambient pressure. Except for distances very close to the explosive, there is a “negative phase” of the blast wave.[1b] This negative phase is much less extreme than the positive phase, although it lasts somewhat longer. Figure 2 is the blast wave recorded for one test salute used in this

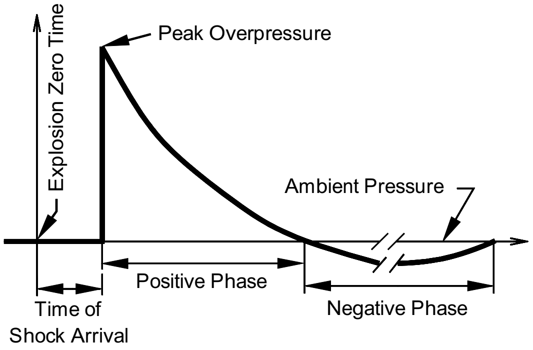

Figure 1. Sketch of a typical blast overpressure wave showing pressure as a function of time.

study. At increasing distances from the explosion, the peak overpressure becomes less, and the duration of the positive phase becomes longer; this effect is illustrated in Figure 3.

For the most part, it is only peak overpressure and the duration of the positive phase that are needed to characterize a blast wave. In terms of the sound produced, peak overpressure determines the loudness of an explosion, and the duration of positive phase presumably determines its tonal quality. That is to say the higher the overpressure, the louder the sound of the explosion. Also a short positive phase is expected to correspond to an explosion with a sharp crack sound, and a long positive phase, to a more mellow boom. Thus, from what is seen in Figure 3, all explosions sound louder and sharper at close range, and become softer and more mellow at greater distances. (For a more complete discussion of the sound levels and their measurement, see reference 2.)

Experimental Method[a]

The flash powders for these tests were each prepared by pre-screening the ingredients, rough mixing until there was uniformity in color, then tumbling at a rate of approximately 60 revolutions per minute in closed containers for one hour. This degree of mixing far exceeds that generally employed by the fireworks industry, but was chosen to eliminate any inconsistencies in test results that are caused by incomplete mixing.

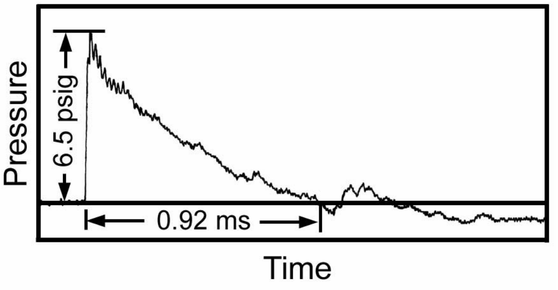

Figure 2. Blast wave from a test salute using 70:30 potassium perchlorate and German dark aluminum.

For each flash powder type, three test salutes were prepared and fired. The test salutes were made using 3 ounce (90 mL) polyethylene bottles with metal screw caps. The containers were chosen to provide an easily reproducible configuration with fairly consistent confinement. Each container was loaded with 50 g (1.8 ounce) of flash powder. A Daveyfire[3] hooded electric match (SA–2001) was used for ignition. The match was installed in the cap of each container using a thermal setting adhesive, see Figure 4. Each test salute container was mounted cap-side down, such that flash powder filled the space between the electric match and its hood. This was done to provide a minor degree of con-

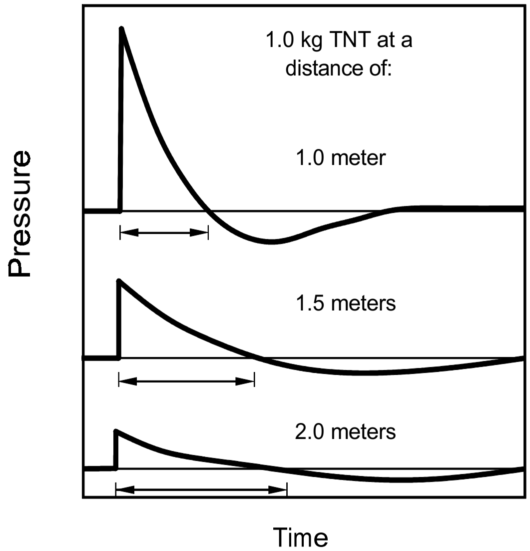

Figure 3. Sketch of the decay of a typical blast wave with distance from the explosion; based on data from Kinney & Graham.[1c]

Figure 4. An electric match installed in the cap of a test salute casing (polyethylene bottle).

finement for that small amount of flash powder, thus perhaps providing a more powerful ignition stimulus. It was anticipated that this would tend to compensate for the relatively weak confinement provided by the polyethylene bottle.

For test firing, the salutes were suspended 3.5 feet (1.2 m) above the ground. A pair of free-field blast gauges (PCB Piezotronics[4] 137A11) were positioned in line at the same height and at a distance of 4.0 feet (1.9 m) from the center of the test salute, see Figure 5. Upon firing the salute, blast overpressure data was collected using amplifying power supplies and a digital oscilloscope (50 MHz), for subsequent plotting, see Figure 6.

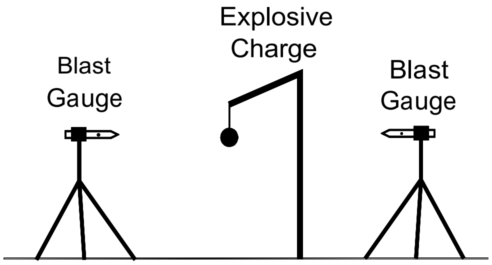

Figure 5. Sketch of the physical arrangement of test salute and blast gauges.

Test Results

In this section, the characteristics of the flash powders and the raw output data are presented. Discussion of the results is deferred to a later section.

Potassium Perchlorate Types

The four types of potassium perchlorate used in this study are described in Table 1.

As determined by microscopic analysis, only the Swedish material has fairly sharp angular particles, such as might be expected from grinding. The other three materials have particles with a more generally rounded appearance, such as might be expected from milling. The screen analysis for these materials is presented in Table 2. Small samples of potassium perchlorate, as received from the supplier, were sieved for three minutes using a vibrating sieve shaker. It is likely that the material contained some moisture and that drying may have produced slightly different sieve analyses. This not with-

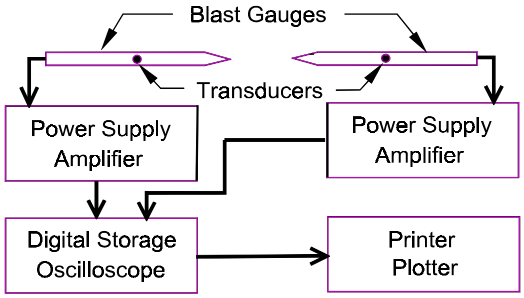

Figure 6. Block drawing for the data collection of blast overpressure data.

Table 1. Types of Potassium Perchlorate Investigated.

Source	Manufacturer	Product Information
Swedish	EKA Nobel(a)	S140, –140 mesh
US	Western Electro Chemical[5]	60 micron
Chinese	Senochem(a)	Hunan China(b)
Italian	Societa Electro-chimico(a)	Borgo Franco(b)

(a) Supplied by Service Chemical, USA.[6]

(b) No other product information available.

standing, the samples were not dried for use in the flash powders because it was believed that their condition, as received, is more typical of how they are used in manufacturing fireworks.

The flash powders used for comparison of the potassium perchlorate types were all 70:30 ratios with Obron[7] 5413 (commonly called German dark aluminum). The results from the four sets of sound pressure output tests are presented in Table 3. The data from the two blast gauges were always very nearly the same, and have been averaged for presentation in the Table.

Aluminum Types

The six types of aluminum used in this study are described in Table 4. In addition to these six aluminum powder types, a mixture of 67% (by weight) Reynolds 400 and 33% Alcan 2000 was also investigated. This was done because it had previously been suggested that a mixture of atomized and flake aluminum provided additional reactivity over either type aluminum alone.[12]

Table 2. Sieve Analysis of the Types of Potassium Perchlorate.

Source	Mesh Fraction (%)			
	+100	100–200	200–400	–400
Swedish	0.0	51.1	39.5	9.4
US	0.3	47.2	44.2	8.3
Chinese	0.1	32.3	50.7	16.9
Italian	0.0	3.0	73.0	23.9

Table 3. Sound Pressure Output for Potassium Perchlorate Types.

Potassium Perchlorate	Peak Over-Pressure (psi)	Positive Phase (ms)
Swedish	6.08	0.82
	6.16	1.00
	6.30	1.10
US	5.90	0.90
	6.20	0.95
	6.44	1.01
Chinese	5.69	0.90
	5.98	1.08
	6.02	1.15
Italian	6.21	0.90
	6.32	0.88
	6.24	0.88

For conversion to SI units, 1 psi = 6.89 kPa.

Table 4. Aluminum Powder Types.

Manufacturer	Product No.	Description(a) *[Morphology]*(b)
Obron	5413	German Dark *[Flake 8μ(c)]*
Obron	10890	American Dark *[Flake 15μ(c)]*
Alcan[9]	7100	American Dark *[Flake 13μ]*
Reynolds[10]	400	Atomized *[Spheroidal 6μ]*
US Aluminum[11]	809	American Dark *[Flake 30μ(c)]*
Alcan	2000	Bright *[Flake 36μ]*

(a) The descriptions German Dark, American Dark and Bright are used in the context generally adopted and understood by the American pyrotechnics industry. For more information on aluminum metal powder types, see reference 8.

(b) Basic particle shape and average particle size in microns. Note that 1 micron (μ) = 10^{-6} meter = 3.9×10^{-5} inch.

(c) Average particle size was estimated by the authors using microscopy.

The flash powders were all made with 70:30 ratios using Swedish potassium perchlorate and the various aluminums. The sound output data from the seven sets of tests are presented in Table 5. The data from each of the two blast gauges were always very nearly the same and have been averaged for presentation in the Table.

Flow and Bulking Agents

The two flow and bulking agents used in this study were Cab-O-Sil[13] (M-5, colloidal silica) and red wheat bran. In the first tests, flash powders were based on 70:30 mixtures of Swedish potassium perchlorate and Obron 5413 aluminum. In one test, three percent Cab-O-Sil was added to the base flash powder. In a second test, ten-percent red wheat bran was added. Another 70:30 flash powder was made using US Aluminum 809; to this base, ten-percent red wheat bran was added. In all tests, the net amount of flash powder, not including the flow or bulking agent, was 50 grams. These results are presented in Table 6.

Table 5. Sound Output Results for Aluminum Types.

Type of Aluminum	Peak Over-Pressure (psi)	Positive Phase(ms)
Obron 5413	6.08	0.82
	6.16	1.00
	6.30	1.10
Obron 10890	5.76	1.00
	6.11	0.96
	5.47	1.03
Alcan 7100	5.61	1.02
	5.61	1.08
	5.12	0.86
Reynolds 400	2.58	1.25(a)
	2.58	1.62(a)
	3.22	1.19(a)
US Aluminum 809	2.30	0.98
	2.54	1.15
	2.72	0.88
Alcan 2000	1.28	1.00
	1.52	1.12
	1.58	0.90
Reynolds 400 + Alcan 2000	2.28	1.15(b)
	2.80	1.18(b)
	1.83	1.07(b)

For conversion to SI units, 1 psi = 6.89 kPa.

(a) In each case, the Reynolds 400 flash powder produced a double blast wave, as shown in Figure 7, resulting in a longer positive phase.

(b) In each case, the use of the Reynolds 400 and Alcan 2000 mixture produced flash powder that also exhibited a weak double blast wave structure.

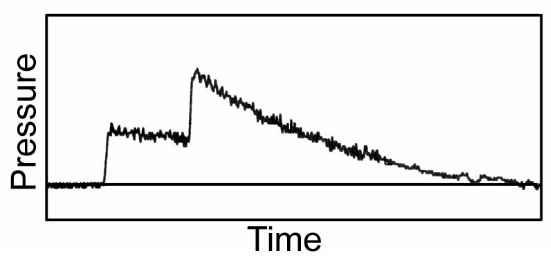

Figure 7. Typical double peaking blast wave recorded for flash powders made using Reynolds 400 aluminum.

Table 6. Sound Output Results Using Flow or Bulking Agents.

Aluminum Type *[Additive]*	Peak Over-Pressure (psi)	Positive Phase (ms)
Obron 5413 *[None]*	6.08	0.82
	6.16	1.00
	6.30	1.10
Obron 5413 *[3% Cab-O-Sil]*	6.32	0.98
	6.18	0.85
	6.12	0.93
Obron 5413 *[10% Red Bran]*	5.61	0.93
	6.36	1.05
	6.02	0.90
US Alum. 809 *[None]*	2.30	0.98
	2.54	1.15
	2.72	0.88
US Alum. 809 *[10% Red Bran]*	1.73	1.00
	1.92	0.95
	2.12	1.05

For conversion to SI units, 1 psi = 6.89 kPa.

Formulations

Many different flash powders are used in fireworks. However, only seven flash powder formulations were used in this study. They are listed in Table 7, along with literature references. These formulations were chosen to provide information on the effect of the choice of oxidizer and the use of sulfur and antimony sulfide. However, beyond that criterion, the choice was somewhat arbitrary. Table 8 lists the sound output results from the test salutes using these formulations.

Discussion of Results

It is important to note that the results and conclusions reported in this article are only valid within the context of this study. For example, only three tests were conducted for each flash powder; the average variation about the mean peak overpressures was about 4% and the average deviation in the duration of positive phase was about 6%. Accordingly, any small differences reported for these parameters may be merely statistical in origin. Further, these results are only valid for the conditions examined, specifically, weak confinement with a moderately powerful ignition stimulus.

Table 7. Flash Powder Formulations Used in Test Salutes.

Ingredient	Flash Formulations (weight percent)						
	1	2	3	4	5	6	7
Potassium perchlorate ($KClO_4$)	70	64	62	70	—	—	—
Potassium chlorate ($KClO_3$)	—	—	—	—	70	64	—
Barium nitrate ($BaNO_3$)	—	—	—	—	—	—	68
Aluminum, Obron 5413 (G.D.)	30	—	—	—	—	—	—
Aluminum, Obron 10890 (A.D.)	—	27	23	30	30	9	—
Aluminum, Alcan 2000 (Bright)	—	—	—	—	—	—	23
Antimony trisulfide (Sb_2S_3)	—	—	15	—	—	9	—
Sulfur (S)	—	9	—	—	—	18	9
Reference	(a)	14	14	(a)	(a)	15	16

(a) This is a common formulation with no specific reference.

Table 8. Sound Output Results for Test Formulations. (Also, see Table 7.)

Formulation No. and Description	Peak Over-Pressure (psi)	Positive Phase (ms)
1) $KClO_4$ + G.D.	6.08	0.82
	6.16	1.00
	6.30	1.10
2) $KClO_4$ + A.D. + S	5.90	0.82
	5.88	0.92
	5.76	0.88
3) $KClO_4$ + A.D. + Sb_2S_3	5.85	0.78
	5.90	0.92
	5.75	0.84
4) $KClO_4$ + A.D.	5.76	1.00
	6.11	0.98
	5.47	1.03
5) $KClO_3$ + A.D.	6.31	0.88
	5.94	1.15
	5.10	0.78
6) $KClO_3$ + A.D. + S + Sb_2S_3	3.50	0.72
	3.77	0.78
	3.64	0.63
7) $BaNO_3$ + Bright + S	0.22	1.00
	0.17	1.20
	0.11	1.00

For conversion to SI units, 1 psi = 6.89 kPa.

Table 9 presents the averages of the sound output data from the tests using potassium perchlorate from different sources. Also in the table are sound pressure levels in dB and relative loudness (*N*). Decibel and loudness values were calculated using the following equations:[17]

$$\text{dB} = 170.8 + 20 \log P \qquad (1)$$

$$\log N = 0.03 \text{ dB} - 1.2 \qquad (2)$$

where P is peak overpressure in psi.

It must be noted that the reported dB levels were calculated using peak overpressures measured with an instrument with an extremely fast rise time. Thus, these values will be somewhat greater than would have been found using conventional sound measuring equipment, even when using their peak-linear mode setting. (For a more complete discussion of sound pressure levels, loudness, and the effect of instrument parameters, see reference 18.) While it is possible that the peak overpressures observed for the Chinese potassium perchlorate are slightly less than for the other materials, it is within the limits of statistical precision of these measurements. Furthermore, it is doubtful that a typical observer would be able to detect such a small loudness difference, even if it were real. Similar comments are appropriate for the slightly larger value for the Italian potassium perchlorate.

Those materials with roundish particle shape (US, Chinese and Italian), rather than sharp angular particles (Swedish), are likely to mix more thoroughly when using procedures typical of fireworks manufacturing. Accordingly, under more typical mixing conditions than used in this study, it is possible these materials would produce slightly louder flash powder salutes.

Table 9. Average Results from Different Potassium Perchlorates.

Potassium Perchlorate Type	Positive Phase (ms)	Peak Overpressure (psi)	Sound Pressure Level (dB)	Relative Loudness
Swedish	1.01	6.18	186.5	≡1.00
US	0.95	6.18	186.6	1.00
Chinese	1.04	5.90	186.2	0.97
Italian	0.89	6.26	186.7	1.01

For conversion to SI units, 1 psi = 6.89 kPa.

Table 10. Average Results from Different Aluminums.

Aluminum Types	Positive Phase (ms)	Peak Overpressure (psi)	Sound Pressure Level (dB)	Relative Loudness
Obron 5413	1.01	6.18	186.6	≡1.00
Obron 10890	1.00	5.78	186.0	0.96
Alcan 7100	0.99	5.45	185.5	0.93
Reynolds 400	1.35[(a)]	2.79	179.7	0.62
US Aluminum 809	1.00	2.52	178.9	0.59
R. 400 + A. 2000	1.13[(a)]	2.30	178.0	0.54
Alcan 2000	1.01	1.46	174.1	0.42

For conversion to SI Units, 1 psi = 6.89 kPa.

(a) The Reynolds 400 aluminum produced double explosions, see Figure 7.

Differences in particle size and shape can play a role in determining burn rate, which in turn would influence the sound levels produced by salutes. However, generally it is the size and shape of the fuel that is of primary importance. Typically, this is because the melting point of the oxidizer is lower than the ignition temperature of the mixture. (See reference 19 for a more complete discussion of the factors affecting burn rate.) Based on the above results, for those potassium perchlorate samples examined, it seems that oxidizer particle size and shape only play a minor role in the sound levels produced.

The average durations of positive phase are also essentially within the limits of statistical precision of the measurements. Accordingly, a significant difference in the tonal quality of the sounds produced by the test salutes would not be expected, except possibly for the Italian material that may produce a slightly sharper sound.

