

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

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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.

# The Physics, Chemistry and Perception of Colored Flames

## Part I

K. L. Kosanke

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### SUMMARY

*The first part of this three-part monograph presents an in-depth examination of the development of light theory; mechanisms of light generation in flames; atomic line, molecular band and continuous spectra; the definition, laws and measurement of color; chromaticity diagrams and how the pyrotechnist can use this knowledge of physics in planning colored flame formulations of optimal purity.*

### 1.0 Preface

In my examination of pyrotechnic literature, I have not been able to find a comprehensive discussion of the physics, chemistry and perception of colored flames, let alone one that could be understood by the average fireworks enthusiast. The standard texts such as Davis (1943), Weingart (1947), Ellern (1968) and Lancaster (1972) treat the subject of color at the most cursory level. Technical reports prepared for the military usually deal with a very narrow aspect of the subject and the reader often must have an advanced knowledge of chemistry to understand them. In none of the pyrotechnic literature is the psychology and physiology of color perception considered. In light of some aspects of E. Land's recent theory of color perception, Land (1974), this may be a most serious omission. In writing this three part monograph, I hope to supply the general pyrotechnic community with a comprehensive discussion of the physics, chemistry and perception of colored flames.

I have attempted to write at a level such that most interested people will be able to follow the discussion, at least at a general level, and many will be able to understand the material in some detail. That is to say, quantum electrodynamics, nonequilibrium thermodynamics and molecular

biology have been kept to an absolute minimum, if not eliminated altogether. I have often substituted analogy, semi-classical explanations, and a little hand waving in place of perfectly rigorous science. In doing this, I have been careful not to distort the science being discussed, but only to make the subject more understandable. I have included numerous drawings, notes and equations as figures. I hope the result is complete, accurate, useful, understandable, and may possibly even makes enjoyable reading.

### 2.0 Introduction

Many of the concepts discussed in this paper are not particularly easy to understand or to work with. It is reasonable to wonder why you should bother to read it and what you will get out of it. The answer is slightly different depending on your scientific background and on what type of pyrotechnist you are. I will assume your scientific background is limited. If you are the cookbook type, and enjoy trying formulations developed by others, you may expect to gain a better understanding of the art you are practicing. I suspect this better understanding will be satisfying and self-rewarding, but will not bear much tangible fruit. If you are an experimenter, developing your own color formulations, a fuller understanding of the physical principles involved should allow you to move faster toward successful conclusions in your development efforts. For example, you will know why and how chlorine donors are important in achieving good strontium reds, but are detrimental to lithium reds. Thus, if you were attempting to develop a good lithium carbonate red, you probably would not waste much time trying to find the best chlorine donor or how to use.

The material presented in this paper is organized along the lines suggested in the title. The first part discusses the physics of colored flame production, including the nature of light, the processes through which light is generated, and the definition and measurement of color. This material is more important than it may at first appear. While it is relatively easy to interest pyrotechnists in the chemistry of colored flame production, chemistry is just the mechanism we use to accomplish the physics of colored light production. Without understanding physically what colored light is, how it originates, and the classical laws of additive color mixing, a discussion of chemistry would be of very limited value. For example, a discussion of the chemistry of ionization buffering would not be very useful or very interesting, unless you understood the physical reason why it can be important in generating intensely colored flames.

The second part of this paper discusses the chemistry of colored flame production, including a brief discussion of some general chemistry, the origin of chemically produced light, the effect of flame temperature and the role of color enhancers.

The last part of this paper discusses the psychology and physiology of color perception, including the classical theory of color perception and the potentially profound implications of Land's theory as it relates to color in fireworks. I suspect that most pyrotechnists, trying to improve their color effects, are spending their time working in the wrong area. They are working hard to squeeze the last little bit of improved color out of the chemistry and physics. I am convinced they would get a better return on their efforts if they studied and worked with the perception of color. I suspect that the most significant advance in pyrotechnics in this half century will not be the introduction of titanium or magnesium/aluminum alloys, but rather achievements resulting from improved understanding of color perception and work like that of T. Shimizu (1976, chapter 15) on the psycho-perception of fireworks.

## 3.0 The Physics of Colored Flames

### 3.1 The Nature of Light

The nature of light is one of the most important concepts presented in this paper. I will use an historical discussion of the evolution of the current theory of light to develop a comprehensive understanding of the nature of light.

#### 3.1.1 Early Theories of Light

Before the seventeenth century, light was generally believed to consist of streams of tiny particles, or corpuscles, traveling between the source of the light and your eye. According to this corpuscular theory of light, the way you saw things was by light corpuscles bouncing off objects and traveling to your eye. Being particles, light corpuscles must travel in straight lines unless acted on by outside forces, such as gravity. However, beginning in the mid-seventeenth century, experiments began to reveal properties of light that could not be easily explained using this corpuscular theory of light. In one type of experiment, it was noticed that beams of light often experience refraction (i.e., they are bent) upon passing between two different materials, for example, on passing between air and water (as in Figure 1). In other experiments it was discovered that light also experiences diffraction (i.e., it bends slightly around corners, as in Figure 2). These properties of light were most difficult to explain using the corpuscular theory of light. The light corpuscles were being bent out of their straight paths, yet there were no known forces acting on them. If, however, light were a wave motion, much like

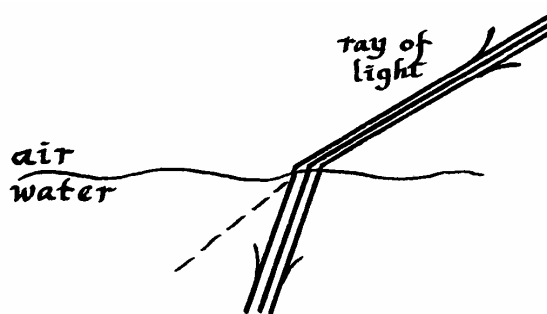


Figure 1. Refraction.



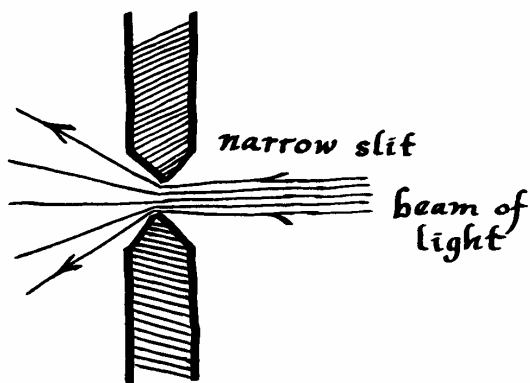


Figure 2. Diffraction.

water waves, then the properties of refraction and diffraction would not only be allowed, they would be expected. Thus the wave theory gradually replaced the earlier corpuscular theory.

The wave theory looked pretty good for about 200 years, until near the end of the nineteenth century. The wave theory still served to explain all the properties of light concerned with its propagation from place to place. However, there were newly observed properties concerned with the ways in which light was emitted and absorbed that could not be explained if light consisted of simple waves. The first hint of a problem came when physicists attempted to explain the spectrum (i.e., the amount of light of various wavelengths) given off by a black body (i.e., a perfect radiator and absorber of heat energy). When such a black body is heated to a high temperature, it begins to glow, giving off visible light. When that light was analyzed in a precise manner, the experimental results simply did not agree with those predicted by theory (see Figure 3). Even after adjusting and readjusting the theory, it failed to explain the results. While this was worrisome, most scientists thought that the differences could be worked out within the wave theory.

The death blow for the wave theory (and what won Einstein a Nobel Prize) was the explanation of the photoelectric effect. It had been observed that under certain circumstances, electrons were emitted from the surfaces of metals when light shone on them (as in Figure 4). Unfortunately, those circumstances were not consistent with what would have been expected from

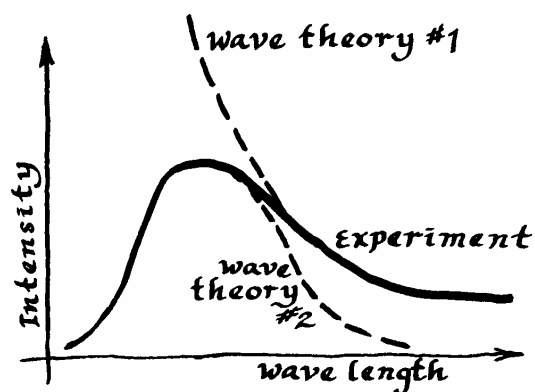


Figure 3. Black Body Spectrum.

the wave theory. It was observed that: 1) for all frequencies of light below a certain threshold, no electrons were emitted no matter how intense the source of light was made; 2) as soon as this frequency threshold was exceeded, electrons were emitted instantly, even if the light source was of very low intensity; 3) above this frequency threshold, varying the intensity of the light source only affected the number of electrons emitted and not the energy carried off by them; 4) after allowing for the energy necessary to liberate the electrons, the energy carried off by them was proportional to the frequency of the light source. Some of these observations are illustrated in Figure 5.

In the wave theory the amount of energy carried by a light wave was proportional to its intensity or amplitude (see Figure 6 for a graphic representation of some properties of waves). Thus if a certain amount of energy were required to liberate electrons from a metal surface, according to the wave theory, all that should have been necessary would be to increase the intensity of any source of light until electrons

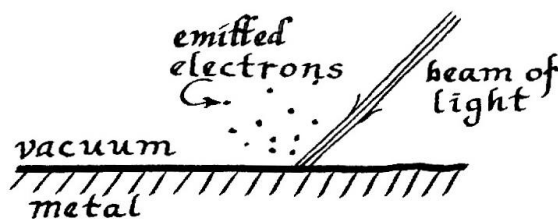


Figure 4. Photoelectric Effect.

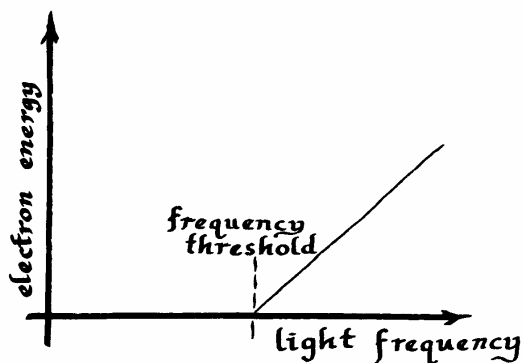


Figure 5. Photoelectron energy.

were emitted. This is contrary to what was observed. Also, the energy carried off by the electrons should have been proportional to the intensity of the light source and not to the frequency. The experiments with the photoelectric effect yielded results so far from those allowed by the wave theory that major adjustments had to be made to the theory of light.

### 3.1.2 Quantum Theory of Light

All the observations regarding the photoelectric effect are consistent with light being little packages of energy, and with the energy of each packet being proportional to frequency. If this were the case, the frequency threshold would represent the amount of energy necessary to free an electron from a metal's surface. If the frequency of light is less than this, none of the light packets have the required energy. If the frequency exceeds the threshold, then each of the light packets has sufficient energy to eject an electron and some liberated electrons should be observed even if the number of light packets (i.e., light intensity) were low. The intensity of the light source would affect the number of electrons emitted and the frequency would affect the amount of energy carried off by the electrons.

All this was consistent with experiments and might sound fine, but doesn't the idea of light packets sound a lot like light corpuscles? Well, it should, but with a new twist: remember, these packets now have a frequency, and therefore a wave length associated with them. What we have is something like a cross between a particle and a wave. That is to say, these light pack-

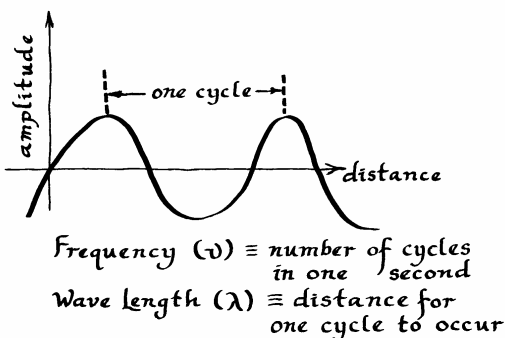


Figure 6. Waves.

ets have some properties that are wave-like (they have a frequency and wave length) and some that are particle-like (they exist as discrete entities with discrete energies). What we have is the quantum theory of light (see Figure 7), in which: 1) light is emitted and absorbed as if it consisted of discrete entities, now called "photons"; 2) light is propagated from place to place as if it consisted of waves of a definite frequency and wave length; 3) photons carry amounts of energy that are proportional to their frequency. Quantum theory is the current theory of light and is the basis for our understanding of the atom as well. (NOTE: In the remainder of this text, photons are described rather indiscriminately, using their energy, frequency, or wave length. This is acceptable because their energy, frequency and wave length are uniquely related using the equations in Figure 8. After specifying any of the three properties, the others can always be calculated.)

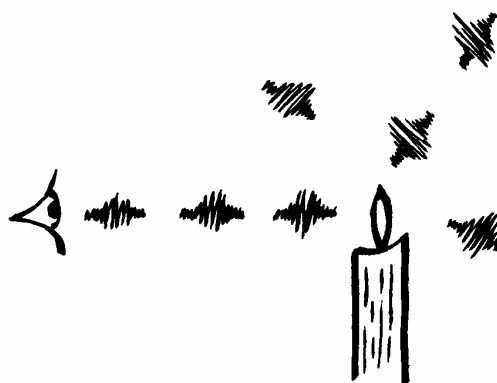


Figure 7. Quantum Theory.

$$E = h\nu \approx \frac{hc}{\lambda}$$

$E \equiv$  energy                       $C \equiv$  speed of light  
 $h \equiv$  a constant                 $\lambda \equiv$  wave length  
 $\nu \equiv$  frequency

Figure 8. Energy of Photons.

### 3.1.3 Definition of Light

Up to this point, we have not been very specific about our definition of light. The reason was largely one of convenience. