*Pyrotechnic Literature Series No. 3*

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

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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 130 articles on fireworks, pyrotechnics and explosives. They recently finished their first book, *The Illustrated Dictionary of Pyrotechnics*. 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 version appeared in *Pyrotechnics Guild International Bulletin*, No. 84 (1993).

# Timing Aerial Shell Bursts for Maximum Safety and Performance

K.L. and B.J. Kosanke

The time chosen for the interval between a shell firing and its burst is sometimes given less thought than it deserves. By carefully choosing the delay interval provided by the time fuse, it may be possible to produce undistorted bursts, with a higher level of safety.

When an aerial shell bursts, while it is nearly stationary, its stars are propelled outward, each experiencing nearly the same aerodynamic drag. Thus the symmetry of the burst is determined only by the construction of the shell, and the pattern will appear to be suspended in the air for its duration. That is to say, a properly made peony will appear as an expanding, near-perfect sphere and will seem to hang motionless in the air as it spreads. See the left column of Figure 1, which is intended to appear as a timed sequence of the burst and expanding pattern of stars from a near stationary spherical shell. On the other hand, if the same shell were to burst while it was in rapid motion, the star pattern would be distorted. This is because the spreading stars would be subjected to a little different aerodynamic force depending on which way they were traveling relative to the motion of the shell. The star pattern will appear smaller and somewhat elliptical. Also the star pattern will be slightly more sparse on the bottom than on the top. Perhaps, most noticeably, the developing star pattern will move in the direction of the original shell motion, and will appear to expand from a point which is not at the center of the pattern. See the right column of Figure 1 for an illustration of the case where the upward motion of the shell approximately equals the burst velocity of the stars. (Readers wishing to learn more about star ballistics are referred to Reference 1.) Thus there are aesthetic reasons why aerial shells are normally intended to burst near their apogee, when their upward motion has essentially stopped.

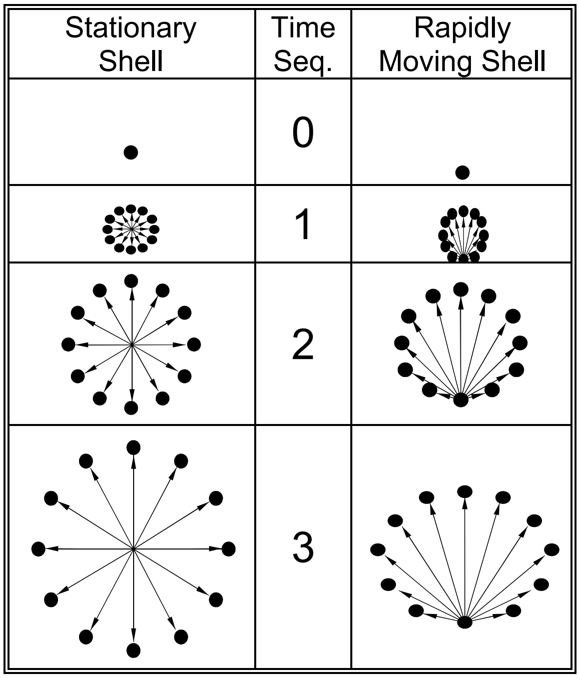

*Figure 1. Time sequence views of stationary and rapidly moving aerial shell bursts.*

The time interval during which the vertical motion of an aerial shell has virtually stopped is longer than many may realize. Aerial shells spend more than four seconds traveling up and down only 70 feet at their apogee, and this is independent of shell size, see Figure 2. These results were generated using the computer model described in an earlier article.[2] This illustrates the trajectory of typical 3, 6, and 12-inch aerial shells fired from slightly angled mortars, where the time elapsing between each point is one second. The plotting of the shell trajectory data is terminated a few seconds after the shell's apogee.

**Table 1. Input Parameters and Results of Computer Modeling.**

| Nominal Shell Size: | 3" | 6" | 12" |
|---|---|---|---|
| Input Parameters: | | | |
| Shell shape | Spherical | Spherical | Spherical |
| Shell Diameter (inches) | 2.75 | 5.56 | 11.50 |
| Shell Weight (pounds) | 0.3 | 2.5 | 18.0 |
| Drag Coefficient[a] | 0.40 | 0.37 | 0.31 |
| Muzzle Velocity (ft/sec) | 300 | 340 | 360 |
| Results: | | | |
| Apogee Height (feet) | 440 | 760 | 1100 |
| Time to Apogee (seconds) | 4.5 | 6.0 | 7.6 |
| ± 70 ft Time Interval (sec) | 4.1 | 4.2 | 4.2 |
| Approx. Ideal Burst Times (sec) | 2.5–3.0 | 4.0–4.5 | 5.5–6.0 |
| Experimental Burst Height (ft)[b] | 406 ± 50 | 776 ± 52 | 1164 ± 134 |

[a] Empirically determined from published data.[2]

[b] Experimentally determined aerial shell burst heights were reported earlier.[3]

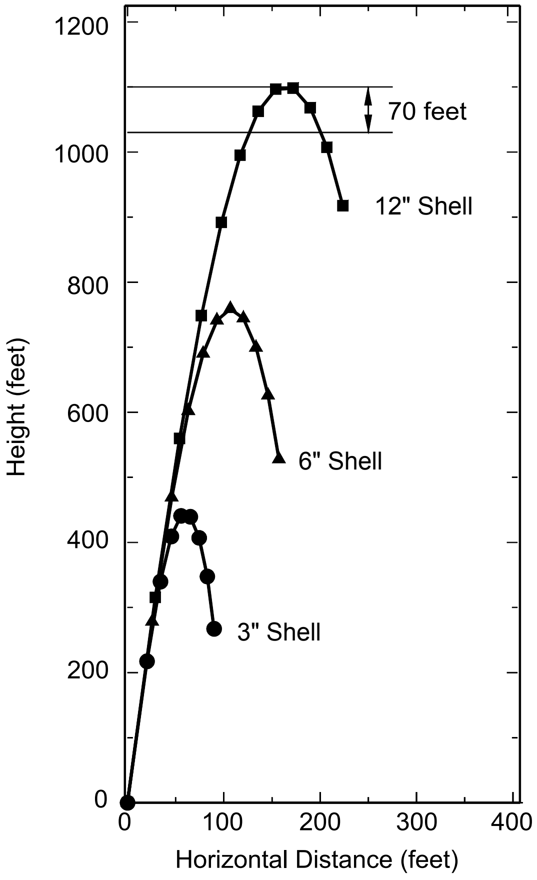

*Figure 2. Trajectories of spherical aerial shells illustrating the approximate 4-second, near-stationary, interval about the apogee.*

Table 1 presents the input data for the computer model, as well as, the results. Included in the results is the approximate time for the shell to travel up and then back down the last 70 feet about its apogee. In each case, this time is about 4.2 seconds, independent of shell size. Thus it is relatively easy to time the burst of an aerial shell to occur during this 4-second period. In terms of fullness and symmetry of the star pattern, because the shell is moving so slowly during this interval, a burst at any time is equivalent. In terms of safety, however, all times are not equivalent. If the burst is planned to occur at or near the start of this interval, there will be added time to allow a damp or sputtering time fuse to complete its task before the shell falls too close to the ground for its stars or components to burn out before endangering people or property. Similarly, on those occasions when shells are mistakenly fired from over-sized mortars, the amount of burning debris reaching the ground will be lessened if the shell has been designed to burst early during the 4-second interval about its intended apogee.

Thus, by selecting the time-fuse delay (length) so that bursts occur 1.5 to 2.0 seconds prior to apogee, safety may be increased without loss in aesthetic performance. These times are included in Table 1 as approximate ideal burst times for the stated input parameters. Obviously, the actual time delays need to be determined by experimentation and will depend on individual shell and mortar parameters.

## References

1) T. Shimizu, *Fireworks from a Physical Standpoint, Part III*, Pyrotechnica Publications, Austin, TX, 1985.
2) K.L. and B.J. Kosanke, "Aerial Shell Ballistic Computer Modeling", *Pyrotechnica XIV*, Pyrotechnica Publications, Austin, TX, 1992.
3) K.L. Kosanke, L.A. Schwertly and B.J. Kosanke, "Report of Aerial Shell Burst Height Measurements", *PGI Bulletin* No. 68, 1989.

An earlier version appeared in *Pyrotechnics Guild International Bulletin*, No. 85 (1993).

# Aluminum Metal Powders in Pyrotechnics

K.L. and B.J. Kosanke

[This article is an updated, enlarged version of one originally appearing in *Pyrotechnics Guild International Bulletin* Nos. 27 and 28 (1981–82).]

Of those chemicals used in pyrotechnics (with the possible exception of charcoal) aluminum metal powders have the ability to produce the greatest variety and range of effects. Thus, mastery of the use of aluminum in pyrotechnics offers both a challenge and a reward. In an attempt to assist in achieving that mastery, this article presents information on aluminum metal powders and their use in pyrotechnics. However, the emphasis is on physical aspects of aluminum metal powders, rather than on aluminum chemistry. The subject of specific uses of aluminum in pyrotechnics has been covered by other authors, and numerous references to such articles are given in the last section of this paper.

## A) Background Information

Aluminum is the third most abundant element found in the Earth's crust (8.13%). It derives its name from alumen, which is Latin for alum (aluminum sulfate). Because aluminum has a great affinity for oxygen, it does not occur naturally as the pure metal. Aluminum is produced in an energy intensive two step process from the natural ore Bauxite, which is a mixture of minerals rich in hydrated aluminum oxides. In the first step (Bayer Process) the Bauxite is refined to alumina (aluminum oxide). In the second (Hall-Heroult Process) the alumina is electrolytically reduced to molten aluminum metal.

From a chemical standpoint, aluminum is very reactive; so much so that particles of aluminum metal become coated with aluminum oxide almost instantly when exposed to air. The formation of an oxide coating is not unusual for a reactive metal; what is unusual is the extent to which aluminum's oxide coating protects the metal from further chemical attack. In most circumstances, aluminum powders behave quite stably in pyrotechnic compositions. However, there are occasions when unwanted (unexpected) reactions have had disastrous consequences. See References 1 and 2 for an introduction to aluminum's potential for undesirable reactivity in damp compositions. In the authors' research and as reported in the literature, it has been shown that weak acids (such as boric acid), potassium dichromate, and silicates tend to passivate aluminum's water reactivity, whereas all bases and many strong acids increase aluminum's reactivity. In all cases this seems to be a result of either a strengthening or an eroding of the protective oxide coating on the aluminum particles.

## B) General Descriptive Terms: Dark, Light, and Bright

The authors suggest that the use of these terms be avoided as being too general to sufficiently describe the wide range of aluminum metal powders presently in use. Also, today, they have come to mean different things to different people, sometimes leading to confusion and poor results. The differences in effects produced by various aluminum powders are profound, and even subtle differences, not easily detectable by eye or feel, can produce significantly different results.

Historically, "dark" referred to extremely fine flake aluminum, because finer flakes generally appear darker. This is a consequence of light scattering from the more numerous irregular particle surfaces. However, an exception is "German dark" aluminum. Here much of the dark appearance results from the presence of carbon, produced during its manufacture (discussed further below). Sometimes different grades of German dark aluminum have been described as Yellow-Head, Blue-Head and Black-Head, all appearing quite dark because of the carbon, but each having different particle sizes. Thus, at

**Table 1. Mesh and Particle Sizes, with Examples.**

| US Standard * Sieve Mesh No. | Space between Wires | | Typical Material |
|---|---|---|---|
| | Inches | Microns** | |
| 14 | 0.056 | 1400 | Coarse sand |
| 28 | 0.028 | 700 | Beach sand |
| 60 | 0.0098 | 250 | Fine sand |
| 100 | 0.0059 | 150 | Popcorn salt |
| *** | | | |
| 200 | 0.0030 | 74 | Portland cement |
| 325 | 0.0017 | 44 | Silt |
| 400 | 0.0015 | 37 | Plant pollen |
| (600) | 0.0010 | 25 | |
| (1200) | 0.0005 | 12 | Red blood cell |
| (2400) | 0.0002 | 6 | |
| (4800) | 0.0001 | 2 | Cigarette smoke |

* The mesh numbers in parentheses do not exist as actual sieves; they are included for comparative reference. For this reason, mesh numbers greater than 325 or 400 are sometimes referred to as "sub-mesh" sizes.

** One micron is a unit of length equaling 1 millionth of a meter (about 1/25,000 of an inch). It is a convenient and frequently used unit to use in describing fine powders.

*** For most people, somewhere between 100 and 200-mesh, powders become "impalpable". Their particles are so small they cannot be felt when a small sample is rubbed lightly between the fingers.

least in the case of German dark aluminums, darkness of appearance is not a useful guide to particle size.

To most pyrotechnists, "bright", not light, is the opposite of the attribute dark. Bright also refers to flake aluminum, but in this case the flakes are large enough (and free of carbon) to appear shiny bright. This effect is enhanced if the flakes are coated with stearin or similar material in the manufacturing process. Although bright aluminum powders are generally larger in particle size than dark aluminums, it must be noted that bright flake aluminum can still be extremely fine and dangerously reactive. Indeed, most flash powders found in Chinese firecrackers contain "bright" aluminum powder.

"Light" usually refers to atomized aluminum metal powders. The particles have a much more 3-dimensional character than flakes. Unfortunately, confusion can arise because some "light" atomized aluminum powders can appear as dark as "dark" flake aluminum, and yet are tremendously less reactive.

It is felt that confusion in describing aluminum metal powders can be avoided by using the more descriptive terms "flake" and "atomized", along with an indication of particle size. Possibly the one exception to this rule is the use of the special term "flitters", which are gigantic flakes, usually in the range of 10 to 80 mesh.

## C) Particle Size Descriptions

Probably the method most commonly used to describe particle size is the specification of the sieve mesh number (screen) that either passes or retains the particles in question. Here mesh number refers to the number of strands per inch (of standard-diameter wire) used to make screen cloth (i.e., 10-mesh screen has ten wires per inch). Note that this means that 1/10-inch particles will not pass a 10-mesh screen because of the width taken by the wire. The diameter of wire used depends on mesh size (i.e., 100-mesh screen has very fine wire as compared to 10-mesh screen). A complicating factor is that there are at least two sets of "standard" and many non-standard wire sizes in use; this means not all 50-mesh screens have the same size gap between their wires. However, the difference is generally not so great as to cause serious problems. Table 1 lists the more commonly used "US Standard" mesh numbers and the resulting space between their wires.

The concept of mesh size seems simple, but exactly what does it mean to describe an aluminum powder as 100 mesh? For any commercially produced powder, individual particle sizes range widely, sometimes extremely widely. Thus it obviously does not mean that each of the particles are exactly 0.0059 inches in diameter. Does it mean that all particles will pass through a 100-mesh screen? It means that to some people, but others say it means that 99%, 90% or even 50% of the material will pass through a 100-mesh screen. Probably the best way to use mesh size is to specify the percentage by weight that passes through one size mesh screen but fails to pass another finer mesh screen. For example, a powder might be described as 95% passing 50-mesh but retained on 150-mesh screen. To be more complete, it would be better to include information on how the particle sizes are distributed throughout a broad range. For example, 3% is +50 mesh, 20% is in the range from –50 to +80, 40% is from –80 to +120, 35% is –120 to +150, and 2% is –150. (In this case, the "+" sign means "fails to pass" or is larger than the specified mesh, and the "–" sign means "passes" or is smaller than the specified mesh.) Such a complete description of the range of particle sizes is lengthy and perhaps offers more information than is actually necessary for most pyrotechnic uses.

As a practical matter, when only a single mesh number is given, such as 325 mesh, it can be assumed that at least half of the material will pass that mesh screen. When a single "+" or "–" mesh number is given, such as +200 mesh or –400 mesh, it can be assumed that most of the material will be "retained on" or "will pass through" that mesh screen, respectively. When a pair of mesh numbers is given, such 100–200 mesh, it can be assumed that most of the material will pass the courser screen but will be retained on the finer screen.

A brief alternative to specifying a single mesh number, but offering slightly more information, is to give the average particle size for a powder. For example, an aluminum powder might be described as having an average particle size of 5 microns. That can be taken to mean that about half of the weight of material is composed of particles larger than 5 microns and about half smaller than 5 microns. Note that a micron is a millionth of a meter or about .0025 inch and is sometimes abbreviated "µ".

## D) Aluminum Manufacturing Processes

There are three different manufacturing processes for aluminum metal powder, plus some significant variations. The first is simply grinding or shredding the material. This method is no longer very common and cannot be used to make the smallest particle size aluminum powders. A ground aluminum powder has a granular appearance, with edges and points appearing quite sharp when viewed under magnification.

Probably the most common method of producing aluminum powders is by atomization. In this case, molten aluminum is sprayed into a gas stream, where the droplets solidify as they fall to a collecting area. A wide range of particle sizes can be made using the atomization process. For example, some of the most fine and most coarse aluminum powders used in pyrotechnics are produced by atomization. One method for separating different sizes of atomized aluminum particles during manufacture is to use air currents, in a process similar to separating wheat from chaff.

When viewed under magnification, all atomized aluminum particles have a roundish appearance, although the degree of roundness can vary greatly. If aluminum droplets are sprayed into an inert atmosphere, surface tension and viscosity will cause them to form fairly perfect spheres before the particles solidify. This material would be described as "spherical" atomized powder. In other instances, the droplets are sprayed into air, which causes a heavy oxide coating to immediately form on the surface of the still molten particles. This acts to quickly freeze the particles into spheroids, somewhat like footballs and door knobs.[3] This material would be described as "spheroidal" atomized powder. See Photos 1 and 2 for examples of spherical and spheroidal aluminum powders. In some cases the particles can have a highly angular appearance. Aluminum produced in this manner is usually quite coarse and appears very much like ground aluminum. The difference being that the angular points and edges appear slightly rounded, not sharp, when viewed under magnification. Sometimes this type of atomized

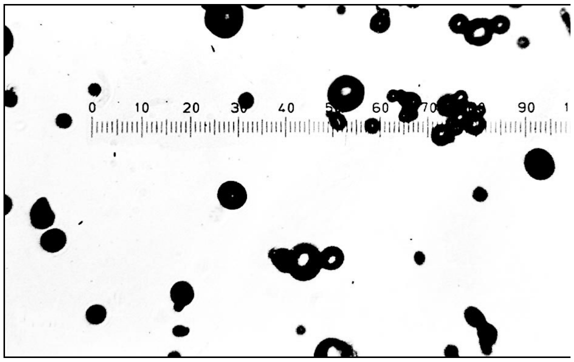

Photo 1. Photomicrograph of 30 micron spherical atomized aluminum powder; each scale division is 10 microns.

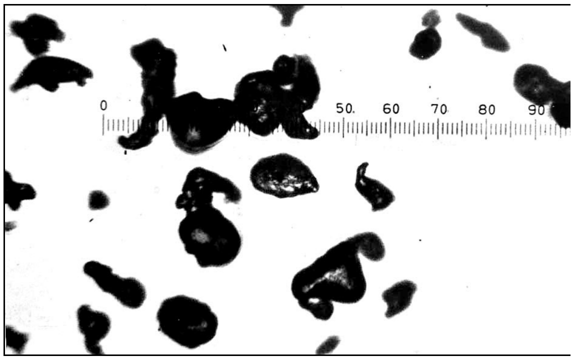

Photo 2. Photomicrograph of 20 micron spheroidal atomized aluminum powder (Alcoa 101,); each scale division is 2.4 microns.

aluminum is referred to as "blown" aluminum (term not recommended). These three different types of atomized aluminum can behave rather differently in pyro-chemical reactions. For that reason the shape of atomized aluminum (i.e., spherical, spheroidal or granular should be included in a complete description).

The third manufacturing process produces flake aluminum. In this case, aluminum particles or foils are either rolled or hammered into very thin flakes, see Photo 3. In any event, a lubricant must be added to the aluminum to prevent the flakes from sticking together and onto the rollers or hammers. Stearic and oleic acid, constituents of natural fats, are commonly used as the lubricant. The presence of the lubricant often gives flake aluminum a slippery feel, and is the reason it resists mixing with water in star compositions. It can also cause the powder to appear extremely shiny. As a note of caution, the removal of the lubricant should never be attempted. This can expose fresh or only partly oxidized metal surfaces on the particles. The resulting air oxidation can lead to self heating of the aluminum powder with potentially dangerous consequences.

One significant variation in manufacturing flake aluminum accounts for much of the dark color in German dark aluminum. Here little or no lubricant is used. Instead the aluminum is rolled on or between very thin sheets of paper. After the rolling process, the material is heated, turning the paper to carbon. German dark aluminum can contain as much as 2.5% carbon.

## E) Effect of Particle Size and Shape on Chemical Reactivity

Pyrotechnic reactivity is a poorly defined term, it is generally taken to mean a combination of how easy it is to initiate a reaction and how rapidly it will proceed once initiated. All else being equal, the smaller the particle size of the aluminum, the more reactive it will be. This is the case because pyro-chemical reactions begin on surfaces of particles, where fuel particles are in contact with oxidizer particles. Thus, the more surface area there is for a given weight of material, the more points of fuel to oxidizer contact exist, and the easier it is to initiate and propagate the chemical reaction. As an example of the difference in surface area between equal weights of different aluminum powders, note

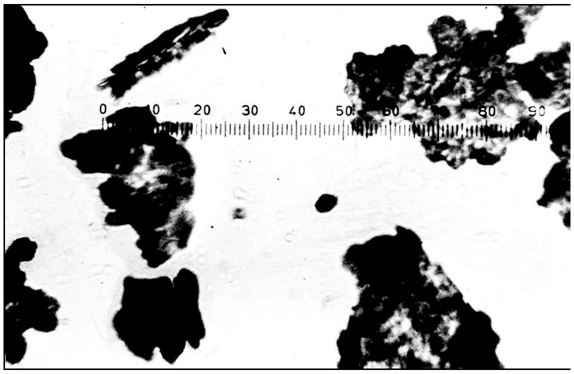

Photo 3. Photomicrograph of 36 micron flake aluminum powder (Alcan 3100); each scale division is 2.4 microns.

**Table 2. Specifications for a Collection of Aluminum Metal Powders Useful in Producing a Wide Range of Pyrotechnic Effects.**

| Aluminum Description | Manufacturer and Product Number |
|---|---|
| **Flake Aluminums**: | |
| Coarse Flitters (flake 10–28 mesh) | Obron 41813/6 |
| Fine Flitters (flake 20–80 mesh) | US Aluminum (Bronze) 813 |
| Flake (–325 mesh, 36 micron) | Alcan 2000 (formerly, Alcoa 9880) |
| Flake (13 micron, American Dark) | Alcan 7100 (formerly, Obron 10890) |
| Flake (3 micron, German Dark) | Obron 5413 |
| **Atomized Aluminums:** | |
| Granular (50–150 mesh) | Alcoa 1222 |
| Spherical (325 mesh, 30 micron) | Mfg. Unknown |
| Spheroidal (–325 mesh, 20 micron) | Alcoa 101 (Alcoa 130, soon) |
| Spherical (400 mesh, 12 micron) | Alcoa S-10 |
| Spherical (–400 mesh, 5 micron) | Reynolds 400 (formerly, Reynolds 131) |

that 5 micron (–400 mesh) particles have 30 times the surface area as the same weight of 150 micron (50–150 mesh) particles of the same general shape.

Another particle characteristic that influences reactivity is particle shape. Particles with sharp angular shapes are more reactive than those with spherical shapes. In part, this is a surface area effect; angular particles have greater surface area than round particles of the same diameter. However, another reason is the sharp points and edges themselves, which tend to heat up easier (faster) than the bulk of the particle. Thus making it easier for chemical reactions to begin at those places.

Flake particles represent an extreme with regard to surface area and also ease of heating. They can easily have more than 10 times the surface area of an equal size atomized particle. Accordingly, flakes will generally be the most reactive for their particle size. The reason this is not universally true is that the flakes, which are protected with large amounts of lubricant, are made less reactive by that coating.

### F) Uses for Different Aluminum Powders

In order to produce the full range of pyrotechnic effects, it is necessary to use of several particle sizes and different forms of aluminum metal powders. This is because aluminum metal powders range so extensively in their pyrotechnic performance, it is simply not possible to achieve a variety of high quality results using only one or two aluminum powders. Table 2 lists a collection of aluminum powders useful in pyrotechnics. Along with descriptions of the powders are manufacturer names and their product numbers. Where the supplier for these materials has changed recently, that manufacturer information is also included.

Table 3 lists some of the ways in which aluminum metal powders are used in pyrotechnics. It is not intended to imply that these are the only uses for these aluminum powders; and, most especially, it is not intended to imply that these are the only aluminum powders suitable for the applications listed. Because the performance of powders, even those with similar specifications, sometimes perform quite differently, only those products with which the authors have had experience are included below. However, it is recognized that it would be useful to include information on the products of other manufacturers; thus some additional information supplied by M. Swisher on other aluminum metal powders has been appended to this article.

## Acknowledgments

The authors gratefully acknowledge the information supplied by D. Tygett of Valimet and C.K. Campbell of Alcan-Toyo America, and the suggestions and comments of R.L. Winokur and M. Swisher. Also, M. Swisher was kind enough to supply the additional information on aluminum powders included as an Appendix.

**Table 3. Common Uses for the Aluminum Metal Powders Listed in Table 2.**

| Aluminum Description | Common Usage | Effect | Notes |
|---|---|---|---|
| Coarse Flitters (Flake, 10–28 mesh) | Stars, waterfalls and fountains | Persistent burning white sparks | (a) |
| Fine Flitters (Flake, 20–80 mesh) | Stars, waterfalls and fountains | Persistent burning white sparks | (a) |
| Flake (–325 mesh, 36 micron) | Stars and fountains | Short burning white sparks | (a) |
|  | Large salutes | Sound (Report) | (b) |
| Flake (13 micron, American Dark) | Medium salutes | Sound (Report) | (b) |
| Flake (3 micron, German Dark) | Small salutes | Sound (Report) | (b) |
| Granular (50–150 mesh) | Comet stars and fountains | Persistent burning white sparks | (a) |
| Spherical (325 mesh, 30 micron) | Glitter stars and fountains | Delayed trailing white or gold flashes | (c) |
| Spheroidal (–325 mesh, 20 micron) | Metal fuel in stars, etc. | Flame brightening | (d) |
| Spheroidal (400 mesh, 12 micron) | Glitter stars and fountains | Delayed trailing gold and white flashes | (c) |
| Spheroidal (–400 mesh, 5 micron) | Large salutes<br>Metal fuel in stars, etc. | Sound (Report)<br>Flame brightening | (b)<br>(d) |

### Table 3 Note (a) Comet Effect — Trailing Sparks

If the aluminum powder used consists of particles that are large enough or well enough protected so they are not completely consumed in a flame, the burning aluminum particles will leave the flame as trailing white sparks.[4] To some extent the size of the aluminum particles is related to the duration of the sparks, with larger particles offering the potential for longer duration effects. In this application, the use of a wide range of particle sizes can be effective by producing a range of both long- and short-duration burning sparks. Thus producing a denser trail of sparks that fade gradually along the length of the comet tail. If the oxidizer used is not capable of igniting coarser atomized aluminums, then a large flake aluminum may have to be used. This type of trailing spark effect is commonly described as a “flitter” effect.[5]

There is an interesting related effect in which a significant delay occurs between the burning of a star that produces golden charcoal sparks and the first appearance of silver aluminum sparks.[6] This effect is commonly termed a “firefly”, “transition”, or “transformation” effect. In these comet stars, generally fine flitter flakes are used.

### Table 3 Note (b) Salute — Flash / Sound Compositions

Making any pyrotechnic composition can be dangerous to prepare and use, because of the possibility of accidental ignitions and the resulting thermal and/or explosive effects. However, because some flash formulas include components rendering them quite sensitive, and because the magnitude of the output from flash powder is particularly large, great care must be exercised during its preparation and use. The smallest particle size, and therefore most reactive, aluminum metal powders should be avoided except when absolutely necessary to obtain a given effect.

When choosing an aluminum powder for use in salutes, reactivity is obviously an important, but not the only, consideration. Obvious choices for high reactivity are the 36-, 13-, and 3-micron flake aluminum powders, and the 5-micron spheroidal aluminum powder. Probably the 3 micron flake aluminum (German dark) is the aluminum powder of choice for the smallest exploding items (e.g., the break-charge for crossettes and for salutes <½" in diameter). However, cost can be a factor in limiting its use.

Density can be another consideration in selecting an aluminum powder. High density powders such as atomized aluminum allow loading a greater weight of composition into a given volume, thus potentially producing a greater effect. However, a problem with compositions containing atomized aluminums sometimes arises because of their tendency to compact with time. Compacted flash compositions tend to burn more slowly which can render them much less effective. However, the addition of a small percentage of fine flake aluminum or a bulking agent such as bran can help prevent compaction problems. Also the use of a mixture of flake and atomized aluminum has been reported to be a particularly effective combination for flash powders.[7]

For large salutes and salutes with strong cases, reactivity is not as important as it is for smaller, more weakly encased salutes. For larger salutes it is just as effective to use safer and less expensive aluminums with larger particle sizes. In part, this is because reaction rates dramatically increase as pressure increases. Thus a stronger case over comes the lower intrinsic reactivity of larger particles by allowing pressures and reaction rates to build before the case ruptures. In a somewhat similar fashion, in large salutes, pressures can rise to higher values because of an effect termed inertial confinement.[8]

For a more complete discussion of the preparation and use of flash compositions, see References 9 and 10. For information on some safety problems with flash powders and other metal fuel compositions, see Reference 11.

### Table 3 Note (c) Glitter Effect — Trailing Delayed Flashes

In glitter, the reactivity of the aluminum metal powder can play a role in determining the color (gold — yellow — white) of the flashes. Fine flake aluminum powder (<40 micron) often produces yellowish-gold glitter flashes, even in the absence of a sodium salt. On the contrary, large atomized aluminum powder (10–20 micron) often produces yellowish-white flashes even when a sodium salt is present. It has been hypothesized[2] that this is a result of differing flash temperatures. The more reactive fine flake aluminum flashes at a lower temperature, tending to produce a yellow glitter flash even without sodium. Whereas the less reactive large atomized aluminum requires a higher temperature to flash, producing a brilliant white flash that can only be turned yellowish-white by the presence of sodium. When even larger particles of aluminum (such as 30 micron spherical, atomized) are used in glitter formulations, burning particles of aluminum will be propelled from the glitter flashes. This produces a very delicate effect at close range, that one is tempted to call flittering-glitter. Winokur[2] stated that it is possible to produce a similar effect using a mixture of different aluminum powders.

Spherical, atomized aluminum seems to produce distinctly superior glitter (large puffy flashes that are more brilliant) when compared with those produced by spheroidal atomized aluminum. Fish[12] hypothesized that the reason may be the lower and more uniform reactivity of spherical aluminum. The lower reactivity might delay the onset of a glitter flash until more glitter-flash-oxidizer (potassium sulfate) is produced. This might cause the flash to be more violent (larger, puffier) when it does occur. Also, this might result in flashes that are more energetic which would be more brilliant. It would be remiss to leave the impression that the shape of atomization is the single controlling factor in producing excellent glitter. There are many other important factors, but their discussion is beyond the scope of this article. For more information see references 5, 13, and 14.

### Table 3 Note (d) Metal Fuel — Flame Brightening

The use of metal fuels in star formulations increases the amount of energy produced during burning. Some of this extra energy can be used to vaporize additional amounts of color generating salts included in the star composition. This can have the effect of producing more deeply colored flames. Also some of the extra energy produced can be left to increase the flame temperature, thus providing additional energy for the light generating process. This has the effect of producing brighter colored flames.

Aluminum is a reasonably good metal fuel for flame brightening; its chief competitors are magnesium and magnalium (magnesium / aluminum alloy). Aluminum is the safest to use and is cheaper than either magnesium or magnalium. The use of aluminum as a color star fuel tends to make the flame appear opaque. This can be a desirable quality. However, it also adds white light to colored flames, which acts to washout the color somewhat. This is caused by the formation of aluminum oxide particles which then incandesce in the flame. The use of magnesium, in conjunction with sufficient chlorine donor, does not produce this oxide effect, and therefore can produce colored flames of higher purity. However, the use of magnesium as a flame brightening fuel can present significant safety problems. For a more complete discussion of the use of metal fuels in colored flame compositions, see Reference 15.

In choosing an aluminum fuel, one should select the least expensive aluminum that contains particles small enough to be completely consumed in the flame. This is because the production of a small number of short-lived, trailing silver sparks has a most unpleasing appearance. Note that the authors have not found it possible to satisfactorily produce both flame brightening and a silver comet tail by use of a large-particle aluminum powder. When this has been attempted, the color of the star seriously degrades before a tail of pleasing density has been achieved. The use of titanium metal powder is the answer to produce such an effect.[16] Finally, in attempting to brighten flames, one should avoid using flake aluminum (it is too messy) and extremely fine aluminum (it is more reactive than necessary, and therefore less safe).

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## Appendix

**[M. Swisher supplied the following information on other aluminum powders in mid-1991.]**

### Notes on German Aluminums

The names "black head", "blue head", and "yellow head" are designations applied by Hummel Chemical Co. in its catalogue to German aluminums sold by that firm. It should be noted that Hummel is not the manufacturer and these are not the manufacturer's terms. I believe these aluminums are made by Gloria Bronzefarbewerke, which has a much more extensive line of powdered aluminums than just these three. They designated their products, as do US manufacturers, by part numbers. I have seen their information in the past. I do not, however, have anything in my files from them.

The term "pyro" aluminum originally came from the manufacturing process, not from the intended pyrotechnic use. Several methods are used; the foiled paper being burnt then milled, which the Kosankes mentioned is one; in another, aluminum is milled with stearin but then baked in a vacuum to decompose the stearin. I do not know the others. The particle shape produced depends upon the method used. (This information comes from Dr. Mike Stanbridge via Jerry Taylor.)

### Notes on Other Aluminum Grades Used in Fireworks

One of the most commonly used atomized grades is Reynolds #120. I have, in my experience, found this to be one of the best and most versatile aluminums for tremalons (flitter, glitter).

A grade I have seen once or twice, but do not know the origins of, is described as "sparkler grade". In appearance it is neither atomized nor a ball-milled flake. It seems to be somehow mechanically comminuted, by some type of grinding process.

### Final Note

Those wishing to avoid ambiguity in the description of aluminum powders have really only one choice. That is to use the manufacturer's name and part number. Most serious manufacturers of fireworks do this in their private formularies. Even so, the natural variability of the product is sometimes defeating. In a drum of US Bronze #812 "coarse flitters" you will find finer material at the bottom than you will find in the top of a drum of their #813 "fine flitters". Flitters have a way of stratifying, and also the individual flakes break down from larger to smaller as the aluminum is stirred, moved, or mixed. In a case where flitters are used, and the effect depends upon precise particle sizing, there is often no choice but to undertake a laborious process to separate the desired "cut". I have found this necessary, for example, in making the charcoal-aluminum star.

**Descriptive Table of German Manufactured Aluminum Products.**

| Hummel Designation | Description | Use |
|---|---|---|
| "Black head" | The <u>black</u> aluminum (as distinct from dark); "alluminio nero" | Flash powder |
| "Blue head" | A dark grade which could be called an "alluminio scuro", in practice something like a 50:50 mixture of black head with USB #809 | Salutes, illuminating stars |
| "Yellow head" | The sample I saw was a "bright" grade but was denser than (e.g., USB #808 or #810). | Electric and tremalon stars, gerbs, falls, etc. |

**Descriptive Table of Customary Identifications and US Aluminum Bronze Product Numbers.**

| US Bronze No. | Description | Use |
|---|---|---|
| 809 | “dark”, the “alluminio scuro” of the Italians | flash powders, strong white and yellow stars, some tremalons |
| 808 | “light pyro” or “bright”— the “alluminio bianco” of the Italians | silver stars with chlorate or perchlorate (“electric” stars), some tremalons |
| 810 | “bright” (coarser than #808) (“alluminio brillante”) | silver (“electric”) stars; rosette powder, fountains, some tremalons |
| 813 | fine “flitters” (20–80 mesh) “alluminio in scagile” | silver (“electric”) stars, fountains, falls, charcoal/aluminum stars |
| 812 | coarse “flitters” (10–30 mesh) | gerbs, falls, too coarse to put in cut stars |

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# Explosions and Detonations

K.L. Kosanke

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The proper use of technical and scientific terms is fundamentally important for clear and effective communication. It is also a mark of a professional to use the vocabulary correctly. Toward that end, the following brief article is offered. There are a series of notes [a–e] included for additional and qualifying information at the end of the text. However, it is suggested that the article be read first in its entirety before diverting to read the notes.

Too often the word detonation is incorrectly used in place of the more general term explosion. While it is true that all detonations are explosions, most definitely not all explosions qualify as detonations. Thus care should be exercised before declaring an explosion to be a detonation. The definition of a detonation adopted by the US Bureau of Alcohol, Tobacco and Firearms (BATF) is taken from the Institute of Makers of Explosives (IME).[1] Specifically, a detonation is defined as:

*"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."*[2] *[a]*

Note that it is the capacity for detonation which the BATF and others use to characterize high explosives. Specifically, high explosives are defined as:

*"Explosive materials which can be caused to detonate by means of a blasting cap when unconfined, (for example, dynamite, flash powders, and bulk salutes)."*[3] *[b]*

By contrast, note that the IME defines deflagration as:

*"An explosive reaction such as a rapid combustion that moves through an explosive material at a velocity less than the speed of sound in the material."*[2]

Further that the BATF defines low explosives as:

*"Explosive materials which can be caused to deflagrate when confined, (for example, black powder, safety fuses, ..., and 'special fireworks' ...."*[3] *[c]*

Thus, in discussing explosives and pyrotechnic materials, unless one has specific knowledge of the speed of sound in the unreacted material, and the speed of the reaction under specific conditions, the term detonation should not be used. Rather, the more general term, explosion is the correct choice [d,e].

**Notes:**

[a] There may be a number of reasons why this definition for detonation is a better rule-of-thumb than it is the best technical definition. However, it works well for the vast majority of explosives and is the one invoked by regulation. A more complete discussion of this subject might be interesting to a few but is well beyond the scope of this short article.

[b] There are at least 108 published formulas for flash powder, many of which differ radically from the rest. It must be noted that there are almost no published results of measurements of the speed of sound in various flash powders and very little data on the speed of their explosive reactions. Thus, it is not clear that there is sufficient data to suggest that ALL flash powders and ALL bulk salutes meet the definition of high explosives. Nonetheless, it is important to recognize that since 1990 the BATF has made this declaration regarding flash powders and bulk salutes.

[c] It must be noted that there is at least a potential difficulty with the definitions for high and low explosives. Specifically, explosives can exist which are not covered in either definition. For example, consider an explosive which only deflagrates when left

unconfined. Such an explosive falls below the definition for a high explosive. Suppose, however, that it is capable of detonation when confined. Thus the explosive exceeds the definition for a low explosive. This undefined class of explosives might be of no consequence if it were not possible (likely) that at least some explosive materials fall into that category. This is of concern because confinement acts to greatly accelerate the reaction rate of pyrotechnic explosives; thus making it possible (probable) that some will only transition to detonation when confined. If this is the case, then it is reasonable to ask, why has it been overlooked? One likely reason is because the explosives considered by the IME (e.g., those used in large quantity for commercial blasting) tend to fall clearly into the high explosive category and essentially all the rest clearly fall into the low explosive category. It is primarily in the fireworks and match trades where likely candidates for the undefined category would come. Unfortunately, there is no representation of these very small industries in the IME. It is also reasonable to ask whether there are explosives which are known to fall into the "only detonates when confined category?" None come immediately to mind, but recognize that essentially none of the pyrotechnic compositions used by the fireworks trade have ever been tested to find out. In fact, interest in this area has only begun to develop since the BATF moved flash powder and bulk salutes from the low to high explosive category.

[d] There is one exception that should be made to this rule; that is for the very strong explosion of an aerial shell inside a mortar. It is quite possible (probable) that many of these are not actual detonations. However, use of the descriptive term "shell detonation" is so firmly entrenched, and there would be much confusion if a new term were introduced, that it should not be changed. However, most definitely, the word "detonate" should not be used to mean ignite or fire, as in "going out to detonate some aerial shells for a fireworks display". It is surprising how often this is heard, and it is not even close to being correct usage.

[e] It is believed by some, that, if upon initiation an unconfined explosive material reacts to produce an explosive "bang", then a detonation must certainly have occurred. It is true that unconfined detonating (high) explosives always produce such a bang. However, the converse, that unconfined deflagrating explosives do not produce such an explosive bang, is not universally true. For example, it is well known that Black Powder, which is a low explosive, when present in sufficient quantity, can produce an explosive bang. This is because all that is necessary is that the rate of the explosive reaction exceed the speed of sound in air (≈330 m/s). When ever this occurs, a shock wave will be produced in the air surrounding the explosive, and this is heard (felt) as an explosive bang. If the explosive is a solid mass, the speed of sound in the unreacted explosive will exceed the speed of sound in air. Thus for such an explosive, if its reaction rate was between the speed of sound in air and the speed of sound in the explosive, it would produce a bang when unconfined but the reaction would be a deflagration and not a detonation. This is what can happen with Black Powder when present in sufficient quantity.

## Acknowledgment

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# Fireworks Displays—Abnormally Dangerous Activity ? ? ?

K.L. Kosanke

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Most of the fireworks display industry is aware of the ruling of the Washington state supreme court, which declared the conducting of fireworks displays to be an abnormally dangerous activity.[1] In part, that ruling was based on their considered opinion that, by their very nature, fireworks displays could not be performed safely. One ramification of declaring fireworks to be an abnormally dangerous activity is that in the event of an accident, negligence is no longer a consideration regarding liability. In legal parlance this is referred to as "strict liability". Under normal liability, in order to win a judgment it must be shown that a defendant was negligent (i.e., failed to conduct himself as a "reasonable" person would have under the same circumstances). Thus, if a display operator and crew always do what reasonable persons would, they would not be negligent and would be victorious if sued. (At least this is true in theory.) However, under strict liability, about all that a plaintiff needs to prove in court to win a judgment is that they were injured. Obviously, this is a far easier task, and a situation likely to have ramifications affecting insurance rates and a sponsor's willingness to put on displays.

Obviously the situation in Washington state is of concern for display companies doing business there, but the concern extends beyond Washington state. Courts in other states are being petitioned by plaintiff's attorneys attempting to win similar rulings. Legal precedence being what it is, the decision by the Washington state supreme court is being cited as part of the legal argument in other states. For example, in Arizona a judge recently ruled that fireworks displays were "inherently dangerous", thus making a sponsor liable for the misconduct of the display company it hired.[2] In part the finding was based on the Washington state case.

Since display companies are concerned about having fireworks displays declared an abnormally dangerous activity it would seem foolish for any display company to act in a manner that would make it more likely that the strict liability standard will come to be applied in more states. Even if there might be a short term gain for the company, the long term result will hurt that company along with everyone else in the industry. This is one reason that many in the industry have applauded *NFPA-1123 (1990), Code for the Outdoor Display of Fireworks*. By addressing more display practices, in greater detail, and often with a higher standard of performance, the code helps to make it less likely that an individual display company will engage in conduct that harms the entire industry. For this reason I was surprised recently by the actions of a major display company. The following account is presented in the hope that similar conduct, on the part of this or any other company, will be discouraged. Because some of the details of the incident may be in dispute, and because it is only the type of inappropriate activity that needs to be discouraged, the company, display dates and the site will not be identified.

The incident involves a display in which most 8, 10, and 12-inch shells were fired from paper mortars placed directly into very moist sand. The contract for the display required following NFPA-1123, which requires that:

> *"2-3.3.1. Under conditions when paper mortars may be damaged by placement in damp ground, paper mortars shall be placed inside a moisture resistant bag prior to placement in damp ground."*

It was about 34 hours before the time of the display when the moisture damage problem was identified and confirmed by inspection. Except for the opening barrage and finale, about 80% of the display had already been loaded. The company representative on site refused to acknowledge the problem and thus refused even to attempt to limit its seriousness by removing the mortars and placing them in plastic bags as clearly required by NFPA code. Instead, the display company representative raised the following objections and reservations:

- The code states "damp ground", not damp sand, and thus it does not apply;
- This is the way the company always does it, and they have never had a problem;
- If the mortars are placed in plastic bags, they will pop completely out of the sand and up into the air, thus possibly falling on and damaging other equipment;
- The moisture had/would penetrate through no more than two or three layers of paper;
- There was not enough time left to correct the problem;
- If the company were made to put the mortars in plastic bags, they would refuse to fire them for "safety" reasons;
- The use of plastic bags was itself a safety problem because they would catch fire from sparks, and there would be premature ignitions;
- Those who wrote the NFPA code lacked the experience required to understand the problems associated with mortars in plastic bags;
- Any minor loss in strength had already occurred and placing the mortars in plastic bags would not help and might even make the problem worse;
- Based on their reputation, the company would guarantee there would be no problem with the performance of the mortars;
- Using plastic bags in damp sand was not a standard industry practice;
- If they were forced to put mortars in plastic bags, and then fire shells from the mortars, they would not accept any responsibility for the consequences;
- It was too dangerous for the crew to pull the shells from the mortars in question so that the mortars could be put into plastic bags;
- If the shells were pulled, their fusing could be damaged to such an extent that they could not be safely fired.

The display site inspector was unusually knowledgeable for an "authority having jurisdiction"; he had many years experience performing displays, inspecting displays, and investigating display accidents. For the following reasons, he had added concern regarding the moist sand issue:

- About five years earlier a spectator had been injured on that site as a result of a paper mortar that had blown-out because of being placed in moist sand;
- Most of the 8, 10, and 12-inch shells to be fired from the mortars in this display were chain fused in numbers exceeding the limits set by NFPA-1123 in paragraph 2-3.3.6;
- The largest caliber mortars were shorter than recommended by the NFPA-1123 in paragraph A-2-3.6.3;
- The chained mortars were in plastic garbage cans, which were weaker and, because of the shape of their bottoms and their top heaviness, were more likely to tip over than metal drums;
- The chain-fused, garbage-can mortars were immediately adjacent to racks that were not staked to the ground, did not have feet attached, were only sparsely interconnected using 1" × 2" lumber, and contained ABS plastic mortars (not HDPE) with no spacing between the individual tubes.

Despite the protestations of the display company representative, it was ordered that the mortars be pulled and bagged to halt the further absorbing of moisture. However, after about 25% of the mortars, those in the wettest sand, were bagged, and the inspector had left the site, the crew reverted to loading and wiring the rest of the display. By the time it was discovered that the mortar pulling and bagging had not been completed, it clearly was too late to be done without delaying the display at least one day. Because of the desire (need) to not delay the display; the fact that the local fire department had been on site and issued the final permit without an inspection; and the feeling that spectators were unlikely to be injured because the separation distance was a little greater than that required by NFPA-1123 for non-chain fused 12-inch shells, the sponsor decided to allow the display to proceed.

The display was conducted and, as feared, there were a number of mortar failures and associated problems. Luckily, there were no spectator or crew injuries. Following the display it was discovered that 23 of the mortars in question had failed. (The count ranged from 19 to 29 depending on who did the counting; I counted at least 23, but there was some question about what parts came from which mortars.) Essentially all of the failed mortars were the ones that had not been bagged. All of the failed mortars had ripped up from the bottom to the approximate level of the sand or they had failed from blown plugs because their fasteners tore out. In no case was the failure a result of shell malfunction within the mortars (confirmed by close observation during the display). All of the failed mortars were visibly swelled and water could be squeezed from their walls by pinching with finger pressure alone. In examining the 12" wooden mortar plugs, it was found that some had been made from about a 6" length of tree trunk (nearly the correct diameter but not completely round) with the bark still in place and others were made from only three 1½" thick plugs for a total thickness of 4½ inches. In all cases the plastic garbage cans holding the failed mortars had split open and tipped over. In several cases adjacent garbage can mortars and racks had been tipped over, and their mortars realigned and racks destroyed. Luckily, in only one case did a shell fire horizontally from a tipped mortar and travel a significant distance. In many cases the shells from the blown mortars still fired to a reasonably safe altitude. In at least half of the cases burning debris from the low breaking shells fell to the ground, some fell beyond 840 feet from the mortars, but none within about ten feet of spectators. In one case a shell fell back to the ground, broke open producing a substantial fire ball and damaging some wiring. In short, considering what could have happened, they were very lucky. Following this article are some photographs of the scene after the display.

Following the display the company representative proclaimed that the loss of 23 large caliber paper mortars (about 10% of those actually fired) was normal for any display company.

Before concluding by making my point for this article, let me acknowledge that:

- The display was very well received by the spectators;
- The shell count was large and for the most part the quality was good;
- The choreography was good; and
- The crew performed heroically under absolutely miserable weather conditions, including several days of intermittent showers and pouring rain, separated by periods of incredible heat and unbearable humidity.

The point of this article could have been that:

- It was inexcusable to have put the public at this level of unnecessary risk;
- It was inappropriate to frustrate a sponsor and authority having jurisdiction by inventing lame excuses and rationalizations to avoid taking needed corrective action; or that
- Having agreed to take corrective action, it should have been completed, and their failure to finish the task should not have been concealed.

These could have been the reason for this article, but they are not. The point is that it is a serious disservice to the fireworks display industry to claim that such poor conduct and the resulting high rate of equipment failure is typical of the best the industry can do. This is tantamount to an acknowledgment that fireworks displays cannot be performed safety, and thus supports the contention that fireworks displays are an abnormally dangerous activity. If this were true, it would be one thing, but it is certainly not true. When a display company refuses to take responsibility for its activities and characterizes its shameful performance as the norm for the industry, it serves to inappropriately and unnecessarily injure the whole display industry.

## Acknowledgments

The author's gratefully acknowledge the safety officials involved in this incident who reviewed the text for accuracy; however, we have not named them in order not to reveal the site of the display.

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# Lancework — Pictures in Fire

B.J. and K.L. Kosanke

***ABSTRACT***

*Lancework set pieces can be one of the most interesting forms of fireworks. If one uses high-quality lance formulas, skillfully designed lance figures, provides clever animation, or tells an interesting story, the entertainment value of lancework can reach the heights it should. This article describes the methods used by the authors to design, construct and display lancework set pieces. There are also short appendices written by C. Jennings-White, M. VanTiel, and R. Winokur, wherein they present their views on some points relating to this article.*

## Introduction

Lancework set pieces can be one of the most interesting forms of fireworks, especially if they are animated or otherwise engage the audience. Most audiences have seen an American Flag, "WELCOME", or a company name or logo at a fireworks show. These set pieces generally burn for about a minute, and that's a long time to look at the same thing. However, when they are looking at a set piece and then it moves, a delightful reaction is heard, and that is what fireworks displays are all about — entertaining the audience.

In addition to their entertainment value, there are other reasons to consider including more elaborate lancework in fireworks displays. The recently revised National Fire Protection Association (NFPA) separation distance requirements may significantly limit the size of aerial shells that can be used in many fireworks displays. Thus smaller fireworks sites may have to rely more heavily on ground displays. In addition, ground displays can be used to refresh the spatial perspective of the audience. Normally, during the performance of a display, ever larger shells or more rapid firing are required to maintain the entertainment level. For example, immediately after displaying a magnificent six-inch, color-changing chrysanthemum, the appearance of a three or four-inch shell (or even a five-inch shell) may not be very impressive. However, if the display operator interrupts the aerial display and presents an interesting set piece, then that same three or four-inch aerial shell will be much better received. When it is possible to use this method of improving the perceived appearance of smaller aerial shells, the entertainment value of the display can be increased at no additional cost.

The methods described in this article are those used by the authors during a period in the early and mid 1980's when they performed fireworks displays. These methods produced good results; other methods that were tried were less successful. However, it is not intended to imply that these methods are the best or only methods that will produce good results.

There are three short appendices at the conclusion of this article. These were written by C. Jennings-White, M. VanTiel and R. Winokur, and they present their views on some points relating to this article.

## Lancework Design and Frame Construction

Where does one start to design a lancework set piece? First, the basic idea must be formulated; for example, a skit in which a military tank is one of the players. The next step is to sketch the tank design. It should be as simple as possible. People only need enough detail to identify the item; their mind's eye will fill in the rest. For example, there is no need for drive and idler wheels, just outline of the main elements that make it a tank: the track, turret, and gun barrel (see Figure 1, top). Too much detail may make the design less recognizable and will require more lance tubes. This will add to the cost and certainly will produce more smoke, which can detract from the appearance of the set piece, especially with an unfavorable wind. Finally, in considering various tank designs, consider how it is to be perceived. If it is a comic skit, the tank

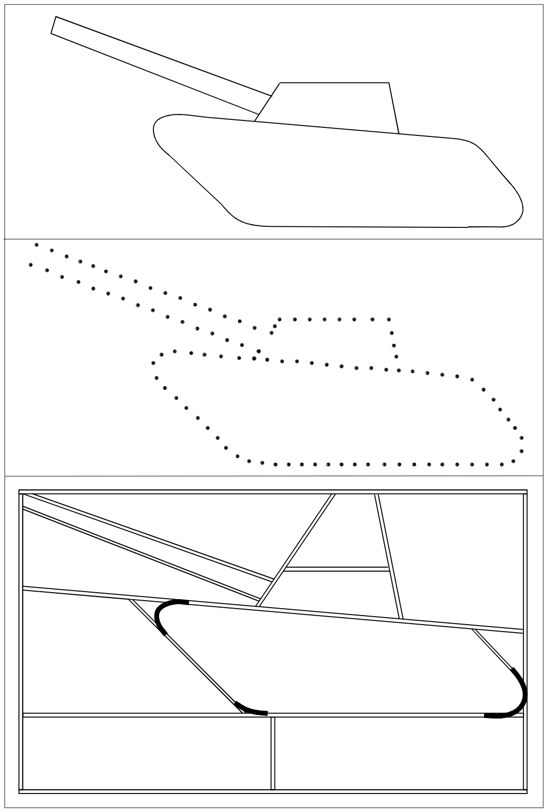

*Figure 1. (Top) Sketch of a tank design for a lancework set piece. (Middle) "Dots Only" view of how set piece will appear as a burning lancework. (Bottom) Sketch of lance frame showing frame members and rattan segments.*

should not appear menacing; so shorten the gun barrel and increase the height of the track and turret. If it is supposed to be racing forward, increase the forward angle on the track.

Once pleased with the basic sketch, transfer it onto and 8 ½ × 11-inch sheet of paper to check out how it will appear as a lancework. Using something like a broad-pointed, felt tip pen, make fairly "fat" dots, about ½-inch apart around the sketch. Start by placing dots at the end of each line segment (at each corner or where there are sharp changes in direction); then, fill in the rest of the dots. If a pen that readily "bleeds" through the paper is used (e.g., a "Sharpie" pen by Sanford), the paper can be turned over to see only the dots, and not the lines from the drawing (see Figure 1, middle). Such a "dots only" view is how the design will actually appear and should be used to evaluate the design. Observe the drawing at a distance of about six to eight feet. If the mind's eye can still clearly see what was in your sketch, the design is headed in the right direction. It may take several tries before settling on a design and dot pattern that is clearly recognizable and has the appearance being sought. Sometimes it is necessary to add some "helper" dots, these are dots placed closer than the normal spacing to make sure that the eye follows the intended outline (e.g., in Figure 1 (middle) where the gun barrel meets the turret). For the same reason, it is often helpful to slightly decrease spacing around bends, especially tight bends. In other areas the spacing will need adjusting so that after a dot is placed at each corner, and the dots filling the remaining space are roughly equidistant from each other. Once the necessary adjustments have been made, ask someone else what they see when viewing the drawing from about eight feet away. If it is obviously a tank and gives the desired impression (comic, menacing, fast moving, etc.), it is time to construct the lance frame.

A well-designed lancework set piece, one that is animated or part of a skit telling an interesting story, should be well received in many different venues, and even if repeated at the same location after a few years. Thus, set pieces should be made sturdy enough to be reusable. This requires some additional effort to strengthen and maintain the lance frames, but it represents a substantial cost savings over a span of only a few years. The authors' standard frames were six by ten feet as this was the size of the trailer used to transport the lancework set pieces (more on this later). For larger set pieces, multiple panels would be joined on site. Occasionally, smaller frames were used, but they were always made six feet long to span the mounting rails in the trailer.

To design the lance frame, start with the basic sketch of the figure to be portrayed, and draw the frame boundary (e.g., 6 × 10 feet). Next, identify all straight lines of the design and extend them to meet the frame or until they meet another straight line segment. These lines correspond to what will become a wooden member of the lance frame. Since it is necessary to have cross bracing in a lance frame, when practical, that cross bracing should be placed to correspond with parts of the design. This makes the strongest frame for the least weight (see Figure 1, bottom). It may be necessary to include some additional lines (frame members) where more strength is needed. Next, indicate on the frame where rattan will be needed for curved sections (shown as solid bold lines in Figure 1, bottom). When there are few if any straight line segments in the design, place the bracing so that the rattan is supported about every 18 inches, but avoid adding unnecessary bracing (additional weight). Finally, for later use in constructing the frame, determine and record all dimensions.

The wooden framework is constructed from one by two inch material (actually 3/4 × 1-5/8-inch). One by two's from a lumberyard are generally of too poor quality. Thus it is probably best to start with reasonably good one by four's and rip them to the one by two size, saving only the portions that are reasonably straight and knot-free. In addition, Masonite triangles about six inches across were added for bracing to strengthen all corners, both front and back around the edge of the frame (see Photo 1). If lances needed to be placed in a braced area, then bracing would only be on the back side.

Although it is possible to use a hammer and nails to assemble a frame, a pneumatic stapler/nailer is greatly preferred. In part, this is because it saves time. More importantly, the frames are somewhat delicate and hammering on them causes more damage than is desirable.

The wooden frame members serve as the base for the placement of the lance nails on the straight segments of the design. For this, either double-pointed nails or thin, 1½-inch brads were used. In the latter case, a side-cutter was used to remove the heads after driving the nails into the wood about ½-inch. The spacing of the lance nails needs serious consideration. If the nails are placed quite close, the design may be more easily perceived by the audience. However, there is added cost, plus, during operation the design may be obscured by the additional smoke generated. An average spacing of four to six inches is probably best for most designs.

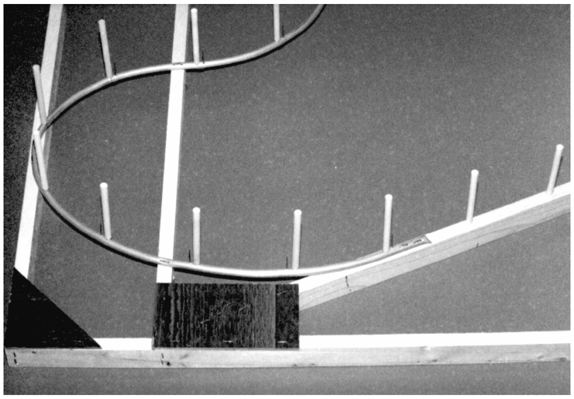

*Photo 1. Photo of a lance frame illustrating frame members as lance supports, aluminum rattan and Masonite frame bracing. The frame components remain unpainted in order to be more easily seen in photo.*

The traditional rattan was not used in the method described here; rather what the authors came to call "aluminum rattan" was used. Actually, this is coaxial cable used by the cable TV companies for their trunk lines. It comes in various sizes, but what was used is about ½-inch in diameter. It has a central copper wire suspended in plastic foam, inside a thin aluminum tube. It has two very desirable characteristics. First, it is inexpensive (often free) as the cable company has many short ends, and, because of the mix of materials, most scrap yards do not want it. Second, and more importantly, once it is bent into a shape, it will hold that shape permanently or until re-formed to adjust the lancework figure. However, before bending the material into shape, generally, it is best to install the lance "nails". Using a pneumatic staple gun with ½-inch wide by 1½-inch long staples, drive staples through the cable (aluminum rattan). If a small work stand is made with holes that are four and six inches apart, this can serve as a work station with a built in gauge for rapid stapling every four or six inches. Note that the staples provide two "nails" at each point; a redundant nail for later use if one becomes damaged beyond use. Also, if there is a critical lance point (e.g., a single lance for an eye), the extra "nail" can be used for a second lance, thus guaranteeing that the eye appears during the performance. Once stapled, the rattan is ready to be formed into the needed shapes. Care must be taken in making tight bends so that the cable does not kink. However, with a little practice, even fairly tight bends can be easily made. When the segments have been formed into shape, they can be stapled into place on the lance frame. As a minimum, the ends of each rattan segment must be firmly attached to the frame (i.e., there should be no dangling ends). Photo 1 illustrates the lance frame construction technique described here.

As the final step, lance frames should be painted with a dark, low gloss paint. In addition to increasing the life of the frame and reducing injuries from wooden splinters in later years, the dark paint eliminates reflected light; so the frame appears invisible to the audience.

## Lance Manufacture

There are several sources, both domestic and foreign, for commercially manufactured lance. However, to some extent the cost and certainly the quality of the product leaves much to be desired. The purity of the color is generally poor and most produce incredible amounts of smoke. In fact, some produce so much smoke, that in absolutely calm conditions, the burning lance design can be totally obscured. For these reasons, it was felt that commercially produced lance available at the time was not acceptable. Thus an effort was undertaken to find or develop good lance formulas and an expedient method for lance tube filling.

Commercially manufactured lance tubes are available. Those from Ace Paper Tube (Cleveland, OH) are 5/16-inch diameter, waxed, with spun-closed ends, are 4-5/16-inch long, and are available in a variety of colors. Unfortunately, these tubes have quite heavy walls (about 0.015 in.), which, when waxed, are not easily consumed by the burning lance. It is important that not more than about ¾-inch of lance tube ash be allowed to accumulate as the lance burns (a phenomenon sometimes called "chimneying"). This is because ash extending much beyond the burning surface will seriously weaken, if not completely destroy, the flame color. Thus, if heavy-walled tubes are to be used, it is necessary to have lance formulas that can consume the tubes as they burn. Of course, as an alternative, it is possible to make one's own thinner-walled tubes (Lancaster, 1992). For convenience, the authors used commercially manufactured tubes and developed lance-tube-consuming color formulas. The resulting formulas, listed in Table 1, produce extremely little smoke (especially in a desert climate), and the colors are all good to excellent, even when viewed in daylight. Since, these formulas were developed over a period of only a few days, working part time, it is likely that additional developmental efforts would yield further improvements in performance. Note also that these compositions all use ammonium perchlorate and some combine ingredients that may cause problems in more humid climates. Thus, at least some added precaution may be appropriate if they are to be generally used. As an alternative, T. Shimizu (Lancaster, 1992) presented a series of good lance formulas. How-

**Table 1. Primary Color Lance and Lance Prime Formulas.**

| Chemical | Red Star | Red Lance | Green Lance | Blue Lance | Lance Prime |
|---|---|---|---|---|---|
| Ammonium perchlorate | 31 | 37 | 37 | 39 | — |
| Potassium perchlorate | 31 | 10 | 10 | 15 | 58 |
| Red gum (Accroides) | 15 | 8 | 8 | 3 | 6 |
| Hexamine | — | 8 | 8 | 5 | — |
| Strontium nitrate | — | 30 | — | — | — |
| Strontium carbonate | 23 | 7 | — | — | — |
| Barium nitrate | — | — | 37 | 14 | — |
| Manganese dioxide | — | — | — | 3 | — |
| Rice starch | — | — | — | 6 | — |
| Paris green[(a)] | — | — | — | 5 | — |
| Copper metal | — | — | — | 10 | — |
| Silicon (325 mesh) | — | — | — | — | 12 |
| Titanium (325 mesh) | — | — | — | — | 12 |
| Charcoal (air float) | — | — | — | — | 12 |
| * Burn Rate (sec/inch) | — | 25 | 23 | 24 | — |

(a) Paris Green is actually copper acetoarsenite.

* As determined by C. Jennings-White.

ever, these were less successful at consuming lance tubes and, because of their low density, were not suitable for the rapid lance tube loading technique discussed below.

The basis for the authors' lance formulas was a red star formula, published by S. Bases (1978), that was described as slow burning and possibly suitable for a lance. The burn rate was appropriate for lance and the color was excellent. Unfortunately, the composition did a poor job consuming commercial lance tubes as it burned. The growing length of ash pipe as the lance tube burned would weaken then destroy the color. Simply increasing the percentage of oxidizer did not work as it weakened the color and still did not burn off the ash pipe. Eventually it was discovered that using strontium nitrate and hexamine consumed the lance tube ash well enough for use. Thus the Bases' formula was modified; replacing some potassium perchlorate and strontium carbonate with strontium nitrate, and replacing some red gum with hexamine (see Table 1).

The green lance formula is simply the red lance formula with barium nitrate substituted for the strontium salts. The blue formula was considerably more difficult to develop because copper nitrate cannot be used because of its hygroscopicity. After many trials, a formula was found that produced good color and consumed the ash from the lance tubes. Unfortunately, to get a good color, copper metal had to be used. Note that some pyrotechnists believe that the combination of copper metal and ammonium perchlorate presents a potential safety problem. While the authors never had a problem with this combination in the desert, it is not certain that others would not, especially in more humid regions of the country. Also, when this formula was developed, Paris green (copper acetoarsenite) was still available and often used in blue star compositions. Copper oxychloride could probably be substituted directly for the Paris green and, with some additional development, the use of copper metal might be eliminated. For a possible starting point, one might consider Shimizu's (1980) blue formulations B-1, B-2 or B-3 in Table 4. The prime formula was developed to ignite easily, burn hot, produce short whitish spark (for aesthetic reasons), and contain an alcohol soluble binder (discussed further below).

The red and green formulas combine ammonium perchlorate and a nitrate, thus raising the question as to whether hygroscopic ammonium nitrate might be formed. This double decomposition reaction requires the presence of moisture to proceed. Thus the question might seem to be whether a humid climate might allow the reaction to proceed. However, because the relative solubilities of the reactants are both much less than the products, the possibility of forming a significant amount of ammonium nitrate is eliminated. This is true for both strontium nitrate and barium nitrate, but is just the opposite for potassium nitrate. Thus the red and green formulas should not draw moisture from the air, but a potassium nitrate based prime could. This is the reason why the prime used had potassium perchlorate as the oxidizer.

Table 2 lists a series of formulas for colors achieved by mixing primary colors. The methodology is essentially that described by J. Baechle (1989) and R. Veline. For example, yellow is made by mixing the red and green compositions. The beauty of this method is that it makes it almost trivial to adjust the color to suit ones need or preference. For example the yellow can be shifted toward orange by reducing the percentage of green composition. Analogously, yellow can be shifted toward chartreuse by reducing the percentage of red composition. In much this same way, many different colors and shades can be created.

**Table 2. Composite Color Lance Formulas.**

| Composition | Yellow | Orange | Chartreuse | White | Purple | Aqua |
|---|---|---|---|---|---|---|
| Red lance comp. | 25 | 60 | 14 | 14 | 60 | — |
| Blue lance comp. | — | — | — | 28 | 40 | 25 |
| Green lance comp. | 75 | 40 | 86 | 58 | — | 75 |
| * Burn Rate (sec/inch) | 24 | — | — | — | 25 | — |

* As determined by C. Jennings-White.

When making lance composition in preparation for loading into tubes, it is important to know approximately how much to prepare. Using the commercial tubes mentioned above, about 65 lances can be filled per pound of composition (approximately 7 grams of composition per lance).

One traditional method of filling lance tubes is the “rod and funnel” method. This involves using a small stemmed funnel that fits a short distance inside the end of a lance tube. The funnel is filled ½ to ¾ full of composition. Then by working a small rod up and down through the composition and into the lance tube, composition is passed into the tube and compacted somewhat, at the end of each stroke.

The rod and funnel method works well and is quite efficient when filling only a few lance tubes (less than a few hundred). However, when thousands of tubes need filling, other methods should be considered. Commercially, a commonly used method is gang pressing. In this method, the lance tubes are held securely in a matrix and compaction is accomplished using a matching set of rods mounted in a block. After each increment of composition is added to the tubes, the set of rods are inserted into the tubes to consolidate the powder. Another method, developed by the authors, proved to produce satisfactory results, used less expensive equipment and was possibly faster. This method might be called “inertial compaction” and is described below.

With inertial compaction, empty lance tubes are first loaded tightly into a container; during initial trials, a three pound coffee can was used. Later a special container was constructed (see Figure 2), which held more tubes and provided a ready method of removing the filled lance tubes. The container was basically a box made of aluminum, approximately 8 × 8 × 6 inches deep. It had an overhanging lip, which served as a handle. Inside the container were two inserts, which could each hold 200 lance tubes, and allowed the completed lances to be more easily raised from the main container. On those occasions when less than 400 tubes of one color were needed, wooden blocks were inserted to take the place of 100, 200 or 300 tubes.

Once the lance tubes were loaded (snugly packed) into the container, loose lance composition was dumped in and spread around using a small (one or two inch) paint brush. Only enough composition was used to approximately fill all the tubes with loose composition. Then the container was firmly and repeatedly bumped (dropped from a height of a few inches) against a solid wood surface for a total of at least 50 blows (requiring about 30 seconds). As the lance composition compacted itself with each blow, the level of lance composition in the tubes was lowered. Then more loose composition was added to refill all the tubes, after which the container was bumped again to further compact the composition. The process was repeated until after compaction (bumping) the level of composition in the tubes remained within about 1/8-inch of the top.

This remaining space was filled with prime, which contained red gum. After loading the loose prime and brushing it around, the container was again briefly bumped to compact the prime. Finally, the exposed tops of the lance were sprayed with a small amount of isopropyl or ethyl alcohol. The alcohol dissolves some of the red gum to activate it as a binder. When the alcohol evaporates, the prime becomes reasonably hard and seals the weakly compacted com-

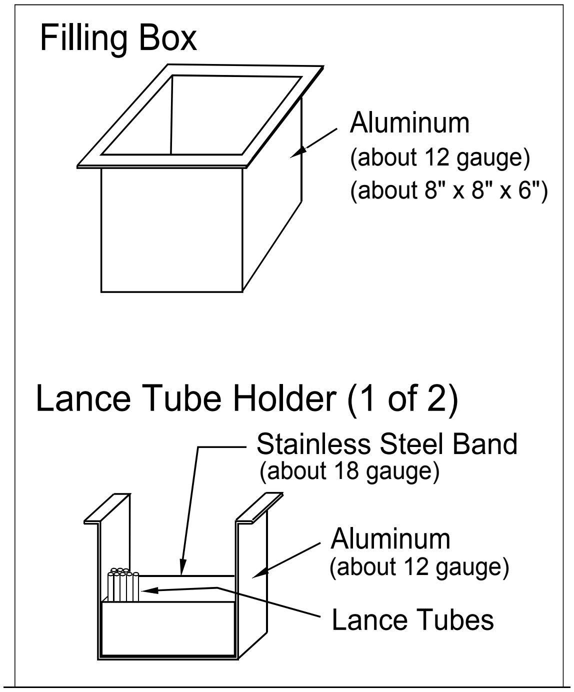

*Figure 2. Drawing of the lance tube filling box and one of two lance tube holders, which were contained within the filling box.*

position in each tube. Normally it took about 15 minutes to complete the filling of one container of 400 lance tubes.

Since the lance tubes were tightly packed into the filling container, not much lance composition was wasted by filling the spaces between the tubes. However, the excess composition was collected and re-used, even though it contained a small amount of prime. For this reason, it is important that the prime be chemically compatible with the lance formulas.

Manufacturing safety should always be of some concern, perhaps even more so in this case because of the compaction technique described. Note that the box is made of aluminum and the bumping surface is wood. These are quite forgiving in terms of likelihood of accidental ignition due to impact. Although the lance formulations reported in Tables 1 and 2 were not tested for their impact sensitivity, it is suspected that they are likely to be of relatively low sensitivity. Lance compositions are generally slow burning and thus are less likely, than star composition, to react explosively when ignited, even in moderately large amounts. Accordingly, accidental ignition of these lance compositions seems unlikely and the chance for explosive burning seems minimal. Nonetheless, the bumping surface should be kept clean with respect to lance composition, there should be no more composition in the immediate work area than necessary, containers should be kept covered, completed lance should not be allowed to accumulate in the work area, there should be only one person working in the lance loading area, and there should be at least one other person working nearby that could lend assistance in case of an accident.

One drawback to this manufacturing method is that the completed lance tubes are not completely clean on the outside. Nonetheless, they work well and can be cleaned if desired. One cleaning method is to simply wipe the tubes with an alcohol dampened cloth.

Often commercially produced lance is filled a short distance on the bottom with clay or fine sand. This can be useful in adjusting burn times of the various compositions so that all colors of lance burn out after nearly the same length of time. For those compositions that burn slower, more inert filler can be used at the bottom of the lance tube. The inert filler also acts to extend the life of the lance nails, because they are not exposed to burning composition. If desired, small fixed amounts of clay or fine sand can be preloaded into each lance tube before loading them into the filling container.

For this tube-filling method (inertial compaction) to work, it is necessary that the lance composition be fairly dense, and for all the components of the formula to have about the same density. This is one reason why Shimizu's lance formulas, mentioned earlier, were not used. They all contain wood meal (ultra-fine wood dust), which produces a composition that is light and fluffy. This greatly retards, or eliminates, the ability to sufficiently compact the composition in the tubes with just bumping. Also, the wood meal has such a low density compared to the other ingredients that it tends to separate out, rising to the top, during the bumping process. This tends to produce essentially incombustible layers of wood meal along the length of the lance tubes. Also, there was a period when the ammonium perchlorate most commonly available to the fireworks trade was extremely fine mesh. Use of this material caused the compositions to compact very poorly using the bumping method; it is preferred that the ammonium perchlorate (and other ingredients) be no finer than about 100 mesh.

An interesting variation is the making of color changing lance. This requires that the tubes be filled part way with different color compositions. To be effective, it is essential that all tubes in a group change color essentially simultaneously. About the only way to accomplish this is first to fill each tube with measured amounts of composition. After each tube is filled with the first composition (last color burned), it is compacted as described above. Then each tube is filled with the next color composition and compacted. After all the different color compositions have been loaded, the final step is the filling with prime as described above. In this way lance with one or more color changes can be prepared.

Completed lance were normally stored in plastic containers or in plastic bags in boxes. On occasion lance were stored for several years before use without any detectable deterioration. However, no attempt was ever made to determine their useful lifetime or whether problems might arise with their long-term storage particularly in more humid climates. It is important to avoid rough handling of the lance, because the prime coating can be broken and the loose powder below can then spill out.

## Final Lance Set Piece Assembly

The first step in set piece assembly is to press the correctly colored lance on each nail of the frame. This is done by holding the lance tube firmly along its body and pushing it onto the nail. Occasionally, when the frames were not to be stored for a long time and did not have to be transported a great distance, the tubes were not glued in place. This is possible because the filled tubes hold fairly tight to the nails, particularly after the nails have been burned from previous use. In addition, the frames were always transported horizontally, with the lance tubes pointing upward, thus there was less tendency for the tubes to loosen. However, for more positive attachment, the lance tubes should be glued into place with a small amount of glue applied to their bottom ends. This can be rapidly accomplished using a small shallow tray filled with about ¼-inch of carpenter's. (Hide glue and RTV cement are other alternatives.) The spun-closed end of the lance tube is dipped momentarily into the glue just before it is placed onto the nail. If desired, more glue support can be achieved by using glue thickened with an inert filler such as diatomaceous earth or wood meal.

The next step is to attach fuse to the collection of lance tubes. Many people use masking tape to hold the quick match to the lance tubes; others use string, looped first around the quick match and then around the frame to hold the match against the end of the lance tube. Masking tape does not hold particularly well, especially when exposed to the sun on a hot day; and the string method seems quite labor intensive. As an alternative, the authors used two-inch wide, plastic packaging tape of reasonably high quality to quickly secure the quick match. This method worked most efficiently when two people worked together. As the quick match is held across the top of a lance tube, a three or four inch length of tape is placed across the quick match and onto the sides of the tube. Next the two sticky surfaces of the tape, on either side of the lance tube, are pressed together, which draws the quick match down even tighter against the end of the lance tube. Photo 2 demonstrates the appearance of the taped lance tubes. This operation is repeated for the fusing of all lance tubes on the design. The plastic packaging tape sticks extremely well even to slightly dusty or waxed lance tubes, and it has no tendency to loosen with time or under direct sun.

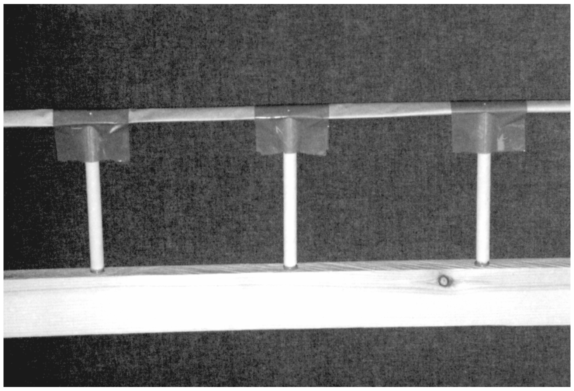

*Photo 2. Photo of quick match attached to lance tubes using plastic packaging tape.*

The quick match should be cross-fused in several places, providing multiple ignition paths, and thus better insuring the ignition of the entire design. This can be accomplished by simply holding crossing lengths of quick match together and applying a piece of plastic packaging tape to each side as shown in Photo 3. Similarly, when two or more smaller lance frames are assembled into a single larger unit on site, multiple (redundant) ignition paths should be installed between the individual smaller frames.

The final step is to poke ignition holes through the quick match into the end of each lance tube and through both pieces of quick match at each crossing point. This is easily accomplished using a poking tool such as also shown in Photo 3. This was made by simply gluing a double-pointed nail into the end of a piece of wood dowel. (As an alternative, there are leather working tools that can be used as poking instruments.) These ignition holes are essential to achieve a high percentage of lance tube ignitions. As quick match burns, hot gases are forced along its interior between the black match and the paper wrap. When those pressurized hot gases reach one of the holes poked into a lance tube or crossing point, the burning gases jet out

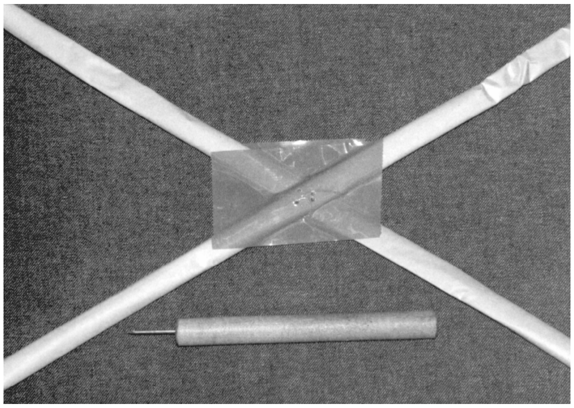

*Photo 3. Photo of a quick match cross fusing and ignition hole poking tool.*

through the hole igniting what it contacts, lance or other quick match. The poking process also breaks the prime on top of the lance tubes making it more ignitable.

Many in the fireworks industry use narrow staple guns to poke the ignition holes and further attach the quick match to the lance tubes. However, because these staple guns occasionally produce sparks when operated, the use of staple guns should be avoided (Ofca, 1989 and Winokur, 1985).

When spectators see a lance frame before a display, many will recognize it as a lancework and try to figure out what design it will produce. Probably their best clue is the pattern formed by the quick match. If the quick match follows directly around the design, it is relatively easy to successfully identify the design. In order to challenge these spectators, and hopefully surprise them, the authors found it preferable to run the quick match in a pattern which obscures the design. Often this can be accomplished when the extra quick match ignition paths and cross fusing mentioned above are included.

If the set piece is to be fired manually, a length of quick match, long enough for the shooter to easily reach, should be left at some point along the set piece. If the set piece is to be fired electrically, an electric match needs to be installed in the quick match fusing.

When quick match is used to light lance tubes, the entire design is ignited within a second or two. This is accompanied by abundant fire and sparks, and appears almost explosive. Often this effect can add to the drama of the presentation. However, there are occasions when a lancework scene is intended to unfold more slowly and serenely. On occasions, when the use of quick match works against the mood being sought, fast ICI igniter cord (plastic coated, brown, burning about one-foot per second) can be used instead of quick match. The time taken for design ignition ranges from less than five seconds to more than 15 seconds, depending on how the fuse is attached and where it is ignited. In addition to being slower, it burns almost silently by comparison with quick match. Also, some have reported that priming the lance tubes is unnecessary when using this type of fuse. The ICI igniter cord is available from Ladshaw Explosives (New Brunfels, TX) at a cost comparable to quick match. The plastic coating offers good protection from accidental ignition from sparks during a display. It is attached to the lance tubes just like quick match; however, there is no need to poke ignition holes because this fuse produces molten metal sparks as it burns. The fuse is quite light weight and flexible, making it particularly easy to work with. The authors used this fuse about 60% of the time.

## Final Display Arrangements

Completed lancework set pieces were often stored in a trailer built for transporting them to the display site. It was metal frame construction with metal siding, making it fire and weather resistant. The trailer held 12 frames horizontally, which were slid in on rails, much like the racks in an oven. Because of the limited number of displays performed by the authors each year, generally all the sets needed over the Fourth of July could be assembled in advance and stored in the trailer. On the day of a display, the frames needed would be loaded in the top most positions and other display materials could be loaded into the space below. On site, the lance frames would be left in the trailer, protected from weather and other possible damage, until just before the display.

Often lance set pieces are better viewed when raised above the ground; other times, because of obstructions, they may not even be visible if the frames are not raised in some manner. Most commonly, this is accomplished by mounting the frames on two by four poles, which are then

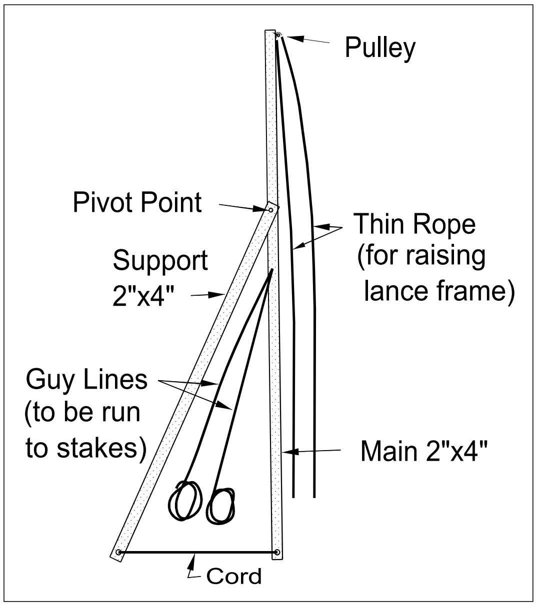

*Figure 3. Sketch of an "A-Frame" used to elevate and support lance frames during displays.*

erected and secured in some way. Unfortunately, unless the poles are strongly braced, they have a tendency to fall down, especially if an unexpected breeze comes up suddenly. Obviously, few, if any, lancework could survive such a collapse. The preferred support system would be easily transportable, inexpensive, strong and reusable. One solution is the use of "A-frames", shown in Figure 3.

The A-frames consist of two 2 × 4's, one longer than the other, that are loosely bolted together where the shorter one ends. This allows the two boards to pivot about this point. A hole is drilled into the base of each of the boards a cord is tied between the two legs to prevent their spreading too far when being erected. Near the pivot point two ropes are attached on either side of the 2 × 4's. These serve as lateral support guys and are tied to strong metal stakes driven into the ground on either side of the A-frame. (Reusable metal stakes can easily be made by cutting concrete reinforcing steel, "rebar", into short lengths.) Finally, a pulley is attached near the top of the long board with a thin rope threaded through it, long enough for the ends to nearly reach the ground. Pairs of A-frames are erected, about six feet apart, well before the time of the actual display. Then just before the display a lance frame is tied to the ends of the ropes and raised aloft by pulling on the other end of the ropes. This may seem complicated, but they erect quite easily and are quite sturdy even in moderate winds. They also offer the advantage of easily allowing the temporary lowering of the lance frames in the event of strong winds or rain. A-frames can also be used to support display items like Niagara Falls or cable used to suspend moving items like line rockets and small lanceworks. A variety of lengths of A-frames, ranging in height from eight to 24 feet, are useful. They should be painted dark colors for the same reasons as the lance frames. They bundle-up nicely and can be easily transported on racks over trucks or trailers taken to the display site.

It is distracting to the audience, and takes some of the mystery and drama from the presentation, to see a person running around carrying a flare (fusee) to light lanceworks. For this reason the authors always electrically fired their set pieces. Occasionally, this was accomplished by running wires back to the main firing control panel. However, since many lancework set pieces require the presence of an operator for their animation, a hand held firing control unit was often used, see Photo 4. The unit is powered by four C-cells mounted in an external battery pack on the back of the unit, which checks for electrical continuity, and can fire up to five independent circuits. It has separate output plugs for firing single circuits, up to three circuits, and for all five circuits. When it was nearly time to discharge a set piece, the operator would approach the display, plug in and then fire the item(s). In this way the audience never knew which ground display was about to be fired, and when the item was animated in some manner it was not obvious that there was a person in the vicinity who was probably responsible for the movement. (Of course, in those cases where it is practical, the lancework can be driven pyrotechnically.)

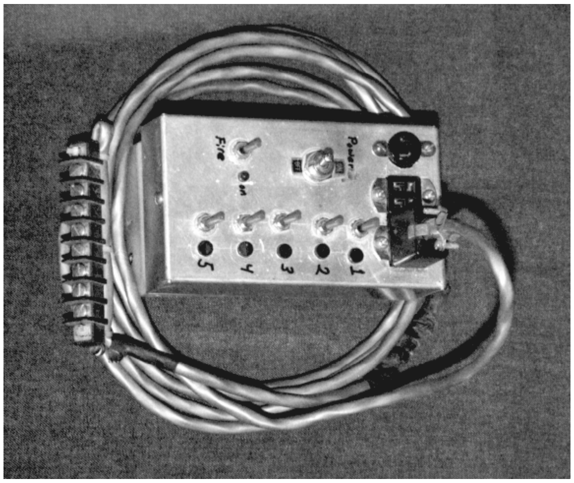

*Photo 4. Photo of a hand held electrical firing unit used for the ignition of set pieces. It is capable of testing continuity and firing up to five circuits.*

## Lancework Presentations

As mentioned in the introduction, a lancework set piece that sits there and does nothing other than burn for 60 seconds is little short of boring. Generally a sponsor should be dissuaded from having these items in the display. Most notable among lancework to be avoided are "WELCOME" and "GOOD NIGHT". They are a waste of time and money during a properly staged display. If you can not make the audience feel welcome by your presentation of the fireworks, no mere sign will accomplish it. Similarly, if the spectators can not identify the finale, then there was not a proper development of the display and it was a pitiful finale. However, for some stationary lancework, there is little or no choice. Among those are sponsor's logos; some sponsors will forego these for more crowd pleasing lancework, others will not. Of course the one stationary display, about which there is no choice on July 4th displays, is the American flag. In this case the solution to boredom is augmentation. After the flag set piece has burned for a while, augment the item with additional fireworks, then a little later augment with still more and grander fireworks. This concept is illustrated in Figure 4 with the American flag (top); then after about 20 seconds it is augmented with some fountains (middle); finally, after about another 20 seconds it is augmented with fountains and Roman candle batteries (bottom). When a company logo or similar stationary lancework is required, again use the concept of augmentation to hold the audience's interest.

While on the subject of the American flag, there are some other points that need mentioning. Obviously the rectangular flag, as used in Figure 4 for simplicity, can be enhanced by adopting a wavy pattern, depicting a flag waving in the breeze. It can be further enhanced with the addition of a flag staff and halyard. However, anyway it is configured; the flag is more nearly a solidly painted display, as opposed to an outline. Thus it generally requires many more lance tubes than other lancework designs of similar

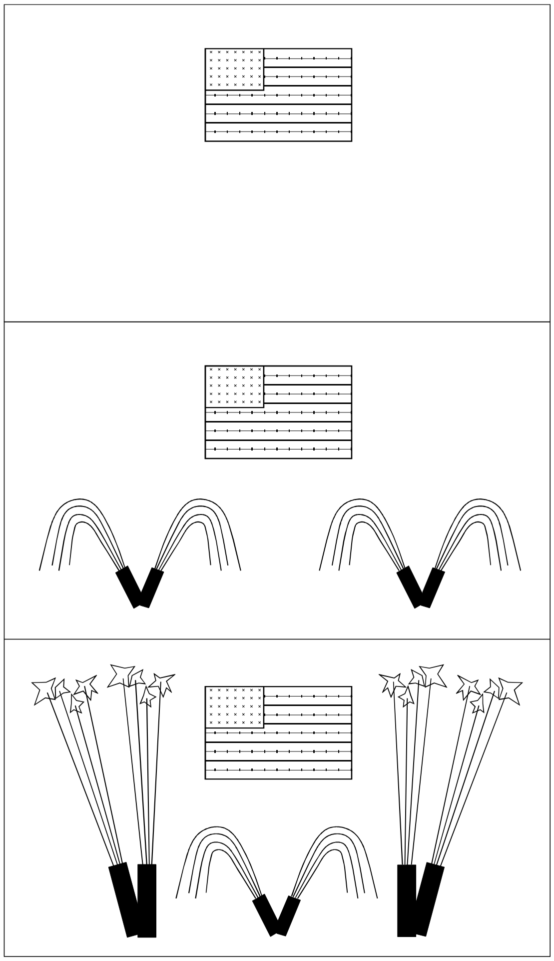

*Figure 4. (Top) Sketch of American flag lancework. (Middle) Example of flag set piece augmented with fountains. (Bottom) Example of flag set piece augmented with fountains and candle batteries.*

size. Obviously this means more cost for lance and assembly, which is of some importance. Perhaps less obvious, but more importantly, it means much more smoke, which can seriously detract from the performance. In addition to using low smoke lance formulations, one can reduce the number of stripes from 13 to 11. This will reduce both smoke and manufacturing cost by 15%, and essentially no one will notice the missing stripes. Also, do not attempt to include 50 stars; in fact, do not include any stars. It is the blue field plus red and white stripes that define the flag. Adding stars, washes out the effect of the blue field and adds unnecessarily to smoke production.

In the introduction it was suggested that most lancework set pieces should be animated or otherwise engage the audience. "Animated" simply means that the item or part(s) of it should move, this will surprise most spectators and please all of them. By "otherwise engage the audience" can mean nothing more than augmentation as described above, but generally it means to use individual lancework figures as characters in a skit. The remainder of this section will demonstrate such animation and engagement by discussing some examples.

Perhaps the simplest example of animation is that demonstrated in Figure 5. Top left is the figure of a pumpkin, a sad pumpkin. Top right is a happy pumpkin. The manner of changing the pumpkin's mood is illustrated at the bottom of Figure 5. Here the horizontal row of connected dots is intended to represent the mid-section of the pumpkin's mouth. At either end of that section is attached a thin board with four additional lance tubes. These boards are only attached to the framework on the end toward the middle of the pumpkin mouth, and that attachment point is a pivot. The outer ends of the boards have a thin cord attached, which is fed through eyelets on the lance frame. The board to the left is illustrating the sad pumpkin mouth, while that on the right is for the happy pumpkin. This design was once used in a display, staged for Halloween, at a State Home for the retarded. First the lancework was ignited as the sad pumpkin (orange pumpkin, green stem, red eyes and mouth). Of course, pyrotechnicians are familiar the expression, "Fireworks Make *Pumpkins* Happy". Thus, after the set piece burned for awhile, a collection of fountains and other items were ignited in the vicinity of the pumpkin, which caused its expression to change into the happy pumpkin (by pulling the cords). Obviously this was a trivial addition to the lance design, but the degree to which it contributed to a delightful reaction of the audience would be hard to overstate. This display was enhanced by being performed to some circus music. During the sad pumpkin phase, the music being played had been recorded at half speed, then when the augmenting fireworks were being shot, the speed of the recording was corrected, reinforcing the pumpkin's mood change.

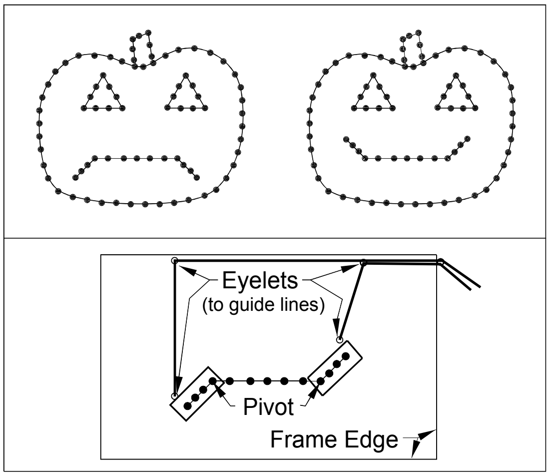

*Figure 5. (Top Left) Sad pumpkin figure. (Top Right) Happy pumpkin figure. (Bottom) The simple mechanism used to manipulate the pumpkin's mouth.*

A some what more complicated example of this type of animation is presented in Figure 6. This is a sequence of views of a fire breathing dinosaur (dragon) in action. The top view is the initial presentation to the audience (green dragon with a bright red eye). After about 20 seconds, the dinosaur rears back its head and belches out some red fire with silver sparks. After another 20 seconds, the dinosaur leans forward, belching more fire and sparks, this time igniting a candle battery of angry bees, which finally causes the dinosaur to again rear back its head.

To avoid the chance of premature ignition of the candle battery and also to be certain of ignition on cue, the candle battery was fired electrically. For the dinosaur to have a friendly appearance, it was made to look somewhat like the Flintstone's Dino, with a bulbous nose. Because

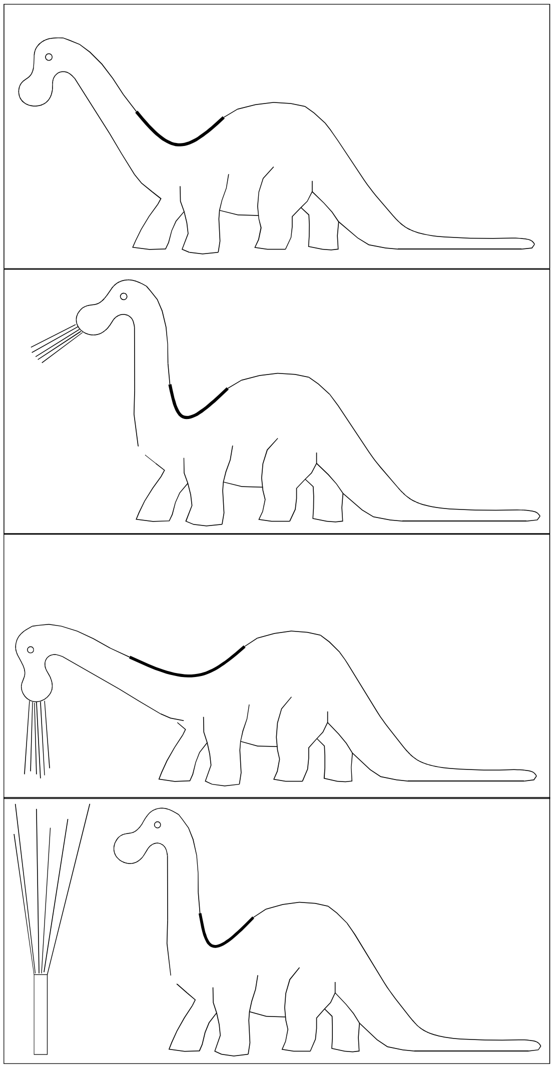

*Figure 6. Sketches of dinosaur lancework. (Top) Initial view. (Upper Middle) Dinosaur rears head back and breathes fire. (Lower Middle) Dinosaur lowers head and breaths fire, which "ignites" a candle battery (Bottom) causing the dinosaur to again rear its head back.*

the eye is a particularly important part of the lance figure, it was made with two lance tubes, thus doubling the chances at least one would light.

The mechanism of the Dinosaur's animation is illustrated in Figure 7. Here note that the entire head is a separate part of the figure, and is attached at a pivot point near the bottom of its neck. Motion of the head is controlled with a thin cord attached to the back of its neck, by an operator standing at the end of the frame. The puffs of red fire are created using red lance composition "spiked" with 20 to 40 mesh titanium. This is loaded loosely into a tube and ignited with an electric match. The aspect of this design that makes it work is a segment of "flexible rattan". The flexible portion is a piece of ½ inch garden hose with a series of lance attachment points, which are two inch brads nailed through the hose and tightly through a small disk of 1/8-inch tempered Masonite. The hose section is only attached at the ends, leaving the middle to take various natural bends as the head is manipulated. In this case the light hearted mood of the lancework might be enhanced by using Tchaikovsky's "Dance of the Sugar Plum Fairies" as musical accompaniment.

A simple example of another type of animation, where the whole figure moves, comes from the same show at the State Home discussed above. In this case the lance figure was that of a ghost. What is one obvious characteristic of ghosts? They float through the air, and, it will be a little scary if it floats toward the observer. In this instance, the ghost figure was attached to a cable running from the top of a 24 foot tall A-frame (discussed above), running about 50 feet toward the audience where it was attached to an eight foot tall A-frame. The lance frame was ignited while high in the air. After a while, a mine was discharged under the ghost, and it swooped part-way down toward the audience. This sequence was repeated a couple more times, each time coordinated with the music.

Basically this same method of animation (frame on a cable) can be used to provide an interesting variation of the "Fish in Niagara Falls".

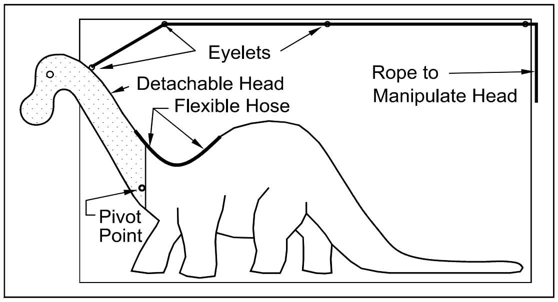

*Figure 7. Construction details for dinosaur lancework, illustrating mechanism and location of "flexible rattan" segment.*

This is where a lancework consisting of two or three fish is ignited (before, after, or simultaneously) below a standard Niagara Falls. For one possible variation, initially have the falls and fish separated, right to left, thus having the fish out of the water. Then after both are ignited, have the fish swim into the falls. That is to say have the fish lance frame suspended on a cable, then with a cord, pull the fish under the flowing falls. Another variation starts out the same with the fish out of water, but this time the falls are moved to where the fish are. This uses a stationary lance frame, but the falls have to be operated in a manner somewhat like a curtain on a rod. By varying the program like this, the same lancework can be used for the same display for several years running, and those people most enjoying the performance will be those that have seen the previous versions.

Animation can also combine moving parts of a figure and motion of the figure itself. Probably the most complicated example of this was a steam locomotive, appearing much like the "Little Engine that Could". In this case a cute little steam engine first appears, with its driver wheel, piston rod and cylinder, smoke stack (funnel), etc. Then after a little while it begins to puff smoke and fire from its stack and it starts to move along the ground. At the same time, and consistent with its motion, its drive wheel rotates and piston rod moves, along with its other wheel.

The smoke and fire are accomplished with a battery of tubes mounted behind its stack, each charged with several grams of black powder and perhaps some fine titanium. The battery is fused with a moderately fast fuse such as Thermolite (Cooney's Explosives, Hobbs, New Mexico). The delay between the initial tubes should be about two seconds, and the delay between tube firings should decrease as the engine speeds up. The speed of Thermolite used will depend on the size and arrangement of lances being used. Of course, the motion along the ground is accomplished with a person pulling on a rope. The wheels are plywood disks mounted on bearings at their center. Its rotation is made to be consistent with the motion of the engine by simply having the wheels touch the ground, thus having the motion of the figure along the ground provide the rotation of the wheels. There are, however, a couple of things that should be made more clear. First, the lance frame needs to be attached to a skid of some sort to keep it from falling over when pulled along the ground. Any of a number of designs will work; the authors used an out rigger from the back of the frame with a wheel on it. This along with the train wheels made the lancework easy to move and easy to setup. In order to keep the moving piston rod from knocking off the lance tubes on the driver wheel it had to be moved out in front of the wheel to provide clearance for the lance tubes. Similarly, where the piston rod moved inside the cylinder, it is necessary to have clearance for the lance tubes on the piston rod. It is also necessary to have the cylinder be solid (thin plywood) so that the lances on the piston rod will not be seen as they seem to move inside it.

Another effective way to use lancework is in the acting out of a brief skit. A simple example of this is illustrated in Figure 8. The first scene rivals two cute little tanks facing one another. One, "Nasty Tank", decides to be a bully by starting to fire on "Good Tank" who just sits there and takes it. The audience may start to cheer now rooting for Good Tank to start firing back, which it never does. Finally, "Powerful Tank" erupts onto the scene unleashing a short intense burst of gunfire toward Nasty Tank. There is a powerful explosion and Nasty Tank is no more. By now the crowd is cheering madly. This provides lots of entertainment and a message too. Be careful about picking fights, there will always be someone bigger, tougher, or meaner than you.

A few points need mentioning regarding the mechanics of the tank skit. The cannon fire from Nasty Tank should be slow paced and anemic, such as that which might be produced using a single "color with bangs" roman candle. The cannon fire from Powerful Tank should be brief but intense, such as might be produced by a battery of single shot silver comets fused to fire essentially simultaneously. There is a large salute (about three-inch) mounted directly behind Nasty Tank, which is fired at the same time the comets from Powerful Tank arrive on target. Nasty tank disappears, but not because it is blown up, which could send debris toward and possibly into the spectators. Nasty Tank is setup leaning slightly forward toward the audience, only kept from falling by a light cord securing it from behind. This cord is tied around the large

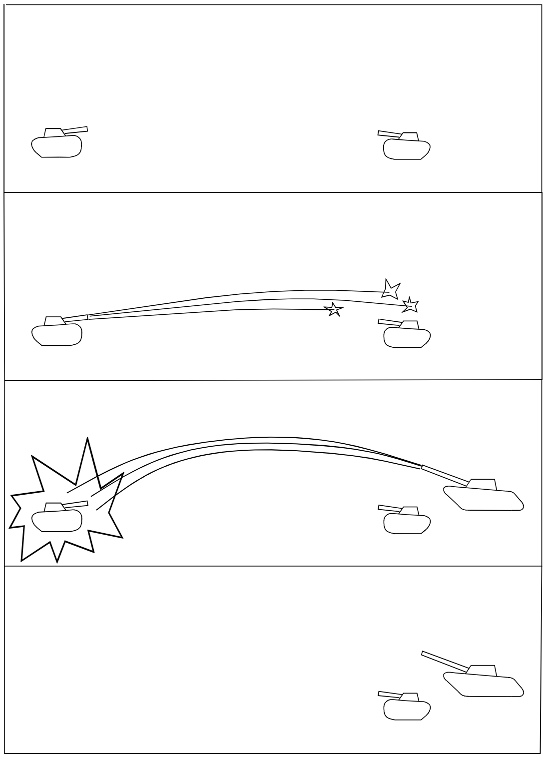

*Figure 8. Sketches of a tank battle scene. (Top) Initial view. (Upper Middle) "Nasty Tank" begins to fire at "Good Tank". (Lower Middle) After a while "Powerful Tank" appears, fires at Nasty Tank, which explodes violently. (Bottom) No more Nasty Tank.*

salute mentioned above. When the salute explodes, the cord is severed, allowing Nasty Tank to fall forward snuffing out or obscuring the lance flames in the grass as it hits the ground.

There are two other skits with much the same message as the tank skit. The first might be called "Little Fish, Big Fish". In this case, the first scene is of Little Fish and a worm in front of it. Little Fish moves forward, opens its mouth, swallowing the worm, which disappears inside. Next Big Fish appears behind Little Fish. Big Fish swims forward, opens its mouth, swallowing Little Fish. The only detail needing mention here is that the fish need to have big mouths and they must be solid so that what is seen to be eaten disappears. The other skit with similar theme begins with a hot air balloon inflated but on the ground and a figure of a man standing nearby. The burners in the balloon are fired, after which the balloon rises slowly into the air. Next someone in the balloon throws out a bomb blowing up the guy on the ground. Then an old biplane suddenly appears in the air above the balloon, it fires a burst of machine gunfire at the balloon, causing it to plummet to the ground. In this case, the balloon burners are specially made short duration fountains. The balloon is initially on the ground but has been set in front of a pair of 24-foot tall A-frames. Using ropes, the pulleys on top of the A-frames, and (strong) manpower, the balloon can be raised and later lowered. The biplane is supported off the ground using another pair of A-frames.

As one last example of a skit with moving parts, consider the following, used in conjunction with a series of annual displays fired for the Junior College World Series of Baseball. Imagine how a scene might appear with some kids playing baseball behind a fence, such that only part of the action and not the kids themselves can be seen. This is illustrated in Figure 9 in which the fence is actually the outfield fence in the ball park. In the first scene, the ball has been pitched and is approaching the batter (bat). The batter swings striking the ball and the crack of the bat is heard (and seen too). This is produced by a salute on top of a thin pole such that it is positioned just behind where the bat appears to contact the ball. The ball is now moving in the opposite direction sailing toward the outfield. At the last minute a gloved hand is seen reaching up from behind the fence to catch the ball. At this point there are three ways for the skit to conclude. In version one, the ball stops in the middle of the glove, the catch having been successfully made. This is noted by displaying the word "OUT" on a lancework banner above the glove. In version two, the ball approaches the gloved hand still rising and the ball continues over and beyond the glove. Obviously a home run that can be announced on the banner as "GONE". In the final version, the ball stops momentarily in the glove then falls to the ground. Obviously this is an error, which is announced as "OOPS". The beauty of this skit is that it can be re-played again and again; each year with the audience never being sure what will happen, and each year with the most favorable response coming from those in the audience that have seen one or another version of the skit before.

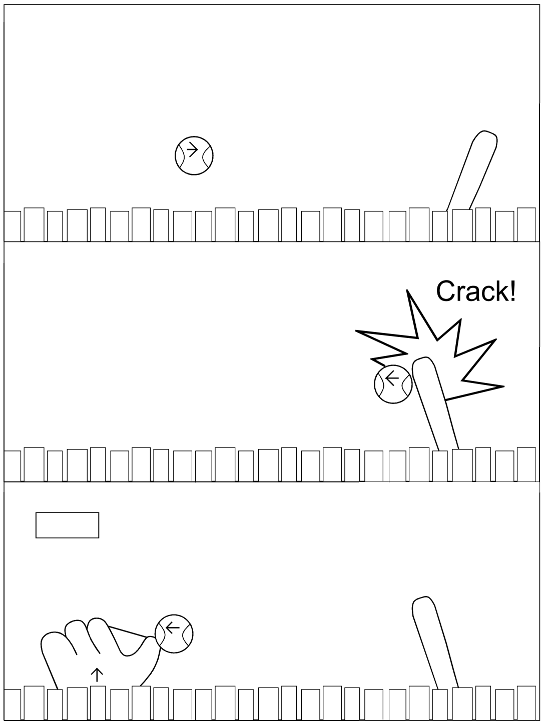

*Figure 9. Sketches of baseball scene. (Top) The baseball is seen approaching the bat. (Middle) The bat is swung forward, striking the ball with an explosion and sending it in the opposite direction. (Bottom) As the ball continues to move, a giant mitt reaches up to catch the ball.*

## Conclusion

Lancework set pieces can be one of the most crowd pleasing types of fireworks, or they can be a bore. It is strictly up to you and your imagination. If one uses high quality lance formulas, skillfully designs the lance figures, provides clever animation or tells and interesting story, the entertainment value of lancework can reach the heights that it should.

## Acknowledgments

The authors wish to express their gratitude for the assistance of G. Roberts in the design and construction of some of the lancework discussed in this article. Further, the authors wish to thank the Pyrotechnica Staff and especially C. Jennings-White, R. Winokur and M. VanTiel for their technical comments and editorial assistance, and for their contributions appended to this article.

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# Appendix A

## Supplemental Lance Formulations

Clive Jennings-White

| Ingredient | Red | Orange | Yellow | Aqua | Blue | Purple | White |
|---|---|---|---|---|---|---|---|
| Ammonium perchlorate | 30 | 75 | — | 30 | — | 50 | — |
| Potassium perchlorate | 35 | — | 60 | 5 | 55 | 20 | 75 |
| Accroides resin | 5 | — | — | 10 | — | 10 | 20 |
| Hexamine | 10 | — | — | 4 | — | — | — |
| Strontium carbonate | 20 | — | — | — | — | 10 | — |
| Barium nitrate | — | — | 15 | 45 | — | — | — |
| Shellac | — | 15 | 15 | — | — | — | — |
| Calcium carbonate | — | 10 | — | — | — | — | — |
| Sodium oxalate | — | — | 10 | — | — | — | — |
| Benzoic acid | — | — | — | 5 | — | 5 | — |
| Cupric carbonate | — | — | — | 1 | — | — | — |
| Lactose | — | — | — | — | 25 | — | — |
| Cuprous chloride | — | — | — | — | 15 | — | — |
| Parlon | — | — | — | — | 5 | — | — |
| Cupric oxide | — | — | — | — | — | 5 | — |
| Dextrin | — | — | — | — | — | — | 5 |
| Burning Rate (sec/inch) | 29 | 25 | 30 | 20 | 22 | 23 | 24 |

### Comments on Supplemental Lance Formulations in above Table

*Red* — A slight modification of S. Bases' (1978) formulation number 4. This might be suitable for use in particularly humid climates, where strontium nitrate could cause a problem. Otherwise the formulation given in Table 1 is superior in all respects.

*Orange* — A formulation given by T. Shimizu (1981). This very superior orange lance composition is effective in both hand rolled and commercial lance tubes. However, it may not have a sufficient density for the filling method described in the text.

*Yellow* — A formulation given by T. Shimizu (1983), which is a good balanced yellow, but it produces a fair amount of smoke as it does not contain ammonium perchlorate. One should not assume that it is free of hygroscopicity problems, because the combination of barium nitrate and sodium oxalate undergoes double decomposition to produce sodium nitrate.

*Aqua* — A modification of J. Baechle's (1989) system five aqua. This works well in both hand rolled and commercial lance tubes. The color is more towards the green than that produced from the composition in Table 2.

*Blue* — Previously published (Jennings-White, 1990). This composition is useless in commercial lance tubes, but in hand rolled tubes the effect is second to none. However, there is substantial smoke production because there is no ammonium perchlorate.

*Purple* — Previously unpublished. This works well in both hand rolled and commercial lance tubes.

*White* — A slight modification of Ellern's (1968) formulation number 39. This produces a "warmer" white than the composition in Table 2, and also it has the advantage of formulation simplicity. It is effective in both hand rolled and commercial lance tubes. However, there is substantial smoke production because there is no ammonium perchlorate.

# Appendix B

## Some Additional Thoughts

Martin VanTiel

*Lancework Burn-out* — An artistic preference, when the lancework nears burn-out, is to lead the audiences view into the sky. This will distract their attention away from the lancework while each lance finally burns out in a disorderly fashion. In the minds of the audience, the lancework will be remembered in its full glory while the display continues. This can easily be accomplished by the use of a flight of rockets or tailed aerial shells.

*3D Lancework Design* — A further development in the presentation of lancework which one should not overlook, is that of the third dimension. Three dimensional lancework has the advantage of being viewed generally from all directions unlike 2D framework designs. This is well suited for displays where the audience is not situated in one viewing position. Also, due to the relatively non-hazardous nature of lancework ground displays, they are generally situated in close proximity to the audience and viewing at obtuse angles is not very rewarding. The 3D lancework can be rotated or moved on a trolley arrangement, so that all sides can be viewed. The artistic potential is limited by time and cost, but novelty, amazement and wonder will be enjoyed for a lot longer.

*Lancework Chemistry* — There are some aspects of chemistry that need to be considered with lance compositions. One very important aspect is that the lance tube is to be considered as fuel. The lance tube is required to burn away during operation and therefore lance compositions generally have a high percentage of oxidizers in order to accomplish this. An oxygen rich flame is not considered to provide the best color and therefore one must find a balance between tube burning and flame color. Obviously the thinner the wall of the lance tube, the easier a composition can be developed to burn the tube away.

The use of low energy fuels, (defined as organic compounds having a high percentage of oxygen, chlorine or nitrogen) such as cellulose (or wood meal), hexamine or PVC, require small amounts of oxygen to burn completely. These fuels can be used at a moderate percentage to give oxygen rich combustion to enable the tube to burn away. These low energy fuels also have lower flame temperatures, which are useful in blue lance compositions. High energy fuels (defined as hydrocarbon compounds with little or no other elements) such as stearic acid, wax, gums and resins require large amounts of oxygen to burn completely. High energy fuels must be incorporated at a low percentage so that the tube may burn away.

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**Red and Green, High Energy Fuel Lance Compositions.**

| Ingredient | Red | Green |
|---|---|---|
| Ammonium Perchlorate | 80 | 60 |
| Strontium Carbonate | 10 | — |
| Barium Nitrate | — | 30 |
| Fuel | 10 | 10 |

The use of ammonium perchlorate has obvious advantages in lance compositions, no smoke (dry air), no ash, available chlorine. The disadvantage of ammonium perchlorate is that it is not suitable for use with potassium nitrate compositions because of the possible production of hygroscopic ammonium nitrate.

Another consideration can be the use of suitable organometallic compounds based on copper, strontium, barium, etc. (cost and availability permitting) with ammonium perchlorate along the lines of Bleser's (1987) blue formulation based on copper benzoate. This provides two component compositions readily adjusted to suit color and tube burning.

# Appendix C

## Some Lancework Ideas

Robert M. Winokur

An inspection of display fireworks company catalogues from the 1940's, '50's, and '60's reveals an assortment of lancework illustrations that are a valuable source of ideas for those wishing to build lanceworks. Below I have summarized some of these and added a few derived from my own experience. I claim no special originality for any of these ideas. Indeed, catalogues spanning over 100 years often contain identical or very similar drawings, indicating significant "borrowing" between companies. Some of the lanceworks are listed with little or no explanations of mechanisms of animation. The reader will need to devise the mechanisms themselves, although in most instances movement can be achieved without especially complicated designs. In fact, a serious attempt should be made to keep all mechanisms as simple as possible to avoid technical "traps" which can cause failures during a performance. In a few instances I have provided brief explanations and recommendations with regard to structural designs, animation mechanisms, and pyrotechnic considerations. It is hoped that this list will become a useful and convenient resource when planning lanceworks.

*Rocket to the moon* — A large lancework rocket with a gerb as the motor is pulled along a cable towards a crescent-shaped lancework moon. Rocket—red, gerb—silver, and moon—white or yellow.

*Sea lion bounces a large ball on his nose.*

*Old time car* — Wheels turn, radiator steams and car backfires (small ground bombs).

*Mother circus elephant washes baby elephant while the baby sits in a tub* — Spray from Mother's trunk achieved with a silver gerb.

*Pelican eats multiple small fish* — Movable bill on the pelican catches a number of "fish" in the form of either line rockets or small lancework fish pulled on a cable.

*Liberty bell with crack* — Patriotic theme.

*Boy fishing with pole catches a fish.*

*Basketball player dribbles a ball.*

*Golfer hits a number of balls and finally gets the ball into the hole on the green.*

*Cartoon characters* — Snoopy, Sesame Street characters, Disney characters, Warner Brothers' characters (Bugs Bunny, Porky Pig, Elmer Fudd, Daffy Duck). These must be relatively large if they are to be recognizable. Permission may be needed in some instances.

*Caricature of politicians* — These can be very entertaining but need to be built larger than many other lanceworks to be effective.

*Cinderella* — A fairy god-mother changes a pumpkin into an elaborately decorated coach.

*Bee hive with bees* — The hive is a lancework, bees themselves can be hummers from hummer candles or mines, or various Chinese whistle items such as "News Transmitters". The Chinese offer a number of small hummer devices. One is even called "small bees".

*Green caterpillar becomes a colorful butterfly* — Any number of designs for a caterpillar may work well. I have used the one pictured in Figure C-1. After about 20 seconds, the knobs on the antennae begin to spin (small wheels) and the legs move. After the caterpillar is extinguished, and the audience perhaps believes this is the end of the performance, a large butterfly ignites having colored and animated spots on its wings (wheels with color pots or color saxons).

*Lawn Sprinkler Causes Flowers to Grow* — Silver gerbs angled at about 45 degrees and mounted on a horizontal wheel, sprinkles the ground. (The gerbs used must have titanium or aluminum particles of sufficient size to reach the ground or the effect is lost). Lancework flowers are ignited while flat on the ground and then

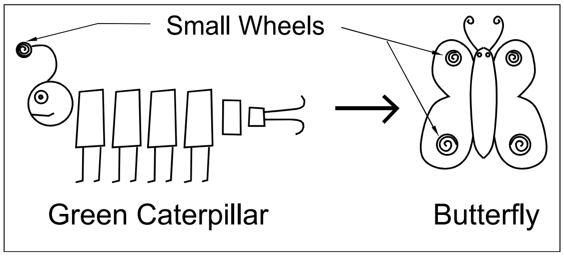

*Figure C-1. Green caterpillar becomes a colorful butterfly.*

pulled slowly into a vertical position. If this is done on a hillside, the flowers can be seen to grow out of a green field produced by green lances positioned on frames, which remain horizontal on the ground. There is danger of having the entire scene obscured by smoke because of too many lances being used at one time. If the scene is made very large and the green field is composed of widely spaced lances, the smoke can be lessened.

*Duck, Egg and Duckling* — A large white mother duck ignites, and about 20 seconds lager, a large white egg ignites below and behind her. After another 10 seconds, the egg forms a crack (a separate circuit ignites a set of lances forming the crack. These must be protected from igniting at the same time as the egg). After another 10 seconds, the egg splits open on a hinged frame and a small, "cute" yellow duckling ignites on a separate frame near the egg. The duckling is then "walked" across the field, at first away from the mother duck and egg, but then to a position immediately behind the mother (but not so close to the egg that it will be obscured). The motion of the duckling can be caused by simply having a black clad pyrotechnician pick up the frame, which initially rests against a couple of supports and with gloved hands and safety glasses "walk" the frame using a rocking and bobbing motion. This skit can be extremely successful in audiences having large numbers of small children.

*Transformation Lanceworks* — These are somewhat complex items in which a picture is embedded within another picture. Lances of two burn times are used (for example, 30 and 60 seconds). When the short lances become extinguished, a "new" picture comes into view. See *A History of Fireworks* by Alan St. H. Brock (1949), pages 223–226 and Plate XXII (facing page 192) for a description of transformation lanceworks.

*Giant Firecracker* — A large tubular firecracker sits at a 45 degree angle and has a yellow fuse that is about ♍ as long as the cracker, see Figure C-2. The fuse is composed of shortened lances, the shortest burning only 10 seconds and positioned at the far tip of the fuse. Progressively longer lances are positioned towards the cracker until several 30 second lances are situated immediately adjacent to the cracker's end. At the end of the 30 seconds, a large (preferably titanium) ground bomb explodes behind the frame severing a cord, which is suspending the upper half of the hinged firecracker frame. Thirty second lances must ignite at this same moment to produce the appearance of jagged broken ends of the cracker. The broken edges must not become ignited during the initial 30 seconds. The ground bomb must be suspended well above the ground so as not to throw debris and must be perfectly timed. I recommend it be done electrically. The shortened (cut) lances used in the fuse must be re-primed to insure ignition. The hinged frame must be carefully constructed to fall apart from its own weight but not to disintegrate into a crumpled heap on the ground.

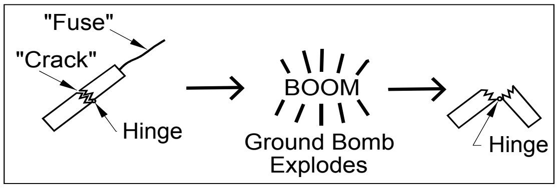

*Figure C-2. Giant firecracker.*

*Human Face* — This is one of my favorite ideas and although I have only had an occasion to use it twice, it has enormous crowd-pleasing potential, see Figure C-3. It consists of a large (the larger the better) round or oval face with changing expressions and moving pupils. Elaborations easily done include eyebrows for more expressive faces, hair (by use of carefully positioned multiple gerbs), and a movable mouth (using flexible hose or other suitable material). The eyes should be large and the pupils composed of three or more lances spaced about 2 inches apart in a triangle or other tight pattern. Expressions obtained with very simple lines include: happy, sad, sad with tears, "scary", dumb, very dumb, angry, ugly, vicious, surprised, quizzical, sly, disgusted (with a tongue), and sleepy (with half-closed eyelids). Moving eyes can be used with wonderful results. Small wheels can be used as eyes and can be made to spin in reaction to fireworks shot, or perhaps the ignition of an adjacent female face. Winking can be accomplished by having one eye on a revolving board that swings to face away from the audience and then back again towards the audience. (A strobe

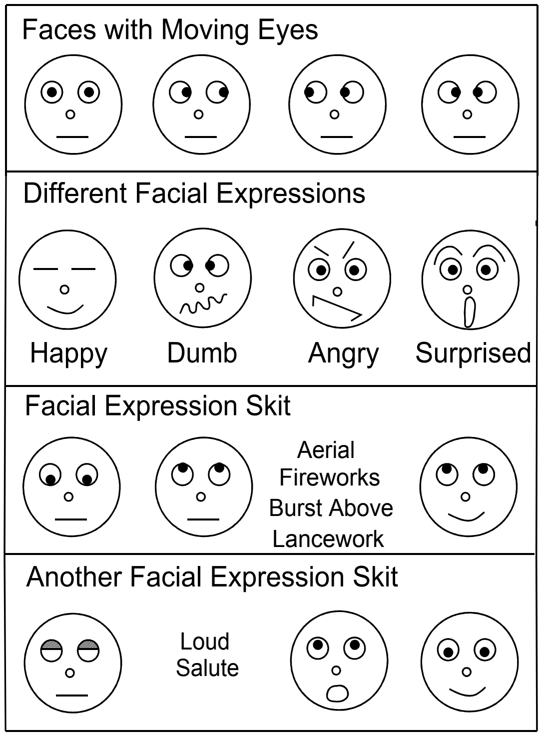

*Figure C-3. Human Face.*

pot might be effective to achieve a winking eye.) Skit possibilities are virtually endless. Very few pictures hold the attention better than that of a face. The human brain is very sensitive to subtle expressions and we have the propensity to see and make relevant even small changes in a face. The lancework designer should experiment with many drawings of faces in order to find appropriate ones that meet the needs of a skit. The drawings presented here represent only a few of the many possibilities.

An earlier version appeared in *Fireworks Business*, No. 120 (1994).

# Successful Bidding and Performance on Government Fireworks Display Contracts

K.L. and B.J. Kosanke

Over the years the authors have had experience with government contracting from both sides: in selecting and monitoring contractors for the government and as holders of government contracts. In this article we would like to share some general information about contracting with the federal government and about contracting for fireworks displays in particular. However, readers are cautioned that there are some differences in the manner in which various government departments let contracts and then monitor those contracts. Thus there is no guarantee that the process, as described in this article, is completely accurate for any particular situation.

In preparation for contracting for a fireworks display a "Request for Proposal" (RFP) is prepared by the government agency. This presents all of the government's contracting requirements and the specifications for the display. The RFP is sent to a collection of display companies that have proposed in the past or have requested to receive the solicitation package. In recent years some contracts have been a small business set aside; as a result, a few of the largest display companies are excluded from consideration. After receiving and studying the RFP, potential bidders draft and submit their proposals.

In most cases, the process of selecting a contractor is in essence a two step process in which **TOTALLY** different rules apply. In the first step the **ONLY** consideration is whether the proposal is "Responsive" or "Non-Responsive" (more on this later). Only those proposals declared to be responsive make it to the second step, where the **ONLY** consideration is the price for the display. As a slight complication, the responsive bidders may be asked for their "Best and Final" price, at which time they are free (encouraged) to trim their proposed price in hopes of being the low bidder, the one that will be awarded the contract.

It might seem that this is an inappropriate way to contract for a display, and many in the government might agree. Nonetheless they are required to follow "Federal Acquisition Regulations" (FAR's). As a result, fireworks displays are purchased very much like nuts and bolts, with the artistry of the display occasionally suffering as a result. For example, suppose there are only two proposals that are responsive (i.e., meet all the government's minimum requirements for the display). Suppose one just meets the minimum shell count and the other promises a substantially greater shell count. All else being equal, the larger display should be the better one. However, if the bidder proposing the larger display has a higher price, even by just one dollar, the government must choose the lower priced proposal. This seems foolish, as obviously the larger display, for only a dollar more, is the better value. The reason it is not foolish, at least as far as government procurement regulations are concerned, can be seen in a second example. Suppose instead, this is a contract for nuts and bolts, and detailed specifications have been established for them that completely satisfy the government's needs in every way. Again there are two bidders to supply the nuts and bolts; the first bidder proposes just to meet the specifications, while the second bidder proposes not only to meet the specification but also hand polish each nut and bolt to a perfect mirror finish. If the first bidder has the lower price, that is the one who will be awarded the contract. This is as it should be; why should the government spend any of our taxes, even just one dollar, for something that is not needed (like polishing nuts and bolts to a mirror finish). While this makes perfect sense when purchasing nuts and bolts, for the most part, it does not make good sense for a fireworks display. (A fireworks display should be purchased more like the commission for a piece of art, where the price is set and then the best proposal for that amount wins.)

From the above discussion it should be clear that price is ultimately very important. However, the proposed price will not even be considered unless the proposal is first found to be responsive. For a proposal to be responsive, it must address each and every item identified in the RFP. Further it is necessary that each of these responses meet or exceed the minimum requirement established for that item. Note, as in the example above, that no extra points are given for substantially exceeding any or all requirements. Accordingly there are two excellent reasons not to propose to significantly exceed any RFP requirement. In the first place, exceeding the requirements will cost more. While this may result in a superbly responsive proposal, it may also be one which must later be rejected on the basis of cost. Secondly, any promises made in the proposal must be kept after award of the contract. Since, generally, the government will be holding a 100% performance bond paid in advance by you, and since they have the authority to assess "liquidated damages" (deductions to the contract price) for any promises not kept, they have two mighty big sticks to encourage a contractor to meet their commitments.

A point by point discussion of each requirement listed in past government RFP's for fireworks displays might be useful for potential bidders; however, that would turn this short article into a book, which would be of little interest to most readers. Accordingly the subject will not be pursued further in this article.

Some government displays can be referred to as "prestige" shows, ones that a company may want to perform for the prestige derived from having done it. For this reason many companies bid these shows at the absolute lowest possible prices. Often this is little more than about half the fair market value for the display or about the wholesale value of the fireworks alone. Accordingly, unless one is an importer, buying considerably below wholesale, and willing to forego almost any hope of profit, it will not be possible to propose a low enough price for those prestige shows. In fact, to be able to meet the shell counts required in the RFP and still get the price low enough, one probably has to be able to manufacture or purchase specially made low value "filler shells". These are shells that have impressive names and hopefully look good when shot in barrages, but which are relatively inexpensive. Moral and ethical considerations aside, unless a significant number of this type of shell are used, it will be difficult to win some government display contracts and still break even on the display.

Since some government contracting officers feel that past contractors have occasionally tried to cheat by not fulfilling their obligations, they have tightened many of their practices and exercise more control over their contractors. For example, contracting people may be on site at all times and may insist on verifying all aspects of compliance with the proposal. Most notably, there generally will be a 100% inventory of the shells promised, right down to manufacturer and type. During loading, monitors will usually be present to prevent unauthorized substitutions of cheaper shells or pulling shells without any substitution. Following the display, there will be a mortar by mortar inspection to determine exactly which shells have not been fired. Accordingly, attempts to lower costs with this type of cheating will not be possible.

Rarely is it easy to do business with the government. However, many potential problems can be eliminated by using care not to propose more than you are willing to deliver and with good advance planning with lots of attention to details and contingencies. Nonetheless, in order to win government display contracts, a company has to be willing to forego almost any hope of profit.

An earlier version appeared in *American Fireworks News*, No. 150 (1994)

# Electric Matches and Squibs

K.L. and B.J. Kosanke

The terms electric match and squib are often used interchangeably in the fireworks industry. However, there are at least two good reasons not to do this, one technical and one legal. Technically, these are two different items both in terms of form and function. Legally, although both are Class C explosives (Explosives, 1.4g), squibs are on the BATF Explosive Materials List, which invokes all the regulatory requirements normally reserved for Display Fireworks, Blasting Caps and Dynamite.

Figure 1 is a sketch of an electric match. The item consists of a short length of high resistance wire (bridge wire) mounted across copper cladding on an electrically insulating substrate. The high resistance element is surrounded by a heat sensitive pyrotechnic composition. Coated on top of this first composition may be a second less sensitive composition that enhances the pyrotechnic output of the device and to some extent serves to protect the first composition. Finally, there is normally a coating of material (often nitrocellulose lacquer) to further protect and strengthen the electric match compositions. Wires to facilitate making electrical connections (leg wires) are usually pre-attached to the electric match. Photo 1 shows a collection of electric matches.

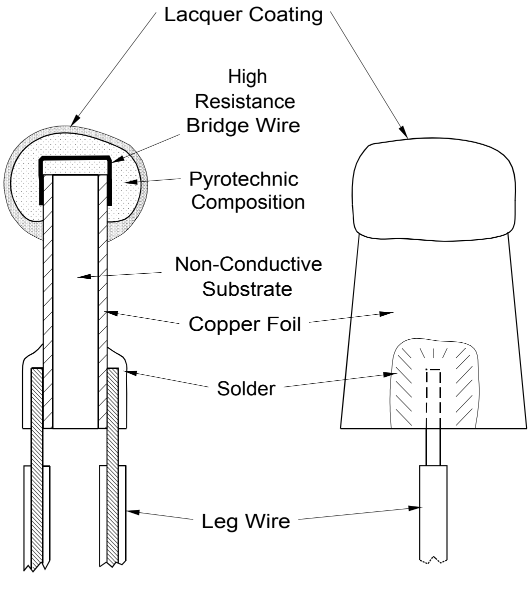

*Figure 1. A sketch illustrating the construction of a typical electric match.*

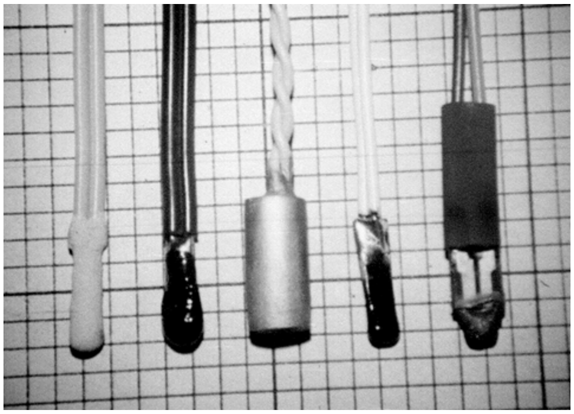

*Photo 1. A photograph of some typical electric matches. (The grid in the background is 0.1 inch.)*

The function of an electric match is to produce a small burst of flame somewhat like that produced by the composition on a safety match. The output is initiated by the passage of an electrical current through the device. This heats the bridge wire and in turn ignites the pyrotechnic composition. It is the amount and duration of the electric current that determines whether an electric match will ignite. Figure 2 (courtesy of Atlas Powder Company, Dallas, TX)[1] illustrates the firing characteristics for Atlas matches as a function of current and time for which it is applied. Note that "all-fire current" is defined as the minimum current that is required to cause 100 of 100 matches to fire, when applied for a specified amount of time. (It is the authors' belief that when no time is specified, it is assumed to be 5 seconds.) "No-fire current" is defined as

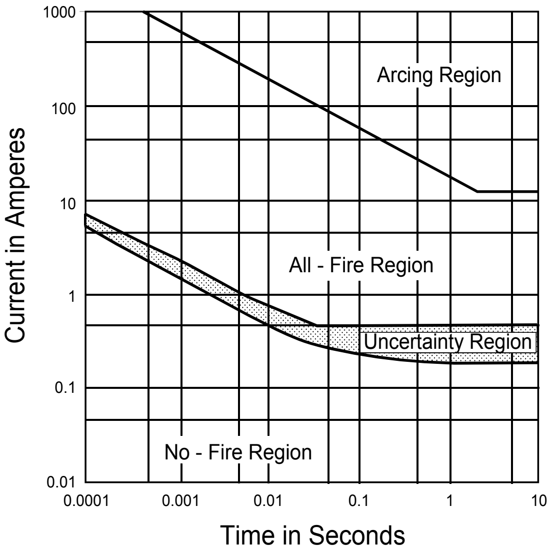

*Figure 2. Electrical response characteristics of Atlas electric matches. (Reproduced through the courtesy of Atlas Powder Company, Dallas, TX).*

the maximum current that can be applied that results in 0 of 100 matches igniting, when applied for the same amount of time. Between these two regions in Figure 2 is another narrow region in which it is uncertain whether the electric match will ignite.

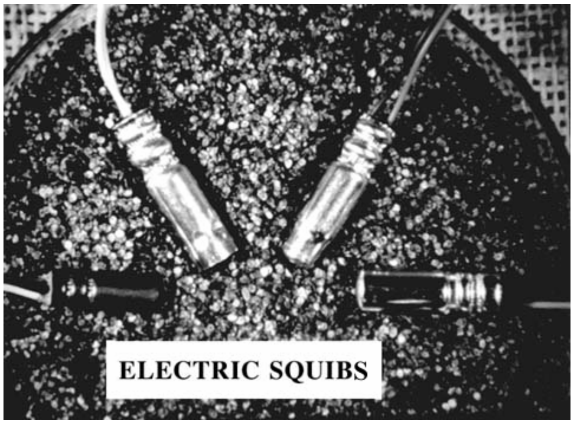

*Photo 2. A photograph of some typical electric squibs. (Supplied by George Jackson, FLETC.)*

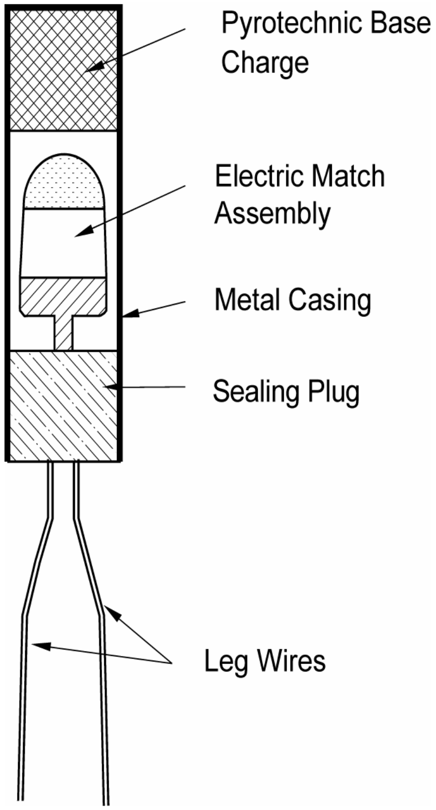

*Figure 3. A sketch illustrating the construction of a typical electric squib.*

It is true that electric squibs contain an electric match as an initiator; however, squibs contain substantially more pyrotechnic material, a base charge. Also, squibs have an external casing, usually made of metal, giving them an appearance similar to that of a miniature detonator (blasting cap). The effect of these two added elements greatly magnifies their effect upon functioning. In fact some squibs are so powerful as to allow them to initiate high explosives,[2] making them essentially equivalent to a small detonator. Figure 3 and Photo 2 illustrate the construction and appearance of squibs.

Regarding the correct identification of electric matches and squibs, there are some clarifications that should be made with respect to Photos 1 and 2. Note that the electric match pictured in the center of Photo 1 has an appearance somewhat similar to that of a squib. However this device is essentially solid plastic with only a small recess in the end, in which the bridge wire and match composition are contained. Similarly, the electric match on the right has an inert plastic sleeve over the point where its leg wires attach to the match tip. Also note that there is a small difference in scale between Photos 1 and 2, with the items in Photo 1 appearing slightly larger relative to those in Photo 2.

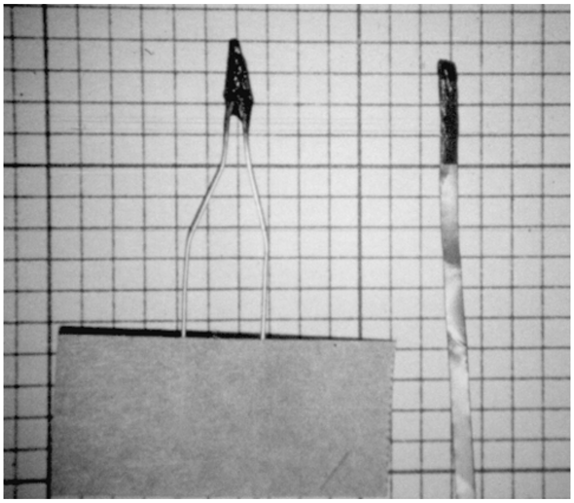

*Photo 3. A Photograph of two types of model rocket igniters. (The grid in the background is 0.1 inch.)*

Thus it should be fairly clear that electric matches and squibs are substantially different classes of items. Presumably that difference is one reason for squibs being on the BATF Explosive Materials List. As most readers already know, the presence of an item on this list invokes stringent storage, record keeping and licensing requirements on the item's possession, sale and use. Thus squibs are definitely BATF regulated items. The regulatory status of electric matches is not entirely clear. Some might argue that they are included under the general category of "igniters", which is on the explosives materials list. However, note that model rocket igniters, such as those shown in Photo 3, are definitely a form of electric match. These are available for purchase in literally thousands of hobby shops and are certainly not considered to be regulated. Further, the BATF is certainly aware that millions of electric matches are used annually to ignite fireworks and that most are being sold, stored and used as unregulated items by fireworks companies.

It is a mark of a professional to know and use the vocabulary of his field. Also, because of the difference in regulatory status, and because of the limited experience of some enforcement personnel in identifying and differentiating between electric matches and squibs, it is little short of foolish for anyone in the fireworks trade to carelessly refer to electric matches as squibs. [It might be of some interest to note that care was taken in revising *NFPA 1123-1990, Code for the Outdoor Display of Fireworks*, to use the correct term (i.e., electric match).]

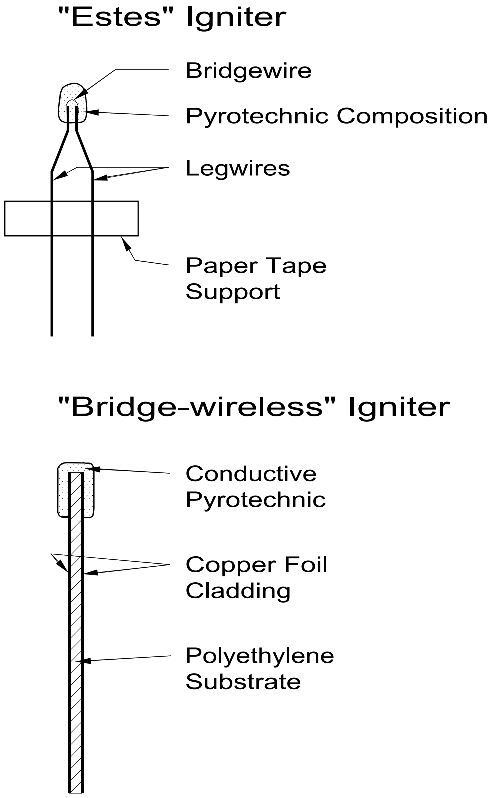

*Figure 4. Sketches illustrating the construction of two types of model rocket igniters.*

The authors gratefully acknowledge the assistance of George Jackson, Federal Law Enforcement Training Center, for providing the photograph of the squibs and other technical data; and Paul Cooper, Sandia National Laboratory, for a review of this article.

**References**

1) Atlas Powder Company, *Explosives and Rock Blasting,* Atlas Powder Company (1987).

2) J.H. McLain, *Pyrotechnics: From the Viewpoint of Solid State Chemistry*, The Franklin Institute Press (1980).

An earlier version appeared in *American Fireworks News*, No. 153 (1994).

# "Skip Burning" of Visco Fuse

K.L. and B.J. Kosanke

In late December 1978 more than 100 serious injuries were reported in eastern Kentucky, apparently the result of defective visco fuse.[1] The defective fuse had been used by a manufacturer of M-80's and other illegal consumer devices. These devices "exploded as soon as they were lit", apparently while still being held in the hand. While the authors' interests were peaked by this report, it was not possible to investigate the cause of the malfunctioning fuse because none was available for testing. Many years later, while discussing the accidents at the 1989 PGI Convention, Eldon Hershberger said that he had a small amount of fuse dating back to approximately that time, and the fuse had an unreliable burn rate. He stated that the fuse generally burned normally, but every once in a while the burning seemed to instantly advance ½ to 1 inch. He had purchased the fuse from a hobbyist supplier in the late 1970's. This sounded like it might be the defective fuse we wished to have for testing. Eldon was kind enough to supply two short lengths for evaluation.

Before undertaking the study of the suspect fuse, it seemed appropriate to first study the performance of well-behaved visco fuse, both when burned normally and when subjected to various external influences (temperature, pressure, and physical abuse). The results of this study were reported a few years ago.[2] Although work on the suspect fuse was completed shortly thereafter, and the results reported at the 1990 Western Winter Blast, this article was not completed until now.

Figure 1 illustrates the construction of visco fuse, also referred to as hobby fuse or cannon fuse. The fuse powder core contains about 25 mg/cm of powder. Generally within the core is a single thread, whose presence facilitates the uniform flow of powder during manufacturing. Surrounding the powder core are two layers of thread, wrapped in opposite directions. The inner wrap is wound with the threads touching one another, completely and tightly encircling the powder core. The outer wrap often consists of fewer threads with gaps in between. The threads constitute much of the bulk of the fuse, keep the powder core intact, and provide resistance to side ignition. The exterior of the fuse is coated with nitrocellulose lacquer (typically containing green or red dye), which provides water resistance to the fuse.

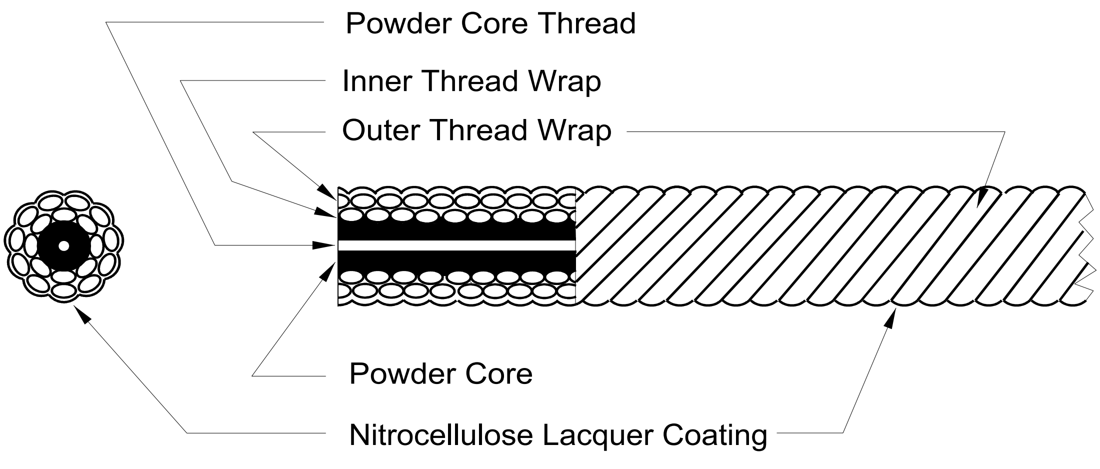

*Figure 1. Drawing illustrating the general construction of visco fuse.*

**Table 1. Fuse Powder Weight Percentages by Sieve Mesh Fractions.**

| | Percentages for Mesh Fraction | | | | | |
|---|---|---|---|---|---|---|
| | +40 | 40–60 | 60–80 | 80–100 | –100 | –60 |
| Ensign-Bickford (Very Old / Red) (Military Production) | 33 | 32 | 14 | 10 | 12 | |
| American Visco Fuse (Recent Production) | 14 | 39 | 17 | 12 | 17 | |
| Average of E.B. and Amer. Visco Fuse | 24 | 35 | 15 | 11 | 15 | 41 |
| Suspect Fuse Sample #1 | 48 | 31 | 11 | 6 | 4 | |
| Suspect Fuse Sample #2 | 47 | 32 | 10 | 6 | 5 | |
| Average Suspect Fuse Samples #1 & #2 | 48 | 31 | 11 | 6 | 4 | 21 |
| 1/8 in. "Instantaneous" Shell Leader | 66 | 27 | 3 | 2 | 3 | |
| 1/4 in. "Instantaneous" Shell Leader | 83 | 9 | 2 | 1 | 5 | |
| Aver. "Instantaneous" Shell Leaders | 74 | 18 | 2 | 2 | 4 | 8 |

A close examination of the exterior of the suspect fuse did not reveal problems with its construction. The diameter was consistent, suggesting that the amount of powder in the core was approximately constant and that there was a full complement of inner threads. The lacquer coating was present in a typical amount.

Since the supply of suspect fuse was limited, it seemed prudent not to destroy a significant amount of it before the nature of its defect was determined. Accordingly, the first test was to X-ray the fuse. It was hoped that this would allow a close examination of the powder core without sacrificing any fuse. Although several attempts were made, this approach was not successful. The powder core was almost invisible. The atomic number of the atoms making up the powder core and those in the threads and nitrocellulose were not sufficiently different to provide the needed X-ray contrast.

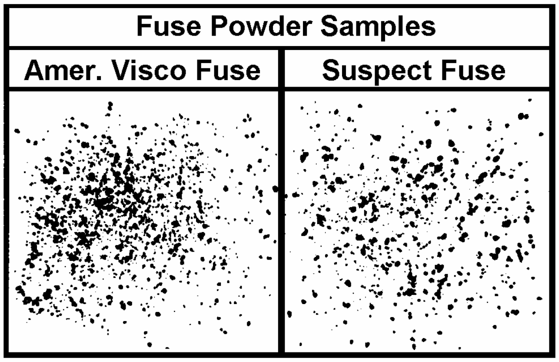

*Photo 1. Photograph of fuse powder extracted from the suspect fuse (right) and normally burning fuse (left).*

In order to examine the powder in the suspect fuse, several inches of fuse were sliced longitudinally and the powder retrieved. The physical appearance of the fuse powder seemed to be somewhat coarser than normal. For a comparison, fuse powder was collected from some properly behaving American Visco Fuse.[3] This powder appeared to be of finer granulation than the suspect fuse powder. Photo 1 provides a visual comparison of the fuse powders. To quantify the difference, enough fuse powder was collected from both types of fuse for a sieve analysis. Because it was unknown whether the powder granulation was constant along the length of the fuse, short samples were taken every few inches. Approximately 0.35 g of powder was collected from one piece of the suspect fuse,

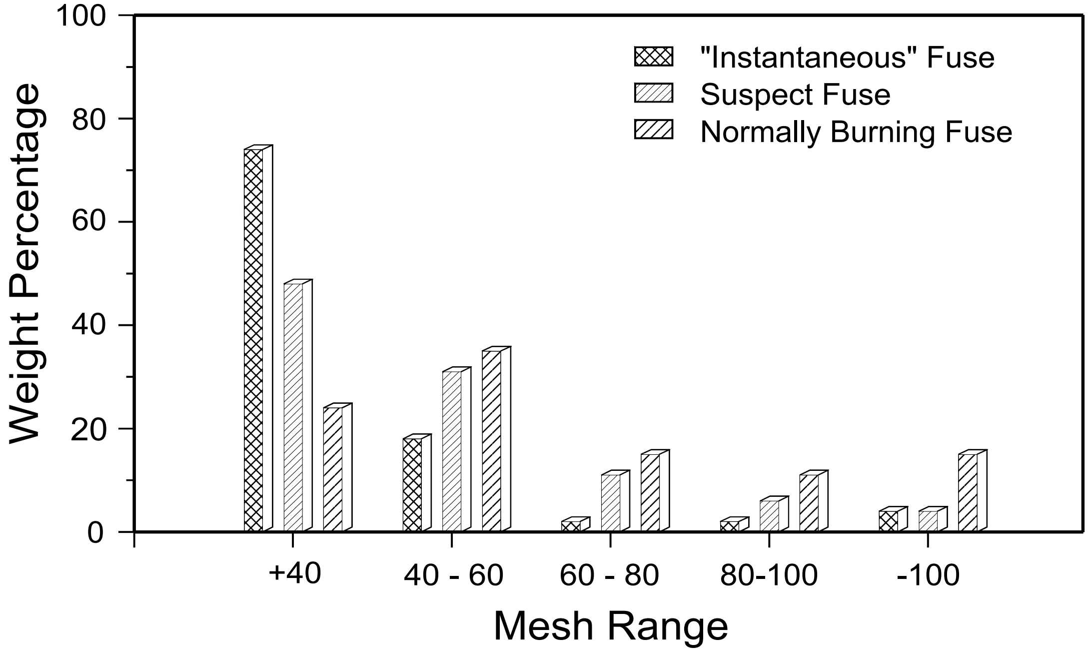

*Figure 2. Bar graph of fuse powder weight percentages as a function of mesh fraction.*

and about 0.42 g of powder was collected from normally behaving American Visco Fuse.

With less than half a gram to work with, screening with normal 8-inch diameter laboratory sieves could introduce significant errors due to lost or trapped powder. Accordingly, special small sieves, approximately 3/8-inch in diameter, were fabricated with 40, 60, 80 and 100-mesh screens. Upon sieving, there was an obvious difference in the granulation of the two powder samples. As confirmation of the difference, fuse powder was also collected from a sample of old Ensign-Bickford visco that had been made for the military, and also from the second piece of suspect fuse. The results for the four fuse samples are listed in Table 1 and graphed in Figure 2. The well-behaved fuses had approximately twice the percentage of –60 mesh powder. However, it was still necessary to consider whether this was actually the reason for the erratic performance of the suspect fuse.

For fuse to burn at a constant slow speed, it must experience parallel burning as opposed to propagative burning. (See Reference 4 for a more complete discussion of parallel and propagative burning.) When a gas generating pyrotechnic material consists of uniformly large granules, such that fire paths exist between the grains, high speed propagative burning will take place. As the size of the grains is reduced and the range of particle size is broadened, the tendency for slow parallel burning is increased. Accordingly, the difference in granulation observed in the fuse samples could be the reason for their different behavior.

As partial confirmation of this theory, two additional fuse powder samples were examined. For a year or two in the mid-1980's, some reloadable consumer fireworks shells were imported with a nearly instantaneous fuse that was about 1/8 inch in diameter. This fuse appears much like thin time fuse, and was made with a compressed paper sheath around a powder core, with an outer wrap of threads holding it together. At about the same time, some 2½- and 3-inch display shells were imported with a larger (1/4-inch) version of the same fuse (See Photo 2). Powder was collected from samples of these two types of instantaneous fuse and then analyzed to determine the particle size distribution. These results are also presented in Table 1 and Figure 2. Note that the ratio of –60 mesh powder is approximately 4:2:1, for the normally behaving fuse, the suspect fuse, and the instantaneous fuse, respectively. Also, particle size is more evenly distributed for the normally performing fuse. The greatest and

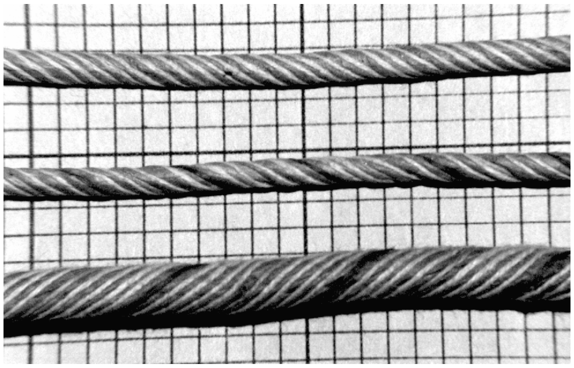

*Photo 2. Photograph of three samples of "Instantaneous" fuse shell leaders.*

least percentages of the mesh fractions are 35 and 11%, respectively, whereas, the greatest and least are 48 and 4% for the suspect fuse, and 74 and 2% for the instantaneous fuse. This tends to support the theory that the erratic burn rate reported for the suspect fuse was the result of the coarser granulation and more narrow particle distribution size of its fuse powder.

Recall that, because of the limited supply of the suspect fuse, no burn tests had yet been performed. Now, with a viable theory in hand, the time seemed right to sacrifice much of the remaining fuse in a series of burn rate tests. A collection of 14 five-inch long fuse segments were prepared. Each length of fuse was ignited and its burning closely observed. The burn time and nature of burning were recorded for each piece of fuse. The suspect fuse demonstrated two different types of burning, what might be referred to as "normal-burning" and "skip-burning". Normal burning is slow and constant-rate burning, as expected for visco fuse, whereas skip-burning is a near instantaneous advance of the apparent burning surface in the powder core. Typically these advances would consume 1/2 to 3/4 inch of fuse. Normal burning predominated, with a skip-burn occurring on average about once every five inches. Each skip-burn was accompanied by a noticeable "jetting" sound, and occasionally the fuse would be propelled through the air, if it was not held in place.

In the parlance of burn types, the normal burning would seem to correspond to parallel burning and the skip-burning would seem to be propagative burning. Apparently the powder in the suspect fuse contains sufficient fine grained material, such that a large percentage of the fire paths are reasonably well blocked, and, generally the burning proceeds normally. However, occasionally, enough fire paths are sufficiently open to allow a short portion of the suspect fuse to skip-burn, a temporary transition to propagative burning. By contrast, in the instantaneous shell leader fuse, it would seem that the amount of fine grained material is so low, that it always burns propagatively.

At this point some consideration was given to how to prove this theory. One approach would have been to prepare an amount of black powder, some with the granulation matching that in well-behaved fuse and some with a lower than normal amount of fines like in the suspect fuse. Then both powder samples could be made into fuse, to determine how it burns. In this way, the only difference in the two types of fuse would be the granulation of its fuse powder. If the first behaved normally and the other skip-burned, this would support the theory. Another approach would have been to eliminate the possibility that there was something strange in the chemical composition of the powder core in the suspect fuse.

However, neither of these approaches was taken. In part, this was because of the cost involved, but mostly it was because information provided by individuals in the fuse-making trade, tended to support the theory. First, it was learned that it is common to add a mixture of fine-grained potassium nitrate, charcoal and sulfur to commercial black powder. (This was confirmed by microscopic inspection of a sample of fuse powder.) The reason given for using the fine-grained rough black powder was not one of economics but to lower the burn rate of the fuse. Then it was learned that, at the time of the M-80 injury incidents, the reason for the malfunctioning of this particular fuse was rumored to be well known, at least to a few industry insiders. As the story goes, the fuse maker normally used a mixture of different granulations of commercial black powder. Unfortunately, one day the person making fuse ran out of the mixed powder and substituted some coarser grained commercial powder. Apparently, by the time the skip burning problem came to light, the fuse had been sold, and the M-80's had been made and distributed. With this information as confirmation of the theory advanced above, there seemed little reason to proceed with further investigation.

At this point it may be appropriate to address the reasons for writing this article. First, it is hoped that the story is at least a little interesting. Second, it serves as a good example of parallel and propagative burning, how they come about, and the important consequences that can result when unexpected burn type transitions occur. Finally, perhaps it illustrates the wisdom expressed in the warning "Do Not Hold in Hand!"

The authors wish to gratefully acknowledge Eldon Hershberger for providing the suspect fuse samples, Stan Addison for X-raying the fuse, and Quinton Robinson, Jerry Gitts and others for information about visco fuse making.

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An earlier version appeared in *American Fireworks News*, No. 150 (1994).

# Electric Ignition of Shock Tube Firing Systems

K.L. Kosanke

NOMATCH™ is a new system for igniting fireworks that replaces quick match with shock tube plus flame-to-shock (or electric-to-shock) and shock-to-flame attachments. The system was introduced by B & C Products, Inc., with a press release included in the July 1994 Issue of *American Fireworks News*, an article in the July 1994 issue of *Fireworks Business*, and a demonstration and seminar at the 1994 Pyrotechnics Guild International (PGI) convention.[1] There was considerable discussion, among the PGI convention attendees, of the potential usefulness of this new system in various fireworks environments. The safety and performance advantages of the system seem obvious.[1] Below is a brief discussion of two low cost alternatives for electric ignition of shock tubing. For the most part, these are well known and commonly used methods; however, probably not among those in the fireworks trade. It is hoped that this information is interesting and possibly will aid in the introduction of this system.

Shock tube is initiated by the simultaneous application of flame and pressure. (Some information on shock tube, its construction and manner of functioning, was presented in an earlier article.[2] The flame and pressure can be supplied by a number of sources, such as a small explosion, as might be provided by a small arms ammunition primer. This is the method commonly used in the blasting industry.

At the PGI convention, ODA Enterprises was selling a one circuit capacitor discharge (CD) "Blasting Box". This unit reportedly charges to about 300 volts and delivers about 8 joules of energy. The unit is different than some on the market, in that it does not have a series resistor to limit the firing current in the event of firing into a short circuit. In the application described below, this is an important difference. ODA Enterprises was also selling electric match heads, with the Nichrome bridge wire, but without any pyrotechnic coating. When these uncoated match heads are fired by the CD Blasting Box, the energy is sufficient to produce a flash of fire and a modestly loud "snap" (i.e., flame and pressure). Having used similar but more powerful devices to initiate shock tube in experiments in the laboratory, it seemed worth while to consider whether the ODA Blaster Box and match tips would successfully fire shock tube. Bill Ofca, B & C Products, speculated that it would.

Upon return from the PGI Convention, a test of the ODA Blaster Box and match tips' ability to initiate shock tube was undertaken. In this test, Ensign-Bickford "Noiseless Trunkline" (shock tube) was used. The match tips were positioned in front of the shock tube simply using a short length (≈0.5 in.) of 1/8 in. (internal diameter) Tygon tubing, see Figure 1. Using this arrangement, 10 of 10 successful ignitions of the shock tube resulted.

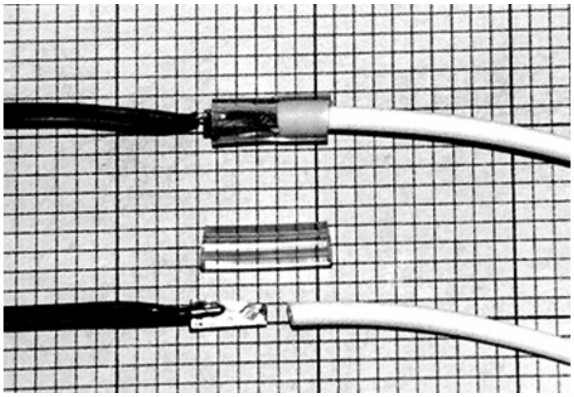

*Figure 1. Illustration of positioning/attachment of bare electric match tip for firing shock tube.*

Another common method for igniting shock tube was demonstrated by Gerald Laib during a lecture at the 1993 PGI Convention. This is to simply cause an electric spark at the end (or preferably just inside) of shock tube. In a conversation with Scott Anderson, it was suggested that a device could be made, somewhat like the Pyrodigital firing module, except that instead of having plug-ins for electric match wires, there could be plug-ins for shock tube. On the inside end of the connector there would be a small spark gap which would be actuated by a signal from a computer. In this way, shock tube could be initiated directly by the spark discharge, without using a match tip. After firing a series of shock tubes attached for one display, they could be removed, and for a subsequent display, new shock tubes inserted for the next use of the firing module.

Upon return from the PGI Convention, a test of the reusable spark gap was conducted, again using Ensign-Bickford Noiseless Trunkline. Two configurations were tried. In one case, a simple spark gap was made by inserting a tight fitting pair of wires into a short length (≈0.4 in.) of shock tube, which was then cut off to expose the ends of the pair of the wires centered in the shock tube. This spark gap and the shock tube to be initiated, were simply connected using the same piece of Tygon tubing described above, see Figure 2. Using this arrangement, 10 of 10 pieces of shock tube were fired using the discharge of a 0.05 mF capacitor charged to about 6 kV. Note that connection of the capacitor to the spark gap was made by causing a spark to jump between the capacitor lead wire and the spark gap. Accordingly, only a small fraction of the 1 joule of energy delivered by the capacitor was dissipated by the spark gap for the shock tube. In a commercially produced system, the spark energy would likely be produced using solid state electronics and a transformer attached directly to the spark gap.

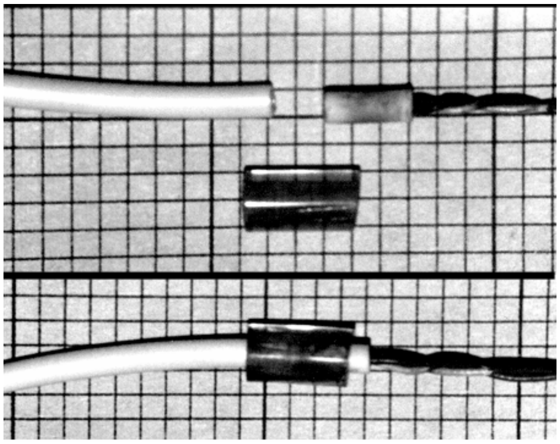

*Figure 2. Illustration of positioning/attachment of a simple spark gap for firing shock tubing.*

As a test of an inexpensive reusable attachment system, a spark gap was built into a compression fitting for 1/8-inch tubing, see Figure 3. In this case, the shock tube is simply inserted into the fitting and the nut tightened to hold it in place. In this fitting, there is a somewhat elastic compression ferrule, such that it can be used repeatedly, providing it is not over tightened. Using this system, multiple successful firings of shock tube was achieved. However, because of haste in assembling the unit, the spark gap was not properly centered, and higher spark energies were required.

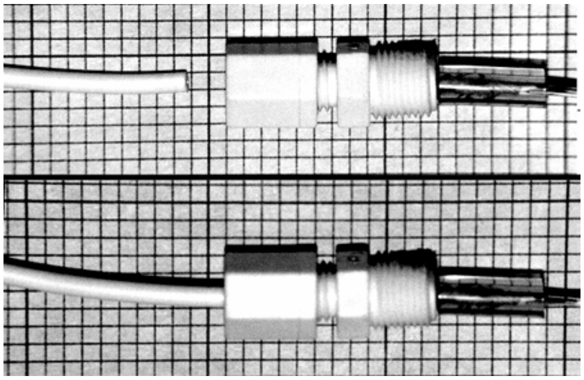

*Figure 3. Illustration of reusable connector for shock tube fired using a spark gap.*

It would seem the NOMATCH™ firing system offers significant potential for improved safety and reliability in firing aerial shells, particularly under adverse conditions. It is hoped the above article contributes by identifying some low cost electric initiation systems for shock tube.

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An earlier version appeared in *Fireworks Business*, No. 128 (1994).

# The Role of the Expert Witness

K.L. Kosanke

There is a good deal of misunderstanding as to the role of the expert witness in our legal system. Because of this; because I think the subject is intrinsically interesting; and because no one else has chosen to present the subject in an article for the fireworks trade, I have decided to make an attempt at an explanation. However, it should be understood that I have not made a study of law or of our legal system. Accordingly, while I believe I am correct, I can only give my understanding and belief as to the proper role of the technical expert witness.

Rule 702, of the Federal Rules of Evidence, provides:

If scientific, technical, or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training, or education, may testify thereto in the form of an opinion or otherwise.

Before continuing, let me first address a few things about Rule 702. The "trier of fact" is the judge or jury depending on who will render the decision in the case. A "fact in issue" is something like, "Was the firework defective?" or "Could the accident have happened as alleged?" Rule 702 specifically applies only in federal court cases; however, most states have adopted similar or identical rules for experts.

You can see from Rule 702 that the expert witness' job is simply to explain things. These things may be technical or scientific, they may be about codes or standards, or they may be about typical practices in an industry. Accordingly, in the role of an explainer, the expert is not testifying **for** or **against** either side in a case. True, the expert is hired and paid by one side, but the proper mental perspective of the expert is to be unbiased in his approach to the case. This is as it must be, because an expert witness can not alter the laws of physics, change the language of a code, or alter the way an industry makes its products. Although that may sound simple and straight forward, there is a little more to it, which makes it less simple or straight forward.

In a scientific investigation, it is common to study the subject until the result is proven to a high degree of certainty. However, in civil law suits, the burden of proof is not as great. In civil law suits the requirement is only to be more certain than not (i.e., to be at least 51% certain). In particular, this applies to the degree of certainty the expert witnesses have regarding their opinions. Probably no expert witness ever has all the information, all the test results, or all the evidence they would like to have before having to formulate their opinions. Sometimes the reason for this is a matter of money; it is the attorneys (and their clients) that control the budget and give the directions for an expert to proceed. However, often, it is simply because the desired information is not available, there is nothing to test, or some important evidence was never collected. Either way the expert will be asked for formulate opinions based only on what has been established at the time. As a result, it is not unusual for an expert to be much less than 100% certain about his opinions. Accepting this as the way the system works, you can see one reason why it is relatively easy for two experts to honestly arrive at different conclusions. Neither may have much of the information they want (need). Each may only be a little more the 50% sure they are correct. They may have reached their different conclusions as a result of relatively small differences in their interpretation of the "facts" of the case. Is that ideal, possibly not, but that is the way the system was set-up, and it was not set-up that way by the expert witnesses.

Law suits are rarely simple matters. This too contributes to differences of opinion between experts. For example, in trying to ascertain what caused an accident, an expert witness will need to discover the "facts". The starting place is to consider what the eye witnesses have said about the incident. When there are 10 witnesses, there may well be 10 (at least slightly different) accounts of the accident. This is true even when everyone is attempting to tell the absolute truth as they know it. In trying to determine exactly what happened, different experts might place different weight on the various eye witness statements. If that is the case, then the "facts" used by two experts may not be exactly the same. Accordingly, with requiring only 51% certainty, the two experts might honestly arrive at substantially different conclusions regarding the same incident.

The point explored in the preceding paragraph, is not the only way in which two expert witnesses might honestly arrive at different opinions. People often reach different conclusions simply because they have somewhat different backgrounds or different belief systems. This happens every day in essentially all fields of endeavor (religion, politics, education, etc.), and it happen with experts as well. In itself, this does not make one expert right and the other one wrong; in itself, this does not make one expert honest and the other dishonest. They may simply have different ways of looking at things. (That is why the jury is there, to decide which point of view is the most convincing.)

Perhaps at this point in the discussion, it is appropriate to consider the role of an attorney. In our legal system, an attorney's job is to advocate for the interests of his client; and, for the most part, that is quite independent of the client's culpability. Accordingly, what does a good attorney do if the expert witness he hired is telling him things that do not support the client's case? Certainly, the first thing the lawyer is likely to do is explore in detail with the expert the bases for his opinions. It is possible that the expert has overlooked something. It is possible the expert and lawyer have interpreted witness statements differently, so they are basing their thoughts on different "facts". If the attorney comes to see the case more like the expert, then in the best interest of his client, he might keep the opinions of his expert confidential and try to settle the case as favorably as possible. If the attorney wishes to continue to aggressively pursue the case, he might hire another expert and hope the new expert's opinions are more favorable. If this happens, and he has not formally identified the original expert as his expert witness, the attorney will probably choose to identify the new expert as his one and only expert. Are these things fair and ethical for the attorney? To the extent I understand our legal system, it may well be unethical for the attorney to do any less.

From what was said above, it should be apparent that expert witnesses' opinions will often be contrary to what their clients might prefer to hear. However, there is another reason why this may be the case. When there are relatively few persons working as experts in a given field, then in the best interest of their client, attorneys will sometimes employ a strategy that might be called "the preemptive strike". That is to say, the attorney might hire the two or three best experts. The attorney might actually use each of the experts, but if he does not, at least the other side will be denied the use of those experts. This practice can also be effective if the attorney hires experts that may be likely to formulate opinions that would aid the opposing interests in the case. Is this fair or ethical, frankly I do not know.

I said above the proper role for the technical expert witness is to provide information about science, codes, or industry practices. Thus, an expert does not testify **<u>for</u>** or **<u>against</u>** either side, but is acting in the capacity of what might be described as "a friend of the court". In fact, it is permissible for the court to hire and direct the activities of the technical experts. Although this is rarely done, I suspect that most expert witnesses would greatly prefer this practice. That would make it easier for the expert witness to be fair and impartial.

Perhaps at this point it would be useful to consider the ramifications of an expert witness who chooses to only work for one side, always for the plaintiff or always for the defense. Is this consistent with the role of a technical expert witness as an unbiased explainer of science, codes, or practices? Probably not; it would seem likely that it was an expression of his personal bias. Beyond the question of whether the use of biased experts is in the overall best interest of justice; is it beneficial for the side he chooses to work for? Probably not; I have been told by a law professor and attorneys that juries are excellent at detecting biased experts, and that juries discount what such experts have to say. If that is true, then pro-industry (or anti-industry) experts are of little or no benefit to the side they choose to work for.

There is, perhaps, another reason it is good to have expert witnesses that regularly work at the request of both sides. Reporting services now provide transcripts of expert testimony on computer disk. Thus, an attorney can call up on his PC, everything an expert has ever testified to, on any subject, and have it in a matter of seconds. Under these circumstances, any expert witness that tended to "adjust" his opinions to support the interests of the client, will soon be detected, will be crucified in court, and will have a very short expert career. In contrast, when experts only testify for one side, this check on their impartiality is not available. Their biases can go undetected, and even become more extreme with time.

Anyone that has been involved in a lawsuit as a litigant knows that it is unpleasant and expensive. Perhaps, there should be a better way to resolve disputes, like some form of binding arbitration. Unfortunately, we do not have that better way, or it is rarely used. In order for the current system to function, even as well as it does, expert witnesses are necessary to help explain the technical issues of the case. To that extent the expert witness provides an important service. In fact, especially in criminal cases, some expert witnesses feel they have a moral obligation to participate when asked.

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# Measurement of Aerial Shell Velocity

K.L. and B.J. Kosanke

## Introduction

In addition to satisfying general curiosity, there are technical questions requiring knowledge of aerial shell velocity. For example, a calculation of how far down range aerial shells will have traveled at various times after having been fired from highly angled mortars requires knowledge of the shell's muzzle velocity and its effective drag coefficient. In particular, the authors (along with Mark Williams) plan to determine the maximum horizontal range of aerial shells which burst after the normal time fuse delay. This study could be conducted empirically by firing different size shells from mortars at various angles. However, such an approach could be prohibitively expensive and time consuming, and it probably would not allow the examination of as many cases as desired. As an alternative, the question could be examined using a computer model of aerial shell ballistics.[1] This would be relatively inexpensive and any combination of shell velocity, shape, and mass; time fuse delay; and mortar angle could be considered. However, without verification using results from actual testing, the modeled results would always be at least a little suspect. Accordingly, the best choice is to conduct a number of field tests to verify the correct performance of the computer model, and then to model the cases of interest. This article is the first in a series, which will describe the down range study introduced above.

To verify the correct performance of the ballistics computer model, it is necessary to know the velocity of aerial shells. In this article two techniques for measuring aerial shell velocities are described. One technique makes the velocity determination within a few feet of the muzzle of the mortar (muzzle velocity). This method is a slight refinement of that used by E. Contestabile.[2] The other method measures velocity by determining the shell's location at points throughout its trajectory. This method is a slight modernization of a method described by T. Shimizu.[3]

## Muzzle Velocity Measurements

Velocity measurements can be made by measuring the time taken for a body to travel between two points separated by a known distance. As such, the measurements are the average velocity between the points. However, if the points are close enough together, such that the velocity does not change significantly during the short time interval for the object to move between the two points, the measurement closely approximates the body's instantaneous velocity. Probably the most common method used for this measurement is to setup one or more pair of "trip wires" [a] for the moving object to cross, with a clock started when the first trip wire is broken and then stopped with the breaking of the second trip wire. This is shown schematically in Figure 1. In this case, the average velocity ($V$) of the object is:

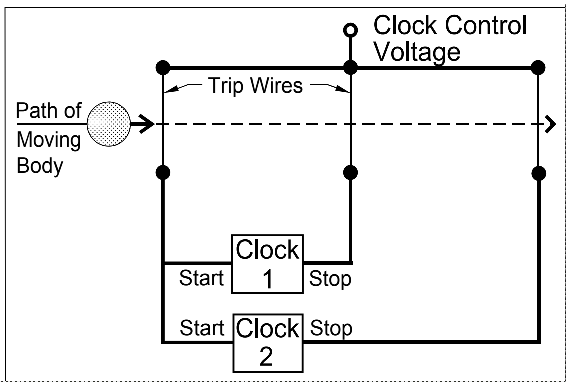

*Figure 1. Block drawing of a simple "trip-wire" system for measuring the velocity of a moving body.*

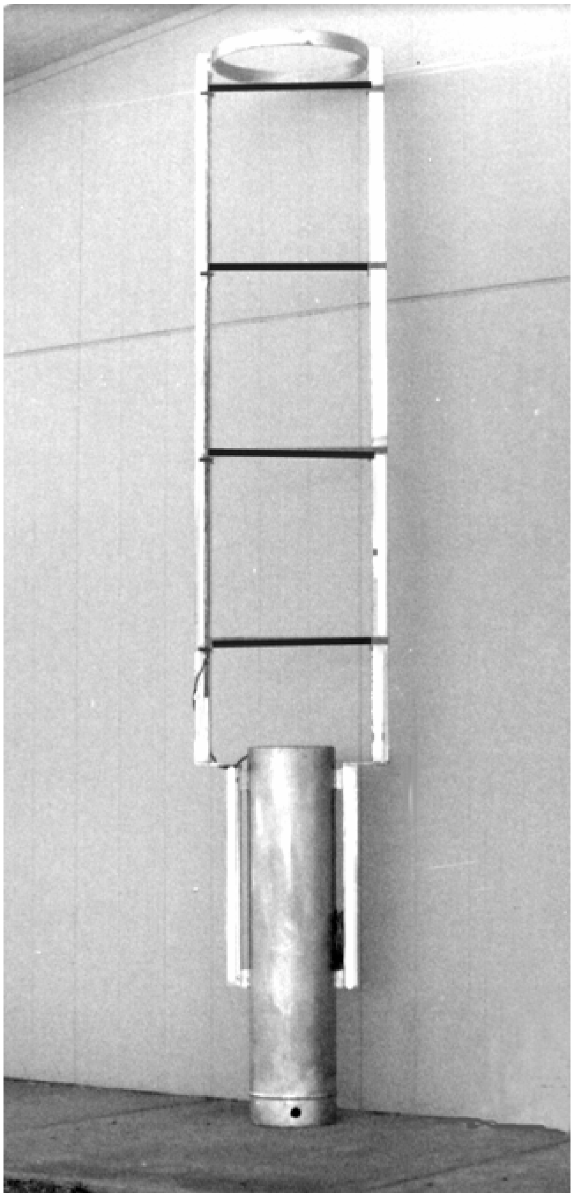

*Figure 2. Photograph of a 10-inch test mortar. Colored tape has been used to indicate the location of trip wires.*

Eq. 1. $V = D / t$

where $D$ is the distance between the trip wires, and $t$ is the time interval.

In the case of aerial shell muzzle velocity measurements, these trip wires need to be strong enough to withstand the blast of burning gases, yet weak enough not to impede the aerial shell. The authors used 0.019-inch diameter insulated copper wire. The wire is held between electric terminals, which hold the wire strong enough not to come loose as a result of the blast of lift gases preceding the shell, but weak enough for the wire to pull loose without being stretched by the passing shell.

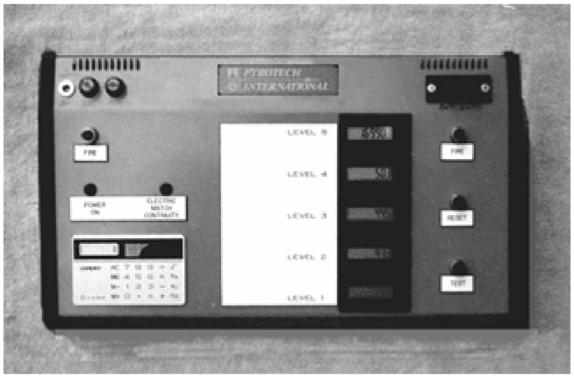

*Figure 3. Photograph of the multi-clock electronics package.*

The method used by Contestabile[2] employed grids of wires as trips; however, he reported occasional difficulty with debris propelled ahead of the shell severing the wire grid before the shell arrived. To reduce the likelihood of such problems, care should be taken to limit the presence of material such as the paper lift bag and quick match shell leader, which could constitute such debris. Also the grid can be limited to just a pair of wires, thus offering a minimum target for debris to strike. Contestabile used two grids, placed 1 meter (3.28 feet) apart, with the first grid located 1.7 m above the muzzle of the mortar. In the apparatus used by the authors, the first trip wire was only 1 foot above the mortar and there were three additional wires each at two foot intervals. This allows a total of three velocity measurements. One of the test mortars, with colored tape at the positions normally occupied by the trip wires, is shown in Figure 2. The electronics package, which fires the electric match and then times the breaking of the trip wires, was designed and fabricated by Gary Fadorsen of Pyrotech International, and is shown in Figure 3.

As an example of some muzzle velocity measurements, consider the data in Tables 1 and 2. These are the results from a series of measurements of six identical 3-inch cylindrical shells fired from finale mortars (17.5 inches long).

It seems that the individual 2-foot timing method only produces results with a 1 sigma precision of about ± 1 ms. Thus, even though the Pyrotech instrument records times to 0.1 ms, the values reported in Table 1 are given to the nearest ms. It had been hoped that greater precision could be achieved with this method. The timing uncertainty is presumed to be the result of variations in the orientation of the shell upon striking the wire and differences in the amount of yield of the wires before the timing circuits open. The net result is that only the average velocity over the total 6-foot interval is precise enough to be useful. Perhaps with further refinement of the method, the precision can be increased so that 2-foot average velocities can be generated. This would allow an examination of the slowing of shells in the first few feet after leaving the mortar.

**Table 1. Raw Data from Measurements of Muzzle Velocity of 3-inch Cylindrical Shells.**

| Shell | Trip Wire Break Times (ms) | | | |
|---|---|---|---|---|
| No. | 1 | 2 | 3 | 4 |
| 1 | 59 | 69 | 82 | 89 |
| 2 | 109 | 121 | 133 | 145 |
| 3 | 94 | 104 | (a) | 124 |
| 4 | 63 | 74 | 84 | 95 |
| 5 | 94 | 105 | 114 | 124 |
| 6 | 81 | 92 | 103 | 115 |

(a)This data value was not recorded.

**Table 2. Average Velocity Results for 3-inch Cylindrical Shells.**

| Shell | Velocity Measured Between Trip Wires (ft/sec) | | | |
|---|---|---|---|---|
| No. | 1 & 2 | 2 & 3 | 3 & 4 | 1 & 4 |
| 1 | 200 | 150 | 290 | 200 |
| 2 | 170 | 170 | 170 | 167 |
| 3 | 200 | — | 200[(a)] | 200 |
| 4 | 180 | 200 | 180 | 188 |
| 5 | 180 | 180 | 200 | 200 |
| 6 | 180 | 180 | 170 | 176 |
| | | | Average | 188 |

(a) Measured between trip wires 2 and 4.

All electric matches were fired with a current of about 3 amperes, which is expected to produce a firing time of less than 1 ms.[4] Accordingly, the wide range of times to the breaking of the first trip wire, by shells with similar velocities, is somewhat surprising. This seems to say some interesting things about the dynamics of the combustion of apparently identical lift charges. However, discussion of this subject is better left for another article.

## Aerial Shell Trajectory Measurements

If an aerial shell could be tracked throughout its flight, such that its position can be established at a series of known times, using Equation 1, it is again possible to determine its average velocity during each time interval. Note that in the previous method it was the time required to travel a known distance that was measured, and in this method it is the distance traveled during a known time interval that is measured. To see how this might be accomplished, consider the method described by Shimizu.[3] If a time exposed photograph is taken of an aerial shell with an attached star, there will be created a record of the shell's path. If the trajectory of the shell is nearly perpendicular to the location of the camera, the shell's position as seen in the photograph will be an accurate 2-dimensional representation of its path. If the camera's field of view has been calibrated, such as by taking another picture with a series of landmarks, each of which are visible and separated by known distances, the trajectory of the shell can be quantified. The remaining piece of information needed to establish the shell's velocity along its path is the time elapsing as the shell travels along the path. In the method described by Shimizu this was accomplished by taking the time-exposed photograph through a rotating disk with a hole in it. Shimizu's disk was rotated at a rate of 25 revolutions per second. In this way the photograph appears as a series of points, each point indicating where the shell was located at each 1/25 of a second throughout its flight.

In the method used by the authors, the still camera and rotating disk were replaced with a video camera. Video cameras record 60 distinct images (fields) per second and VCR's (at least the more expensive newer ones) play back the individual still images one at a time [b]. Thus it is possible to record and play-back 60 images of the shell's position for each second during its flight. If a transparent plastic film is temporar-

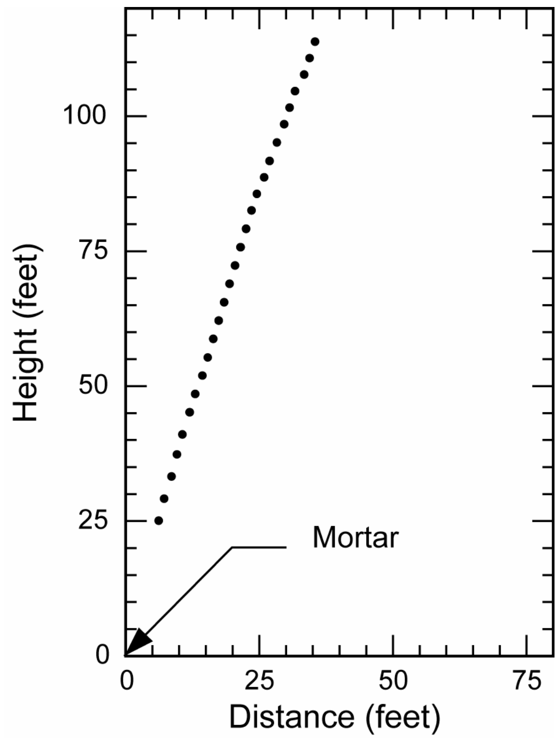

*Figure 4. Trajectory of a 4-inch cylindrical aerial shell just after exiting the mortar.*

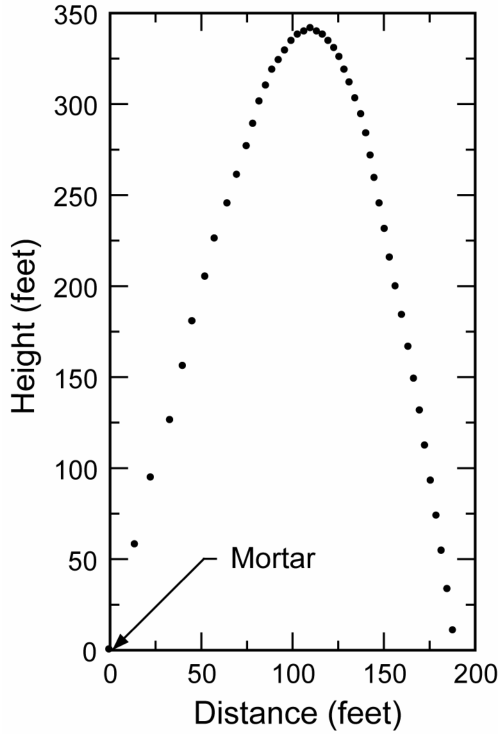

*Figure 5. A plot of the entire trajectory of a 4-inch cylindrical aerial shell.*

ily taped to the face of the video monitor, the location of a shell at each 1/60 of a second during its flight can be plotted using a fine tipped marking pen [c,d]. Depending on how the camera has been set up and the velocity of the shell at that time, the shell may move only a very little during each 1/60 second. In that case it may be preferred to plot the position of the shell once every 6 or 12 images (i.e., every 0.1 or 0.2 seconds). In this study two cameras were used, one zoomed in to measure the shell's velocity as close as possible to its exit from the mortar, and the other taking a wide angle view encompassing the entire flight path of the shell. The results recorded by the two cameras are illustrated in Figures 4 and 5. In these figures the effect of parallax [d] and round-off errors can be seen as slight inconsistencies in the plotted locations of the shell. Such errors tend to cancel out over extended or averaged measurements.

There was one additional modification to the Shimizu method. The externally attached light producing star was replaced with an internal flare, which was mounted to be flush with the exterior of the shell. In this way, the aerodynamics of the shells are not significantly affected by the light source.

To analyze the trajectory data it is necessary to convert it to numerical form. This can be done by removing the plastic film from the video monitor and laying it over graph paper. Alternatively, it is possible to use a plastic film which already has a graph produced on it (such as would be accomplished by making an overhead projection transparency of a piece of graph paper). One way or the other each shell point needs to be converted to an x-y value, and then, using the landmark calibration data, converted to full scale vertical and horizontal distances. At this point, Equation 1 can be used to calculate average velocity between any pair of points along the shell's path. Finally, using the time information (by counting images), the time to apogee and impact can be determined.

When an aerial shell fires, a large amount of fire projects out of the mortar before the shell exits. This fire makes it impossible to see the aerial shell with its internal flare until a short time after it leaves the mortar. For example, in Figure 4, the first shell trajectory point was recorded about 0.1 second (6 video fields) after fire is first seen in the mortar. At that time the shell has already risen about 25 feet. Using the data of Figure 4, average shell velocities were calculated for each tenth second from 0.2 to 0.5 seconds. The results were: 221, 204, 194, and 187 feet per second, respectively.

In Figure 5, each twelfth point along the shell's trajectory was plotted. This corresponds to one point every 0.2 second along its path. In this case, the shell reached its apogee of 340 feet 4.0 seconds after firing. It fell back to the ground at a point 190 feet down range, 9.2 seconds after firing.

Aerial shells tend to tumble after leaving the mortar. When that tumbling is such that the flare is sometimes blocked from view of the camera by the body of the shell, the light from the flare will intermittently dim or disappear. When this happens, it is possible to measure the rate of that tumbling. In a data set similar to that shown in Figure 5, it was determined that the tumble rate of the shell was 5.3 revolutions per second, and was essentially constant throughout the flight of the shell.

## Conclusion

There are other methods, and many variations and refinements that can be used to measure aerial shell velocities. The methods described here are not original and may not be the best for all applications. However, they are the ones most commonly used by the authors and seem to produce adequate results.

## Acknowledgments

The authors gratefully acknowledge the assistance of Mark Williams and Scot Anderson for reviewing a draft of this article. In addition, the assistance of Gary Fadorsen, Pyrotech International, in assembling the muzzle velocity timing apparatus is appreciated.

## Notes

[a] A trip wire as defined here need not be an actual wire. One possibility considered for aerial shells was to use light beams as the trip wires, such as is often used to measure the muzzle velocity of bullets. However, because of the smoke and fire that exits a mortar well before the aerial shell, this method was discarded as impractical.

[b] The individual images seen on a TV screen are "frames", each of which consist of two 1/60 second "fields" (a and b) through a process called interlacing. In pause mode, VCR's produce an interlaced version of just a single field. Upon advancing to the next still image some VCR's advance two fields. These VCR's are sometimes referred to as a–a machines, and there is 1/30 second elapsing between the still images. Other VCR's (generally the more expensive ones) are so-called a–b machines, which advance only one field at a time and have a time interval of 1/60 second between still images. In measuring shell velocities, it is important to know whether 30 or 60 images are reproduced per second; however, all else described herein is the same.

[c] This should be a pen that will write on "anything", such as Sanford's "Sharpie" permanent marker, which comes in normal and fine tip configurations.

[d] Because of the thickness of the glass on the picture tube of the video monitor, it is necessary to take steps to avoid errors from parallax when marking the screen. This can be done by looking with one eye and attempting to always position one's eye perpendicular to the point on the screen. Note that small errors from parallax will tend to cancel-out in an extended series of measurements. Another problem with the video monitor is the slight curvature of the screen, which makes it difficult to firmly attach the plastic film. Both problems can be eliminated by using a "frame grabber" and dumping the video display to a computer for analysis.

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# Control of Pyrotechnic Burn Rate

B. J. and K. L. Kosanke

## *ABSTRACT*

*There may be many times when a fireworks manufacturer will want to adjust the burn rate of pyrotechnic compositions. Sometimes this may be for matters of esthetics and other times for safety. For example, all of the following are unacceptable:*

- *Strobe stars that flash with so low a frequency that they fall to the ground still burning.*
- *Color stars that burn so rapidly that they occasionally explode when a shell flowerpots.*
- *Rockets that fail to lift-off because their thrust is too low.*
- *Rockets that explode upon firing because internal pressures exceed the casing strength.*
- *Salutes that burn like fountains instead of exploding with violence.*
- *Flash powder that explodes when unconfined, even in small quantity.*

*In each case, taking action to adjust burn rate should solve the problem.*

*Depending somewhat on how they are counted, there are at least 15 factors that control pyrotechnic burn rate. A manufacturer that understands how these factors act to affect burn rate may better anticipate when product performance difficulties will occur. Also, such a manufacturer will be better prepared to modify product formulations to correct any problems that do occur. Each of the burn rate control factors act by affecting one or more of the following: activation energy, heat of reaction, and efficiency of energy feedback. In this paper, the 15 factors are presented, explained and examples given.*

## Introduction

In the burning of most pyrotechnic compositions it is necessary to balance competing processes to achieve the maximum desired effect. For example, when flame temperature of a color star is too low, the result can be low light output because there are an insufficient number of electrons reaching excited states. However, conversely, when flame temperature is too high, the result can be bright but washed-out colors because the color producing molecules have thermally decomposed. In addition to aesthetic ramifications, safe performance can also require a balance between too little and too much output. For example, when the thrust produced by a fireworks rocket is too low, the result can be an explosion of the rocket at ground level because the rocket failed to fly into the air. Conversely, when the thrust is too high, the result can again be an explosion at ground level because the internal pressure exceeded the strength of the motor casing.

One mechanism, useful in adjusting pyrotechnic output, is the control of burn rate. Burn rate determines the rate of energy release, and thus to some extent the flame temperature of a star. More directly, burn rate determines the

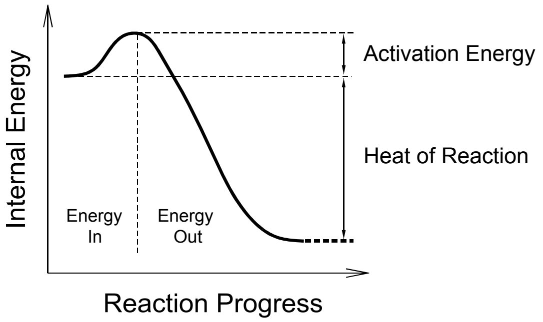

*Figure 1. Changes in internal energy as a pyrotechnic composition ignites and burns.*

rate of gas production from a propellant, and thus the thrust from and internal pressure within a rocket motor. Accordingly, an understanding of the ways in which burn rate can be adjusted, can be useful in modifying pyrotechnic formulations to maximize their performance and safety. In this article, after a brief theoretical discussion, which forms the basis for understanding how each factor acts to modify burn rate, 15 factors that affect burn rate are presented, discussed and examples given.

## Pyrotechnic Ignition

Pyrotechnic materials are said to exist in a "meta-stable" state. That is to say, under normal circumstances they are stable (they do not spontaneously ignite); however, once ignited, the combustion reaction is self-sustaining producing an excess of thermal energy. The reason pyrotechnic materials do not spontaneously ignite under normal conditions is that ignition requires the input of energy into the composition. Once ignited, however, the pyrotechnic material burns thus producing energy. This two step energy relationship is illustrated in Figure 1, which is an attempt to graph the internal energy of a tiny portion of pyrotechnic composition during its ignition and burning. The first step, when energy is added to the composition to cause its ignition, is seen as an increase in the internal energy of the material. Within the formalism adopted for this article, the minimum energy required for ignition is called the "activation energy" for the pyrotechnic composition, and is abbreviated as $E_a$. It is the requirement for the input of energy, to ignite a pyrotechnic material that allows pyrotechnic compositions to be safely made and stored prior to use. If it were not for this activation energy barrier, fuels and oxidizers would ignite on contact. In the simplest of terms, it is possible to think of the required addition of energy as what is needed to raise the material to its ignition temperature. The second step, when the burning composition produces energy, is seen as a decrease in internal energy. The net amount of energy produced during burning is the "heat of reaction" for the composition, and is abbreviated as $\Delta H_r$.

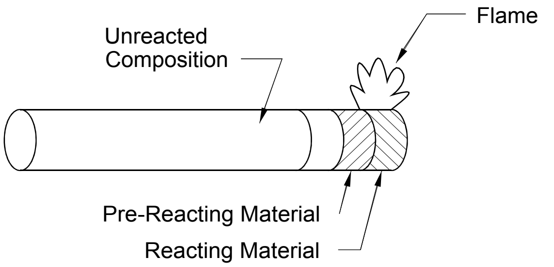

*Figure 2. Burning "propagating" along a stick of pyrotechnic composition.*

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

In the simplest of terms, pyrotechnic propagation can be thought of as continuing self-ignition. Consider Figure 2, which is a sketch of a stick of pyrotechnic composition, and which can be thought of as a series of thin disks of material. The end disk, designated as reacting material, has ignited as described above. As this layer of material burns it produces energy, most of which is lost to the surroundings. However, some of the energy is transferred to the next disk, designated as pre-reacting material. If the amount of energy delivered to the pre-reacting layer exceeds its activation energy requirement (i.e., it receives more energy than is required for its ignition), then it too will burn. If this process is repeated for each disk of composition, then the burning will propagate through the entire stick of pyrotechnic material.

**Table 1. Factors Controlling Burn Rates of Pyrotechnic Compositions.**

| Controlling Factor | $E_a$ | $\Delta H_r$ | $F_{fb}$ | Section |
|---|---|---|---|---|
| Choice of fuel and oxidizer | X | X | X | A |
| Fuel to oxidizer ratio |  | X |  | B |
| Degree of mixing |  | X |  | C |
| Particle size | X |  |  | D |
| Particle shape | X |  |  | E |
| Presence of additives | X | X | X | F |
| Presence of catalysts | X |  |  | G |
| Ambient temperature | X |  |  | H |
| Local pressure |  |  | X | I |
| Degree of confinement |  |  | X | J |
| Physical form |  |  | X | K |
| Degree of consolidation |  |  | X | L |
| Geometry |  |  | X | M |
| Crystal effects | X |  | X | N |
| Environmental effects | X | X | X | O |

It is possible to quantify the requirement for propagation in what could be called the "propagation inequality". Propagation within a pyrotechnic composition will continue only so long as the amount of energy fed back to the next layer ($E_{fb}$) exceeds its activation energy, i.e.,

$$(1) \qquad E_{fb} > E_a$$

The amount of energy fed back equals the heat of reaction times the fraction of energy fed back ($F_{fb}$), i.e.,

$$(2) \qquad E_{fb} = \Delta H_r \cdot F_{fb}$$

Thus the propagation inequality becomes,

$$(3) \qquad \Delta H_r \cdot F_{fb} > E_a$$

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

There are three mechanisms by which energy can be transferred from the reacting to the pre-reacting layers: conduction, convection and radiation. In conduction, thermal energy, as atomic and molecular vibrations, is passed along from hotter to cooler regions. The factors maximizing conductive heat transfer include compacted composition, metallic fuels, and metal casings or core wires. In convection, hot gases penetrate the composition along the spaces between grains (called "fire paths"). The factors maximizing convective heat transfer include uncompacted composition, and granulated or cracked composition. In radiation, thermal radiation (infrared) is emitted from the flame (mostly from incandescent particles in the flame) and is absorbed by reacting composition. The factors maximizing radiative heat transfer include abundant solid and liquid particles in the flame, and dark or black pyrotechnic composition.

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

## Factors Controlling Burn Rate

Burn rates are reported as either mass burn rates or linear burn rates, with units of either the mass consumed per time (e.g., grams/second) or the distance the flame front progressed per time (e.g., cm/second). In this article, unless stated to the contrary, the term burn rate will mean linear burn rate.

**Table 2. Decomposition Energies for a Few Common Pyrotechnic Oxidizers.**

| Oxidizer | Product | Decomposition Energy (cal/g) | Ref. |
|---|---|---|---|
| $KNO_3$ | $K_2O$ | –1500 | 4 |
| $Fe_3O_4$ | Fe | –1150 | 4 |
| $Ba(NO_3)_2$ | BaO | –400 | 4 |
| $KClO_4$ | KCl | 9 | 4 |
| $KClO_3$ | KCl | 87 | 8 |
| | $K_2O$ | 410 | 8 |

There are at least 15 factors known to affect the burn rate of pyrotechnic compositions. These are listed in Table 1. For each factor listed, the change in burn rate is produced by chemical effects, physical effects, or both. More specifically, the most important of these effects are the three terms in the propagation inequality: activation energy ($E_a$), heat of reaction ($\Delta H_r$), and the fraction of energy fed back, ($F_{fb}$). High burn rates are generally favored by any combination of low activation energy, high heat of reaction and efficient energy feedback. Low burn rates tend to be the result of the opposite in each case. Table 1 also suggests which of the three mechanisms typically predominate for each burn rate controlling factor. This is indicated with an "X" in the appropriate column(s).

The remainder of this article is a discussion of how each of the 15 factors acts to affect burn rate. Included in Table 1 is a designation of the subsection of this article where that discussion can be found. It must be acknowledged, however, that some explanations have been greatly simplified, and less common situations may not have been addressed. Also, in these discussions, at times the concept of activation energy may be more of a construct used to help explain, rather than being treated rigorously on a scientific level. For additional information about ignition and pyrotechnic burning, the reader is referred to previous articles of the authors[1–3] and one or more of the standard reference texts on pyrotechnics.[4–7]

## A) Choice of Fuel and Oxidizer

The choice of fuel(s) and oxidizer(s) can significantly affect activation energy, heat of reaction and the efficiency of energy feedback. Accordingly, the selection of fuel and oxidizer has the potential for having a major influence on pyrotechnic burn rate.

Regarding activation energy, a significant consideration is the amount of energy required for an oxidizer to make its oxygen available to react with the fuel. Some oxidizers require input of a large amount of energy, while others actually produce energy in the process of releasing their oxygen. This can be seen in Table 2 where the decomposition energies for a few common oxidizers are listed. (Note: A negative number indicates that an input of energy is necessary, while a positive number means that energy is produced during decomposition.)

Regarding heats of reaction, when fuels combine with oxygen, different numbers and strengths of chemical bonds are formed. This can significantly affect the amount of energy produced by the combustion reaction. Table 3 lists heats of reaction for some common fuels combining with oxygen.

Regarding the efficiency of energy feedback, recall that energy can be fed back from reacting to unreacted material by conduction, convection and radiation. The choice of chemicals can affect the efficiency of all three feedback mechanisms. For example: metal fuels have high thermal conductivity thus aiding in conductive feedback; organic fuels produce much gas, which can increase convective energy transfer; and dark colored fuels, such as carbon, can increase the absorption of radiant thermal energy.

## B) Fuel to Oxidizer Ratio

There is always an optimum fuel to oxidizer ratio, one which produces the fastest burn rate. This often corresponds to the situation where

**Table 3. Heats of Reaction for Some Common Fuels Reacting with Oxygen.**

| Fuel | Product | Heat of Combustion (cal/g) | Ref. |
|---|---|---|---|
| Al | $Al_2O_3$ | 7400 | 9 |
| Mg | MgO | 5900 | 9 |
| PVC | — | 4400 | 7 |
| Dextrin | — | 4200 | 9 |
| S | $SO_2$ | 2200 | 9 |

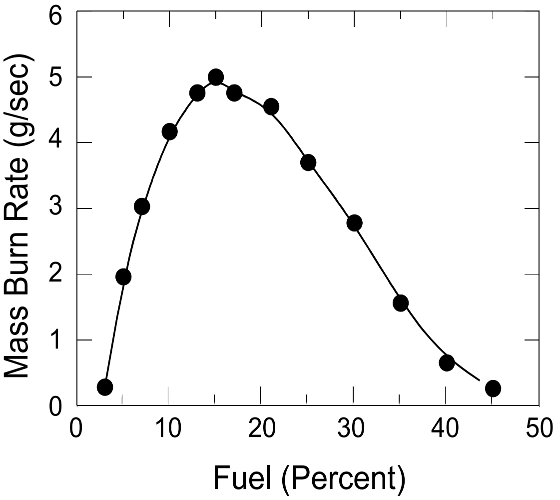

*Figure 3. Burn rates for various mixtures of boron and barium chromate.*

the reaction will be essentially complete with little fuel or oxidizer remaining after the reaction. When the fuel to oxidizer ratio deviates from this optimum value, burn rates are reduced. The burn rate continues to fall as the deviation from optimum increases. This can be thought of as mostly a result of a lowering of the heat of reaction for the pyrotechnic composition, although activation energy and efficiency of energy feedback can also change. The heat of reaction falls because, as the fuel to oxidizer ratio deviates from optimum, there will be an increasing amount of fuel or oxidizer left over at the end of the reaction. Less energy is produced, simply because this unreacted material will not have contributed to the production of thermal energy. The activation energy may change because of changes in the heat capacity of the composition and possibly changes in the ignition temperature. The efficiency of the energy feedback can change as a result of changes in the physical properties of the composition as the fuel to oxidizer ratio changes.

As an illustration of the effect of fuel to oxidizer ratio, consider the burn rates derived from data reported for mixtures of boron and barium chromate,[10] presented in Figure 3. (Note, however, that this is a case where the maximum burn rate would seem to occur when there is a considerable excess of fuel.)

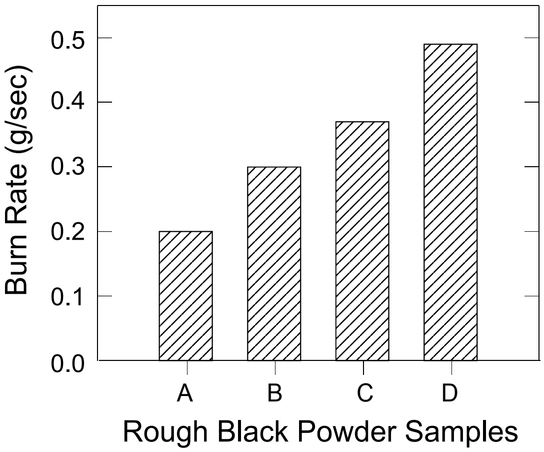

*Figure 4. Mass burn rates of samples of rough Black Powder with varying degrees of mixing.*

### C) Degree of Mixing

When a pyrotechnic composition is poorly mixed, it will generally have a lower burn rate than the same composition that is well mixed. In essence, this is because, while the entire volume of the poorly mixed pyrotechnic composition may have the optimum fuel to oxidizer ratio, there will be many small regions where the fuel to oxidizer ratio is far from optimum. Within each of these regions, what was said above for burn rate dependence on fuel to oxidizer ratio applies. In the final analysis, however, the heat of reaction for the total amount of composition may not be significantly reduced. This is because essentially all of the material will eventually react, as fuel or oxidizer physically migrates from region to region, but this takes time (i.e., the burn rate is reduced).

A series of samples of rough Black Powder were prepared and burned to measure their burn rates. Each sample was a loose 1 gram pile of –100 mesh material, ignited about half way up on one side of the pile using a hot wire igniter. Burn times were determined by a (field by field) review of a video recording of the burning. Sample A was dry mixed by passing several times through a 60 mesh screen. Sample B was dry mixed for several minutes using a mortar and pestle. Sample C was wet ball milled for 4 hours, dried and crushed to –100 mesh with a mortar and pestle. The charcoal and sulfur for sample D was dry ball milled for 4 hours; then with the potassium nitrate added, and wet ball

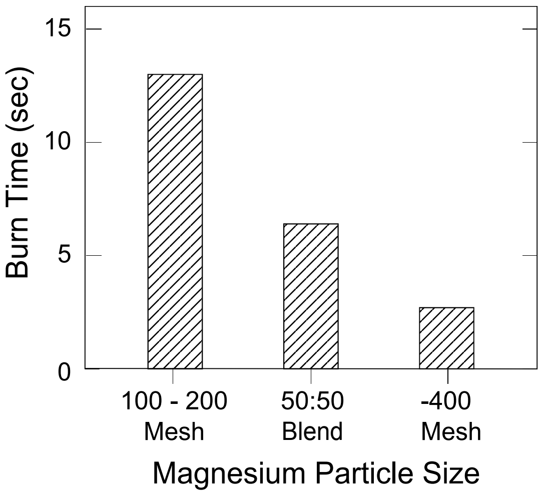

*Figure 5. Burn times for flares made with varying magnesium particle size.*

milled for 8 hours; then dried and crushed to –100 mesh with a mortar and pestle. The average mass burn rates for three measurements of each sample of rough Black Powder are shown in Figure 4.

**D) Particle Size**

As the size of individual fuel and oxidizer particles is made smaller, the burn rate increases. It is difficult to overstate the degree to which particle size, especially that of the fuel, can affect burn rate. The particle size effect can be considered to be the result of reducing the effective activation energy, because smaller particles require less energy to be heated to the ignition temperature. Also, since only those atoms on the surface of particles are available to react, then, as particle size is reduced, the fraction of atoms on the surface increases. Further, presumably as a result of an increasing fraction of atoms on the surface of particles, some researchers have reported increased heats of reaction for smaller particle sizes.

For a demonstration of the effect of magnesium particle size on the burn times of flares,[10] see Figure 5. (Note: The author did not specify the formulation for the flare composition.)

For most pyrotechnic compositions, it is the particle size of the fuel, with their typically high melting points, that has the greatest effect on burn rate. The reason that the size of oxidizer particles is of less importance is that most oxidizers melt or have decomposition temperatures at or below the ignition temperature of the pyrotechnic composition. For a comparison of the relative magnitude of the effect of fuel versus oxidizer particle size,[10] see Figure 6. These are burn rates for a loose pyrotechnic composition with strontium nitrate (60%), magnesium (25%), and PVC (15%). Note the relatively small effect of using coarse oxidizer as compared with using coarse fuel. (The mesh range for the fine magnesium was 200/325 and the coarse magnesium was 30/50 mesh; however, the author did not report the mesh ranges for the strontium nitrate.)

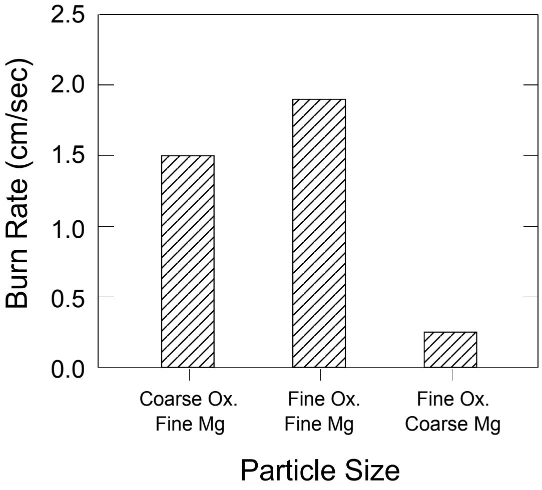

*Figure 6. Burn rates for a red flare composition with varying fuel and oxidizer particle sizes.*

**E) Particle Shape**

Particle shape affects burn rate in much the same way as particle size does; with a variation of effective activation energy as the controlling mechanism. Some shapes (e.g., thin flakes) are easier to raise to the ignition temperature than are others. Thin flakes also tend to have greater percentages of atoms on the surface. All else being equal, the order, from lowest to highest burn rate, are particles of the following shapes: spherical, spheroidal, granular and flake. As with particle size, it is the particle shape of the fuel has the greatest effect on burn rate. Again the reason is that fuels tend to have melting points higher than the ignition temperature of the pyrotechnic composition, whereas, oxidiz-

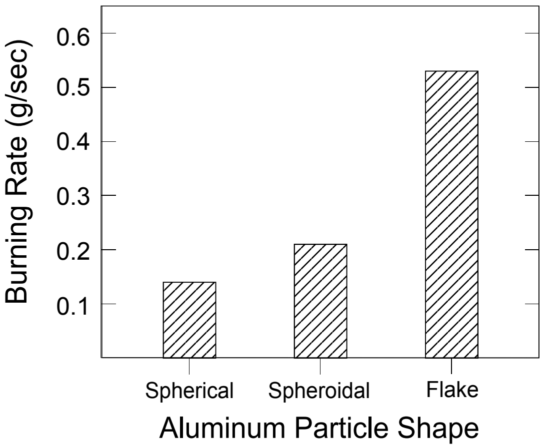

*Figure 7. Mass burn rates for a composition using different fuel particle shapes.*

ers tend to melt or decompose at temperatures at or below the ignition temperature using different fuel particle shapes.

A series of samples were prepared that contained 64% potassium perchlorate, 27% aluminum, and 9% red gum. In each case the average particle size for the aluminum was 20 microns; however, three different particle shapes were used: spherical atomized, spheroidal atomized, and flake. The pyrotechnic composition was pressed into 1 cm diameter paper tubes using a constant loading force. The burn times for 3.5 gram samples were measured using a stopwatch, and mass burn rates calculated. Average results from three measurements of each particle shape are presented in Figure 7.

**F) Presence of Additives**

It is possible to think of most pyrotechnic compositions as a pyrogen plus additives; where the pyrogen is the fuel and oxidizer, and the additives are those things that produce the intended pyrotechnic effect. Some common examples of additives are: large granular fuels which produce sparks; agents which produce or enhance colored flame or smoke; a binder to hold a composition together, including the residual solvent used to activate a binder; and a stabilizer or neutralizer to retard undesirable chemical reactions. Usually the presence of additives lowers burn rates and the amount of lowering increases with increasing percentage of additives. This can be the result of raising the effective activation energy, lowering the heat of reaction, or both.

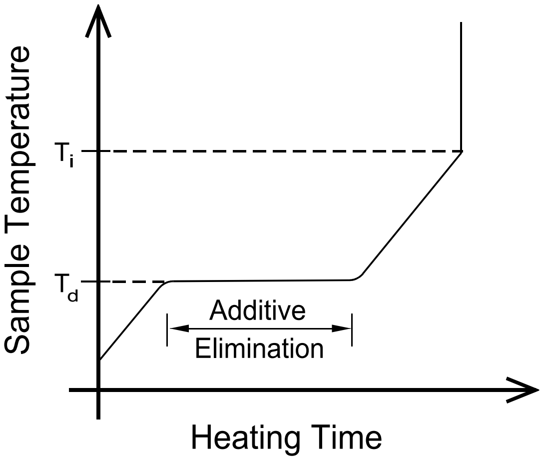

*Figure 8. How an additive can act to raise the activation energy of a composition.*

To see how an additive can act to raise the activation energy of a pyrotechnic composition, consider the case where sodium bicarbonate is added to a glitter composition as a delay agent. The sodium bicarbonate decomposes, consuming energy and releasing carbon dioxide, at 270 ºC, which is its decomposition temperature ($T_d$). This is below the ignition temperature ($T_i$) of the composition, which is probably about 350 ºC. As a tiny portion of the glitter composition is heated, (see Figure 8) initially the temperature of the composition rises. However, when the temperature reaches 270 ºC the sodium bicarbonate begins to decompose, consuming energy, thus keeping the temperature from rising further. After a period of time, when all of the sodium bicarbonate has decomposed, the temperature will again rise. At the ignition temperature, the temperature rises very quickly as burning begins. Since more energy is required for the composition to reach its ignition temperature, the activation energy is higher. As a consequence, more time is required for each tiny portion of composition to reach its ignition temperature (i.e., the burn rate is lower). (Note that the driving off of residual water in a pyrotechnic composition acts in much the same way as the above example.)

A quantity of rough Black Powder was prepared by wet mixing, drying, and grinding to –100 mesh. A series of samples were made that

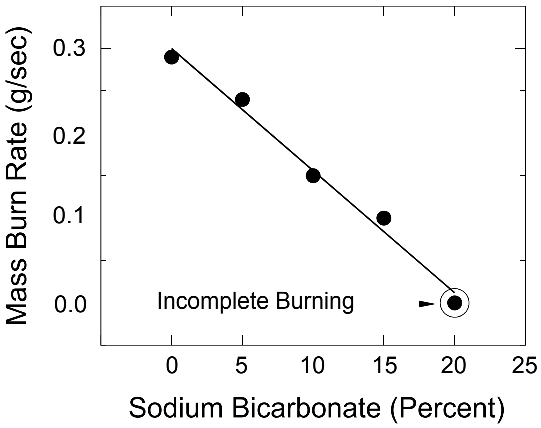

*Figure 9. Mass burn rate for rough Black Powder with sodium bicarbonate added.*

contained various amounts of sodium bicarbonate. The samples were burned by igniting loose 1 gram piles with a hot wire on the side about half way to the top. The times for complete burning were recorded. The result of the addition of sodium bicarbonate on mass burn rate is shown in Figure 9. The value for the mass burn rate for the samples with 20% sodium bicarbonate is uncertain because the samples generally would not burn completely.

As an example of how an additive can act to lower the heat of reaction of a pyrotechnic composition, consider the addition of a barium carbonate to neutralize trace amounts of acid present in a pyrotechnic composition, or strontium carbonate to act as a color agent. The carbonate is neither oxidizer nor fuel, and thus does not produce energy upon burning of the pyrotechnic composition. Accordingly, on a pound for pound basis, the composition produces less energy. In addition, as the composition burns, the carbonate will consume energy by decomposing, which reduces the heat of reaction still further.

While most additives to pyrotechnic compositions lower burn rate, it is sometimes possible to increase the burn rate of a pyrotechnic composition with an additive. When this is the case, it is generally the result of increasing the heat of reaction and/or improving the efficiency of energy feedback. The use of a small amount of a metal fuel is a common way this is accomplished. For example when zirconium is added to a red tracer mix (R328), a significant increase in burn rate results,[10] see Figure 10. This, presumably, is the result of both increasing the heat of reaction (high energy metal fuel) and increasing the efficiency of energy feedback (high thermal conductivity).

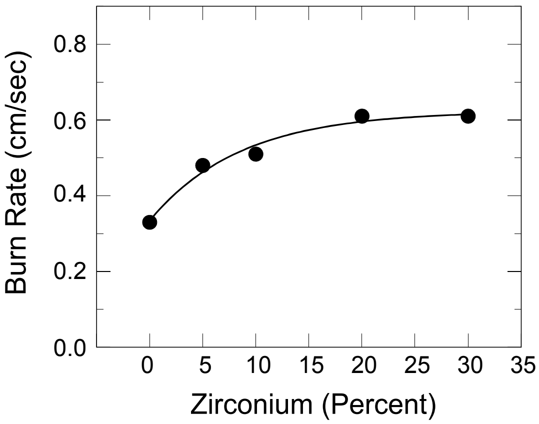

*Figure 10. Burn rate for red tracer mix (R328) with zirconium added.*

### G) Catalysts

Catalysts are a special class of additives. They are chemical agents that increase the rate of chemical reactions, normally without being consumed in the process. Pyrotechnically, burn catalysts act to lower activation energy, typically by reducing the decomposition temperature of the oxidizer (i.e., the temperature at which oxygen is made available). Red iron oxide, potassium dichromate, and manganese dioxide are some burn catalysts used in pyrotechnics. For example, the addition of manganese

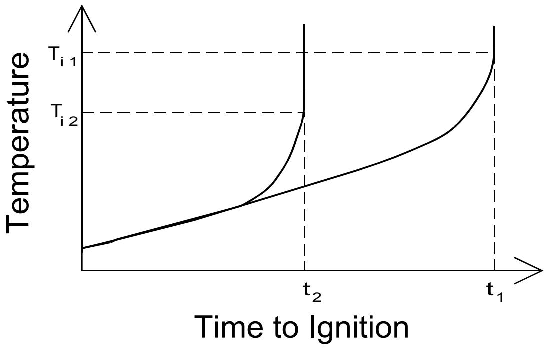

*Figure 11. How a burn catalyst produces an increase in burn rate.*

dioxide to potassium chlorate will lower its decomposition temperature by 70 to 100 ºC.[11] A reduction in the oxidizer's decomposition temperature, in turn, acts to lower the ignition temperature of the composition thus increasing its burn rate. How this occurs is illustrated in Figure 11. If the addition of a burn catalyst acts to lower ignition temperature (e.g., from $T_{i1}$ to $T_{i2}$), less time will be required for any tiny sample of composition to be heated to its ignition temperature (i.e., $t_2 < t_1$). Accordingly, as a stick of pyrotechnic composition burns (Figure 2), less time is needed for the ignition of each successive thin disk of composition (i.e., the burn rate increases).

A series of samples were made with potassium perchlorate plus potassium dichromate (70% total) and shellac (30%). The amount of potassium dichromate varied from 0 to 4%. Four gram samples of the mixtures were pressed into 1 cm diameter paper tubes, using a constant loading pressure. Pairs of tubes with the same mixture were burned to determine their average burn rate. The results are shown in Figure 12.

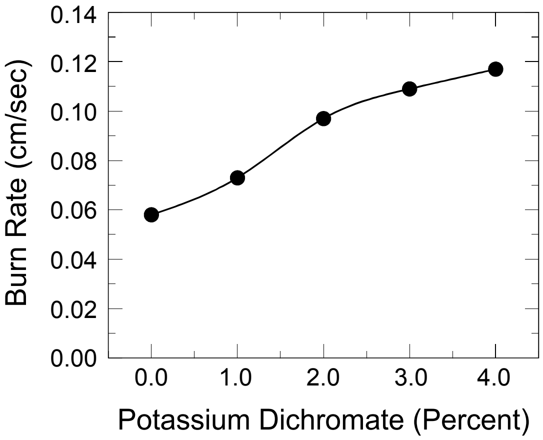

*Figure 12. Burn rates of a pyrotechnic composition with varying amounts of potassium dichromate.*

### H) Ambient Temperature

Pyrotechnic burn rates increase as the ambient temperature rises, because of a reduction in activation energy. In essence, this is a consequence of the unreacted composition starting out closer to its ignition temperature. Accordingly, less energy is required to bring it to its ignition temperature. This is illustrated in Figure 13, where two tiny samples of the same pyrotechnic composition are heated to cause their ignition. The sample with the higher initial temperature ($T_1$) requires less time ($t_1$) to reach the ignition temperature ($T_i$) than the sample initially at temperature $T_2$.

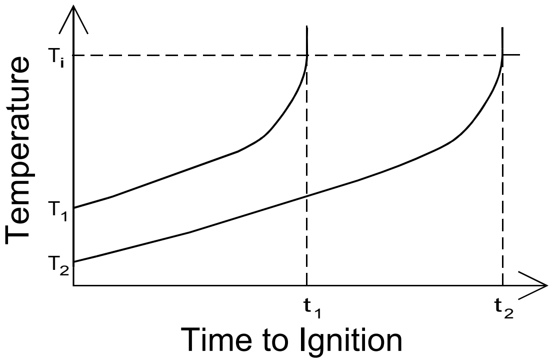

*Figure 13. The effect of ambient temperature on burn rate.*

As part of a study to determine the characteristics of visco fuse,[12] a measurement was made of the effect of temperature on its burn rate. In this study, groups of 10 pieces of 12.7 cm long fuse were cooled or heated to various temperatures and then burned to determine the effect of temperature on their burn rate. The results of the study are shown in Figure 14.

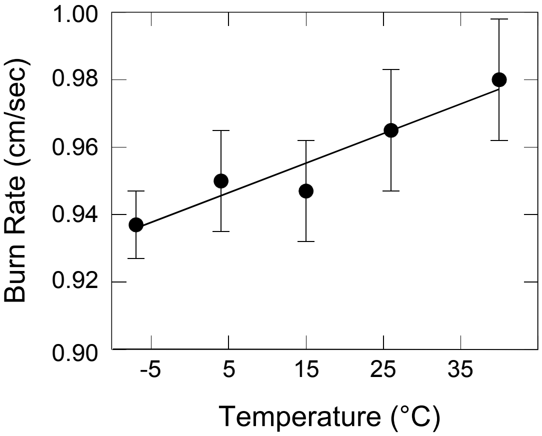

*Figure 14. Burn rate of visco fuse as a function of ambient temperature.*

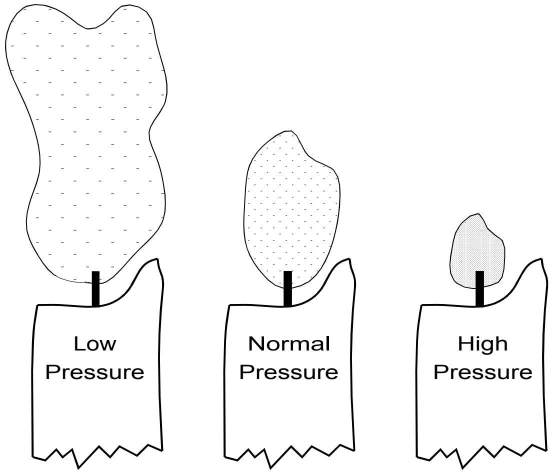

*Figure 15. An illustration of the effect of local pressure on a candle flame.*

## (I) Local Pressure

Gas generating pyrotechnic compositions generally produce a flame upon burning. For these compositions, the nature and relative position of the flame produced varies as a function of local pressure. As the pressure is increased, the flame envelope becomes smaller, the flame burns hotter, and it is held in closer proximity to the burning surface. This is illustrated in Figure 15, which is a representation of a candle burning under varying local pressure. As the pressure rises, so does the burn rate, because the hotter flame held closer to the burning surface increases the efficiency of energy feedback. Although generally not considered to burn with a flame, the burn rate for a smoke composition (oil red, 50%; potassium chlorate, 30%; and lactose 20%) illustrates the effect of pressure, see Figure 16.[6]

The relationship between burn rate ($R$, in cm/sec.) and local pressure ($P$, in atmospheres) can be expressed mathematically as:

(4) $R = a \cdot P^b$

where $a$ and $b$ are constants depending on the pyrotechnic composition. Some values for $a$ and $b$ are given in Table 4.

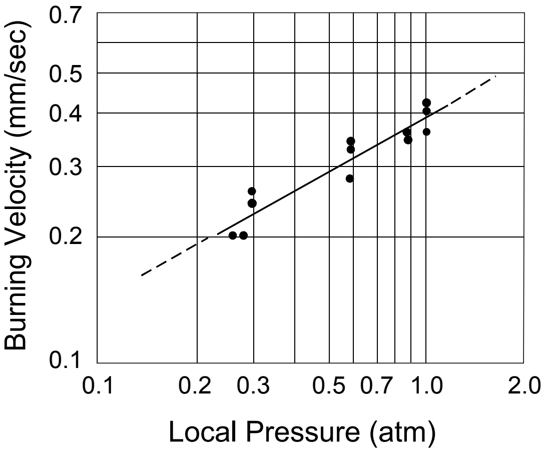

*Figure 16. Burn rate of a smoke composition as a function of local pressure.*

**Table 4. Pressure Dependent Burn Rate Constants for Pyrotechnic Compositions.**

| Composition | *a* | *b* | Ref. |
|---|---|---|---|
| Smoke Composition (above) | 0.038 | 0.44 | 6 |
| $KClO_4$ (80%) + Mg (20%) | 0.14 | 0.39 | 6 |
| $KNO_3$ (80%) + Mg (20%) | 0.25 | 0.30 | 6 |
| $KClO_4$ (60%) + Mg (40%) | 0.33 | 0.33 | 6 |
| $KClO_4$ (60%) + Al (40%) | 0.43 | 0.37 | 6 |
| Black Powder | 1.21 | 0.24 | 7 |

## J) Degree of Confinement

The effect of burning pyrotechnic compositions under confinement is complicated. However, the activation energy is not changed, and neither is the heat of reaction, unless significantly different chemical products are formed as a result of confinement. Burning of gas-producing pyrotechnic compositions under confinement, can be thought of as burning under conditions where, until the confining vessel bursts, the efficiency of energy feedback is extremely high. During unconfined burning most of the energy produced is lost to the surroundings as escaping combustion products and radiation. However, when the composition is confined, essentially all of the energy being produced is retained, and is available to ignite unreacted pyrotechnic material. Also, because the gaseous products are retained, there will be the effect of pressure accelerated burning, as discussed above. Accordingly, confinement can act to greatly increase the burn rate of gas-producing pyrotechnic compositions, and it would be difficult to overstate the effect that confinement has on burn rate. For gas-less pyrotechnic compositions, there is considerably less effect from confinement.

**K) Physical Form**

The physical form of the pyrotechnic composition can make a great difference in its burn rate. Mostly this effects the efficiency of energy feedback and was discussed in more detail in an earlier article on burn types.[3] Generally, for gas producing pyrotechnic compositions, granulated compositions (with so-called fire paths) have high burn rates; large solid masses of composition (with no fire paths) have low burn rates; and fine powders, which can experience burn type transitions, can have highly unpredictable burn rates. Of the three feedback mechanisms, convective energy feedback is the most important. For granulated materials, where fire paths exist, the hot burning gases produced by the reaction can rapidly penetrate between the grains into the unreacted composition, igniting more material in the process, producing more burning gas, penetrating further, in an accelerating process. In this way all of the pyrotechnic composition can come to be ignited very quickly.

In an experiment to demonstrate the tremendous effect physical form can have on burn rate, two transparent plastic tubes, 0.32 cm in diameter, were filled with Black Powder. In one case, loose 2Fg Black Powder was poured into the tube; in the other case, meal powder was loaded into the tube in small increments and compacted by high pressure to form a dense solid mass. The compacted material burned at a rate of about 1 cm/second; whereas, the granular material burned at a rate more than 1000 times greater, explosively shattering the open tube.

Shimizu points out that burn rate is dependent on the cross sectional dimension of fire paths.[6] Both small and large cross sectional areas result in relatively low burn rates; however, in between, the burn rate can be very much greater. He discusses this using the burn rate of quick match as an example. For quick match, the fire path is the space between the black match core and the loose paper sheath. Figure 17, adapted from Shimizu,[6] illustrates the effect of varying the gap between the match core and the paper wrap. When there is no fire path gap, the burn rate is relatively low; then as the gap between match and paper increases, the burn rate rapidly increases to a maximum value; there after, further gap increases result in a lowering of burn rate, back to the value for burning in open air.

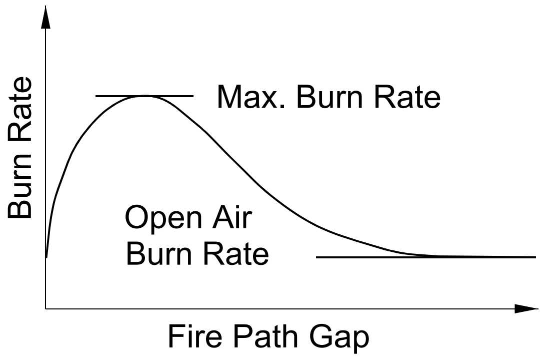

*Figure 17. Quick match burn rate as a function of fire path gap.*

**L) Degree of Consolidation**

Degree of consolidation is sometimes referred to as loading pressure and is related to the degree of compaction of pyrotechnic composition as it is made into grains or packed into a device. The effect of varying loading pressure is to change the efficiency of energy feedback. However, whether higher loading pressure increases or decreases the burn rate depends on the nature of the pyrotechnic composition.

If the pyrotechnic composition is gas-producing and convective heat transfer is an important mode of energy feedback, then high loading pressure generally decreases the burn rate by decreasing gas permeability. That is to say, even in quite tightly compacted compositions, some fire paths remain. These will tend to have small diameters, and will be blocked after short distances, but they do aid in the convective feedback of thermal energy. As the loading pressure is increased, these residual fire paths become thinner and shorter, reducing their effectiveness in aiding energy feedback, and thus decreasing the burn rate.

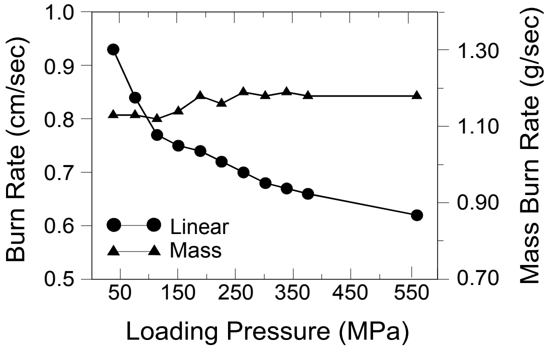

*Figure 18. Linear and mass burn rate of Pyrodex® as a function of loading pressure.*

As an example, consider the effect of increasing loading pressure on the burn rate of granular Pyrodex® (HF-4) when pressed into 1.2 cm tubes.[13] (Pyrodex® is a Black Powder substitute, based on potassium perchlorate, often used in muzzle loading weapons.) Figure 18 is a graph of the result of increasing loading pressure on both the average linear and mass burn rate. Measurements were made using groups of three samples at each pressure. Note the significant decrease in linear burn rate. Note further the near constant mass burn rate; this is the result of the density of the pressed composition increasing as it is compacted more tightly by the increased loading pressure.

Presumably it is the collapse of the fire paths between the initial grains of powder that is responsible for the change in burn rate. Thus it may be interesting to consider the effect of using powder with different particle sizes. Figure 19 is a graph of the result of using three different granulations of Pyrodex® compacted into 1.2 cm tubes with a loading pressure of 225 MPa.[13] Note that only the –60 mesh material is significantly different. This might have been predicted, because this is the powder with the smallest and probably widest range of grain size. Accordingly, when compacted, this material should have the smallest and most frequently blocked fire paths.

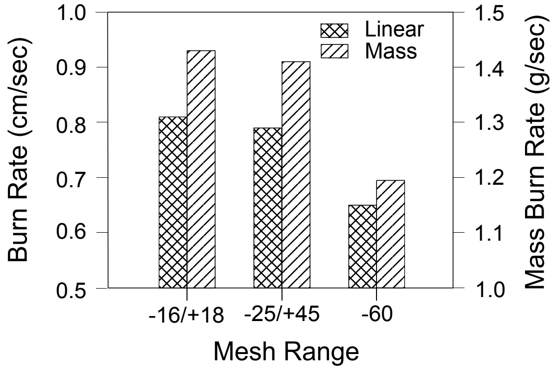

*Figure 19. The effect of grain size on the linear and mass burn rate of Pyrodex®.*

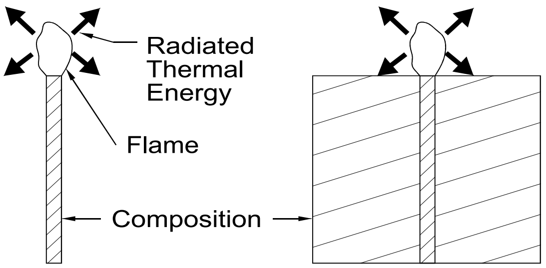

*Figure 20. Radiant energy feedback for blocks of pyrotechnic composition.*

Conversely to the above examples, if a pyrotechnic composition produces little or no gas upon burning and conductive heat transfer prevails, higher loading pressure generally increases the burn rate. This is because, for such a pyrotechnic material, added compaction increases thermal conductivity, increasing the efficiency of energy feedback, and thus increasing the burn rate.

**M) Geometry**

Geometric effects are changes in burn rate brought about by changes in size and shape of the pyrotechnic composition. For the most part, this is the result of small changes in the efficiency of energy feedback. For example, as the size of a grain of composition increases, a slightly greater percentage of the radiant thermal energy produced during burning is radiated back to heat the burning surface. This is illustrated in Figure 20. In the case shown on the left, almost all of the radiated thermal energy is lost to the surroundings. The case illustrated on the right is an attempt to consider the effect when a much larger block of composition is burned. However, for simplicity, only the burning of the same small portion (seen to the left) is considered. In this case, almost all of the thermal energy radiated in a downward angle will strike the surface of the composition, thus contributing to the feedback of energy. The effect is to increase the burn rate for larger blocks of pyrotechnic composition. In an experiment to demonstrate this effect, meal powder was compacted into tubes using a constant loading pressure per surface area. Two different size tubes were used, with diameters of 0.8 and 1.6 cm. Four trials of each, resulted in an average burn rate for the larger sample which was about 10% greater; a small but real difference.

Another example of geometric effect is the "erosive burning" that occurs along a hole or channel running through a grain of pyrotechnic composition.[3] For purposes of this article, geometric effect is also taken to include effects such as caused by the thermal conductivity of inert materials in or surrounding the pyrotechnic composition. For example, because of increased thermal energy feedback, a composition pressed into a thin metal tube (or having a metal wire internally along its length) will often have an increased burn rate compared with one pressed into a paper tube (or without the wire).

### N) Crystal Effects

Crystal effects include a number of diverse effects all relating to properties of crystal lattices. One crystal effect may result from the ability to store some of the energy from milling or grinding in a crystal lattice.[5] Following the accumulation of this lattice energy, there seems to be a temperature dependent relaxation time during which the stored energy is lost. During the period when significant energy remains stored in the crystal lattice, the effective activation energy for the material is reduced, potentially increasing burn rate. Other crystal effects can be the result of using materials with different methods of manufacture, which produce crystals with different lattice structures, different numbers of defects, and different amounts of trace impurities. Another possible crystal effect, which may be important in some transitions from burning to explosion, is the piezoelectric effect. It is felt by some that this has the potential for significantly increasing energy feedback by converting compressive pressure forces into an electrical ignition stimulus.[14]

### O) Environmental Effects

Most changes in burn rate that occur during storage are the result of the factors discussed above. For example, during repeated temperature cycles, cracks may be produced in a rocket propellant. The resulting (often catastrophic) increase in burn rate is indirectly discussed in Section K. The crack produces a fire path which increases the energy feedback to unreacted composition. Similarly, the deterioration of a star with a metal fuel, which slowly oxidizes during storage, can be thought of in terms of additives (Section F). In this case fuel and oxidizer are being converted to mostly unreactive chemical products. Although these types of environmental effects can act to change burn rates, and are important considerations in the storage of pyrotechnic materials, they are generally not seen as mechanisms to control burn rate.

There is at least one environmental effect that actively controls burn rate; that is wind speed. The speed at which a burning pyrotechnic moves through the air will affect the fraction of energy fed back. Consider the case illustrated in Figure 21; in the case of the moving

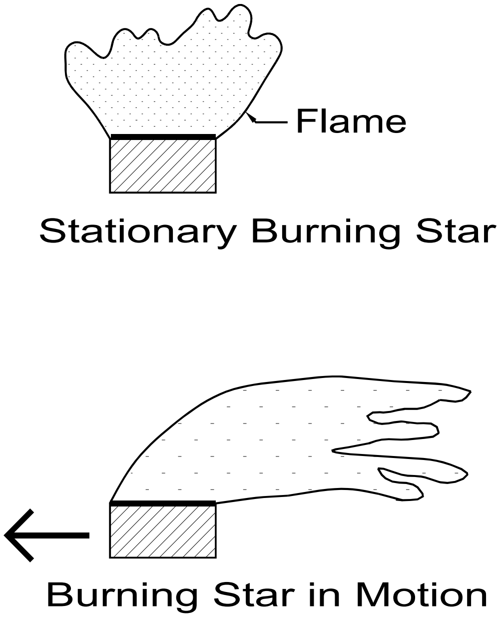

*Figure 21. An illustration of the effect of air movement past a star.*

star, the flame will be pushed away from the star by the air movement past it. That this occurs is confirmed by Figure 22, which is a photograph of a group of stars propelled through the air from an exploding shell. It is fairly clear that the stars (dark dots) have their flame envelopes (light areas) trailing behind them. The effect of this is to reduce the fraction of energy feedback, and thereby lower the burn rate. In other cases the effect of a wind over the burning surface will be to supply extra oxygen for burning, which in some cases can act to increase the burn rate.

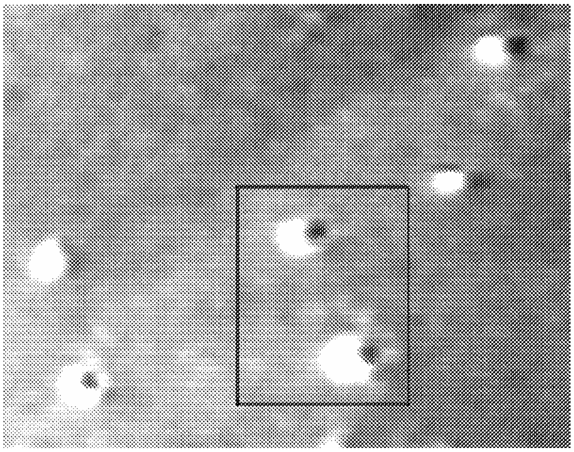

*Figure 22. A photograph of high speed burning stars.*

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# Hypothesis Explaining Muzzle Breaks

K.L. and B.J. Kosanke

***ABSTRACT***

*Muzzle breaking aerial shells continue to be a significant cause of serious injury for persons discharging display fireworks. The problem is greatest for manually fired displays, where the person igniting the fireworks remains in close proximity to the mortar. Over the years, many possible causes for muzzle breaks have been suggested. Unfortunately, most of these explanations are incapable of withstanding close scientific scrutiny, and there has been no published study that has tested any of the potential explanations. Without knowing the cause(s) for muzzle breaks with some certainty, it is difficult (or impossible) for a manufacturer of aerial shells to know what measures might be taken to reduce or eliminate the chance of their occurrence.*

*Probably the best known characteristic of muzzle breaks is that they occur almost exclusively in the largest diameter (most potentially dangerous) aerial shells. Probably at least 90% of muzzle breaks occur in aerial shells 205 mm (8 in.) or larger. This is true, even though at least 90% of all aerial shells fired are smaller than 205 mm (8 in.). Thus any theory for the cause of muzzle breaks must account for this observation. The authors hypothesize that either setback or very small fire leaks lead to the occurrence of muzzle breaks, and that the dynamics of the propulsion of fireworks from mortars and the explosion of aerial shells is such that the chances for muzzle break occurrence is greatest for large diameter shells. In an attempt to test the hypothesis, a series of measurements were performed to determine the exit times of aerial shells from mortars and the times to explosion of shells after internal ignition. Results of these measurements are each somewhat surprising; they tend to support the hypothesis and provide insight into the mechanisms of aerial shell flowerpots.*

## Introduction

It is fortunate that, when manually igniting fireworks aerial shells using proper procedures, most of the common aerial shell malfunctions should allow the display crew to escape serious injury. For example, “flowerpots”, which are relatively weak explosions of shells inside mortars, should not result in crew injuries if: the mortars are angled away from the crew, shell loading is not being performed immediately adjacent to shell firing, minimal personal protection is worn, and the ready box (shell storage container) is covered and located upwind from the mortars. It is unfortunate that there are two less common types of aerial shell malfunctions for which proper procedure does not offer much protection against serious crew injuries. These two malfunctions are: 1) “shell detonations” (so-called, but probably not true detonations), which are powerful shell explosions inside mortars, in which the entire energy of the pyrotechnic contents of a shell is released essentially instantly, and they are powerful enough to generally destroy the mortar, hurling debris in various directions; and 2) “muzzle breaks”, which are explosions of aerial shells just after leaving the confinement of the mortar, and which propel shell casing fragments and burning contents in all directions at great speed.

The first step in the process of eliminating these two more dangerous types of shell malfunctions is the identification of the mechanism for their occurrence. Unfortunately, while speculation abounds as to the causes, there has been no systematic study published that confirms or dispels them. In this paper, a hypothesis explaining muzzle breaks is proposed, data collected to test that hypothesis is presented, and the results are discussed.

## Background

In the past, theories have been advanced to explain muzzle breaks. Among the suggested causes are:

1) Extremely fast burning time fuse on the aerial shell;
2) Inertial effects that cause ignition of the shell when the contents radically shift position as the shell exits the mortar. (At this time, the shell experiences its maximum deceleration after having just experienced its maximum acceleration.),[1] and
3) Partial vacuums, created inside shells from lift gases rapidly flowing past a small hole on the exterior of a shell while it is still inside the mortar, and which then act to suck fire into the shell as it exits the mortar.[2]

There is one well-known characteristic of muzzle breaks for which any proposed theory must account. That characteristic is, having normalized for the numbers of various sized shells fired, almost all muzzle breaks occur with shells 205 mm (8 in.) and larger. For the most part, none of the above three theories successfully account for this characteristic.

1) Fast fuse: There is no reason to suppose that extremely fast burning time fuse is only used on large diameter aerial shells.
2) Inertial effect: Published data for spherical aerial shell muzzle velocities suggest that there is little or no systematic difference that is shell size dependent.[3,4] Since small diameter shells experience the greatest deceleration immediately after leaving the mortar, it might be expected that small diameter shells would experience the greatest normalized frequency of muzzle breaks.
3) Partial vacuum: A combination of published and unpublished data suggests that while mortar pressures tend to increase with shell size, relatively small diameter cylindrical shells experience the same mortar pressures as large diameter spherical shells.[4,5] Thus there is no reason to suppose that large diameter shells, which tend to be exclusively spherical shells, would be more prone to experiencing this problem than small cylindrical shells. In fact, based on their manner of construction, it is more likely that cylindrical shells (thus, small shells) are more likely to have a small hole in the proper location to cause this malfunction. Finally, an unpublished study suggests that the partial vacuums that can be created in this manner are probably too weak to cause fire to be sucked into the shell upon exiting the mortar.[6]

Because of the apparent difficulties with the above theories, it seemed useful to contemplate whether any other explanations could be advanced that were more consistent with the observation that muzzle breaks predominantly occur in large diameter aerial shells. Below, after some additional background discussion, is a hypothesis that fits this observation.

When an aerial shell, with an electric match installed in its lift charge, is fired from a mortar, it appears that the firing is instantaneous upon energizing the electric match. Obviously, however, that is not the case. Time is required for the ignition of the electric match; more time is required for flame to spread through the lift charge and for mortar pressure to build; finally time is required for the aerial shell to be accelerated up the mortar. Similarly, when a small flame, such as from an electric match, is introduced into an aerial shell, it appears that the shell explodes instantaneously upon energizing the electric match. But again, this is obviously not the case, as it takes time for the flame to propagate through the volume of the shell and for pressure to build to the point of exploding the shell casing.

The total internal volume of spherical aerial shells increases as the cube of the inner diameter of the casing. Presumably, the total void space between the internal components in the shell also increases roughly in proportion with the total volume. Because of the larger void space, it should take longer for the pressures to build to the point of explosion. Also, because of increased linear dimensions, it should take longer for flame to spread through a large aerial shell. Thus, large diameter aerial shells should require more time to explode than a small shell, after the introduction of a tiny flame.

In the context of muzzle breaks: ignition of the contents of the shell could be caused as the result of a small fire leak in some part of the shell; or from friction sensitivity of internal

**Table 1. Inert Aerial Shell Characteristics and Air Temperature during Tests.**

| Test | Shell Size | | Actual Shell Diameter | | Shell Mass | | Lift Mass | | Approx. Air Temp. | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | mm | (in.) | cm | (in.) | g | (oz) | g | (oz) | °C | (°F) |
| Spherical Shells: | | | | | | | | | | |
| 7 | 76 | (3) | 6.6 | (2.61) | 135 | (4.8) | 28 | (1.0) | 27 | (80) |
| 4 | 102 | (4) | 9.5 | (3.74) | 360 | (12.7) | 28 | (1.0) | 21 | (70) |
| 9 | 102 | (4) | 9.5 | (3.74) | 335 | (11.8) | 46 | (1.6) | 21 | (70) |
| 11 | 127 | (5) | 11.9 | (4.68) | 625 | (22.1) | 50 | (1.8) | 27 | (80) |
| 10 | 155 | (6) | 14.4 | (5.66) | 1140 | (40.3) | 85 | (3.0) | 24 | (75) |
| 13 | 205 | (8) | 19.3 | (7.60) | 2700 | (95.4) | 155 | (7.1) | 21 | (70) |
| 12 | 205 | (8) | 19.3 | (7.60) | 2700 | (95.4) | 200 | (7.1) | 24 | (75) |
| Cylindrical Shells: | | | | | | | | | | |
| 2 | 76 | (3) | 6.7 | (2.64) | 125 | (4.4) | 28 | (1.0) | 4 | (40) |
| 6 | 76 | (3) | 6.7 | (2.64) | 125 | (4.4) | 28 | (1.0) | 27 | (80) |
| 5 | 76 | (3) | 6.7 | (2.62) | 180 | (6.4) | 28 | (1.0) | 27 | (80) |
| 8 | 102 | (4) | 9.2 | (3.62) | 500 | (17.7) | 50 | (1.8) | 27 | (80) |
| 3 | 102 | (4) | 9.2 | (3.62) | 500 | (17.7) | 50 | (1.8) | 35 | (95) |
| 1 | 155 | (6) | 14.1 | (5.56) | 1870 | (66.1) | 125 | (4.4) | 4 | (40) |

components producing a point of ignition during the acceleration of the shell ("setback").

Based in part on the observation that the muzzle velocities of aerial shells are largely independent of shell size,[3,4] it is worth speculating whether the times to exit for large shells are significantly greater than for small shells. If there is not much difference in the exit times, there is a possible basis for explaining muzzle breaks. That is to say, it is possible that muzzle breaks occur almost exclusively in large diameter shells, because:

- Mortar exit times for aerial shells are independent, or only weakly dependent, on shell size;
- While times to explosion of large shells are substantially longer than for small shells.

Thus after introduction of a point of ignition inside a shell:

- Small shells are more likely to explode while they are still inside the mortar (as a flowerpot);
- Whereas at least some large shells have time to exit the mortar before they explode (as a muzzle break).

In order to determine whether this hypothesis has any merit, it is necessary to know something about mortar exit times as a function of shell size, and of the times to explosion of aerial shells as a function of shell size. Because there is no published data of this type, and because such data is interesting beyond the context of this muzzle break hypothesis, the authors undertook a project to generate some of that information.

## Aerial Shell Mortar Exit Times

Mortar exit times were measured for 76- to 205-mm (3- to 8-in.) spherical aerial shells, and for 76-, 102- and a few 155-mm (3-, 4- and a few 6-in.) cylindrical shells. In almost all cases, six identical shells were fired and the results averaged. All aerial shells were fired using an electric match (Davey Bickford N 28 B) installed into the lift charge. The current applied to the electric match, ≈6 amperes, is sufficient to have caused their ignition in less than 1 ms (0.001 second).[7] In all cases: the aerial shells were inert; the lift charge was placed in a small plastic bag attached to the bottom of the shell; the lift charge caused the shell to rest about 2.5 cm (1 in.) above the bottom of the mortar, except for the 205-mm (8-in.) shells where the larger lift bag held the shell about 3.8 cm (1.5 in.) above the bottom of the mortar. Characteristics of the sets of aerial shells used in

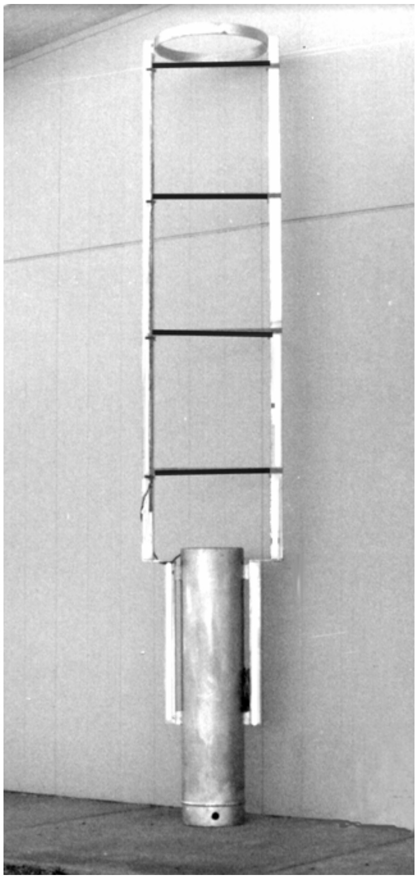

*Figure 1. Photograph of a test mortar with colored tape indicating locations of trip wires.*

these tests are presented in Table 1. Generally, shell and lift masses chosen for the test shells are averages of measurements made on collections of 10 to 20 live shells of one size but from various manufacturers.

In these tests, only inert shells were fired. This is because: it was intended that the same data be used for other purposes, in which the total flight times of the shells are needed; the cost of about 80 aerial shells ranging up to 205 mm (8 in.) was prohibitive; during most of the testing there was a ban on open burning, including fireworks, because of extreme fire danger in Colorado. In only two tests of 76-mm (3-in.) cylindrical shells, were the shells made of paper; all other shells had smooth plastic exteriors. Also, with Chinese aerial shells, one is never quite certain what quality lift charge has been used. Accordingly, to increase the likelihood that these results are consistent with those that would have been found for typical live shells, the lift powder used was a mixture of lift powder previously salvaged from oriental shells. It had a granulation ranging from about 4F to 6F. The lift powder for all the cylindrical shells was Goex 2F A-blasting powder.

The characteristics of the mortars used in the tests are shown in Table 2.

**Table 2. Steel Test Mortar Characteristics.**

| Size | | Diameter | | Length | |
|---|---|---|---|---|---|
| mm | (in.) | cm | (in.) | cm | (in.) |
| 76 | (3) | 7.9 | (3.11) | 50.8 | (20.0) |
| 102 | (4) | 10.3 | (4.05) | 60.7 | (23.9) |
| 127 | (5) | 12.9 | (5.09) | 75.9 | (29.9) |
| 155 | (6) | 15.4 | (6.08) | 75.7 | (29.8) |
| 205 | (8) | 20.3 | (8.01) | 90.9 | (35.8) |

For increased reliability, two different methods were used to determine aerial shell exit times. One method involved the measurement of the shells' muzzle velocity, using the times at which a series of trip wires are broken after the shells leave the mortar.[4,8] Figure 1 is a photograph of a test mortar with colored tape indicating the location of the trip wires. The trip wires are thin (0.48 mm) plastic insulated copper wires, stretched between electrical contact points. The wires are somewhat loosely secured at their ends, such that the wires typically pull free before stretching and breaking as the shell passes. Figure 2 shows the electronics package which fires the electric match in the lift charge and then provides the timing as each wire is broken. The unit was constructed by Pyrotech International specifically for this purpose and has a

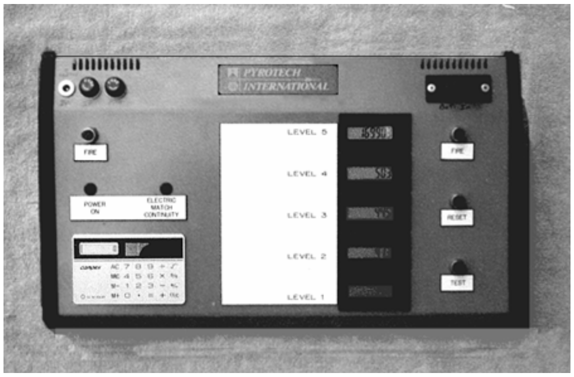

*Figure 2. Photograph of the electronic firing and timing unit.*

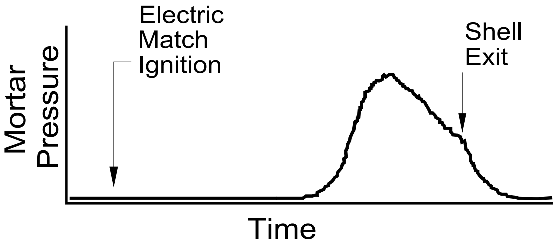

*Figure 3. Typical mortar pressure versus time curve for a shell firing.*

timing resolution of 0.1 ms. The first trip wire is 0.30 m (1 ft) above the mouth of the mortar, and the others are at 0.61-m (2-ft) intervals. Having determined each shell's muzzle velocity, and having measured the time to the first wire break, exit times can easily be calculated with a precision of a few milliseconds. Because of uncertainty as to the amount of wire flexing before pulling free or breaking, the accuracy of these measurements is probably several milliseconds.

The second method used to measure exit times was to monitor the gas pressure profile in the mortar as the shell fires.[4] Mortar pressures were monitored using a quartz pressure sensor (PCB 101A04) and the data stored digitally, usually with a sampling rate of 5000 readings per second. The pressure sensor was mounted in the center of the steel plate that closes the bottom of the mortar, much like was done in Reference 4. Figure 3 is a typical pressure versus time curve. A break in the pressure curve can be seen as the shell exits the mortar and the pressure drops more rapidly to one atmosphere. Since the digital oscilloscope was triggered by the energizing of the electric match, and knowing the oscilloscope time base setting, the exit time for the shell can be read directly from a print out of the data. Technically, the pressure measured at the sensor drops a short time after the shell actually leaves the mortar. However, because of uncertainty as to the speed of sound in the high temperature mortar gases, and because the correction would only be about one millisecond, no correction was made for this in the shell exit times. The precision of this method is about a millisecond, and the accuracy is probably no more than a few milliseconds.

It is a little surprising that for about 60% of the time taken for the shell to exit the mortar, the pressure in the mortar remains near zero (see Figure 3). It seems likely this is correct, because there was good agreement between the two exit time measurements. Also, in a series of tests to measure the time for small electrically ignited salutes to explode, it was confirmed that the electric matches were functioning in significantly less than 2 ms. Apparently, during the initial near zero pressure part of the graph, the flame is spreading through the lift charge. Then, only after most of the powder is ignited and producing gas in the partial confinement of the mortar, does the pressure rise significantly above zero. (If interested, see Reference 9 for a more complete discussion of the effect of pressure and confinement on burn rate.)

Generally there was good agreement between the two different methods of measuring shell exit times. However, there were occasional problems with the trip wire data caused by debris (mostly electric match wires) exiting before the shell. Also, on a few occasions, the pressure data was noisy, because combustion residue had collected on or had blocked the pressure sensor, making it impossible to accurately identify the exit time of a shell. On a couple of other occasions the time base setting or trigger level setting of the oscilloscope was such that pressure data was not recorded. When the pressure data was of high quality, that was used to determine exit times, and the trip wire data was only used as confirmation. When there was any problem with the pressure data, exit times were determined from the trip wire data. The average results for aerial shell exit times are presented in Table 3.

In Tests 4 and 9 on 102-mm (4-in.) shells, the primary difference was that the amount of lift powder was increased from 28 to 46 g. This increase in the amount of lift powder resulted in a decrease in average shell exit times from 51 to 36 ms. In Tests 12 and 13 on 205-mm (8-in.) shells; the only difference is that the amount of lift powder was decreased from 200 to 155 g. This decrease in the amount of lift powder resulted in an increase in shell exit times from 31 to 38 ms. This is consistent with what might have been predicted; it is mentioned here because it illustrates that the data are sensitive to the shell parameters chosen for the inert test

**Table 3. Aerial Shell Exit Time Results.**

| Test No. | Shell Size mm | (in.) | Exit Times (ms) | Average Exit Time (ms) | Remarks |
|---|---|---|---|---|---|
| Spherical Shells: | | | | | |
| 7 | 76 | (3) | 42, 70, 34, 35, 27, 62 | 45 | |
| C7 | 76 | (3) | 32, 70, 34, 35, 27, 62 | 43 | Corrected, See Below |
| 4 | 102 | (4) | 70, 48, 52, 34, 52, 48 | 51 | 28g Lift |
| C4 | 102 | (4) | 53, 48, 52, 34, 52, 28 | 48 | Corrected, See Below |
| 9 | 102 | (4) | 40, 28, 42, 30, 37, 37 | 36 | 46g Lift |
| 11 | 127 | (5) | 56, 33, 45, 46, 37, 37 | 42 | |
| 10 | 155 | (6) | 34, 43, 36, 32, 47, 42 | 39 | |
| 13 | 205 | (8) | 34, 45, 36, 32, 45, 34 | 38 | 155g Lift |
| 12 | 205 | (8) | 32, 25, 35, 32, 32 | 31 | 200g Lift |
| Cylindrical Shells: | | | | | |
| 2 | 76 | (3) | 54, 103, 89, 58, 88, 76 | 78 | 125g Shell, Temp. ≈4 °C |
| 6 | 76 | (3) | 70, 28, 39, 30, 26 | 39 | 125g Shell, Temp. ≈27 °C |
| C6 | 76 | (3) | 53, 28, 39, 30, 26 | 35 | Corrected, See Below |
| 5 | 76 | (3) | 36, 32, 38, 36, 52, 42 | 39 | 180g Shell, Temp. ≈27 °C |
| C5 | 76 | (3) | 23, 32, 38, 36, 52, 42 | 37 | Corrected, See Below |
| 8 | 102 | (4) | 40, 30, 30, 37, 27, 35 | 33 | Temp. ≈27 °C |
| 3 | 102 | (4) | 64, 29, 35, 37, 36 | 40 | Temp. ≈35 °C |
| C3 | 102 | (4) | 49, 29, 35, 37, 36 | 37 | Corrected, See Below |
| 1 | 155 | (6) | ≈100, ≈40, 62 | 67 | Temp. ≈4 °C |

shells. Because shell and lift masses were averages from collections of live shells from various manufacturers, and because flight times of these test shells were in good agreement with earlier measurements made on live shells, it is felt that the performance of the test shells is similar to that which would have been obtained, had live shells been used.

The test results for 76- and 102-mm (3- and 4-in.) cylindrical shells seem to be a little shorter than those for spherical shells. This seems to be consistent with what might have been predicted for shells whose shape provides less "loading space" (also called "dead volume"). However, data should be collected for larger cylindrical shells before concluding for certain that cylindrical shells typically have shorter exit times.

Some firings occurred during winter while collecting data for other purposes. The exit times from these tests are substantially longer than those measured in tests performed during the summer. This suggested a significant temperature effect, consistent with what was reported by others for mortar pressures.[10] However, in a pair of tests, 3 and 8, run on identical test shells, but at temperatures differing by 8 °C (15 °F), contrary to what was expected, the exit times for the higher temperature shells were slightly longer. Thus, at present, it is not clear what the temperature effect is on aerial shell exit times. Nonetheless, in an attempt to minimize any temperature effect, all data used to test the muzzle break hypothesis was collected between 21 and 27 °C (70 and 80 °F).

While performing the tests, it seemed as though another temperature effect was influencing the results. It seemed that the first few shell firings had significantly longer shell exit times than later firings. It was suspected that this might be the result of the mortar heating from the shell firings, which, in turn, was causing a heating of the lift charge of the next shell being loaded into the mortar. Accordingly, to limit any effect this was having on the data, beginning with test series 8, as little time as possible (only 4 to 6 seconds) was allowed to pass between loading and firing the test shells. The data in Table 3 was later examined to determine if this effect was real. For each of the identical shells fired in each test series, the exit time observed for that shell was compared to the average for the group of shells. The deviation from the average was expressed as a percentage, with

**Table 4. Shell Exit Time Deviations from the Average.**

| Test | Exit Time Deviations (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| Series | 1 | 2 | 3 | 4 | 5 | 6 | Shell Type |
| 3 | 60 | –28 | –12 | –8 | — | –10 | 102 mm Cyl. |
| 4 | 37 | –60 | 2 | –33 | 2 | –6 | 102 mm Sph. (28 g) |
| 5 | –8 | –18 | –3 | –8 | 33 | 8 | 76 mm Cyl. |
| 6 | 79 | –28 | 0 | –23 | –33 | — | 76 mm Cyl. |
| 7 | –7 | 55 | –24 | –22 | –40 | 38 | 76 mm Sph. |
| Ave. 3–7 | 32 | –5 | –7 | –19 | –10 | –2 | |
| 8 | 18 | –9 | –9 | 12 | –18 | 6 | 102 mm Cyl. |
| 9 | 11 | –22 | 17 | –17 | 3 | 3 | 102 mm Sph. (46 g) |
| 10 | –13 | 10 | –8 | –18 | 21 | 8 | 155 mm Sph. |
| 11 | 33 | –21 | 7 | 10 | –12 | –12 | 127 mm Sph. |
| 12 | — | 3 | –19 | 13 | 3 | 3 | 205 mm Sph. (200g) |
| 13 | –11 | 18 | –5 | –16 | 18 | –11 | 205 mm Sph. (155g) |
| Ave. 8–13 | 8 | –4 | –3 | –3 | 2 | 0 | |

positive numbers corresponding to exit times longer than the average and negative numbers, less than average. Next, the results for each of the 6 shells from test series 3 through 7 were averaged, and the same was done for the shells in test series 8 through 13. The results are shown in Table 4.

Note that:

- The first shell fired in test series 3 through 7 had an exit time that averaged 32% longer than average.
- All other shells in test series 3 through 7 had exit times less than average.
- The first shell fired in test series 8 through 13 had an exit time that averaged 8% longer than average.

Accordingly it can be concluded that:

- The mortar temperature effect primarily affected the first shell firing in each series.
- The corrective action, minimizing the time in the mortar before firing, mostly corrected the problem.

In order to have a more consistent set of data, it was decided to adjust the shell exit times for the first shell fired in test series 3 through 7. This was accomplished by reducing those shell exit times by 24%, the difference between 32 and 8%. These values are included in Table 3, with a "C" prefix to the test number and the remark "Corrected, See Below". Note that the average shell exit times were lowered about 3 ms as a result of making this correction.

Figure 4 is a presentation of the aerial shell exit times data for spherical shells, using corrected times for test series 4 and 7. The trend line for the data is the linear least square fit. It appears certain that shell exit times do not increase with increasing shell size. Further, and surprisingly, it seems likely that shell exit times actually decrease slightly with increasing shell size. Near constant or decreasing times are consistent with what would be necessary for the muzzle break hypothesis proposed above.

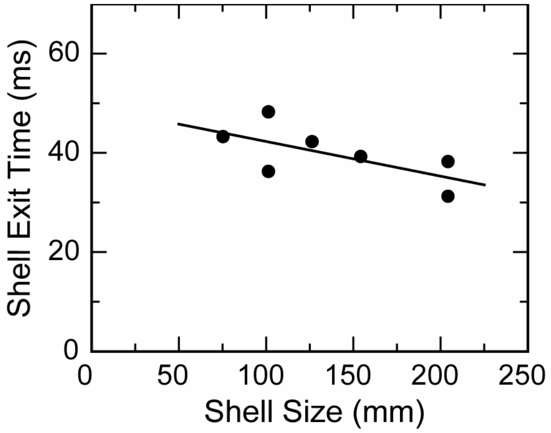

*Figure 4. Graph of spherical aerial shell exit time as a function of shell size.*

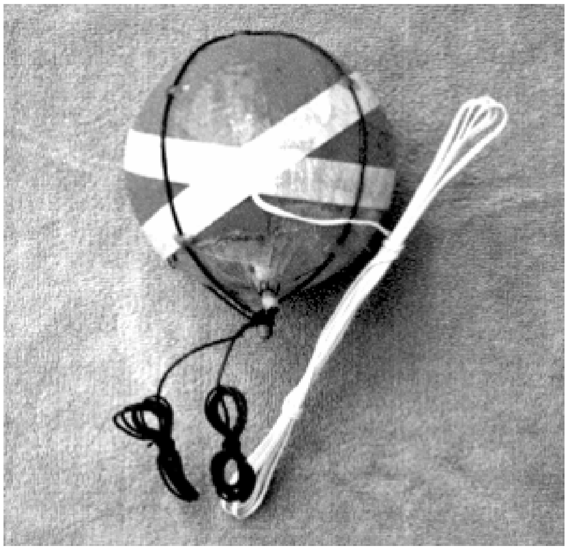

*Figure 5. A typically prepared shell used in measuring burst delay times.*

## Aerial Shell Burst Delay Times

Burst delay times were measured for spherical aerial shells ranging in size from 76 to 255 mm (3 to 10 in.). The shells were ignited using an electric match inserted into the shell. This was accomplished by making a small hole, only slightly larger than the electric match, by remotely pressing a pointed tool through the shell casing, a little above or below the equator of the shell. The tip of the electric match was inserted about 1.5 cm (0.6 in.) into the shell. The hole was closed using three layers of strapping tape encircling the shell in different directions. As a sensor to indicate the bursting of the shells, two loops of wire encircling the shell were used. The loops crossed the poles of the shell at about a 90° angle. These wires were held in position using small dabs of hot-melt glue along its length. The configuration of a typically prepared test shell is shown in Figure 5. To make the measurement, the test shell was suspended above the ground, then electrically attached to the timing and firing apparatus. The electric match was energized with sufficient current to cause its ignition in less than one millisecond. The contents of the shell were thus ignited, causing the shell to burst (explode). As the casing expands and fragments, the loops of wire break. Figure 6 is a photograph of one of the tests using a 205-mm (8-in.) aerial shell. Burst delay times were determined using an electronic timer to measure the time between application of current to the electric match and when the wire loops break. The same apparatus was used in these measurements that had been used earlier to determine the times of breaking of the trip wires.

For the burst delay times to be representative of typical shells, the shells used in these measurements came from seven different manufacturers. These manufacturers were: Yung Feng (Y), Horse (H), Temple of Heaven (T), Onda (O), Red Lantern (R), Sunny International (S), and Flying Dragon (F). In the data presented

*Figure 6. A photograph of the test of a 205-mm (8-in.) Aerial shell.*

below, the manufacturer is identified using the code letter listed for each manufacturer. Burst delay times are presented in Table 5.

It would have been preferred to have tested a larger number of shells, and to have used a wide and consistent set of manufacturers for each shell size. However, this was not possible because of economic constraints.

While most of the burst delay times for each shell size are fairly well grouped, there are occasional values that are significantly longer than the rest of the group. The most extreme example is the delay time for the Horse brand 205-mm (8-in.) shell, which was 329 ms as compared with 52 and 96 ms for the other two shells. Similarly was the 122 ms for the 76-mm (3-in.) Temple of Heaven shell and the 104 ms for the 102-mm (4-in.) Red Lantern shell, are significantly longer than the burst delay times for the other shells in the groups. It is felt that these longer delay times were real. This is because, in each of these three cases, the time interval, between pressing the button to energize the electric match and when the shell explosion occurred, was noticeably longer than for the other shells. The cases of longer than normal burst delay times may represent some type of anomalous ignition of the shells' contents, in which the fire transfer from the match was substantially less effective than in the other cases. This notion is supported by the fact that in two other cases, although the electric match fired normally inside the shell, the contents were not ignited and the shells failed to explode. In both cases, a second attempt produced a shell explosion with the delay time typical for shells of that size. In order to not bias the data by including the abnormally long burst delay times, they were excluded when calculating the average delay times for each size shell.

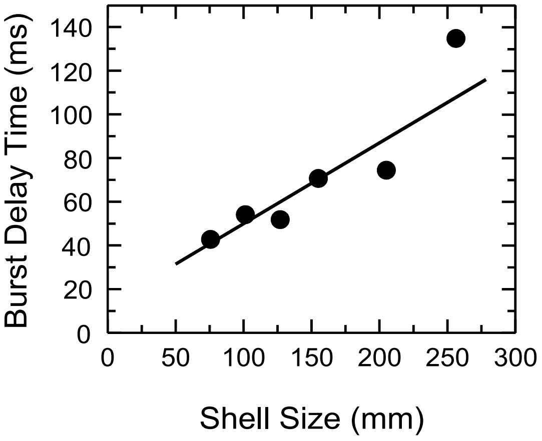

*Figure 7. Average Shell Burst Delay Times as a Function of Shell Size.*

Average shell burst delay times, as a function of shell size, are presented in Figure 7. In the linear least squares fit to the data, the average delay times were weighted according to the number of shells of each size that were included in the average. In Figure 7, it is apparent there is a significant increase in burst delay times for larger shells. This is consistent with what is necessary to support the proposed muzzle break hypothesis.

**Table 5. Aerial Shell Burst Delay Times.**

| Shell Size | | | Average Delay Time |
|---|---|---|---|
| mm | (in.) | Burst Delay Time (ms) / Manufacturer | ms |
| 76 | (3) | 30/S, 32/S, 36/Y, 41/S, 48/T, 76/H, 122/T | 43(a) |
| 102 | (4) | 21/S, 44/Y, 50/R, 51/H, 53/R, 78/T, 81/S, 104/R | 54(b) |
| 127 | (5) | 26/S, 40/S, 59/O, 62/R, 73/T | 52 |
| 155 | (6) | 54/H, 55/S, 77/T, 82/F, 89/T | 71 |
| 205 | (8) | 52/Y, 96/Y, 329/H | 74(c) |
| 255 | (10) | 134/O | 134 |

(a) The burst delay time of 122 ms was not included in the average.
(b) The burst delay time of 104 ms was not included in the average.
(c) The burst delay time of 329 ms was not included in the average.

## Discussion

The trends in both the shell exit time and burst delay time data are consistent with the hypothesis presented as a possible explanation for muzzle breaks. However, there are two time related matters that need to be examined more closely. Figure 8 is a graph of the least squares fits to the data presented in Figures 4 and 7. According to the hypothesis presented, muzzle breaks occur when aerial shells (whose contents become ignited by a fire leak or from inertial setback) exit the mortar before they have time to explode. Recognize that the two lines in Figure 8 only represent average times as a function of shell size and that individual shell exit times and burst delay times vary widely about these averages. Figure 8 correctly predicts that muzzle breaks are more likely for large shells. However, it incorrectly predicts that, for most in-mortar shell ignitions, the shell will exit the mortar before it explodes (i.e., it incorrectly predicts that muzzle breaks are more likely than flowerpots). For example, the average exit time for a 127-mm (5-in.) shell is about 40 ms and the average burst delay time is about 50 ms. Accordingly, for shells fired and ignited internally as in these tests, a typical 127-mm (5-in.) shell will have left the mortar about 10 ms before it explodes as a muzzle break (50 – 40 = 10).

The apparent inconsistency identified in the last paragraph must be dealt with; however, before doing so, consider the following additional problem. An internal ignition of an aerial shell, either as a result of small fire leak or inertial setback, will not occur until the pressure in the mortar has risen significantly above atmospheric pressure. Without significant mortar pressure, burning gases will not be forced into tiny crevices or holes in shell casings, or glue seals around time fuses. Without significant mortar pressure, the shell will not be accelerating and there will not be a setback effect. Note in Figure 3 that the first indication of mortar pressure rise does not happen until at least half the time has passed between electric match ignition and the shell exits the mortar. This just serves to exacerbate the apparent timing inconsistency mentioned in the last paragraph. The fire that eventually causes the shell to explode is not introduced at the same time as the electric match fires in the lift, but rather, only after about half the shell exit time has elapsed. Accordingly, for the typical 127-mm (5-in.) shell, with an exit time of about 40 ms and a burst delay time of about 50 ms, the times do not start together. The 50 ms burst delay time does not start until the mortar pressure begins to rise about half way through the shell firing process. Thus, for shells fired and ignited internally using the method of these tests, the shell will have exited the mortar 30 ms before it explodes (50 – 40/2 = 30). If this is correct, then the question should be, why do not essentially all in-mortar internal shell ignitions result in muzzle breaks, almost to the exclusion of flowerpots?

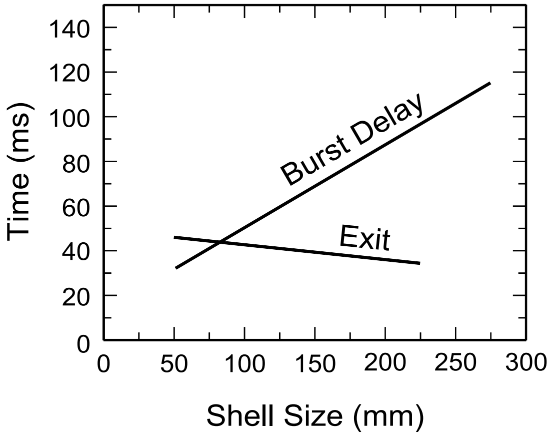

*Figure 8. Average mortar exit and burst delay times as a function of shell size.*

The discussion that follows is supposition, in that no supporting data was collected. Hopefully, however, the discussion is based on a combination of well established pyrotechnic principals and logic. For pyrotechnic material, the rate of flame spread depends on the level of ignition stimulus. Accordingly, a powerful ignition stimulus, such as a small explosive charge, is expected to cause more rapid flame spread through a pyrotechnic composition than would ignition of the same material from contact with a hot wire. When the contents of an aerial shell are ignited, and if the rate of flame spread is high, material will be ignited more quickly, producing gaseous combustion products more quickly, and bursting the shell sooner. Accordingly, it would be expected that aerial shell burst delay times are dependent on the level of ignition stimulus used, with shorter delay times expected for more powerful stimuli.

Consider the following scale of ignition stimuli. On the weak stimulus end is ignition as a result of a pair of stars in a shell rubbing together during setback. On the strong stimulus end is ignition caused by the time fuse pushing into the shell, opening a large hole and allowing the entrance of a large amount of burning lift gas. The ignition of an electric match produces a significant flame and radiating sparks. (The Davey Bickford product brochure[11] illustrates the output of an electric match.) On the above crude ignition stimulus scale, the ignition stimulus provided by an electric match, must be somewhere near the middle. Accordingly, it would be expected that the possible sources of ignition of the contents of aerial shells within mortar would result in average burst delay times both longer and shorter than those observed in this study using electric matches.

During the firing of an aerial shell, any ignition stimulus, equal to or weaker than that of an electric match, would be expected to almost exclusively produce muzzle breaks. This is because such ignition stimuli should result in burst delay times equal to or longer than those reported in this study, which are already long enough to produce mostly muzzle breaks. It is only those ignition stimuli that are significantly stronger than that produced by an electric match that would be expected to produce flowerpots.

## Conclusions

1) It is somewhat surprising that: mortar pressure does not begin to rise significantly until about half the shell exit time has elapsed; and large aerial shells appear to have shorter exit times than small shells.
2) Since flowerpots greatly out number muzzle breaks, this study suggests that most causes of in-mortar ignition of the contents of aerials shells must be produced by powerful ignition stimuli. This would include, catastrophic shell casing failure as might be caused by too weakly constructed shells or by shells that jam inside the mortar. Another possibility is that time fuses are being removed because they have been pushed into shells by high pressure lift gases, or that they are perhaps pulled loose as a result of spherical shells rotating while traveling up the mortar. Still another possibility is that the powder in the time fuse is loose and allows the high pressure lift gases to blow through, directly into the shell.
3) On average, any weak ignition stimulus, such as ignition caused by inertial setback, is expected to only produce muzzle breaks, not flowerpots.
4) The range of mortar exit times for sets of identical shells is surprisingly wide. Typically the longest time is two to three times the shortest time. This suggests that the dynamics of flame spread and combustion are highly variable from shell firing to shell firing.
5) Significantly longer average exit times were observed for the two low ambient temperature data sets and for the first shell fired in each data set. This is consistent with temperature effects observed by others.[10] Further, this suggests that muzzle breaks may be statistically more likely during manually fired displays when there are repeat firings from the same mortar during a display.
6) The range of shell burst delay times for shells from a variety of manufacturers is surprisingly wide. Typically the longest time is two to three times the shortest. However, on occasion, the longest is five or six times the shortest. In part this is probably due to differences in the pyrotechnic materials and the construction techniques used. However, as in Conclusion 4, it is likely this is also the result of significant variability in the dynamics of flame spread and combustion.
7) Further studies should be performed to confirm these data and to better identify the causes of muzzle breaks and flowerpots. Some additional work is planned by the authors; specifically, examining the effect of greater and lesser ignition stimulus on shell burst delay times. However, others are encouraged to input to the discussion of these results and to conduct additional studies.

## Acknowledgments

The authors wish to acknowledge the assistance of Gary Fadorsen (Pyrotech International) for construction of the muzzle velocity timing apparatus.

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# Basics of Hazard Management

K.L. and B.J. Kosanke, and C. Jennings-White

The consequences of accidents can be devastating to those immediately involved and their relatives. However, the ramifications of accidents can extend much further. This is illustrated in what Richard Green (Idaho National Engineering Laboratory)[1] has described as "The Four Horsemen of Our Own Apocalypse", specifically:

> ACCIDENTS, INJURIES, LITIGATION, and LEGISLATION.

In effect, this is a chain in which Accidents produce Injuries, which often result in Litigation, the notoriety from which helps generate pressure for more restrictive regulation (Legislation). With this view, it is accidents involving individuals that produce increased regulation, or at least provide an excuse for increased regulation. Because regulations not only affect those individuals having accidents, but also the fireworks community as a whole, the whole community has a stake in eliminating fireworks accidents. It is the hope of the authors that this article will contribute by stimulating thought and discussion of some basic Hazard Management concepts.

Obviously there are potential hazards associated with the manufacture and use of fireworks. It is through the techniques of "Hazard Management" that the goal of "Safety" is achieved. Thus, perhaps the place to begin is to look at the definition of safety. The dictionary will generally say *something is safe if it involves no risk of mishap, error, etc*. However, by this definition, there is no activity engaged in by people that is safe, because there is always some risk of mishap or error in literally every activity undertaken by people. For example:

| Activity | Possible Mishap |
|---|---|
| Eating | Choking on food |
| Walking | Stumbling and spraining ankle |
| Sitting in a chair | Being struck by a meteor from outer space |

Thus perhaps a better definition for safety is that *"something is safe when the (attendant) risks are below an acceptable level."*[2] This is the definition used in Hazard Management and is the one used in this article.

There are three elements in the Hazard Management Process:

> RECOGNITION, EVALUATION, and CONTROL.

Recognition is simply the identification of possible or potential hazards. In pyrotechnic manufacturing, in addition to all of the normal industrial hazards, there are those hazards related to accidental ignition and to chemical toxicity. For displays there are the hazards associated with malfunctioning fireworks and people doing foolish things (e.g., body parts over loaded mortars; spectator encroachment, etc.). For consumer fireworks there are the hazards from misuse of fireworks and from defective items. In a formalized Hazard Management Process, in the Recognition phase, one would simply make a list of all potential hazards.

Having identified potential hazards, the next step is to evaluate each hazard for its "Attendant Risk". For each potential hazard, risk evaluation involves two factors "Consequences" and "Probability". To illustrate the way in which consequence and probability combine to determine risk, consider the following examples:

- Activity – Jumping off a roof to see if you can fly.
- Consequence – Severe (personal crash landing).
- Probability – High.

    ➡ Risk — Unacceptable (Unsafe)

Because the consequence of a negative result to the activity is severe and the probability of that outcome is high, most people correctly conclude the activity has an unacceptable risk. As another example, consider:

- Activity – Swimming in the ocean.
- Consequence – Severe (being eaten by a shark).
- Probability – Very low.
  - ➡ Risk — Acceptable (Safe)

While the consequence of a negative result is at least as severe as in the first example, the probability of that happening is quite low. Thus, most people correctly conclude that swimming in the ocean has an acceptable risk and is reasonably safe. As a final example, consider:

- Activity – Flipping a coin to decide which movie to see.
- Consequence – Trivial (watching the poorer movie).
- Probability – Relatively high (50%).
  - ➡ Risk — Acceptable (Safe)

Here, even though the probability of a negative result is high, most people would decide this activity is acceptable because the associated consequence is trivial. The risk associated with an activity can be acceptable if either the consequence of a negative result is sufficiently trivial or if the probability of getting the negative result is sufficiently low. Of course, the safest activities are those for which both the consequences are trivial and the probability is low.

Having made a list of potential hazards, in the evaluation phase, the severity of potential consequences and their probabilities of occurring must be established. In the most cursory hazard management program this could simply be to highlight those activities having either at least a moderately severe consequence OR at least a modest probability of occurrence. These activities would be candidates for attention. Certainly any hazard having both at least a moderately severe consequence AND at least a modest probability of occurrence will necessarily need to be controlled.

It is possible to take a more quantitative approach to evaluating and ranking hazards. This might be done by defining relative hazard consequence and probability scales. Each of these scales could range from zero to five. Here zero on the consequence scale might correspond to accidents that produce no injury or economic loss (trivial consequence). On the probability scale, accidents that could essentially never happen (near zero probability) might be assigned a zero. On the other end of the scales, five's would be accidents that produce life-threatening injuries (consequence scale) and accidents that happen frequently (probability scale). With such a methodology, each potential hazard would be assigned an appropriate consequence scale value and probability scale value. Then a relative attendant risk value could be calculated by multiplying the consequence and probability scale values together. After this has been done for each identifiable potential hazard, one would have attendant risk values that range from 0 to 25. Hazards with risk values of zero (and perhaps one and two) might be mostly ignored. However, all hazards with high attendant risk values would require serious attention, with the activities producing the highest risk values given the highest priority for immediate control measures.

Control of hazards with unacceptable risks can either take the form of severity of consequence reduction, probability of occurrence reduction, or preferably both consequence and probability reduction.

In pyrotechnic manufacturing, to reduce the consequences of an accidental ignition:

- Expose as few people (or as little property as possible) to any accident.
  - = Separate individual hazardous work areas using barriers or distance.
  - = Use the minimum number of people in each hazardous work area.
  - = Do not mix hazardous and non-hazardous work (workers) in any area.
- Minimize the amount of exposed pyrotechnic material in each work area.
  - = Draw relatively small quantities of raw materials from bulk storage areas.
  - = Remove completed items frequently.
  - = Keep pyrotechnic materials covered.
  - = Store excess materials in day boxes.

- Employ personnel protection strategies.
  - = Use safety shields and operate remotely.
  - = Provide easy, short and direct exits from work areas.
  - = Use personal safety equipment.
  - = Never work completely alone.

To reduce the probability of an accidental ignition:

- Avoid the input of energy to pyrotechnic materials.
  - = No smoking, open flames or high temperature surfaces.
  - = Never scrape dried composition.
  - = Press slowly, do not ram with hammer blows.
  - = Pick up, do not slide, containers to move them.
  - = Eliminate, or cover, hard or sparking tools and surfaces.
  - = Control electrostatic buildup and discharge.
- Consider the potential for problems with the chemistry of pyrotechnic materials.
  - = Learn and avoid sensitive chemical combinations.
  - = Keep work areas and tools clean to avoid chemical contamination.
  - = Monitor for signs of heating or chemical reactions.
  - = When appropriate, use non-aqueous binders.
- Address personnel issues relating to accidents.
  - = Do not work when tired or distracted.
  - = Think and plan activities in advance.
  - = Do not improvise.

In pyrotechnic manufacturing, the importance of minimizing the risk of accidental ignition is obvious. However, the risk of toxic hazards is sometimes given too little attention. For a chemical agent to produce a harmful effect, it must enter the body through ingestion, inhalation, or absorption into or through the skin. The response to toxic hazards typically fall into one of two categories: acute or chronic. An acute response is generally a relatively immediate reaction to exposure to a chemical toxin; and, assuming survival, the response is normally of limited duration. For example, the diarrhea produced by barium poisoning will occur within a few hours of exposure and will persist for a couple of days at most. This is in strong contrast to a chronic response, which may only manifest itself after a prolonged delay and persists indefinitely. For example, the cancer that may result from the use of some smoke dyes may not develop until decades after the initial exposure and may progress with fatal consequences. The control of toxic hazards should follow the same basic strategy described above. Efforts should be made to minimize probability and consequences of exposure. We have prepared a Safety Rating System for Pyro-Chemicals, based on the J.T. Baker, Inc. system. Anyone may obtain a copy of this list of chemicals with Health, Flammability, Reactivity and Contact Hazard Ratings by sending a self-addressed, stamped envelope to K. L. Kosanke, 1775 Blair Road, Whitewater, CO 81527. [A copy is included at the end of this article.]

The hazard management process discussed above for fireworks manufacturing can be applied to fireworks displays and even to the use of consumer fireworks. These will not be discussed in detail here; however, a few examples are given below as illustrations:

Fireworks Displays:

- Consequence minimization:
  - = The crew's use of personal safety equipment.
  - = Spectators kept at NFPA separation distances.
- Probability minimization:
  - = Performing shell inspections shortly before use.
  - = Keep ready box covered and up wind.

Consumer Fireworks:

- Consequence minimization:
    - = Provide complete user directions like "Do not light with body over fireworks."
    - = Do not store inventory in massive amounts at one location.
- Probability minimization:
    - = Do not sell items that have a history of malfunction or misuse.
    - = Use only low temperature sealing methods for assortment packs.

It is difficult to over estimate the human and economic cost of a serious accident. Many hazard management measures are cheap and easy to implement; obviously these should be applied immediately. Others may be expensive to implement, especially if modification of an existing facility is required. For these, a cost benefit analysis may be necessary, and these may require more time before being fully implemented.

## References

1) R. Green, "Booms, Bangs and Debris: A Rocketeer's Primer on Safety", Idaho PGI Convention, 1992.

2) W.W. Lowrance, *Of Acceptable Risk*, William Kaufmann, Inc., 1976.

## SAFETY RATING SYSTEM FOR PYRO-CHEMICALS

0 = None,
1 = Slight,
2 = Moderate,
3 = Severe, and
4 = Extreme.

The safety ratings are given for four areas of hazard concern:

H = Health is danger or toxic effect a substance presents if inhaled, ingested, or absorbed,

F = Flammability is the tendency of the substance to burn,

R = Reactivity is the potential of a substance to explode or react violently with air, water or other substances, and

C = Contact is the danger a substance presents when exposed to skin, eyes, and mucous membranes.

| **Description** | **H** | **F** | **R** | **C** |
|---|---|---|---|---|
| Accroides Resin (red gum) | 1 | 2 | 0 | 1 |
| Acetone (nitrocellulose solvent) | 1 | 3 | 2 | 1 |
| Aluminum (400 mesh flake) | 1 | 4 | 2 | 1 |
| Aluminum (325 mesh, granular) | 1 | 3 | 2 | 1 |
| Ammonium Dichromate | 4 | 1 | 3 | 3 |
| Ammonium Nitrate | 1 | 0 | 3 | 2 |
| Ammonium Perchlorate | 1 | 0 | 3 | 2 |
| Anthracene | 1 | 1 | 0 | 1 |
| Antimony Trisulfide (325 mesh) | 3 | 3 | 2 | 1 |
| Barium Carbonate | 1 | 0 | 0 | 1 |
| Barium Chlorate | 3 | 0 | 3 | 1 |
| Barium Nitrate | 3 | 0 | 3 | 1 |
| Barium Sulfate | 1 | 0 | 0 | 0 |
| Benzene | 4 | 3 | 2 | 1 |
| Boric Acid | 2 | 0 | 0 | 2 |
| Cab-o-sil (colloidal silica) | 2 | 0 | 0 | 1 |
| Calcium Carbonate | 0 | 0 | 0 | 1 |
| Calcium Sulfate | 1 | 0 | 0 | 1 |
| Charcoal (80 mesh) | 0 | 1 | 0 | 1 |
| Charcoal (air float) | 0 | 2 | 0 | 1 |
| Chlorowax | 2 | 1 | 1 | 1 |
| Clay (bentonite, very fine powder) | 1 | 0 | 0 | 0 |
| CMC (sodium carboxymethyl-cellulose) | 1 | 1 | 1 | 1 |
| Copper (II) Carbonate (basic) | 2 | 0 | 0 | 1 |
| Copper (II) Oxide (black, cupric) | 2 | 0 | 0 | 1 |
| Copper Oxychloride | 2 | 0 | 0 | 1 |
| Copper (II) Sulfate (cupric) | 2 | 0 | 0 | 2 |
| Cryolite | 1 | 0 | 0 | 1 |
| Dechlorane | 2 | 1 | 1 | 2 |
| Dextrin (yellow) | 0 | 1 | 0 | 0 |

| **Description** | **H** | **F** | **R** | **C** |
|---|---|---|---|---|
| Gallic Acid, Monohydrate | 1 | 1 | 0 | 1 |
| Graphite (325 mesh) | 1 | 2 | 0 | 0 |
| Hexachlorobenzene (HCB) | 2 | 1 | 1 | 1 |
| Hexachloroethane (HCE) | 2 | 1 | 1 | 1 |
| Hexamine (hexamethylenetetraamine) | 1 | 1 | 1 | 1 |
| Hydrochloric Acid (Concentrated) | 3 | 0 | 2 | 3 |
| Iodine, Sublimed | 3 | 0 | 2 | 3 |
| Iron (II) Oxide (black) | 1 | 0 | 1 | 1 |
| Iron (III) Oxide (red) | 1 | 0 | 1 | 1 |
| Isopropanol (isopropyl alcohol) | 1 | 3 | 1 | 1 |
| Lactose | 0 | 1 | 1 | 0 |
| Lampblack (oil free) | 1 | 2 | 0 | 1 |
| Lead, Granular | 3 | 0 | 0 | 1 |
| Lead Dioxide | 3 | 0 | 3 | 1 |
| Lead Nitrate | 3 | 0 | 3 | 1 |
| Lead Oxide (red, minium) | 3 | 0 | 1 | 1 |
| Magnesium (200 mesh) | 1 | 3 | 2 | 0 |
| Magnesium (325 mesh) | 1 | 4 | 2 | 0 |
| Magnesium Alum. 50/50 (gran., 100–200 m.) | 1 | 3 | 2 | 1 |
| Magnesium Alum. 50/50 (gran., 200–400 m.) | 1 | 4 | 2 | 1 |
| Magnesium Carbonate | 1 | 0 | 1 | 0 |
| Manganese Dioxide | 1 | 0 | 1 | 1 |
| Methanol (methyl alcohol) | 3 | 3 | 1 | 1 |
| Methylene Chloride | 3 | 1 | 1 | 2 |
| Mineral Oil | 1 | 1 | 0 | 1 |
| Nitric Acid (Concentrated) | 3 | 0 | 3 | 4 |
| Nitrocellulose (lacquer 10% solution) | 1 | 3 | 2 | 1 |
| Paraffin Oil | 1 | 1 | 0 | 1 |

| Description | H | F | R | C |
|---|---|---|---|---|
| Parlon (chlorinated natural rubber) | 2 | 1 | 1 | 1 |
| Phosphorous, Red | 0 | 2 | 2 | 2 |
| Picric Acid, Crystal | 2 | 2 | 2 | 2 |
| Polyvinyl Chloride (PVC) | 2 | 1 | 1 | 1 |
| Potassium, Lump | 3 | 3 | 3 | 4 |
| Potassium Bicarbonate | 1 | 0 | 1 | 0 |
| Potassium Chlorate | 1 | 0 | 3 | 2 |
| Potassium Dichromate (fine granular) | 4 | 0 | 3 | 3 |
| Potassium Hydroxide, Pellets | 3 | 0 | 2 | 4 |
| Potassium Nitrate | 1 | 0 | 3 | 2 |
| Potassium Perchlorate | 1 | 0 | 3 | 2 |
| Potassium Permanganate | 2 | 0 | 3 | 2 |
| Potassium Sulfate | 1 | 0 | 0 | 0 |
| PVC (polyvinyl chloride) | 2 | 1 | 1 | 1 |
| Red Gum (accaroides resin) | 1 | 2 | 0 | 1 |
| Shellac (–120 mesh, orange) | 1 | 2 | 0 | 1 |
| Silica (fumed-colloidal, Cabosil) | 2 | 0 | 0 | 1 |
| Silica Gel (60–200 mesh) | 2 | 0 | 0 | 1 |
| Silicon Metal Powder (325 mesh) | 2 | 3 | 1 | 1 |
| Silver Nitrate, Crystal | 3 | 0 | 3 | 3 |
| Smoke Dye | 1 | 1 | 1 | 2 |
| Sodium, Lump | 3 | 3 | 3 | 4 |
| Sodium Azide | 3 | 2 | 3 | 2 |
| Sodium Benzoate | 1 | 1 | 0 | 1 |
| Sodium Bicarbonate | 0 | 0 | 1 | 1 |
| Sodium Carboxymethylcellulose (CMC) | 1 | 1 | 1 | 1 |
| Sodium Chlorate, Crystal | 1 | 0 | 3 | 1 |

| Description | H | F | R | C |
|---|---|---|---|---|
| Sodium Cyanide, Granular | 3 | 0 | 2 | 3 |
| Sodium Hydroxide, Pellets | 3 | 0 | 2 | 4 |
| Sodium Nitrate | 1 | 0 | 3 | 1 |
| Sodium Oxalate | 3 | 0 | 1 | 2 |
| Sodium Salicylate | 1 | 1 | 0 | 1 |
| Sodium Silicate (water glass, liquid) | 1 | 0 | 0 | 2 |
| Sodium Sulfate | 0 | 0 | 0 | 1 |
| Starch, Soluble Potato | 0 | 1 | 0 | 1 |
| Stearic Acid | 1 | 1 | 1 | 1 |
| Strontium Carbonate | 1 | 0 | 0 | 1 |
| Strontium Nitrate | 1 | 0 | 3 | 1 |
| Strontium Sulfate | 1 | 0 | 0 | 1 |
| Sulfur (flour) | 1 | 1 | 0 | 1 |
| Sulfuric Acid (Concentrated) | 3 | 0 | 3 | 4 |
| Talc, Powder | 1 | 0 | 0 | 1 |
| Tetrachloroethane | 3 | 0 | 1 | 2 |
| Tin, Granular (20 mesh) | 0 | 0 | 0 | 1 |
| Titanium Metal Powder (100 mesh) | 1 | 3 | 2 | 1 |
| Titanium Metal Powder (300 mesh) | 1 | 4 | 2 | 1 |
| Titanium Tetrachloride | 3 | 0 | 2 | 3 |
| Trichloroethylene (Stabilized) | 3 | 1 | 2 | 2 |
| Water | 0 | 0 | 1 | 0 |
| Zinc Metal Powder (dust) | 1 | 3 | 2 | 1 |
| Zinc Oxide | 4 | 0 | 3 | 3 |

# Other Publications Available from the Journal of Pyrotechnics, Inc.

## *Pyrotechnic Literature Series*

### *Selected Pyrotechnic Publications of K. L. & B. J. Kosanke, Parts 1–5*

Currently there are five books that are collections of articles that originally appeared in a variety of pyrotechnic publications.

### *Selected Pyrotechnic Publications of Dr. Takeo Shimizu*

#### *Part 1 (1985 to 1994) from the International Pyrotechnic Seminars*

A collection of previously published papers that appeared in the Proceedings of the International Pyrotechnics Seminars from 1985 to 1994.

#### *Part 2. Translated Articles*

A collection of previously published technical papers that appeared in various publications between 1978 and 1995. These articles were translated into English.

#### *Part 3. Studies on Colored Flame Compositions of Fireworks*

A series of seven articles that originally appeared in the Journal of Industrial Explosives from 1958 to 1959. The articles were translated from Japanese by Dr. Shimizu.

## *Pyrotechnic Reference Series*

### *Illustrated Dictionary of Pyrotechnics*

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

The Illustrated Dictionary of Pyrotechnics is 130 pages in length, with a durable binding. There are more than 1200 entries, 130 figures and illustrations, and 50 short tables. It includes scientific and craft terms from fireworks, explosives, rocketry and pyrotechnic special effects.

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

### *Lecture Notes for Pyrotechnic Chemistry*

Lecture Notes for Pyrotechnic Chemistry are the class notes for a three-day course on Pyrotechnic Chemistry. The Course Notes assume only minimal levels of understanding of Chemistry and Pyrotechnics. Each 8½×11" page contains a pair of viewgraphs from the course lectures. The over 400 viewgraphs include many illustrations and tables. Each viewgraph of text is complete enough for the reader to be able to understand the subject being discussed.

### *Lecture Notes for Fireworks Display Practices*

The Lecture Notes for Fireworks Display Practices are the set of class notes from a week-long course on practical and safety aspects of performing fireworks displays. Each 8½×11" page contains a pair of viewgraphs from the course lectures. The 385 viewgraphs include many photographs and tables. Each viewgraph of text is complete enough for the reader to understand the subject being discussed.

## *Journal of Pyrotechnics*

Issues of the Journal of Pyrotechnics appear twice a year and now contain approximately 75 pages. Areas of pyrotechnics addressed include fireworks, pyrotechnic special effects, propellants & rocketry, and civilian pyrotechnics. The Journal is "dedicated to the advancement of pyrotechnics through the sharing of information". This is accomplished with a mix of different types of articles; however, most will fall into two areas. One area is reports on research conducted by both professional scientists and individual experimenters. The other area is reviews of various technical and craft areas of pyrotechnics, some at an advanced level and others at a tutorial level.

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