Table 10 presents the average sound output data from the tests using different aluminum powders. For the test salutes used in this study, the sound outputs fall roughly into three groups. The first group consists of the two Obron products and Alcan 7100; these produced the greatest output, with the Alcan material possibly producing slightly lower sound levels. The Reynolds, US Aluminum, and mixture of flake and atomized aluminums produced significantly lower sound levels. The Alcan 2000 produced the least sound output.

In all cases, except when Reynolds 400 was used, the durations of positive phase were equivalent. Accordingly, it would be expected that the tonal quality of all the test salutes would be the same. With the Reynolds 400, there was some degree of double peaking of the blast wave (see Figure 7). The authors do not have a satisfactory explanation for this; however, it has never been observed in any other tests and is always observed for Reynolds 400. Thus, it seems that it must be a manifestation of the aluminum powder and not an artifact of the measurement. (It has been suggested that the second peak may be a result of a secondary aluminum dust explosion following the rupture of the test salute casing.) For whatever reason the double peak is produced, it would seem that this aluminum would produce a more mellow sound than the others.

Table 11 presents the average sound output data from the tests of flash powders with a flow or bulking agent. Recall that in all cases, the net amount of flash powder was 50 g (1.8 ounce), exclusive of the added flow or bulking agent. With the 70:30 Swedish potassium perchlorate and Obron 5413 aluminum flash powder, the agents had essentially no effect on relative loudness. However, for the flash powder using US Aluminum 809, there was a minor, but noticeable, reduction in relative loudness. It is unlikely there was a significant affect on the duration of positive phase (tonal quality). The addition of flow and bulking agents is expected to facilitate mixing and help keep flash powders from compacting over time. Thus, it is possible

Table 11. Average Results from Flow or Bulking Agent.

Aluminum Type	Flow / Bulking Agent Type	Positive Phase (ms)	Peak Over-Pressure (psi)	Sound Pressure Level (dB)	Relative Loudness
Obron 5413	None	1.01	6.18	186.6	≡1.00
	Cab-O-Sil (3%)	0.92	6.21	186.6	1.00
	Red Bran (10%)	0.96	6.00	186.4	0.98
US Aluminum 809	None	1.00	2.52	179.1	≡1.00
	Red Bran (10%)	1.00	1.92	176.5	0.85

For conversion to SI units, 1 psi = 6.89 kPa.

that their addition would produce greater relative sound output under other conditions than in this study

Table 12 presents the average sound output from the seven flash powder formulations listed in Table 7. In terms of loudness, no formulation out performed the Obron 5413 (German dark aluminum) and potassium perchlorate.

Of the formulations using Obron 10890 (sometimes referred to as American dark aluminum), the addition of sulfur or antimony sulfide, or the substitution of potassium chlorate for potassium perchlorate (formulations 2, 3 and 5) made no difference in loudness. However, there was a shortening of the positive phase duration with the addition of either sulfur or antimony sulfide, which should produce a sound perceived as being less mellow. That the addition of antimony sulfide produced a more brisant explosion was expected, based on common knowledge in the fireworks trade. However, it was not expected that the addition of sulfur would have the same effect. Common experience is that sulfur produces a more mellow sound. At the present, the authors have no satisfactory explanation for this. However, work is continuing to study this. Use of antimony sulfide or sulfur decreased the duration of the positive phase without increasing peak overpressure. This combination of effects means that the pressure impulse produced is less for these flash powders. In turn, that may mean that the blast effect perceived by the audience, the so-called “chest thump”, will be less for salutes using these flash powders.

When both sulfur and antimony sulfide were added and potassium chlorate was used as the oxidizer (formulation 6), the duration of positive phase was reduced further. However, there

Table 12. Average Results from Various Formulations.

Formulation Number and Description	Positive Phase (ms)	Peak Over-Pressure (psi)	Sound Pressure Level (dB)	Relative Loudness
1) $KClO_4$ + Obron 5413	1.01	6.18	187.6	≡1.00
2) $KClO_4$ + Obron 10890 + S	0.87	5.85	186.1	0.97
3) $KClO_4$ + Obron 10890 + Sb_2S_3	0.85	5.83	186.0	0.96
4) $KClO_4$ + Obron 10890	1.00	5.78	186.0	0.96
5) $KClO_3$ + Obron 10890	0.94	5.78	186.0	0.96
6) $KClO_3$ + Obron 10890 + S + Sb_2S_3	0.71	3.64	182.0	0.73
7) $BaNO_3$ + Alcan 2000 + S	1.07	0.17	155.4	0.11

For conversion to SI units, 1 psi = 6.89 kPa.

was also a significant reduction in loudness of the test salutes (presumably a result of its rather low percentage of aluminum). The use of potassium chlorate, sulfur or antimony sulfide in flash powders can increase the sensitiveness to accidental ignition from one or more factors: impact, friction, electrostatic discharge or temperature.[20] The use of a combination of potassium chlorate and sulfur or antimony sulfide is expected to result in a substantial increase in sensitiveness. While a discussion of these effects would be interesting and important, they are beyond the scope of this article.

Under these test conditions, the test salutes made using formulation 7, with barium nitrate and Alcan 2000 (bright) aluminum, resulted in reports of considerably reduced loudness, but with a positive phase duration perhaps a little longer than typical of the other flash powders.

Conclusion

There are a number of inferences that can be drawn from the above data sets; however, these must only be made within the context of these measurements. It is possible that other conclusions would be reached for other experimental conditions. Nonetheless, these data imply:

- The sound output from mixtures prepared with common sources of potassium perchlorate from four manufacturers is essentially equivalent.
- There are significant differences in the level of sound output as a result of using six different common aluminum powders.
- The addition of either of two common flow or bulking agents have essentially no effect on the sound produced (for freshly prepared items).
- The substitution of potassium chlorate for potassium perchlorate in a common flash powder has essentially no effect on the sound produced.
- The addition of antimony sulfide or sulfur reduces the duration of positive phase without increasing the level of the sound produced.

In short, nothing surpassed the level of sound produced by a 70:30 mixture of reasonably high-quality potassium perchlorate and a high quality flake aluminum powder. This is significant because the use of potassium chlorate, antimony sulfide, and sulfur can seriously increase the sensitiveness of flash powders to accidental ignition.

It had been anticipated that, as a follow-on to this study, there would be a study of the sensitiveness of these flash powders. This was posed on the assumption that there was a performance benefit to the use of potassium chlorate and antimony sulfide or sulfur. It was thought that information would allow manufacturers to decide whether the performance gain was worth the added risk of using such formulations. However, since there is no performance advantage, there is no potential benefit and no reason to use formulations that are more hazardous. Accordingly, there is little point in measuring the sensitiveness of those formulations, and plans for that study have been abandoned.

Acknowledgments

The authors are grateful for the technical and editorial input of Bill Ofca and John Bergman in the preparation of this article. Also the contribution of Service Chemical, Western Electro Chemical, and US Aluminum, who provided some of the materials used in this study, are gratefully acknowledged.

Note

[a] In this article, for accuracy of reporting, the actual units of measurement are given first, followed by either their SI or English equivalent.

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An earlier draft appeared in *American Fireworks News*, No. 184, 1997.

New Fast Fuse

K. L. and B. J. Kosanke and R. Webb

An interesting new fuse is being used on consumer fireworks, reloadable aerial shells. Some of this fuse appears quite similar to normal green Visco (hobby or cannon) fuse but with substantially different burn characteristics. Typical Visco fuse burns at a rate of approximately 0.4 inch per second;[1a] the new fuse product burns at a rate of approximately 3 inches per second. Further, under some circumstances, the fuse can burn at a rate of at least 9 inches per second. While there may be some interesting and useful applications for this fuse, its fast burn rate may also pose some considerable danger for an unsuspecting user.

The official name for this new type fuse could not be ascertained, even after checking with several knowledgeable persons in the consumer fireworks trade. The new fuse is made in several varieties. All are approximately 3/32 inch in diameter. Some varieties look quite similar to green Visco fuse. Like normal Visco fuse, one type is made with crossing wraps of thread around a powder core and is coated with what appears to be green lacquer. Except for the fact that it is more flexible than Visco fuse and the inner wrap of threads have some space between them, it appears nearly identical to common Visco fuse (see Figure 1). Another variety of the fuse has a somewhat loose wrap of thin paper around its powder core with a sparse wrap of threads holding the fuse together. In one case, this fuse is coated in what appears to be green lacquer, again giving it an appearance very much like green Visco fuse. In another case, there is no lacquer coating, and the threads are red and green, giving it a noticeably different appearance. This appears to be much the same fuse that was described in an earlier article.[2a] For the present article, it is important to note that only the first type of fuse described (with crossing thread wraps) was available in sufficient quantity to be studied. This is important because the added confinement of the paper-wrapped fuses possibly (probably) causes them to have a burn rate even greater than the 3 inches per second reported above.

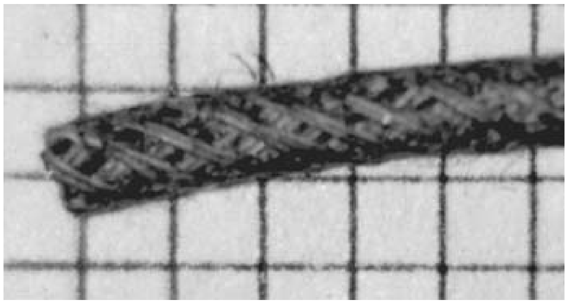

Figure 1. "New Fast Fuse", each square is 0.10 inch.

Upon visual observation, the fuse powder was noticeably coarser than that normally used in Visco fuse. Under a microscope the powder had the appearance of 100% commercial Black Powder, without the presence of any raw Black Powder components, which are often present in Visco fuse powders. A test with concentrated hydrochloric acid suggested that the powder did not contain a chlorate. A sieve analysis was performed on a small sample of the fuse powder. Those results, compared with that typically found in US production Visco fuse,[2b] are reported in Table 1. Note that for normal Visco fuse, approximately 25% of the powder mass is in grains larger than 40 mesh, and none is larger than 30 mesh. Contrast this with the new fuse powder that has approximately 90% of its grains larger than 40 mesh and 50% larger than 30 mesh. Note further that the fuse powder grain size for normal Visco is widely distributed, –100 to 40 mesh; whereas that of the new fuse is quite narrow, mostly 20 to 40 mesh. (The process of slicing the new fuse axially with a knife, to extract its fuse powder, is expected to have broken some of the coarser grains, producing some additional fine grain powder. This may be the source of some or all of the powder finer than 40 mesh.)

Table of Weight Fractions as a Function of Sieve Mesh Size.

Mesh Range	Normal Visco[2b] (Wt. %)	New Fuse (Wt. %)
+20	0	0
20 to 30	0	47
30 to 40	24	41
40 to 60	35	7
60 to 80	15	2
80 to 100	11	1
–100	15	2

The fast burn rate of the new fuse would seem to be a result of the large and fairly uniform particle size of the fuse powder. Without the presence of finer particles, the fire paths between and around the larger particles are poorly blocked. This allows partially propagative (fast) burning of the fuse, rather than the burning being essentially parallel (slow) as it is for normal Visco fuse. (For a review of parallel and propagative burning, see reference 3.)

When this new fuse burns, it seems to produce more flame than common Visco fuse. The reason for this has not been determined. One possibility is the looseness of the thread wrap. Another possibility is that it contains more Black Powder. (Unfortunately, no attempt was made to determine the amount of fuse powder per length of the new fuse.)

With the belief that the fast burning nature of the new fuse was a result of its partially propagative burning, it was thought that the burn rate would be somewhat sensitive to external factors. For example, if the fuse were encased in some manner such that it was more difficult for the burning gases to escape, the burning would be taking place in a higher-pressure environment. This in turn should increase the tendency for the flame front to advance propagatively, causing an increase in burn rate beyond that predicted by the burn rate equation.[1b]

$$R = A \cdot P^B$$

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

It had been determined previously that applying a layer of heat shrink tubing (such as commonly used in electronics) over normal Visco fuse produced an increase in its burn rate of approximately 40%.[1c] This increase is small enough to be primarily the result of the increase in parallel burn rate expected from the increased pressure. However, with a layer of heat shrink tubing applied to the new fuse, its burn rate increased approximately 300%, to about 9 inches per second. This magnitude of increase must be attributed to an increase in the extent to which propagative burning is occurring.

If the new fuse burns fast because its burning is partially propagative, it is useful to note that there are other factors that may affect its burn rate. Two examples of these factors are the degree of openness of the wraps of thread and the thickness of the lacquer coating. These affect the degree of confinement of the burning fuse, somewhat like the heat shrink tubing. Unless factors such as these are sufficiently controlled during manufacture, it is possible the fuse burn rate will vary significantly along a roll of fuse or from roll to roll.

This new fuse has some useful new applications, such as in the more rapid firing of small board mounted finales. However, because some individuals are unaware of its existence and because of its similarity in appearance to normal Visco fuse, it is possible that some accidents could result. For example, some of this fuse might be harvested from a reloadable shell, or it may come to be sold in bulk at fireworks gatherings. (It is presently being sold separately in a fireworks shop in Belgium.[4]) If this new faster burning fuse is used in applications where it is anticipated that it will burn at the normal low rate of Visco fuse; however, instead it burns at a rate 8 to 25 times faster, an accident could result. In such an event, an unsuspecting user might not have sufficient time to safely retreat, especially if they were not following the advice of not holding the item when lighting it. Even at a fireworks manufacturing operation, if both types of fuse are being used (on different items), because of their similar appearance, it is possible that a rushed or inexperienced worker might use the wrong type fuse on an item. If this were not detected before the sale of the item, again an accident could result.

In the photo, one can see several dark spots between the two wraps of threads. These dark spots are the result of seeing completely through to the Black Powder in the core of the fuse. Accordingly, this new fast fuse is probably less resistant to side ignition than common Visco fuse, especially from sparks. If this is true, that is another mechanism through which an accident might occur for an unsuspecting user.

For these reasons, safety might be improved if the new type fuses were manufactured with a distinctively different appearance from common Visco fuse (e.g., using a lacquer color other than green or red).

The authors are grateful to Bob Weaver for his assistance with the preparation of this article, and to Quentin Robinson, who had previously provided background information about Visco fuse manufacture.

1) K. L. and B. J. Kosanke, "Burn Characteristics of 'Visco' Fuse", *Pyrotechnics Guild International Bulletin*, No. 75 (1991) [a] p 19; [b] p 22. Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke Part 2 (1990 through 1992)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1995).
2) K. L. and B. J. Kosanke, "'Skip Burning' of Visco Fuse", *American Fireworks News*, No. 153 (1994) [a] p 7; [b] 6. Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke Part 4 (1995 through 1997)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1999).
3) K. L. and B. J. Kosanke, "Parallel and Propagative Burning", *Pyrotechnics Guild International Bulletin*, No. 79 (1992). Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke Part 2 (1990 through 1992)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1995).
4) R. Webb, personal communication (1997).

An earlier draft appeared in *American Fireworks News*, No. 185, 1997.

Burn Rate of Clusters of Gold Sparklers

K. L. and B. J. Kosanke

In recent years, it has become generally known that clusters of sparklers burn substantially faster than individual sparklers. However, little if any quantitative data has been presented in the literature. Toward that end, this brief article presents some data collected a few years ago by the authors.

Background

There is a very simple relationship, sometimes referred to as the "propagation inequality", that expresses the necessary condition for propagation of pyrotechnic burning.[1] Expressed in words, for propagation to occur, the amount of energy fed back (E_{fb}) from the burning composition to the not-yet-burning composition must be greater than its activation energy (E_a). Expressed mathematically, the propagation inequality is

$$E_{fb} > E_a \tag{1}$$

In simplest terms, the amount of energy fed back is

$$E_{fb} = \Delta H_r \cdot F_{fb} \tag{2}$$

where ΔH_r is the heat energy produced by the reaction (the enthalpy of reaction), and F_{fb} is the fraction of that heat energy that is fed back to the not-yet-reacting composition. By substitution, equation 1 becomes

$$\Delta H_r \cdot F_{fb} > E_a \tag{3}$$

These relationships are also important in discussing burn rate (the rate of propagation). It is generally true that when the propagation inequality is just barely met, when only slightly more energy is fed back than is needed for propagation, the burn rate will be low. Whereas, when much more energy is fed back than is needed, burn rate will generally be higher. Accordingly, those things that alter the amount of energy being fed back also alter the burn rate. For a given pyrotechnic composition, the amount of heat energy produced (ΔH_r) and activation energy (E_a) are essentially constant, depending almost exclusively on the chemicals in the composition. Accordingly, for a given composition, it is only those things that affect the fraction of energy being fed back (F_{fb}) that affect its burn rate.

When a single sparkler burns, the vast majority of the thermal energy produced is lost to the surroundings (i.e., is not fed back to the yet unburned composition). When two or more sparklers burn in close proximity to one another, some of the energy that would normally be lost from each individual sparkler is fed back to the other sparkler(s). This increases the net amount of energy being fed back. Accordingly, whenever two or more sparklers burn in close proximity, it should be expected that their collective burn rate would increase.

There is another factor that can result in an even more significant increase in the efficiency of energy feedback for clusters of sparklers. It is generally recognized that burning can be roughly characterized as one of two types, sometimes referred to as parallel and propagative burning. (For a review of burn types, see reference 2.) When a single sparkler burns, that is a good example of parallel burning. The burning proceeds rather slowly as layer after parallel layer of sparkler composition is consumed. When a group of sparklers are bundled into a cluster, channels (fire paths) are formed between the individual sparklers. When such a cluster of sparklers burns, some of the hot combustion gases pass down these fire paths to ignite additional sparkler composition, which produces more burning gas, which passes further along the fire path to ignite still more composition. In such a manner, fire quickly propagates to ignite the entire length of sparkler composition.

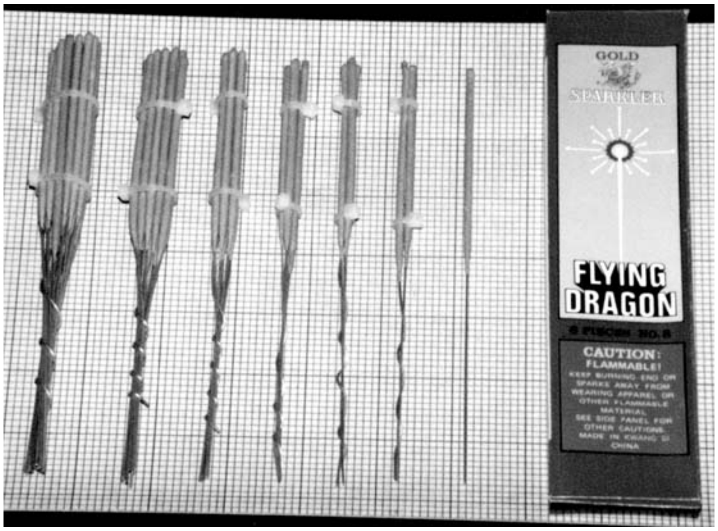

Figure 1. Examples of the sparkler clusters used in this study.

Results

In this study, burning of Flying Dragon No. 8 Gold Sparklers was examined. In addition to individual sparklers, clusters of 2, 3, 4, 6, 12 and 24 sparklers were formed by securing the sparklers with a pair of 1/8-inch wide electrical wire ties and by twisting a sparkler wire around the collection of their handles, see Figure 1. The sparklers were ignited using a small propane torch, and their total burn time was measured using a stopwatch. Timing was started at the first sign of ignition and continued until the very last moment any composition from any sparkler was burning. Because of some uncertainty in identifying precisely when to start and stop the watch, times extending to more than 10 seconds were rounded to the nearest second, and times less than 10 seconds were rounded to the nearest half second. These data are reported in Table 1.

The results of these tests are largely consistent with what was suggested in the background information given above; however, some results were not entirely expected. A cluster of two sparklers produced a significant increase in burn rate (30%) when compared to a single sparkler. When a fire path was formed by clus-

Table 1. Sparkler Burn Time.

Trial Number	Burn Time (seconds) for Clusters of Sparklers						
	1	2	3	4	6	12	24
1	39	30	21	19	10	6.0	5.0
2	38	29	22	13	9.0	5.5	7.0
3	34	28	21	18	6.0	7.0	5.5
4	37	30	19	17	9.5		
5	38	31	23	20			
6	40	30					
7	40	33					
Average	38	30	21	17	8.5	6.0	6.0
B.R. Inc.	0%	30%	80%	120%	350%	530%	530%

B.R. Inc. = Percentage burn rate increase, normalized to single sparklers and rounded to the nearest 10%.

tering three or four sparklers, there was a greater increase in burn rate (≈100%). With clusters of six or twelve sparklers, there were further increases in burn rate. It is a little surprising that the clustering of 24 sparklers was not seen to further increase the burn rate. Presumably, this is a result of having essentially maximized the efficiency of feeding back energy to the unburned sparkler composition. What was most surprising is the dramatic increase in burn rate upon increasing the number of sparklers in a cluster from four to six. At the time of this writing, the authors are not prepared to suggest a specific explanation for these observations, other than citing the possibility that they are statistical manifestations of only doing a small number of tests.

The authors have collected additional data on the burning of clusters of colored sparklers. However, those results and a more complete discussion will be deferred to a future article.[3]

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1) K. L. and B. J. Kosanke, “Control of Pyrotechnic Burn Rate”, *Proceedings of the Second International Symposium on Fireworks*, Vancouver, BC, Canada (1994) p 245. Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke Part 3 (1993 and 1994)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1996).

2) K. L. and B. J. Kosanke, “Parallel and Propagative Burning”, *Pyrotechnics Guild International Bulletin*, No. 79 (1992) pp 18–26. Also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke Part 2 (1990 through 1992)*, Journal of Pyrotechnics, Inc., Whitewater, CO (1995).

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An earlier draft appeared in *Fireworks Business*, No. 158, 1997.

ATF'S Classification of Flash Powder

K. L. Kosanke

This brief article is based on my comments to the US Bureau of Alcohol, Tobacco and Firearms (ATF) concerning their classification of all flash powders as high explosives. In this query, I chose not raise the issues of flash powder storage requirements, quantity limits in process buildings, or any of the issues regarding bulk salutes. I omitted those subjects because I was not prepared to make specific recommendations on those subjects at this time. This article was written for publication because of the possibility someone would find this information useful or interesting.

Background Information

In the current regulations as presented in Publication ATF P 5400.7 (6/90), and first published in February of 1990, the ATF modified the cited examples of high explosives to specifically include flash powder [55.202 (a)]:

> *(a) High Explosives. Explosive materials which can be caused to detonate by means of a blasting cap when unconfined, (for example, dynamite, flash powder and bulk salutes).*

In March of 1990, I made a Freedom of Information request of the ATF for "the specific technical data used by the ATF as the basis of reclassifying bulk flash powder". Their eventual response was to provide a copy of a single Bureau of Mines Internal Report by J. Edmond Hay.[1] Having knowledge of the extent of Mr. Hay's study and the methodology used, I anticipated that there might have been additional data that had not been provided. Accordingly, in June of 1993 I wrote to request any additional data. The response was that the ATF had already given me "all the records retrieved".

In Volume V (1991) of the *Explosives Newsletter*, the ATF responded to my question as to their official definition of what constituted a detonation. It was stated that a detonation is:

> *An explosive reaction, also called a detonation wave, that moves through the material at a velocity greater than the speed of sound in the material.*

In the interim between my two requests to the ATF for their data, I contacted Mr. Hay requesting more specific information concerning the "evidence of a detonation" he had mentioned in his report. He responded:

> *... one of the primary characteristics of detonation is a stable "supersonic" propagation rate. Unfortunately, since we do not know what the sonic velocity of flash powder is, we cannot say with scientific certainty that this rate is supersonic, but our experience with low density granular explosive materials is that the above velocity is "in the ball park" for a detonation velocity, although admittedly on the low side.*

It is important to note that the methodology used in Mr. Hay's study was to encase the flash powders examined "in an acrylic plastic tube … with 0.25-in. wall thickness". This substantial degree of confinement is seriously inconsistent with the ATF's definition of a high explosive being capable of detonation when "unconfined".

In Mr. Hay's study, only two flash powder formulations were tested. Because the chemical and physical nature of these formulations were not identified in his report, one is left to assume they were different from one another and were somewhat representative of typical flash powders being used today. However, even if this is the case, it does not address the issue that there are a very large number of formulations all designated as flash powder. There are 108 different formulations given in one book alone.[2] These formulations fall into several distinct categories, almost certainly with substantially different properties and reaction rates.

In the most recent and possibly most complete scientific examination of the detonability of flash powder,[3] the author states "The combustion can best be characterized as deflagration," even though the flash powders tested were confined in aluminum tubes with a wall thickness of 1.6 mm.

My Question to the ATF

Why do you feel that you have a sufficient scientific basis for your ubiquitous classification of all flash powders as high explosives, when:

- Even the one study you point to was conducted under conditions of substantial confinement, seriously inconsistent with your stated definition for detonation.
- The author of that one study says he cannot say with scientific certainty that a detonation had occurred even when the two flash powders were confined.
- Even the very nature of the two flash powders tested has never been disclosed, thus precluding any confirming study of their potential detonability.
- Other and recent studies have not confirmed that flash powders detonate when unconfined.
- There are a vast number of different flash powders with substantially different properties and reaction rates.

The Solution Proposed to the ATF

Drop the overall classification of flash powder as a high explosive, until or unless there is credible scientific evidence to support that classification in the literature. To do less erodes the credibility of your agency.

If or when credible scientific evidence is produced that supports a high explosive classification for specific formulations or classes of formulations, then adopt that classification, but only for those formulations or classes of formulations.

References

1) J. E. Hay, "Bullet Impact Sensitivity Testing of Class B Fireworks Ingredients and Detonability Testing of Flash Powders", Bureau of Mines, Pittsburgh Research Center, Internal Report Number 4573, 1985. Reprinted in No. 2, *Journal of Pyrotechnics* (1995) pp 36–43.
2) D. Haarmann, *Pyrotechnic Formulary*, 1991.
3) A. Hahma, *Propellants, Explosives, and Pyrotechnics*, No. 21 (1996) pp 100–105.

An earlier draft appeared in *Journal of Pyrotechnics*, No. 5, 1997.

A Survey of Concussion Powders

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ABSTRACT

A collection of six commercial concussion powders were test fired in concussion mortars to determine internal mortar pressure, air blast pressure, and the duration of air blast positive phase. The internal mortar pressures for various powder types and load masses ranged from less than 200 to nearly 100,000 psi (700 MPa). For the same powder loads, the air blast pressures at a distance of approximately 70 in. (1.8 m), ranged from 0.07 to 1.7 psi (12 kPa). This corresponds to sound pressure levels (peak—ultra fast—linear) ranging from 148 to 175 dB, and relative loudness values ranging from 1.0 to 6.8. For the same powder loads, the durations of positive phase ranged from nearly 4 ms down to 0.7 ms.

Keywords: concussion powder, blast wave, mortar pressure, sound pressure level, loudness

Introduction

In an earlier article,[1] the results of a fairly detailed study of one commercial concussion powder (Pyropak™) were reported. The present article reports on a study of a collection of concussion powders from various manufacturers. Since it was not practical to repeat the full study for each of the other concussion powders, it was decided to compare the performance of the powders at only a few selected load masses. All suppliers of concussion powder known to the authors were contacted; all but one agreed to participate in the study and provided samples of their powders.

Since beginning this study, the catastrophic failure of a concussion mortar (without injury) has been reported.[2] This increased both the interest and the relevance of this study, and provided the impetus for an early release of some of the results.[3] The present article is a more thorough presentation and discussion of those results.

It should be noted that the purpose of this study was to measure the performance characteristics of the concussion powders. The purpose was not to rate the performance of the concussion powders. To rank the concussion powders, it would first be necessary to establish a set of evaluation criteria; however, those criteria are likely to be different for various users with different applications. Hopefully, this study provides basic information that both users and manufacturers will find useful, or at least interesting.

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), produced by drilling a hole on-axis into the top end of the steel bar. The mortar used in this study was 2 in. (50 mm) in outer diameter, with a 1-in. (25-mm) hole drilled to a depth of 4.5 in. (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.

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 combus-

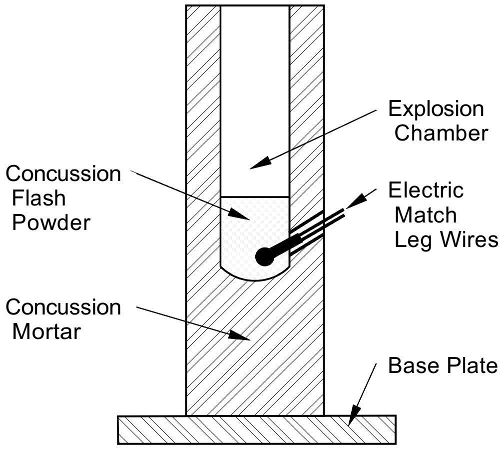

Figure 1. An illustration of the construction and setup of a concussion mortar.

tion products, a downward recoil force is produced. In a previous study, it was demonstrated that the shape of the recoil force curve follows the shape of the internal pressure curve.[1a] Further, it was demonstrated that the magnitude of the recoil force depended on the rigidity of the surface under the mortar. Accordingly, the value of collecting recoil data is diminished and that data was not generated in this study.

Figure 3 illustrates a typical blast overpressure profile. Before the arrival of the blast wave at the pressure sensor, 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 blast shock wave arrives, it produces an essentially instantaneous rise in pressure from ambient to some maximum value. Thereafter, the pressure gradually decays back to ambient pressure. This portion of the blast wave is referred to as the positive phase. Following the positive phase, there usually 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. It is less extreme than the positive phase and lasts longer.

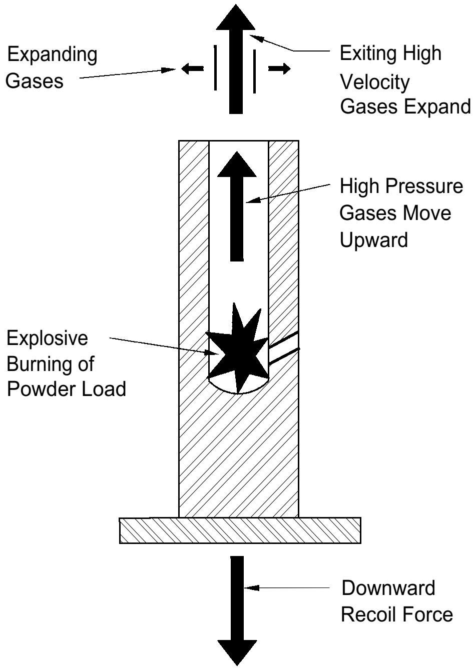

Figure 2. An illustration of the firing of a concussion mortar.

Sound pressure level (*SPL*, in decibels, dB) is a physically measurable quantity and can be calculated from blast overpressure measurements using the relationship shown in equation 1.[4,5][a] Using the recognized standard reference level of 0.0002 dyn/cm^2 and converting pressure to pounds per square inch (psi), this becomes equation 2.

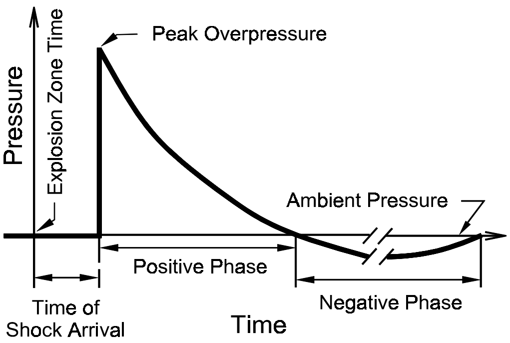

Figure 3. An illustration of a typical overpressure profile (blast wave) produced by an explosion.

$$SPL = 20 \cdot \log \frac{P}{P_o} \tag{1}$$

$$SPL = 170.8 + 20 \log P \tag{2}$$

where P_o is the standard reference value of 0.0002 dyn/cm^2. As can be seen, there is a logarithmic relationship between sound pressure level and peak overpressure (P).

Loudness 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. Loudness values (N, in sones) can be calculated from sound pressure levels using the relationship shown in equation 3.[5]

$$\log N = 0.03 L_n - 1.2 \tag{3}$$

$$N \doteq 10^{(0.03\, SPL - 1.2)} \tag{4}$$

where L_n, loudness level, is equal to SPL in dB for a 1000 Hz tone. Thus, for this study equation 4 was used to calculate approximate loudness.

Because loudness expressed in sones is not a unit of measure with which many readers are accustomed, in this article, loudness is reported as relative loudness. The least loud average concussion mortar air blast was assigned a value of 1.0. Thus a concussion mortar blast reported as producing sound with a relative loudness of 2.0 or 5.0 will be one perceived by the average listener to be approximately two or five times as loud, respectively.

In addition to the loudness of a concussion mortar blast, the tonal quality of the 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 thought 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, and longer phases as more mellow booms. There are at least two reasons for being somewhat cautious about proclaiming that tonal quality correlates with phase duration. First is that tonal quality is a subjective (mental) response to a physical stimulus (the blast pressure wave), and the brain may not process this information as one might expect that it might.[6] Second is that the authors are not aware of any comprehensive study of perceived tonal quality as functions of blast wave phase duration.

It is also conjectured that the rate of rise of the leading edge of the positive phase (dP/dt) may affect tonal quality. It is expected that sharper rises may be perceived as being sharper sounding. However, at the short distance at which measurements of the blast waves were made in this study, all had a near instantaneous pressure rise.

While on the subject of tonal quality of blast waves, it is appropriate to mention that the subject is made more complicated because a complex relationship has been demonstrated between perceived loudness and tonal quality for pure tones.[6] Further, the results for a brief study of spectator responses to the sounds produced by fireworks salutes, suggests a strong correlation between loudness and tonal quality, which, however, is in the opposite direction as that reported for pure tones.[6,7] Accordingly, for the purpose of this article, it will only be assumed that tonal quality correlates with phase duration, at least for equally loud sounds.

Experimental Method[b]

Table 1 lists information regarding the binary concussion powders (so-called A–B mixes) used in this study. The powders are listed in order of the internal mortar pressures they produced, from the lowest to highest pressure. Most of the information in the table was gathered from Material Safety Data Sheets and user instructions provided by the manufacturers. One exception is the fuel to oxidizer ratios that were obtained by simply weighing the contents of the containers for the two components and rounding to the nearest 5%. Not included in Table 1 is information about particle size of the components; it was felt this would be proprietary information of the manufacturers. It should also be noted that some of these samples were provided several years ago; thus, it is possible that the manufacturers will have made changes in their formulations, which are not reflected in this study. Further,

Table 1. Concussion Powder Information.

Supplier and *Product Name*	Fuel(a)	Oxidizer(a)	Fuel : Ox. Ratio(b)	Loading Instructions(c)
Luna Tech (Pyropak®) *Concussion Flash powder*	Magnesium	Strontium Nitrate	50 : 50	1 oz. (28 g) (maximum)
Newco Products *Fast Theatrical Flash Powder*	Magnesium	Potassium Perchlorate	70 : 30	14 g (1/2 oz.) (maximum)
MP Associates *Super Flash Powder*	Magnesium	Potassium Perchlorate	60 : 40	Not Specified
Astro Pyrotechnics *Sound Flash Powder*	Magnesium	Potassium Perchlorate	50 : 50	1 cap full(d)
Theatre Effects *Sonic Chemical*	Aluminum	Potassium Perchlorate	30 : 70	1/4 tsp.(e) (typical)(f)
Precision Theatrical *Concussion*	Aluminum	Potassium Perchlorate	30 : 70	(g)

(a) As specified on manufacturer's Material Safety Data Sheet.

(b) Determined by weighing the contents of a single pair of bottles supplied for testing. The ratios are rounded to the nearest 5%.

(c) As specified in the manufacturer's instructions supplied with the product.

(d) One cap full is approximately 2.7 grams.

(e) One-quarter teaspoon full is approximately 1.7 grams and one heaping quarter teaspoon is approximately 2.5 grams.

(f) There is the additional instruction, "Increase ... slightly if ... not loud enough."

(g) The supplier reports that the powder is supplied with a recommendation to use a mortar with a 1-inch (2.5-cm) wall thickness.

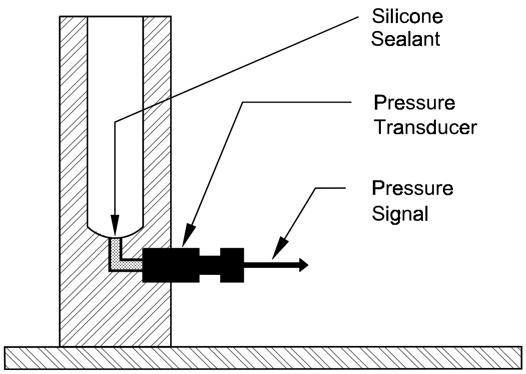

Figure 4. An illustration showing the installation of the pressure transducer.

Astro Pyrotechnics has announced that they have discontinued the general sale of their conconcussion powder.

The test concussion mortar had been modified, as shown in Figure 4, to allow attachment of a quartz piezoelectric pressure transducer for recording internal pressure during its firing. Unfortunately, in retrospect, this was not the ideal configuration. The length of passage to the pressure gauge should have been shorter and more importantly it should not have had a 90° bend. Nonetheless, this is the configuration that was available and that was used. The overall results of this comparative study should not have been significantly affected by using this configuration.

The pressure gauge was a PCB Piezotronics (model 109A02) calibrated to 120,000 psi (830 MPa). To protect the gauge and to keep concussion powder out of the passageway—from the combustion chamber to the pressure transducer—the open space was filled with an opaque silicone sealant (Permatex, High Temp RTV,

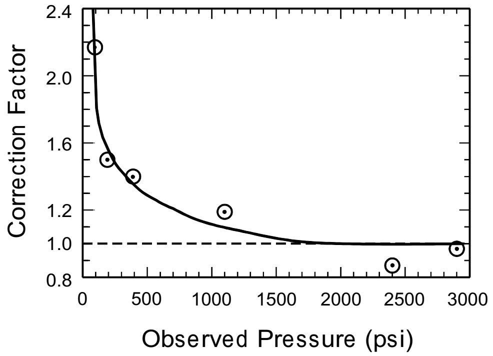

Figure 5. Graph of factors used to correct mortar pressures for the presence of silicone sealant.

#26B). The sealant was allowed to cure for at least a week before use. Occasionally during the testing of concussion powders that produced the highest internal pressures, the silicone sealant loosened and was eroded. On those occasions, the sealant was removed, replaced and allowed to cure before testing continued.

When measuring pressures below approximately 2000 psi (14 MPa), the silicone sealant acts to attenuate the pressure sensed by the gauge. (Presumably, this related to having a long path with a 90° bend between the chamber and the gauge). To develop a pressure correction curve, a series of twenty-four firings were performed using various amounts of Pyropak concussion powder. These results were compared with data collected previously[1b] in which the passageway had been filled with a lightweight silicone grease. The correction factors produced are the average ratio of the values obtained with and without the sealant. These values were plotted in Figure 5 and a smooth curve drawn through the data points.

Air blast overpressures were measured using a PCB Piezotronics free-field blast gauge (model 137A12), setup as shown in Figure 6. This geometry was chosen to duplicate that used in an earlier study,[1] which had been chosen for convenience and because it seemed a reasonable choice. The pressure sensor was shielded from thermal radiation by a thin film of silicon grease that was covered tightly with a 0.001-in. (0.025-mm) film of aluminized Mylar.

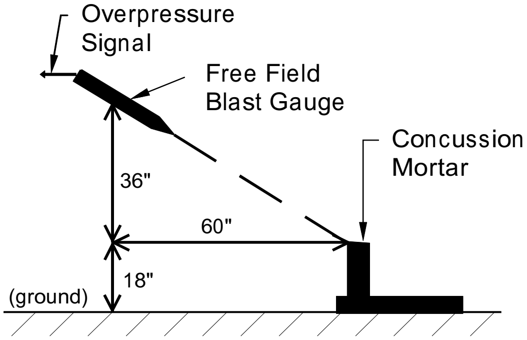

Figure 6. An illustration of the physical setup used to collect concussion mortar air blast overpressures.
(For conversion of units, 1 in. = 25.4 mm)

The electric matches used to ignite the concussion powders in this study were Daveyfire SA-2000. The electric matches were installed near the bottom of the powder charge (see Figure 1). The procedure was to insert the match until it touched the bottom of the mortar, then withdraw it approximately 1/8 in. (3 mm). Over the course of these and earlier tests, the diameter of the electric match hole in the mortar had eroded quite large, to an irregular diameter of approximately 0.25 in. (0.5 cm). In addition, prior repeated use of the mortar had also eroded the bore of the combustion chamber to approximately 1.05 in. (2.7 cm). It is likely these erosions caused the measured internal mortar pressures to be slightly less than might otherwise have been the case.

Output from both PCB transducers (internal mortar pressure and blast overpressure) were fed to amplifying power supplies (PCB model 480D09) and recorded using digital oscilloscopes. Permanent storage and plotting of the data was accomplished using a computer.

Typically each concussion powder was tested with loads of 7, 14, 21, and 28 g. However, when any concussion powder load mass produced an internal pressure that approached 100,000 psi (700 MPa) for any individual firing, or if a series of firings produced pressures that averaged more than 30,000 psi (200 Mpa), no greater loads of that powder were tested. When these values were exceeded for light powder loads, additional tests with various low mass loads were performed.

Results

In this section, the results of the test firings are reported without comment. (The discussion of the results is deferred until the next section.) The results from the individual firings are reported in Tables 2 through 7. Typically, there were three test firings for each load mass with each powder. However, in some cases additional firings were conducted. Sometimes this was because of a failure to successfully capture both types of pressure data for reasons such as data being off-scale. Other times this was the result of some initial testing being performed in a test chamber in which it was felt that there was insufficient space above the concussion mortar to collect reliable air blast data. [This was only a problem for those concussion powders with formulations that were particularly fuel rich (i.e., Pyropak's and Newco's.)] This is discussed further in the next section.

In Tables 2 through 7, the column headed "Pres." presents the data from internal mortar pressure measurements. The column "FWHM" is an abbreviation for Full Width at Half Maximum. This is simply the width of the internal pressure peak, measured at one half of its peak value. It is an indication of the width of the pressure peaks. When the pressure curves have a simple shape (see Figure 7B in the next section), FWHM is a reasonably good indicator of relative peak width. However, when the pressure peaks have an irregular or complex shape (see the other curves of Figure 7) this is a less reliable indicator, but it is still somewhat useful. The column titled "P. Imp." presents pressure impulse data, the area under the internal mortar pressure versus time curves. The column headed "Blast" reports peak air blast overpressure results. The column titled "Pos. Ph." presents the duration of the positive phase portion of the air blast wave. Finally, the column headed "B. Imp." presents the blast impulse, the area under the positive phase portion of the air blast overpressure curve.

Table 2. Results of Measurements Using Pyropak's "Concussion Flash Powder".

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
7	190	7.4	1.4	0.07	4.4	0.11
7	180	7.8	1.1	0.08	3.4	0.11
7	180	8.8	1.2	0.05	3.4	0.08
14	1000	2.0	2.0	—	—	—
14	1600	2.3	4.3	—	—	—
14	630	4.6	2.9	0.21	4.1	0.33
14	1200	2.3	3.1	0.21	3.8	0.46
14	1500	1.9	3.1	0.46	2.9	0.64
21	3500	1.8	6.4	—	—	—
21	2700	2.4	6.3	—	—	—
21	2800	1.6	4.4	0.88	2.1	0.75
21	1600	2.0	3.3	0.87	2.1	0.86
21	1300	1.8	2.3	0.72	2.1	0.81
28	3300	2.2	7.3	—	—	—
28	4000	1.7	7.5	—	—	—
28	2700	2.2	4.9	1.1	2.1	0.99
28	2400	1.9	4.7	1.3	2.3	1.1
28	2300	1.9	4.6	1.5	1.5	1.0

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 oz.)

Table 3. Results of Measurements Using Newco Products "Fast Theatrical Flash Powder".

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
7	1400	1.2	1.7	0.55	2.2	0.48
7	1500	1.0	1.6	0.56	1.5	0.55
7	1400	1.2	1.7	0.58	1.1	0.52
7	—	—	—	0.48	2.1	0.39
14	2800	1.3	3.5	—	—	—
14	2800	1.3	3.3	—	—	—
14	4800	0.84	3.6	—	—	—
14	2600	1.5	3.7	1.0	1.5	0.70
14	3100	1.2	3.7	1.3	1.5	0.68
14	2800	1.4	3.6	1.0	1.3	0.71
21	3200	1.4	4.4	1.6	1.3	0.85
21	4900	1.2	5.7	1.6	1.3	0.88
21	3600	1.8	5.7	1.5	1.6	0.93
28	5100	1.3	6.9	1.8	1.3	0.99
28	5800	1.1	7.1	1.9	1.3	1.1
28	4400	1.7	6.8	1.6	1.3	1.1

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

Table 4. Results of Measurements Using MP Associates' "Super Flash Powder".

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
7	1600	1.4	2.0	0.54	1.8	0.44
7	1700	1.2	2.1	0.81	1.5	0.44
7	1700	1.2	2.1	0.71	1.4	0.45
14	7800	0.50	4.0	1.4	1.2	0.71
14	5700	0.70	3.7	1.5	1.1	0.75
14	5600	0.58	3.7	1.5	1.1	0.75
21	12000	0.48	5.8	1.9	1.2	0.94
21	9900	0.56	5.6	2.0	1.1	0.96
21	13000	0.42	5.6	1.8	1.1	0.96
28	16000	0.30	6.3	2.3	0.94	1.1
28	6700	1.0	7.1	2.1	1.0	1.1
28	15000	0.12	6.5	2.0	0.96	1.1

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

Table 5. Results of Measurements Using Astro Pyrotechnics' "Sound Flash Powder".

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
7	3400	0.56	1.9	1.2	0.92	0.40
7	3600	0.58	2.0	1.2	0.76	0.39
7	3600	0.52	1.9	1.2	0.84	0.41
14	6600	0.51	3.0	1.9	0.86	0.79
14	18000	0.12	3.9	1.6	0.84	0.63
14	7400	0.44	3.8	1.7	0.83	0.61
21	34000	0.14	4.4	2.1	0.87	0.87
21	12000	0.31	4.4	2.1	0.88	0.86
21	47000	0.17	4.3	2.1	0.87	0.87

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

Table 6. Results of Measurements Using Theatre Effects' "Sonic Chemical" Powder.

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
3	3700	0.16	0.89	1.0	0.58	0.21
3	1900	0.30	0.71	0.81	0.47	0.19
3	2100	0.27	0.72	0.78	0.58	0.20
5	4100	0.24	1.2	1.1	0.60	0.32
5	4400	0.22	1.3	1.2	0.65	0.34
5	4500	0.22	1.3	1.2	0.65	0.34
7	5600	0.25	1.8	1.3	0.70	0.43
7	3700	0.21	1.9	1.4	0.70	0.43
7	18000	0.04	2.0	1.3	0.71	0.43
9	18000	0.10	1.9	1.5	0.78	0.52
9	13000	0.12	2.1	1.7	0.78	0.57
9	19000	0.11	2.3	1.7	0.78	0.60
11	44000	0.03	2.6	1.6	0.79	0.61
11	—	—	—	1.7	0.80	0.65
11	92000	0.05	4.6	1.7	0.81	0.66

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

At the end of this section, Table 8 presents averages for the test results from Tables 2 through 7. In addition, average sound pressure levels and relative loudness values are reported in the columns titled "SPL" and "Rel. Loud.", respectively. These were calculated from the peak overpressure data using equations 2 and 4.

Table 7. Results of Measurements Using Precision Theatrical's "Concussion" Powder.

Powder Load (g)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)
2	1300	0.28	0.32	0.62	0.56	0.18
2	4000	0.10	0.38	0.81	0.50	0.21
2	1400	0.20	0.33	0.70	0.50	0.20
2	2000	0.15	0.34	0.77	0.50	0.21
3	5400	0.10	0.61	1.0	0.58	0.27
3	4900	0.11	0.58	1.0	0.60	0.27
3	6300	0.11	0.58	1.1	0.66	0.27
4	9400	0.10	0.91	1.1	0.60	.033
4	9900	0.07	0.88	1.2	0.60	0.33
4	8000	0.08	0.90	1.4	0.63	0.35
5	9500	0.12	1.2	1.4	0.62	0.39
5	19000	0.09	1.2	1.5	0.68	0.43
5	5000	0.19	1.0	1.4	0.63	0.40
6	6000	0.18	1.2	1.3	0.70	0.42
6	11000	0.10	1.2	1.4	0.74	0.44
6	7200	0.17	1.2	1.2	0.71	0.40
7	11000	.012	1.7	1.4	0.74	0.47
7	17000	0.08	1.5	1.3	0.74	0.46
7	19000	0.06	1.8	1.3	0.74	0.47
9	14000	0.15	2.1	1.4	0.77	0.52
9	15000	0.09	2.1	1.4	0.77	0.52
9	86000	0.02	3.1	1.5	0.77	0.55

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

In Table 8, because of the small number of test firings for each load mass, and because of the large variations observed in the individual results, it was felt to be inappropriate to report standard deviations. One reason for including the results from individual test firings (Tables 2 through 7) is that a simple inspection can provide a rough estimate of the variability of the results. Note that relatively little of the variability is thought to be the result of the measurement process, but rather it is from actual differences in the combustion processes from test to test. A consequence of the significant variability of the results is that they are only reported to two significant figures.

Discussion of Results

For test firings of the most fuel-rich concussion powders, it was found that credible data could not be collected in a blast chamber with only an 8-foot (2.4 m) ceiling. The air blast peak shapes observed were seriously distorted compared with those collected in a larger chamber and for less fuel-rich powders. This observation may be consistent with the most fuel-rich powders producing a portion of their blast wave from a fuel-air explosion above the mortars.

Table 8. Average Results for the Various Sources of Concussion Powder.

Powder Load (g)(a)	Pres. (psi)	FWHM (ms)	P. Imp. (psi·s)	Blast (psi)	Pos. Ph. (ms)	B. Imp. (psi·ms)	SPL (dB)	Rel. Loud.
LP 7	180	8.0	1.2	0.07	3.7	0.10	148	≡1.0
LP 14	1200	2.6	3.1	0.29	3.6	0.47	160	2.3
LP 21	2500	1.9	4.7	0.82	2.1	0.81	169	4.4
LP 28	2900	2.0	5.8	1.3	2.0	1.0	173	5.8
N 7	1400	1.1	1.7	0.54	1.7	0.48	165	3.4
N 14	3300	1.3	3.6	1.1	1.4	0.70	172	5.2
N 21	3900	1.5	5.3	1.6	1.4	0.89	175	6.5
N 28	5100	1.4	6.9	1.8	1.3	1.1	176	7.0
MP 7	1700	1.3	2.1	0.69	1.6	0.44	168	4.0
MP 14	6400	0.59	3.8	1.5	1.1	0.74	174	6.3
MP 21	12000	0.49	5.6	1.9	1.1	0.95	176	7.3
MP 28	13000	0.47	6.6	2.1	0.97	1.1	177	7.7
A 7	3500	0.55	1.9	1.2	0.84	0.40	172	5.5
A 14	11000	0.36	3.6	1.7	0.84	0.68	175	6.8
A 21	31000	0.17	4.3	2.1	0.87	0.87	177	7.7
A 28	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
TE 3	2600	0.24	0.77	0.86	0.54	0.20	170	4.5
TE 5	4300	0.23	1.3	1.2	0.63	0.33	172	5.5
TE 7	10000	0.17	1.9	1.3	0.70	0.43	173	5.7
TE 9	17000	0.11	2.1	1.6	0.78	0.56	175	6.5
TE 11	68000	0.04	3.6	1.7	0.80	0.64	175	6.8
TE 13	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
PT 3	5500	0.11	0.59	1.0	0.61	0.27	171	4.9
PT 5	11000	0.13	1.1	1.4	0.64	0.41	174	6.0
PT 7	16000	0.09	1.7	1.3	0.74	0.47	173	5.7
PT 9	38000	0.09	2.4	1.4	0.77	0.53	174	6.0
PT 11	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)

(For conversion of units: 1 psi = 6.89 kPa, and 28 g ≈ 1 ounce.)

(a) LP = Luna Tech / Pyropak; N = Newco Products; MP = MP Associates; A = Astro Pyrotechnics; TE = Theatre Effects; PT = Precision Theatrical.

(b) Pressure limit criterion was exceeded for the next lower load mass, no test was performed for this load mass.

In this study, as in an earlier study,[1] a large degree of variability was observed for internal mortar pressure pulse shapes. Examples of these shapes are shown in Figure 7. It is likely that the peak shapes are real and reflect differences in the combustion process. This is because the type of pressure pulse shape observed tends to be predictable, based on load mass and powder type. Further, it has not been possible to postulate a simple model for how a problem with the instrumentation could produce such widely varying shapes with consistent pressure impulses (peak areas). Another reason to believe the various peak shapes are real is the recoil forces, measured independently in the earlier study, tended to mirror the internal pressure peaks.[1c]

The curve in Figure 7A is typical of that observed for light loads of the low pressure Pyropak powder. There is a cluster of peaks spanning about 12 ms in time, with a maximum pressure of nearly 100 psi[c] (0.7 MPa). When this type of cluster of peaks is observed, there seems to be little consistency in the number of peaks in the cluster, their relative amplitudes, or the spacing between peaks.

The curve in Figure 7B is typical of heavier loads of the Pyropak powder, all loads of the Newco powder, all but the heaviest loads of the MP Associates powder, and the lighter loads of the Astro powder. There is always a single peak, but it is not always symmetric. The peak shown in Figure 7B spans only about 2 ms in time and has a maximum pressure approaching 3000 psi (20 MPa).

The curve in Figure 7C is somewhat typical of the heavier loads of the MP Associates and Astro powders, and the lightest loads of the Theatre Effects and Precision Theatrical powders. These pressure pulses have one or more narrow high-pressure peaks superimposed on a wider, lower more modest pressure peak. On some occasions the pressure pulses have fully developed oscillatory features as seen in the curve in Figure 7C, which only spans about 0.5 ms in time, with a maximum pressure exceeding 10,000 psi (70 MPa).

The curve in Figure 7D is typical for the higher loads (but still only about 10 grams) of the Theatre Effects and Precision Theatrical powders. The prominent portion of the pressure peak spans less than 0.1 ms, and the maximum pressure has risen to well over 50,000 psi (350 MPa).

It may be interesting to note for the powder types and load masses tested, even though the peak mortar pressures increased by a factor of approximately 500, the pressure impulse only increased by a factor of 3. Thus, the primary difference is time span over which the pressure pulse is produced, which decreases by a factor of approximately 200.

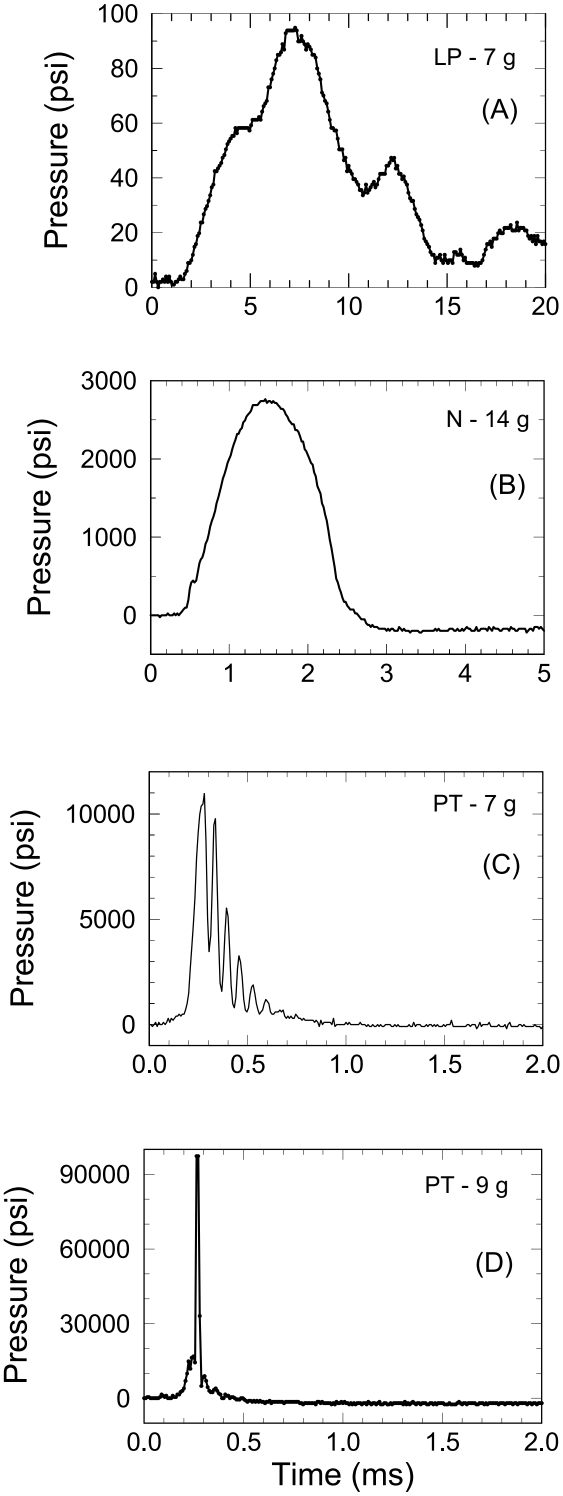

Figure 7. Examples of a variety peak shapes seen in internal mortar pressure data (note the substantial differences in the time scales.)

Table 9. Average Positive Phase Durations for Powder Loads Producing Air Blast Pressures of Approximately 1.5 psi (10 kPa).

Powder and Load (g) (a)	Blast (psi)	Pos. Phase (ms)
LP 28	1.3	2.0
N 21	1.6	1.4
MP 14	1.5	1.1
A 14	1.7	0.84
TE 9	1.6	0.78
PT 5	1.4	0.64

(For conversion of units: 1 psi = 6.89 kPa)

(a) LP = Luna Tech / Pyropak; N = Newco Products; MP = MP Associates; A = Astro Pyrotechnics; TE = Theatre Effects; and PT = Precision Theatrical.

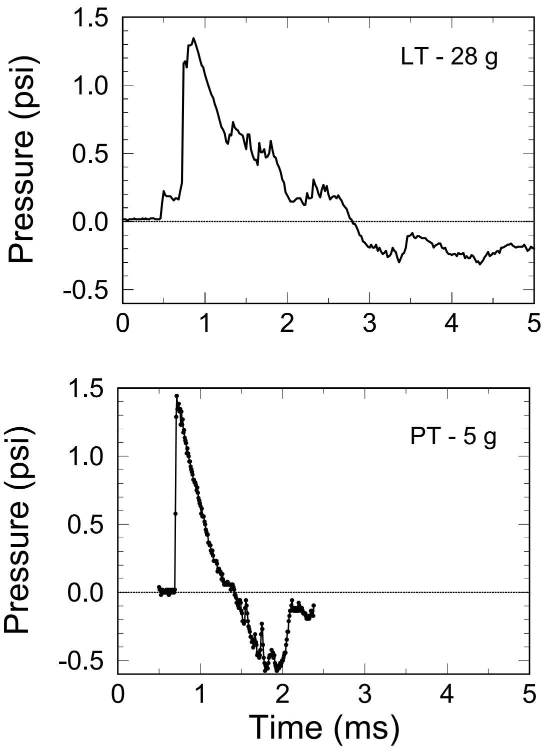

Figure 8. Air blast pressure curves illustrating the approximate range of differences in positive phase durations.

Although the internal mortar pressure curves generally trend as discussed above, still major variations occur for apparently identical loads of the same powder. For example, see Table 5 for 21-gram loads of the Astro powder. Here the maximum pressures were 34, 12, and 47 kpsi (230, 80, and 320 MPa, respectively). Despite the large variation in peak internal pressure, pressure impulse and air blast overpressures are much more consistent. The pressure impulses were 4.4, 4.4, and 4.3 psi · s (30, 30, and 29 kPa · s), respectively, and the peak air blast overpressures were all 2.1 psi (14 kPa). In this case, the total energy being released and the sound pressure levels are quite consistent. Independent of concussion powder type, this was found to be generally true; air blast pressures correlate better with pressure impulse than with peak internal mortar pressure.

If it can be assumed that the tonal quality (sharper crack versus mellower boom) is a function of the durations of the positive and negative phases of the blast wave, then there may be noticeable differences in the tonal quality of sounds produced by the various powders. (Testing with human subjects is planned to investigate this.) Table 9 lists the average positive phase durations for the various powder types, each with load masses that produced approximately equal peak air blast overpressures (loudness). Figure 8 shows the air blast waves for the two extremes of the various cases. It may be of interest to note that the order of powder types in Table 9, by decreasing duration of positive phase, is the same as that in Table 8, where they were listed in order of increasing internal pressures for the same load mass.

A review of the data in Table 8 reveals that the durations of positive phase of the air blasts for the various powders is generally also a function of load mass. However, the functional relationship is different for the various powders. Note that for the three lowest pressure producing powders (LunaTech/Pyropak, Newco and MP Associates) the durations of positive phase decreases for increasing load mass. Note further that the opposite trend holds for the two highest-pressure producing powders (Theatre Effects and Precision Theatrical). Finally, for Astro's powder note that the duration of positive phase is essentially independent of powder load mass.

These relationships are illustrated in Figure 9, which is a graph of positive phase duration versus load mass (each normalized to the values for the smallest load mass) for the different powder types.

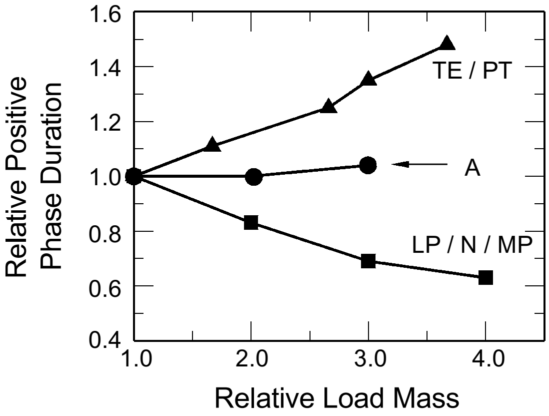

Figure 9. Graph of positive phase duration versus load mass (each normalized to the values for the smallest load mass) for the different powder types.

Conclusion

It was not the intention of this study to rate the performance of the concussion powders tested. In addition, further studies are needed before truly meaningful conclusions can be drawn. Planned studies include: the effect of distance on peak sound pressure levels and the duration of positive phase, and the loudness and tonal quality of the impulse sounds as perceived by human subjects. Accordingly, essentially no conclusions are presented in this paper.

Obviously, the various powders tested have significantly different performance characteristics, thus offering the user a wider range of performance choices than might have been expected. It is hoped that the information in this article proves to be useful to consumers in selecting concussion powders that: (1) fit their needs, and (2) are compatible with the burst strength of their concussion mortars. Also, hopefully the participating manufacturers and other researchers find these results of general interest.

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Notes

[a] Commercial sound pressure level (SPL) measuring instruments, operated in “peak” mode, typically have a time constant of 50 µs. While this is fast for most sounds, it is still fairly slow for an air blast (shock) wave, which has an essentially instantaneous pressure rise, followed by a much slower (but still fast) decay to ambient pressure. Therefore, such an instrument will underestimate actual SPL’s of the sounds of explosions. This is the same type instrument, with the same time constant, that is used to establish acceptable SPL’s for human exposure. On the other hand, the instrument used in this study to measure air blast overpressure, from which sound pressure levels were calculated, has a rise time of only 4 µs. As a result, the instrument used in this study generates higher SPL’s for the sounds of explosions than typical instruments would. This can be important, if the results of this study are compared with results using instruments with slower response or are compared with SPL regulations for acceptable human exposure. For the durations of positive phase seen in this study, the SPL’s reported will range from about 1 to 2 dB higher than would have been measured using typical SPL instruments.

[b] It is fairly common in the authors' laboratory to work using a mixture of SI and English units. In this paper, for accuracy of reporting in the text, the actual units of measurement are given first, followed by their SI or English equivalent, with the same number of significant figures. In tables, generally only the actual units of measurement are reported, and conversion factors are appended to the tables. The authors apologize for any inconvenience this causes.

[c] Note that none of the pressure data presented in Figure 7 have been corrected for the presence of the silicone sealant. This only affects pressures less than about 2000 psi. For example, if corrected, the peak pressure in Figure 7A would actually be nearly 200 psi and not 100 psi as shown.

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An earlier draft appeared in *Fireworks Business*, No. 162, 1997.

Sky Rocket Performance Characteristics

K. L. and B. J. Kosanke

Over the years, we have occasionally had the opportunity to conduct brief studies of fireworks rockets, both sky rockets and smaller bottle rockets. Most recently, an investigation was performed using some Horse Brand sky rockets (Glitterous Lights, Clustering Bees, and Flying Butterflies). This short article is written in the belief that a summary of those results may be of general interest.

In our experience, much of what is reported here for the Horse Brand sky rockets, also applies to other brands of non-whistling sky rockets, and in a general way to smaller rockets. However, since not all brands and types of rockets were investigated, there can be no guarantee the results reported here are universally applicable. Further, there is no guarantee that these exact results even apply to different production lots of Horse Brand rockets.

The approximate characteristics of these rockets are as follows:

- Initial mass, 18 g (0.65 oz)
- Overall length, 400 mm (16 in.)
- Motor outside diameter, 15 mm (0.62 in.)
- Motor length, 70 mm (2.8 in.)
- Propellant mass, 4 g (0.15 oz)
- Motor burn time, approximately 3 s
- Heading mass, 3 g (0.11 oz)

In one series of measurements, thrust profiles were determined for these rocket motors. Figure 1 is a typical graph of propulsive force as a function of time (i.e., a thrust profile). These data were produced using a piezoelectric force transducer to sense the thrust of the rocket motor, and a digital oscilloscope to record the data.

It should be noted that the duration of significant thrust is much less than the total burn time of the motor. Thus, after the initial high thrust phase of the burning (approximately 0.2 s), the rocket is in a coasting mode for approximately 3 seconds. Just how little thrust is produced during this coasting phase, can be seen in Figure 1, where the typical range of times until motor burnout is indicated. A relatively short, high thrust phase such as this is common for the non-whistling rockets that we have investigated to date.

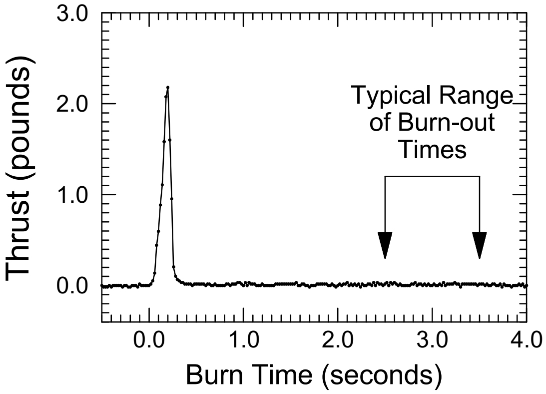

Figure 1. Typical thrust profile of a Horse Brand sky rocket.

Figure 2 is a typical graph of the speed of a sky rocket as a function of distance traveled. This data was collected by monitoring the flight of rockets flown horizontally on a distance calibrated flight range. To accomplish this, two video cameras were used. The first camera viewed the flight of the rockets from their approximate point of origin, to confirm that their flight path did not deviate significantly from their initial alignment down the flight range. The second camera viewed the rocket from a point 200 feet from, and perpendicular to, the flight range. This camera recorded the progress of the rocket along the flight range each 1/60th second, and allowed calculation of the rocket's speed along its path.

In Figure 2, note the obvious ramification of the short thrust phase, specifically that the rocket's maximum speed is reached very early in its flight. In the data shown, the rocket's speed has peaked after only traveling approximately 25 feet down range. Thereafter, the rocket is mostly coasting, and its speed decreases.

As a result of data such as that illustrated in Figures 1 and 2, some safety related conclusions can be drawn. In the discussion to follow, unless otherwise stated, it will be assumed that the subject sky rocket is reasonably well designed, is fired according to instructions, and does not suffer a significant malfunction.

That high velocities are reached very early in its flight has positive ramifications regarding stable and safely-oriented flight. This is because it is during the initial, low speed portion of a rocket's flight that it is least stable and most susceptible to becoming reoriented from its intended direction. For that reason, external guidance such as a "wooden trough or iron pipe at a 75° angle" is required. Thus, if the rocket quickly reaches at least a modest speed, the distance through which such guidance is necessary, is reduced, and safety is enhanced.

That essentially all of the rocket's propulsive energy is expended during the first 0.2 second has another positive safety ramification. For example, were the rocket to become seriously reoriented any time after the first 0.2 seconds (≈30 feet) of its flight, there is insufficient means for the rocket to propel itself away from its current path. That is to say, the rocket will tend to continue with the velocity (speed and direction) it assumes during the reorienting event. In other words, after the reorienting event, the rocket will not be capable of dangerously accelerating in an unsafe direction.

One type of event with the potential for reorientation could be a collision with a massive object. For example, consider a hypothetical case of a rocket colliding with a wall or tree trunk, causing it to be completely stopped but now aimed in the direction of the person that fired it. If this collision occurs after the rocket has traveled approximately 30 feet, the rocket must fall essentially vertically to the ground because no propulsive energy remains. It definitely does not have the ability to return and injure the person that ignited it.

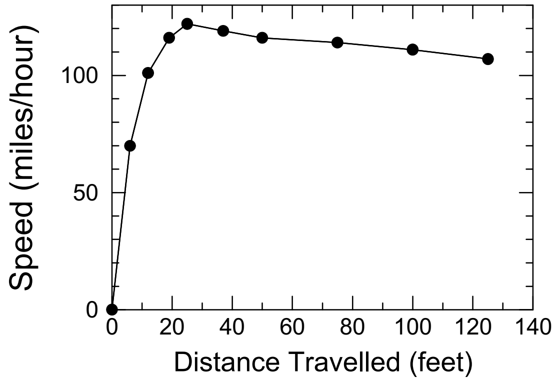

Figure 2. Typical graph of the speed of a Horse Brand sky rocket as a function of distance traveled.

On the other hand, that the rocket quickly reaches a particularly high speed, and thereafter merely coasts to reach its peak altitude, can have negative safety ramifications as well. One such example would be in the case of misuse, where a rocket is launched in the direction of people. In that case, were it to impact a person, the rocket could potentially be traveling with dangerously high energy. In Figure 2, the speed peaked at over 120 miles per hour. (In another test, a speed in excess of 150 miles per hour was recorded) Given the likely mass of the rocket at that point in its flight [15 g (10.54 oz)], this amount of energy upon impact is roughly equivalent to that of a two-pound weight falling from a distance of 11 feet. This is approximately the energy of a hammer falling off the top of a tall step ladder onto one's toe. [Most unfortunately, there was a recent fatality of a child resulting from such a rocket impact to the temple of her head.] If the rocket motors were redesigned slightly, such that the initial velocity was a little less, and the duration of thrust was longer, such accidents could be made less severe.

One way in which peak rocket speed could be reduced, without significantly altering the height it reaches, is shown in Figure 3. This can be accomplished simply by using a motor core that is less deep. Figure 3 illustrates how this would be accomplished and is apparently the method used in the older "Sky Bloom" rockets from West Lake Brand. Figure 4 is the thrust

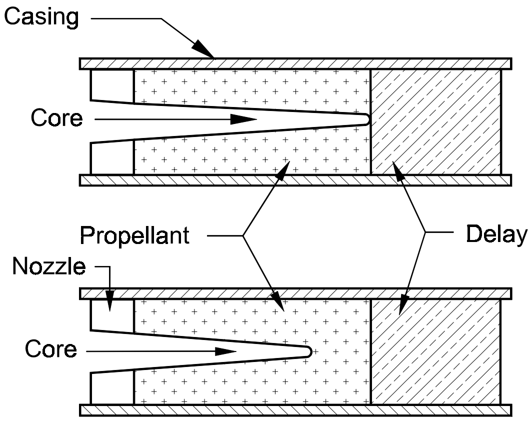

Figure 3. Rocket motors with varying core length.

profile of a typical Sky Bloom rocket. (Note that the peak thrust is about 30% less, and its duration is longer.)

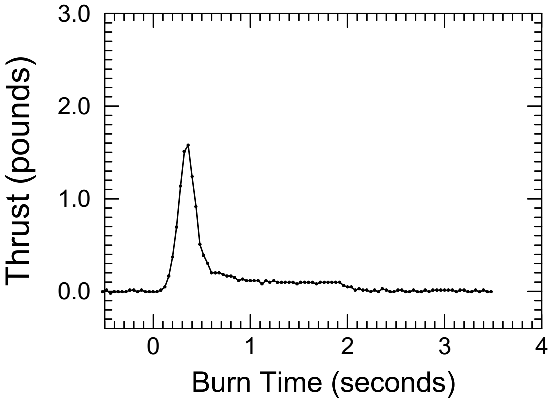

Figure 4. Typical thrust profile of a Sky Bloom rocket.

Obviously, this brief article has not exhausted the subject of sky rocket performance and safety. However, hopefully, it has presented useful information.

The authors gratefully acknowledge E. Brown (Estes Industries) for reviewing this article before publication.

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Performance Comparison Between Old and New Obron German Dark Aluminum

K. L. and B. J. Kosanke

In 1997, Obron Atlantic changed their German dark aluminum. (Their former product number was 5413; the new product was designated 5413 H Super.) We had published the results of a series of sound output tests of various salute powders,[1] which included the effect of using various aluminums, including Obron's old German dark. Because of our past work, and in response to a query on the Internet, we decided to conduct a brief investigation comparing the sound output of these two aluminum powders when used in a common flash powder formulation. This article presents those results.

To some extent, the sound produced by a salute or the forces developed by the break charge of a crossette, depends on the rapidity with which the salute (flash) powder burns. Many factors act collectively to control burn rates of pyrotechnic compositions; however, among the most important for salute powders is the particle size of the aluminum fuel. (For a more complete discussion of the factors controlling burn rate, see reference 2.) Accordingly, if the change in aluminums provided by Obron altered the size distribution of the aluminum particles, it is likely that salutes made with the new aluminum would produce different sound levels.

The color of fine metal powder generally depends on particle size, with finer particles tending to appear darker. However, this does not apply to German dark aluminums, because they contain a small percentage of carbon apparently as a result of the manufacturing process. The new German dark aluminum is noticeably lighter in color than the older material. It is unknown whether this is primarily an indication that less carbon is present. In simply handling the aluminums, it also seemed that the older German dark aluminum was slightly more free-flowing than the newer material.

Bulk density of a powder can be an indication of particle size, with smaller particles tending to produce a less dense (fluffier) powder because of an increased ability to entrap air between the particles. Another factor affecting the bulk density of powder is the range of particle size, with wide particle-size distributions tending to pack more densely than powders with more nearly uniform particle size. (The smaller particles tend to fit into the otherwise wasted space between larger particles.) However, this seems to be less true for flakes than for granular particles.

The bulk density of the two German dark aluminums was measured. This was accomplished by first violently shaking samples of the powder in a closed container to entrain as much air as possible. Then 5 grams of the powder was weighed into a graduated cylinder (chemistry glassware) and placed on a vibrating platform for 30 seconds, thus consolidating the powder to a somewhat standard condition. It was found that the newer German dark aluminum had a bulk density of 0.74 g/cc, which is effectively the same as the older aluminum's bulk density of 0.75 g/cc.

An attempt was made to determine the aluminum's average particle size using light microscopy. This is a difficult task and the results are fairly subjective, not because it is difficult to measure individual particle sizes with a microscope, but because it is difficult to estimate which individual particles are of average size. The results suggest that the newer German dark aluminum has an average particle size of approximately 9 microns, whereas the older material seems to be on average closer to 6 microns. (A micron is one millionth of a meter, or 0.00004 inch.) Although it is difficult to be certain, it seemed that the newer material also has

Table 1. Average Salute Test Results.

Aluminum Type (Obron Atlantic)	Peak Pressure (psi)[a]	Relative Pressure	Sound Pressure Level (dB)	Relative Loudness
5413	5.93	≡ 100%	186.3	≡ 100%
5413 H Super	5.32	90%	185.3	93%

(a) To convert to kPa, multiply by 5.89.

a wider range of particle size, than the older German dark aluminum.

For the tests reported here, the salute powder test compositions were 70:30 potassium perchlorate[3] and German dark aluminum by mass. The compositions were well mixed, using a combination of sieving, diapering, and tumbling. Each test device consisted of a 50-g (1.8-oz) charge of salute powder confined in a 3-ounce polyethylene bottle. This method of construction was chosen to achieve a fairly high degree of consistency in confinement of the salute powder and because it duplicates that used in earlier testing. For each type of aluminum, three separate tests were performed and the results averaged. The air blast output was measured using a free-field blast gauge at four feet from the center of the test salute. (For more information about the methods and equipment used, see reference 1.)

The average results from the three tests of each aluminum are reported in Table 1. Peak pressure is the maximum pressure (in pounds per square inch) measured in the air blast when the test salute exploded. For the relative pressures reported in the table, the value for the older German dark aluminum was defined as 100%. The sound pressure level (*SPL*) produced was calculated from the peak pressure (*P*) using the equation:

$$SPL\ (\text{dB}) = 170.8 + 20 \log (P)$$

Loudness values (*N*, in sones) were calculated using the equation:

$$\log (N) = 0.03\ SPL - 1.2$$

Again, in Table 1, the relative loudness for the older German dark aluminum was defined as 100%. (For more information and references regarding these calculations, see references 1 and 4).

As can be seen in Table 1, the new German dark aluminum, in this brief experiment, was a little less effective than the older material. Peak pressures produced by salutes using the newer aluminum were reduced by 10% and their loudness was reduced by 7%. While this difference is sufficient to be fairly certain there is a real difference (and not just a statistical accident), it is not certain that these results are universally applicable. Each of the two aluminum samples were taken from a single production lot of aluminum powder, and it is not known to what extent there is variation between production lots of the same aluminum powder. In addition, testing was only done under conditions of weak confinement, and these results may not apply to other degrees of confinement.

The authors gratefully acknowledge Obron Atlantic for providing the test sample of their 5413 H Super aluminum.

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Pyrotechnic Ignition and Propagation: A Review

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ABSTRACT

The ideal pyrotechnic is completely stable in storage and handling, yet performs its mission completely, with absolute reliability, upon demand. Many accidents in pyrotechnics are the result of unintentional ignitions during handling and storage. There can also be serious safety ramifications of ignition and propagation failures of pyrotechnic devices. This review article presents a fairly rigorous, but mostly non-mathematical discussion of the ignition and propagation processes.

Keywords: ignition, propagation, heat of reaction, activation energy, spontaneous ignition, thermal run-away, cook-off

Introduction

An understanding of the mechanism of pyrotechnic ignition and propagation will improve one's ability to identify and solve problems with ignition failures (duds) and unintended ignitions (accidents). In addition, many of these same principles play an important role in understanding the control of pyrotechnic burn rate. This article will examine these important topics thoroughly, however, not at a mathematically rigorous level. For more detailed and rigorous discussions, readers are referred to the writings of Merzhanov and Abramov.[1,2]

Pyrotechnic Reaction Energy Considerations

Pyrotechnic compositions are mixtures of fuel(s) and oxidizer(s) and often other materials. They are used to produce energy on demand in the form of heat, light, sound, etc. Pyrotechnic compositions are said to be in a "meta-stable" state. That is to say that under typical conditions they are stable and do not react to release their internal chemical energy unless externally stimulated in some way. Probably the most common stimulus is the addition of heat, such as provided by a burning match or fuse. Ignition is the process of stimulating a pyrotechnic composition to release its internal energy and can be defined as "the initiation of self-sustained burning or explosion of a pyrotechnic material".[3]

Figure 1 illustrates the process of ignition by graphing the internal energy of a tiny portion of pyrotechnic composition during the progress of its chemical reactions and is typical of non-spontaneous exothermic chemical reactions.[4] At the left of the graph, where the process begins, the pyrotechnic composition has a certain

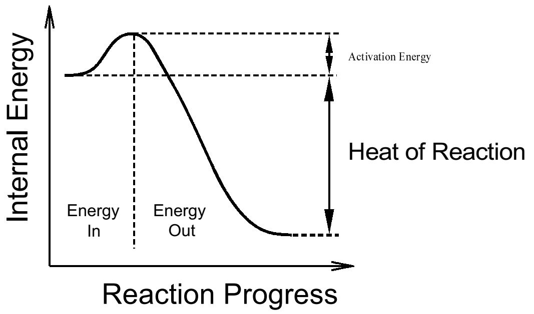

Figure 1. A graph illustrating the flow of energy into and out of a tiny portion of pyrotechnic composition.

Table 1. Heat of Reaction of Binary Pyrotechnic Compositions.[5a]

Fuel	(%)	Oxidizer	(%)	ΔH_r (kcal/g)
Magnesium	(37)	Potassium chlorate	(63)	2.29
Magnesium	(40)	Potassium perchlorate	(60)	2.24
Magnesium	(32)	Barium nitrate	(68)	1.65
Aluminum	(34)	Potassium perchlorate	(66)	2.45
Aluminum	(40)	Sodium nitrate	(60)	2.00
Aluminum	(25)	Iron(II) oxide	(75)	0.96

amount of internal energy. To accomplish ignition, external energy is supplied, such as from a burning match. This addition of energy increases the internal energy of the composition and is seen as a rise in the curve of Figure 1. This is indicated as the "Energy In" part of the reaction. As the process continues, eventually the pyrotechnic composition ignites to release its stored chemical energy to the surroundings. This loss of internal energy is seen as a drop in the curve of Figure 1 and is indicated as the "Energy Out" part of the reaction. The energy that was required to stimulate this release is commonly referred to as the "Activation Energy" (E_a). The net amount of energy produced by the pyrotechnic reaction is referred to as the "Heat of Reaction" (ΔH_r).[a]

Even the smallest particles of fuel and oxidizer in the pyrotechnic composition are clusters of many billions of atoms bound together to form the particle. It is possible to think of the two-step process—energy in and energy out—as first when old chemical bonds are being broken in the fuel and oxidizer, and second, when new chemical bonds are being formed to make the reaction products. This also helps to make it clear why the activation energy[b] requirement acts as a barrier that must be surmounted to initiate the chemical reaction. Until the necessary energy is supplied to break the original chemical bonds, thus freeing individual fuel and oxidizer atoms, they are not available to react with each other to form new chemical bonds.

In a pyrotechnic chemical reaction, a net amount of energy will be produced, providing the new chemical bonds being formed in the reaction products are stronger than the old bonds that must first be broken in the fuel and oxidizer. Table 1 lists the heats of reaction for some two-component (binary) pyrotechnic reactions. The reason that varying amounts of energy are produced is that in each case different numbers and strengths of chemical bonds are broken and formed.

Collections of atoms, such as those bound together in a particle of fuel or oxidizer, are not held in absolutely rigid positions. The individual atoms jostle about (vibrate), back and forth, and up and down. Because of these internal motions, the individual atoms possess energy, often referred to as thermal energy. In the process of jostling with one another, the atoms transfer some of their thermal energy from one to another. The net result of this jostling and energy sharing is that at any instant some atoms have much energy while others have little, and an atom that has much energy now, may have little energy later.

Figure 2 is a graph illustrating the distribution of thermal energies[4] of individual atoms in fuel and oxidizer particles in a pyrotechnic composition at some temperature T_1. The curve goes through the origin of the graph, meaning that zero atoms have zero energy. Thereafter an increasing number of atoms have increasing energy, until a peak is reached, followed by continuously decreasing numbers of atoms possessing higher and higher energies. Also shown in Figure 2 is the activation energy E_a that is required to initiate the pyrotechnic reaction. Note that the composition contains some atoms with energies exceeding the activation energy barrier. (In Figure 2 the number of atoms with energies greater than E_a has been exaggerated for clarity.)

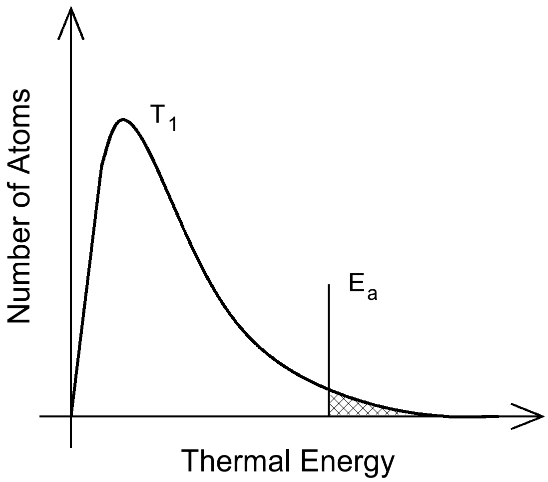

Figure 2. A graph illustrating the thermal energy distribution of atoms in a pyrotechnic composition.

Since some atoms in the pyrotechnic composition already have sufficient energy to react, the question should be "Why isn't the pyrotechnic composition reacting?" The answer is, "It is reacting, but only very, very slowly." To see why this is the case, consider the following: At room temperature, only 1 atom in roughly every million billion (10^{15}) has the needed activation energy to react.[6] Additionally, only the fuel atoms that are in direct contact with oxidizer atoms can react. When considering the fraction of atoms in a tiny particle that are on its surface, and the fraction of surface atoms that are likely to be in direct contact with the right atoms on the surface of other particles, only 1 atom in roughly every thousand billion billion (10^{21}) is capable of reacting at any given time.

Thermal Run-Away and Spontaneous Ignition

If the temperature of the pyrotechnic composition is raised, from T_1 to a higher temperature T_2, as illustrated in Figure 3, on average the atoms jostle around with more energy. More significantly, however, the number of atoms with energies exceeding the activation energy barrier increases greatly.[4] As a consequence, there are now many more atoms capable of reacting, and there is a corresponding increase in the rate at which the reactions occur. Recall, however, that these chemical reactions produce thermal energy; thus an increase in the reaction rate causes an increase in the rate of production of heat; which would seem to produce a further increase in temperature; which causes still more atoms to have energies exceeding the activation energy barrier; which causes a still greater increase in reaction rate and the rate of heat pro-

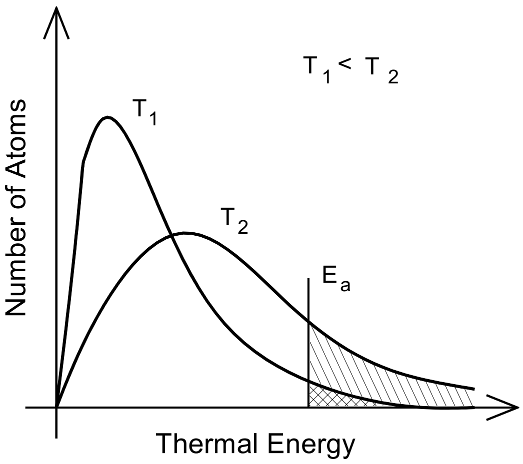

Figure 3. An illustration of the effect of increasing temperature on the distribution of the thermal energy of atoms.

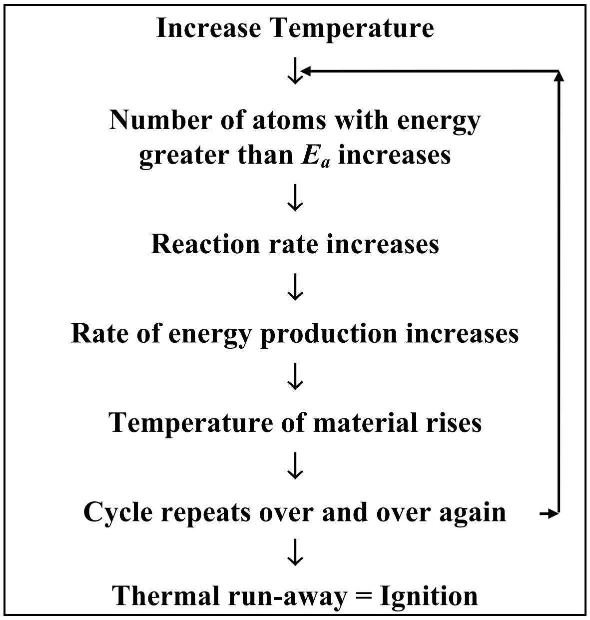

Figure 4. Outline of the accelerating cyclic process leading to thermal run-away and ignition.

duction; which causes a further increase in temperature; etc. This accelerating cyclic process is outlined in Figure 4 and leads to what can be called “thermal run-away” and ignition.

Taken literally, the process outlined in Figure 4, suggests that the slightest temperature rise of a pyrotechnic composition will eventually lead to thermal run-away and ignition. Obviously, as common experience illustrates, this is not correct. The reason is that, thus far, only the rate of thermal energy *production* has been considered, which is only half of the total picture. The rate of thermal energy *loss* from the pyrotechnic composition to the surroundings must also be considered. This more complete energy picture is presented in Figure 5, with both the heat-gain and heat-loss rate plotted as a function of temperature.

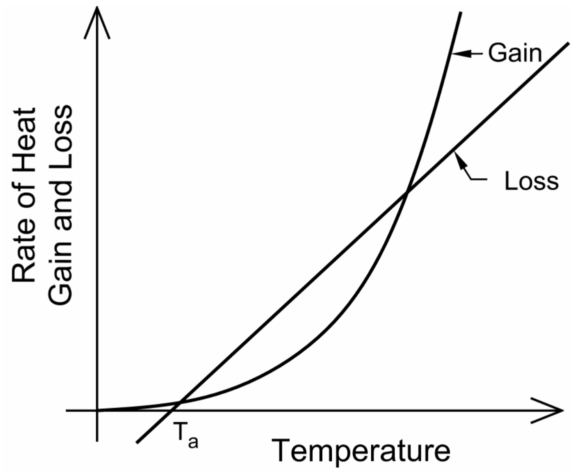

Figure 5. Graph illustrating the rate of heat gain and loss for a pyrotechnic composition as a function of temperature.

The rate of a typical pyrotechnic chemical reaction k follows an exponential relationship,[4] sometimes referred to as the Arrhenius equation:

$$k = Ae^{-E_a/RT} \qquad (1)$$

where A and R are constants, and T is absolute temperature. The rate of heat gain Q_g is just the reaction rate multiplied by the heat of reaction:

$$Q_g = k \cdot \Delta H_r \qquad (2)$$

Thus, in Figure 5, the rate of heat gain curve passes through the origin and rises exponentially (ever more steeply) with increasing temperature.

For a mass of pyrotechnic composition, heat loss from the surface will primarily be from convection through contact with the air. However, any heat generated internally, will first need to be conducted to the surface. Accordingly, for spontaneous heat generation, temperatures at the center of the mass would normally be highest.[c] The rate of heat loss Q_l from the center of the pyrotechnic composition depends on the thermal conductivity of the composition and any packaging, the convective heat loss coefficient, the geometry of the sample (or item), and the difference in temperature between the center of the composition T and ambient temperature T_a. This may be expressed as:[7]

$$Q_l = C\,(T - T_a) \qquad (3)$$

where C is a constant derived from the geometry and thermal properties of the pyrotechnic sample (or item). Accordingly, in Figure 5, the rate of heat loss curve is a straight line crossing the temperature axis at ambient temperature and with a slope equal to C.

To illustrate why, under typical storage conditions, pyrotechnic compositions are metastable and do not spontaneously ignite, as suggested by the process outlined in Figure 4, consider Figures 6 and 7. Figure 6 is an enlarged view of the low temperature region from Figure 5. If a pyrotechnic composition is formulated from materials at ambient temperature, the composition will be at the same temperature, at

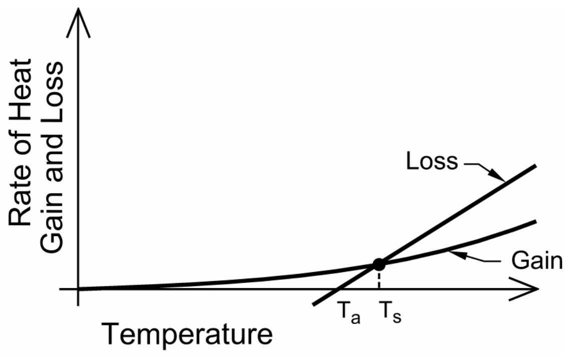

Figure 6. Enlarged view of the low temperature region of Figure 5.

least initially. In Figure 6, note that at ambient temperature, the rate of heat loss is zero, while the rate of heat gain is greater than zero. Accordingly, the temperature of the sample will begin to increase. The temperature of the sample will continue to rise until the rate of gain and loss are equal. This occurs at the crossing point of the "gain" and "loss" curves, where the temperature of the sample T_s has risen to slightly above ambient temperature. (Note that in Figure 6, the temperature difference between T_a and T_s has been exaggerated for clarity.)[d]

Now imagine that for some reason the pyrotechnic composition was momentarily raised from temperature T_s to T_1, somewhat further above ambient, see Figure 7. In this case, both the rate of heat gain of the pyrotechnic composition and the rate of heat loss from the composition, increase. However, the rate of loss is greater than the rate of gain. Accordingly, the net effect will be a loss of thermal energy with time. Thus, the temperature of the composition will decrease and must continue to fall to the temperature where the rates of loss and gain are equal (at temperature T_s). From the above discussion, it can be seen that pyrotechnic compositions are at least meta-stable, in that any small addition of energy will not ultimately cause thermal run-away and ignition.

Figure 7 also shows that if the temperature of the pyrotechnic composition were to be raised momentarily to a still higher temperature T_2, that the results would be quite different. In this case, again both the rate of heat gain and the rate of heat loss increase. However, this time the rate of gain has overtaken the rate of loss. Thus at this temperature, there is a net accumulation of heat, producing a further increase in temperature. In fact, this is an ever-accelerating process, because as the temperature increases, the rate of gain increases much faster than the rate of loss. In this case, the process outlined in Figure 4 does apply and leads to thermal run-away and spontaneous ignition.

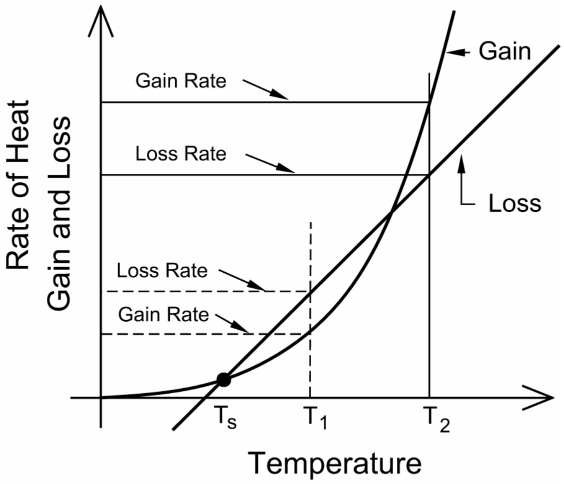

Figure 7. Illustration of the effect of raising the temperature of a pyrotechnic composition.

Thermal Run-Away Temperature[e]

Obviously, the temperature at which thermal run-away can occur for each pyrotechnic composition is of great importance from a safety standpoint. Whenever a pyrotechnic composition is raised above this temperature, it will begin to undergo thermal run-away and will eventually ignite spontaneously. In Figure 8, the run-away temperature is designated as T_r and is the temperature corresponding to where the gain and loss curves cross for the second time. For any composition, this temperature could be established experimentally (with some effort and much time) or mathematically (providing the gain and loss relationships are known).

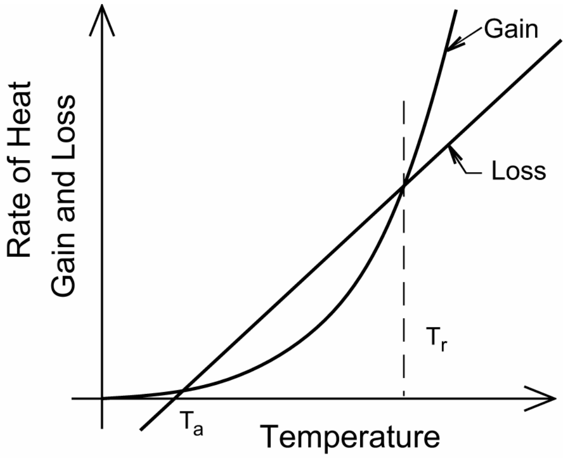

Figure 8. Illustration of the thermal run-away temperature of a pyrotechnic composition, under one set of conditions.

From equations 1 and 2 it can be seen that the rate of heat gain depends on the activation energy and the heat of reaction, which are determined by the formulation of the pyrotechnic composition. The heat of reaction is easy to calculate, providing one knows the equation for the chemical reaction,[5b] or it can be determined experimentally.[5c] Determination of activation energy must be established through experimentation.[9,10] From equation 3, as expressed by the constant *C*, it can be seen that the rate of heat loss depends on the thermal conductivity, the convection coefficient and geometry of the composition, and on ambient temperature. All of these parameters can be determined with only modest effort. However, the rate of heat loss depends on many things other than the pyrotechnic formulation. For example, the degree of compaction of the composition, the size (mass) of the item or sample, and the packaging of the composition all affect the thermal conductivity of the composition or item. Also, the rate of heat loss is a function of ambient temperature. Thus, for each pyrotechnic formulation there is not just one thermal run-away temperature, rather there is one for each of an infinite number of different sets of conditions. This illustrates the problem in trying to use thermal run-away temperature to characterize a pyrotechnic formulation (and why many pyrotechnists have never heard of it).

Spontaneous Ignition Due to Thermal Run-Away

Even though the use of thermal run-away temperature as a way of characterizing pyrotechnic compositions is of limited value, the concept is important because it helps to identify some potentially dangerous conditions where there will be delayed spontaneous ignitions. For example, Figure 9 illustrates the effect of varying sample size. Note that the rate of heat gain (per gram of composition) is unaffected by sample size, but the rate of heat loss is sample-size dependent. Small samples generally lose heat easily and have a rate of heat-loss curve that is steep, with two crossing points, the higher of which is the thermal run-away temperature. As the sample size increases (medium sample size in Figure 9), the slope of the heat loss curve decreases, lowering the run-away temperature more and more with increasing sample size. At some point, for a large sample, there will only be a single point of contact between the curves. This represents the largest sample, under a specific set of conditions, that theoretically will not spontaneously run-away and ignite. For samples larger than this, the rate of heat gain is always more than the rate of loss, and the sample will always run-away thermally. It may take a very long time, but for large enough samples, eventually, there will always be a spontaneous ignition.

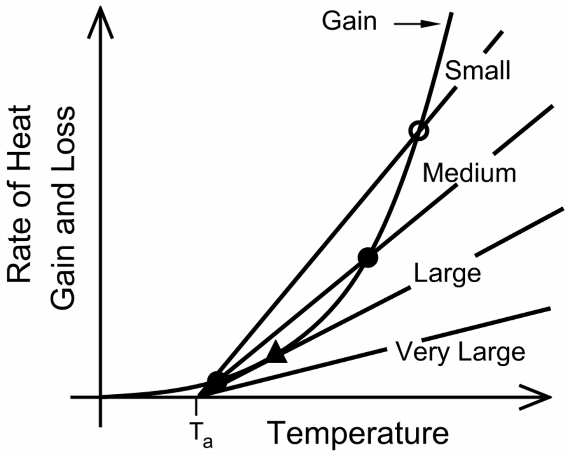

Figure 9. An illustration of the effect of increasing sample size on the rate of heat loss and therefore on thermal run-away temperature.

The rate of heat loss is sample-size dependent because sample size is one factor that affects the constant *C* in equation 3. Another factor is the thermal conductivity of the pyrotechnic composition and its packaging. In Figure 9, poorly conducting compositions and insulating packaging produce effects equivalent to a large sample size.

A somewhat similar situation arises for increasing ambient temperature, see Figure 10. When the ambient temperature is low, samples lose heat to the surroundings fairly easily. This places the heat-loss rate curve fairly high on the heat-gain curve, producing two crossing points, the higher of which is the thermal run-away temperature. As the ambient temperature increases, it becomes more difficult for the sample to lose heat. The slope of the heat-loss curve is unchanged, but its position relative to the heat-gain curve is lower. This lowers the run-away temperature more and more with increasing ambient temperature. At some point, for high enough ambient temperature, there will only be a single point of contact between the curves. This represents the highest ambient temperature, for this type and size of sample, that will not spontaneously run-away thermally (ignite). For ambient temperatures greater than this, the rate of heat gain is always more than the rate of heat loss, and the sample will always run-away thermally. It may take a long time, but, for such hot ambient conditions, there will eventually be a spontaneous ignition.

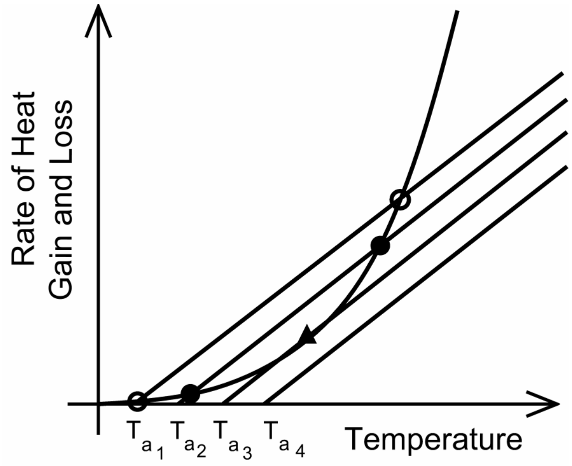

Figure 10. An illustration of the effect of increasing ambient temperature on the rate of heat loss and therefore on thermal run-away temperature.

Just how large a sample and just how high an ambient temperature are required for thermal run-away and spontaneous ignition depends on the chemical formulation and the conditions of its packaging and storage. For some compositions under favorable conditions, it may require a tremendous quantity of material and take an exceptionally long time to run-away and spontaneously ignite. However, under more extreme conditions, or for other compositions, small samples of composition may ignite quickly.

Time to Ignition, "Cook-Off" Tests

The time for any given pyrotechnic composition or device to ignite is a function of the temperature to which it is exposed, as illustrated in Figure 11. If a sample is placed in an oven, its temperature will begin to rise, eventually reaching the temperature of the oven. If the temperature of the oven T_1 is less than the run-away temperature for the pyrotechnic composition, the sample will never ignite (i.e., the time to ignition is infinite).

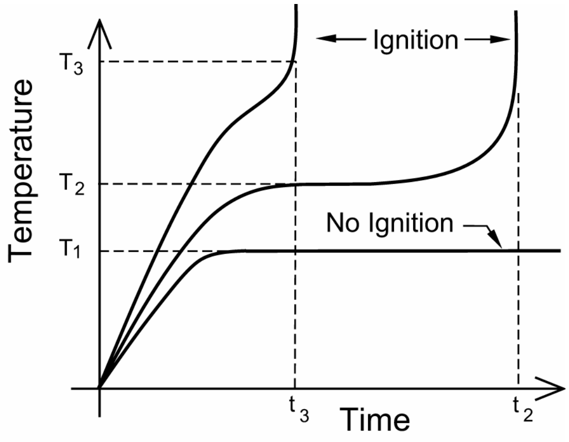

Figure 11. An illustration of the dependence of time to ignition on the temperature to which a pyrotechnic composition is heated.

If the temperature of the oven T_2 is slightly higher than the run-away temperature, upon placement in the oven, the sample will start to heat up and will eventually rise to the temperature of the oven. For a while, it may appear that nothing is happening with the sample. However, inside the sample, heat is slowly accumulating, raising the temperature, at first perhaps imperceptibly. As the internal temperature rises, the rate of reaction increases, increasing the rate of heat gain, and further increasing the temperature (i.e., thermal run-away has begun). As a result of this ever accelerating process, the internal temperature rises ever more rapidly, until eventually there is an ignition, at time t_2 in Figure 11.

If the temperature of the oven (T_3) is significantly higher than the run-away temperature, upon placement in the oven, the sample again will heat up, approaching the oven temperature. However, under these conditions, the sample's temperature rise may not slow very much as it reaches the oven temperature, before thermal run-away is at an advanced state with ignition occurring more quickly at time t_3.

Determining the time to ignition, as a function of temperature, has important ramifications for the storage of pyrotechnics (and explosives). If one were to guess wrong, the consequences of an accidental spontaneous ignition could be disastrous. Tests performed to discover the time-to-ignition and temperature relationship are sometimes called "cook-off" tests.[11] In these tests, samples or items are typically placed in a heated bath, after having thermocouples installed internally. Bath and sample temperatures are monitored as a function of time from the start of the test, and the time to ignition or explosion (if either occurs) is recorded.

Ignition and Ignition Temperature

Ignition is one of the more difficult terms to define in pyrotechnics. Obviously it cannot be defined as when chemical reactions start. As was discussed earlier, some pyrotechnic reactions are occurring all the time, although at a very, very low rate. Even after the thermal run-away temperature has been reached, there may be no obvious sign anything is happening. For most observers, the appearance of a flame (high temperature radiant gases) or at least obvious incandescence of the solid phase is taken as the indication that ignition has occurred. As suggested in Figure 11, at the time of ignition very rapidly accelerating reaction rates produce a near instantaneous rise in temperature, typically from several hundred to two thousand degrees Celsius or higher. Thus, the physical manifestations of ignition develop very rapidly as ignition is occurring.

Ignition temperature can be defined as "the minimum temperature required for the initiation of a self-propagating reaction".[12a] However, from the above discussion, that temperature can vary widely depending on sample conditions and on how long one is willing to wait for the ignition to occur. These problems are mostly eliminated for ignition temperature measurements, because the conditions and delay time are usually specified in the procedure to be used. Unfortunately, there are many different procedures that are used; the *Encyclopedia of Explosives*[13] alone lists 14 different methods. This means there can be more than one ignition temperature reported for the same pyrotechnic composition, depending on which method was used. Fortunately, the various ignition temperatures of the most commonly used methods all tend to be in the same general range, primarily because the measurement conditions of the various methods tend to be somewhat similar. Obviously, however, the most consistent results will be achieved if all measurements are made using the same method. Also, when evaluating reported ignition temperature data, it is useful to know which method has been used. Three hot bath methods and one differential thermal analysis method are described in the following paragraphs.

Hot Bath Method One: Ignition temperature is the lowest temperature of a bath of Wood's metal,[f] to within 5 °C, that results in ignition within 5 minutes for a 0.1 g sample in a preheated small glass test tube inserted 1/3 its length into the bath.[5a]

Hot Bath Method Two: Ignition temperature is the temperature of a bath of Wood's metal that results in ignition in 5 seconds (determined graphically using time to ignition data) for a 1.0 g sample in a thin-walled brass or copper tube (typically a No. 6 detonator shell).[10]

Hot Bath Method Three: Ignition temperature is the temperature of a bath of Wood's metal, heated at a rate of 5 °C per minute, at which ignition occurs for a 0.5 g sample in a tightly corked glass test tube (125 mm long by 15 mm inside diameter with a 0.5 mm wall thickness).[13]

Differential Thermal Analysis Method: Ignition temperature is the temperature of onset of the ignition exotherm for a 10 to 100 mg sample heated at a rate of 50 °C per minute.[14]

A collection of ignition temperatures for a series of two-component, stoichiometric pyrotechnic compositions is presented in Table 2. Shidlovskiy reports the method as one using an electric furnace instead of a bath of Wood's

Table 2. Ignition Temperatures for Binary Pyrotechnic Compositions.[5c]

Oxidizer	Ignition Temperature (°C)				
	Sulfur	Lactose	Charcoal	Mg powder	Al dust
Potassium chlorate	220	195	335	540	785
Potassium perchlorate	560	315	460	460	765
Potassium nitrate	440	390	415	565	890

metal. Unfortunately, he provides no information on the method, other than an estimate of the accuracy of the results to be within 10 °C. (This data was chosen for inclusion because it is the most systematically complete set of data known to the authors.)

It might be of interest to note that a typical pyrotechnic composition raised to its ignition temperature will have about 30 million times more atoms with energies exceeding E_a than at room temperature.[6]

The Effect of Melting and Tammann Temperature

For a pyrotechnic reaction to occur, the atoms (or molecules) must have the required activation energy, and they must be in direct contact with another atom of the correct type. Even for well-mixed solid particles, there are relatively few points of contact between individual particles; see the top illustration of Figure 12. Thus, the number of fuel and oxidizer atoms that are in contact with one another is normally quite small. However, if one of the components melts to flow around the surfaces of the other particles, there is a great increase in the number of atoms in contact; see the bottom illustration of Figure 12.

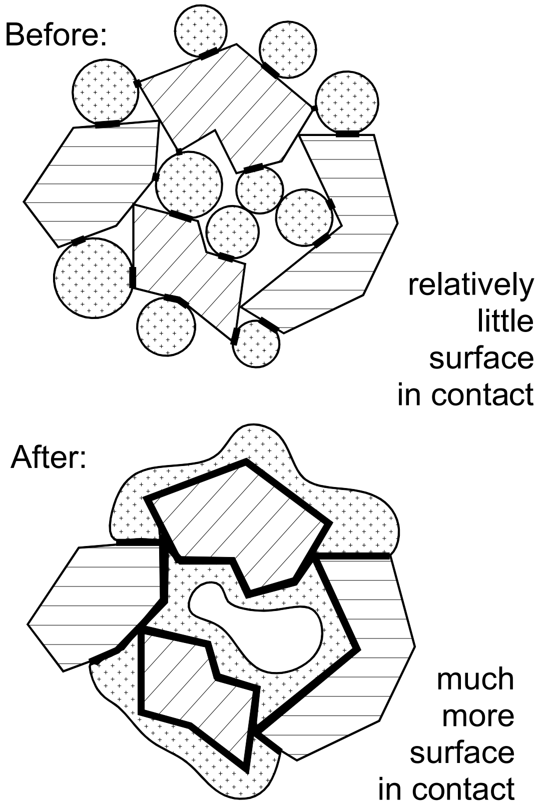

Figure 12. An illustration of the great increase in contact between fuel and oxidizer after one component melts.

Accordingly, melting can have a significant effect on the likelihood of ignition. The potential effect on ignition is outlined in Figure 13. If the percentage of atoms in physical contact increases upon the melting of one component, then more atoms with energies exceeding the activation-energy barrier will be in contact with one another. That means the reaction rate will then be greater, and with it the rate of production of thermal energy, which means that thermal run-away and ignition can occur at a lower temperature than if melting had not occurred. Thus, it is suggested that if a composition is nearing its ignition temperature, and one component of the composition melts, that could result in ignition occurring at that lower temperature. For example, the melting point of potassium nitrate and the ignition temperature of Black Powder are effectively the same.[12b]

Melting can be thought of as occurring when the thermal vibrations of a solid are so strong that many of the bonds, which had been holding the solid together, are broken. While for most

Melting of one component

↓

The percentage of atoms in physical contact increases

↓

More atoms with energies exceeding E_a are now in contact and will react

↓

Rate of reaction increases

↓

Rate of energy production increases

↓

Thermal run-away (ignition) occurs at a lower temperature

Figure 13. An outline of the effect of melting on thermal run-away and ignition temperature.

pure chemicals melting has a sudden onset at a specific temperature, the vibrations of the atoms in the solid become increasingly strong as the temperature is increased toward the melting point. This can be thought of as the loosening of the bonds holding the solid together. It has been suggested that at an absolute temperature halfway to the melting point, the bonds become so loose that there can be a significant commingling of the atoms of particles that are in direct contact.[8b] This temperature is called the Tammann temperature after the researcher making this observation.

Table 3. Tammann Temperatures for Common Pyrotechnic Oxidizers.[12c]

Oxidizer	Tammann Temp. (ºC)
Sodium nitrate	17
Potassium nitrate	31
Potassium chlorate	42
Strontium nitrate	149
Barium nitrate	160
Potassium perchlorate	168
Lead chromate	286
Iron(III) oxide	646

Tammann temperatures are of interest because samples at or above these temperatures demonstrate significantly increased sensitivity to accidental ignition. Table 3 lists the Tammann temperatures for some common pyrotechnic oxidizers.

Propagation and the Propagation Inequality

Having successfully ignited a pyrotechnic composition is no guarantee that the reaction will propagate throughout it. This is because the application of an external stimulus, such as a flame, typically provides thermal energy to only a small portion of the composition, and the ignition stimulus is usually of relatively short duration. After its application, the pyrotechnic combustion reaction will continue to propagate through the composition only so long as the pyrotechnic reaction itself provides sufficient energy to the unreacted composition. What is needed is sufficient energy to raise the unreacted composition above its ignition temperature. This process is illustrated in Figure 14. The portion of the rod of pyrotechnic composition to the extreme right has already been consumed by burning. Just to the left of that is a thin disk of composition that has ignited and is still reacting (burning). Just left of that is another thin disk of composition, labeled “pre-reacting material”, which has not yet ignited. This disk of pre-reacting material will only ignite if it is raised above its ignition temperature, which means that a significant number of its atoms and molecules will have received at least

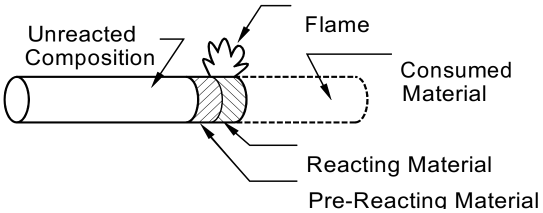

Figure 14. Illustration of a propagating rod of pyrotechnic composition.

the required activation energy E_a.

Most of the energy being produced by the reacting material (the heat of reaction ΔH_r) is lost to the surroundings. However, some fraction of the energy (F_{fb}) will be fed back from the reacting layer to the pre-reacting layer. The actual amount of energy fed back is just the product of the heat of reaction and this fraction (i.e., $\Delta H_r \cdot F_{fb}$). Propagation will occur providing more energy is fed back than is required for ignition of the pre-reacting disk of composition. This statement, then, gives rise to something that could be called the "propagation inequality"

$$\Delta H_r \cdot F_{fb} > E_a \tag{4}$$

As long as this relationship holds true, propagation will continue.

Obviously, the probability of successful pyrotechnic propagation is increased by anything that results in more energy being produced by the burning composition, a greater percentage of that energy being fed back, or a reduction of the activation energy requirement. The heat of reaction and the activation energy are determined by the chemical nature of the composition; unfortunately, a thorough discussion is beyond the scope of this article.[g] Energy is fed back to the pre-reacting layer through any combination of conduction, convection, or radiation. These are more fully considered in Figure 15, where some of the factors influencing the efficiency of these mechanisms are also presented.

Figure 16 is similar to Figure 14 but provides a more compete description of the propagation process, including information on the relative temperatures expected. Zone (**a**) is unreacted pyrotechnic composition, which has thus far been unaffected and remains at ambient temperature. Zone (**b**) is described as the warm-up zone, where the temperature has started to rise above ambient, because of thermal conduction and possibly convection. It is in this zone where reaction rates are first beginning to increase. These reactions are sometimes referred to as "pre-ignition reactions",[8c][h] and contribute relatively little thermal energy. In Zone (**c**), the temperature has risen significantly, at least one component of the composition has melted, and some gaseous materials may be bubbling to the surface. Because of the rise in temperature and the greatly increased contact between fuel and oxidizer, the reaction rate in Zone (**c**) and the production of heat is greatly increased. In Zone (**d**), much of the reaction is occurring in the gas phase; however, some droplets of reacting composition ejected from the surface may be present. Again the reaction rate and the thermal energy being produced have increased substantially from the previous zone, and the temperature has peaked. In the final region,

Conduction:

- **Thermal energy (molecular vibration) is conducted along solids from hotter to cooler.**
- **Factors maximizing conductive feedback:**
  - **Compacted composition**
  - **Metal fuels**
  - **Metal casing or core wire**

Convection:

- **Hot gases penetrate the solid composition along spaces between grains (fire paths).**
- **Factors maximizing convective feedback:**
  - **Uncompacted composition**
  - **Granulated composition**

Radiation:

- **Thermal (infrared) radiation, emitted from flame and glowing particles, is absorbed by incompletely reacted composition.**
- **Factors favoring radiative feedback:**
  - **Solid or liquid particles in flame**
  - **Dark or black composition**

Figure 15. Outline describing the mechanisms of pyrotechnic energy feed back and the factors that affect them.

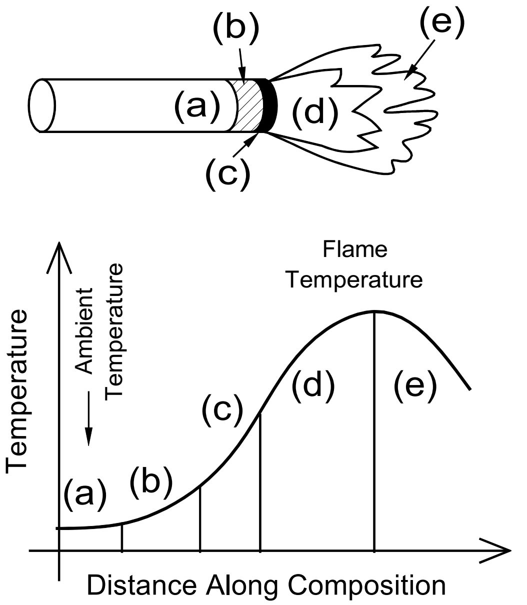

Figure 16. A more complete description of the processes of pyrotechnic propagation:
*(**a**) unreacted composition; (**b**) warm-up zone; (**c**) condensed phase reactions; (**d**) gas phase reactions; and (**e**) reactions complete. (Based on reference 5d.)*

Zone (**e**), the energy producing reactions have ceased, and because of heat loss to the surroundings, the temperature begins to fall significantly.

Conclusion

The subjects of ignition and propagation could have been dealt with much more expeditiously. Specifically, it could simply have been stated that ignition requires raising at least a portion of a pyrotechnic composition to its ignition temperature, and that propagation requires the feed back of sufficient energy for continuing self-ignition of the composition. However, while this would have saved much time, it would have provided little understanding of the important principles involved. Accidents caused by unintentional ignitions continue to plague the pyrotechnics industry. In addition, ignition failures with fireworks, whether leaving an unfired-aerial shell in a mortar that needs to be cleared or resulting in a dud shell left after a fireworks display, have serious potential for accidents as well. Ignition or propagation failures with signaling smokes or flares may cause someone to not be rescued. It is through a more thorough understanding of the basis for ignition and propagation, that pyrotechnists will be better able to solve potential problems before accidents occur.

Acknowledgments

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Notes

[a] More recent usage of this term is “Enthalpy of Reaction”.

[b] The use of the term “activation energy” in the context of solid-phase pyrotechnic compositions has a slightly different meaning than in aqueous or gas-phase chemistry. In aqueous and gas-phase chemistry, molecules can be thought of as reacting individually, or at least in small groups. In that case, activation energy can be thought of as the amount of energy needed for a collision between two individual molecules to cause them to react. However, a typical pyrotechnic composition is composed of solid particles of fuel and oxidizer, with each particle comprised of many billions of atoms or molecules. In this case, activation energy takes on much more of a macroscopic and less precise meaning. For the purpose of this article, activation energy of solid-phase pyrotechnic compositions is generally taken to mean that amount of thermal energy needed to induce a sustained exothermic reaction within a tiny portion of the composition.

[c] Pyrotechnic compositions, especially those of dark color, exposed to bright sunlight may be an exception to the generalization about the highest temperature expected to be in the middle of the composition.

[d] Note that it is assumed the composition is physically at rest (i.e., it is not being mixed, which adds energy to the system).

[e] In some texts thermal run-away temperature is called the critical temperature[1] or the reaction temperature.[8a]

[f] Wood's metal is a eutectic alloy of bismuth, lead, tin and cadmium. It melts at 70 ºC.

[g] Some oxidizers are known for producing compositions with low activation energies (e.g., chlorates), while other oxidizers tend to produce compositions with especially high activation energies (e.g., oxides and sulfates). Fuels with low melting points or low decomposition temperatures (e.g., sulfur, lactose and acaroid resin) tend to form compositions with low activation energies. Metal fuels tend to produce compositions with high heats of reaction.

[h] Pre-ignition reactions are typically reactions taking place in the solid state. While such reactions can be a source of energy, they generally only contribute in a minor way to promoting ignition. In part, this is because solid-state reaction rates are constrained by the difficulty of fuel and oxidizer commingling while both remain solid.

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Burn Rates of Clusters of Colored Sparklers

K. L. and B. J. Kosanke

In recent years it has become generally known that clusters of sparklers burn at substantially greater rates than individual sparklers. However, except for a previous article[1] by the authors, little if any quantitative data has been presented on this subject. That previous article contained data for Flying Dragon No. 8 Gold Sparklers, and a summary of those results is presented in Table 1. As background information, that article also contained a brief discussion of burn types and some factors acting to control burn rates. Any reader wishing to review those subjects can consult that article or two other articles presenting more complete discussions.[2,3] The current article presents some data for 10-inch Red Lantern "Electric Sparklers" (colored sparklers) and discusses some aspects of consumer warnings and directions.

The method used to collect data for this article is essentially identical to that used in the previous article, with the exception that in this study the maximum number of sparklers in a cluster was five. The groups of sparklers were held together using a pair of 1/8-inch wide wire ties around the sparkler composition, and by twisting one wire handle around the others, see Figure 1. Burn times for these sparklers are reported in Table 2 and are averages of four tests for each number of sparklers. The times were determined using a video taped record of the tests, starting the time measurement at the very first sign of burning and continuing until the last burning ceased. Note that data was only collected for red and blue colored sparklers, not for green-colored sparklers, which burned much more feebly.

Table 1. Burn Times for Clusters of Gold Sparklers.

Number of Sparklers	Average Burn Time (s)	Burn Rate Increase (%)(a)
1	38	≡ 0
2	30	30
3	21	80
4	17	120
6	8.5	350
12	6.0	530
24	6.0	530

(a) Burn rate increase is rounded to the nearest 10%.

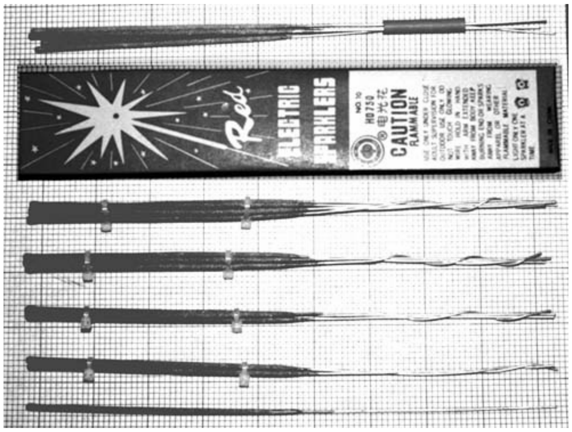

Figure 1. Photo of clusters of Red Lantern colored sparklers.

As can be seen in Table 2, there is indeed a dramatic decrease in the burn time for these sparklers, falling to about 5 seconds, or about one tenth the burn time of a single sparkler. In fact, the increase in burn rate for bundles of 5 red or blue sparklers is greater than bundles of 12 or 24 gold sparklers. Figure 2 illustrates the effect of clustering sparklers with respect to the amount of fire produced during burning. Note that, because of the metal fuel content of sparkler composition, flame temperatures are ex-

Table 2. Burn Times for Clusters of Colored Sparklers.

Number of Sparklers	Ave. Burn Time (s)	Burn Rate Increase[(a)] (%)
1 Blue	51.2	≡ 0
2 Blue	38.3	30
3 Blue	14.6	250
4 Blue	7.7	560
5 Blue	5.2	880
4 Blue[(b)]	10.0	410
1 Red	44.1	≡ 0
2 Red	28.3	60
3 Red	5.6	690
4 Red	5.1	760
5 Red	4.9	800

(a) Burn rate increase is rounded to the nearest 10%.

(b) Cluster held together loosely using only a small tube around the wire handles, as shown at the top of Figure 1.

pected to be considerably higher than that produced by many other fireworks compositions.

As a practical matter, the increase in burn rate is even greater than suggested in Table 2. This is a result of the method used to measure the burn time, which was from the very first sign of burning to the very last burning of any sparkler. The first and last portions of the burning of clusters of sparklers proceed considerably slower than the middle portion of the burning. In an attempt to determine these middle burn rates, another series of measurements were made. In each case, a cluster of four sparklers was used and four separate tests were performed. In some measurements, a pair of thin wire gauge thermocouples (type K) were mounted with their junctions within the cluster of sparklers, and separated by a distance of three inches. (The total length of sparkler composition was approximately five inches.) The thermocouples were wired in reversed series; accordingly, when both thermocouples were at approximately the same temperature, there would be no voltage produced. However, when a high temperature was sensed by the first thermocouple a proportionally large voltage would be produced. Then as that temperature dropped, but especially when a high temperature was sensed by the second thermocouple, the voltage would fall and reverse polarity. In these measurements, a digital oscilloscope was used to record and store the thermocouple data as a function of time when the clusters of sparklers were burned.

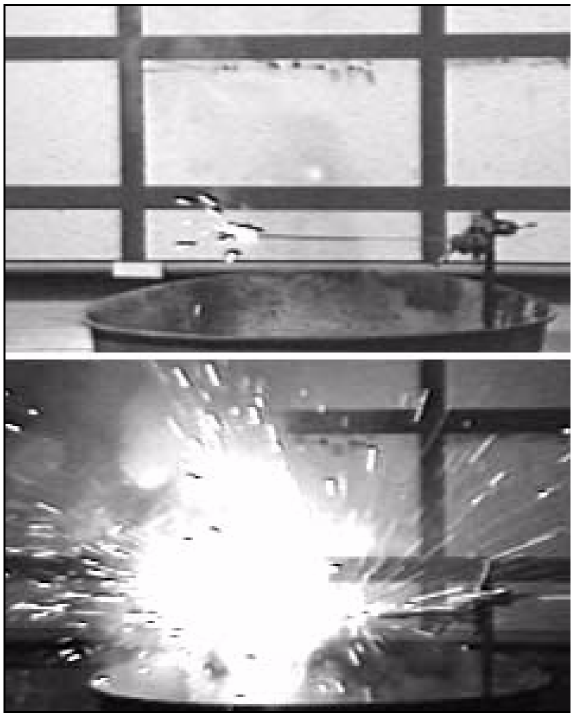

Figure 2. Examples of burning a single colored sparkler (above) and a cluster of four sparklers (below).

The thermocouple method produced usable times for the advancement of the flame front, but the data was quite noisy, possibly because of the messy chemical environment around the thermocouples. Accordingly, another method was used, in which very thin copper wires (36 AWG) were positioned across the clusters of sparklers. Because of the high flame temperature of the burning sparklers, soon after the arrival of the flame front the wire would melt opening an electric circuit, acting as a thermal fuse. By measuring the elapsed time between the melting of the two wires, burn time for the middle three inches of the sparklers could be estimated. The results of both sets of measurements are presented in Table 3. Note that the average time for advancement of the flame front through the middle 60 percent of the length of the sparkler is very short, approximately one second.

Table 3. Burn Times for the Middle 60% of Colored Sparkler Clusters.

Number of Sparklers	Sensing Method	Average Burn Time (s)
4 Blue	Thermocouple	1.17
4 Red	Fuse Wire	0.95

Clusters of sparklers that are not held together as tightly as accomplished using cable ties are not expected to burn as rapidly. The reason is that the hot combustion gases can more freely escape the fire path formed by the group of sparklers. This speculation was confirmed in one brief series of tests, wherein clusters of four blue sparklers were held together using only a thin tube to hold the wire handles together, as illustrated by the cluster of sparklers at the top of Figure 1. Even though the sparklers burned quite rapidly. They did burn slower than those secured using cable ties.

It is fairly likely that a consumer, attempting to light a group of sparklers, would not hold them clustered as tightly together as in these experiments. Thus the majority of consumers attempting to light multiple sparklers would not experience such extreme increases in burn rate. However, it is possible that an occasional consumer would be unfortunate enough to hold a group of sparklers in a tight cluster, such that after lighting, they would burn very quickly and with a substantial amount of high temperature flame. Such a consumer, especially if they were distracted momentarily or were not paying full attention to lighting the sparklers, could easy suffer a serious burn injury to the hand. (Certainly, such serious injuries have occurred.)

The manufacturer of the colored sparklers tested in this study had the foresight to include the direction (warning) on their sparkler boxes "LIGHT ONLY ONE SPARKLER AT A TIME". Perhaps this was in response to the AFSL suggested cautionary message "HOLD AND LIGHT ONLY ONE SPARKLER AT A TIME".

As appropriate as the "light only one sparkler" warning is, there is a problem with it, and it is a problem with no obvious solution. The problem is that warnings are most effective when the reason for them is fairly obvious. For example, the reasons are obvious for the warning "DO NOT TOUCH GLOWING WIRE" and "KEEP BURNING END AND SPARKS AWAY FROM CLOTHING OR OTHER FLAMMABLE MATERIAL". To the contrary, the warning about lighting only one sparkler is not readily apparent to a typical consumer. Thus it would be preferred if a warning could be found that specified or at least implied why this is important.

As final tests for both the No. 8 Gold Sparklers and the 10-inch Colored Sparklers, the remaining nearly full cases of sparklers were ignited. The purpose of these tests was to get an idea whether the sparklers, when still in their individual boxes, would tend to burn in mass. The ignitions were accomplished by aiming the flame from a propane torch at the side of the cartons. In each case, roughly a minute elapsed before any sparklers ignited. In both experiments there failed to be a mass ignition of the sparklers, with only individual boxes of sparklers igniting in a random fashion. Nonetheless, the output from the colored sparklers was much greater than for the gold sparklers. It seemed likely that, had there been many cases piled together, after a period of random ignitions of individual boxes of sparklers, there would have been a near mass ignition of the remaining colored sparklers. It must be acknowledged, however, that these two single-carton ignition tests were very limited in scope. Before any definitive conclusion can be reached about mass burning capabilities, more thorough testing would be required.

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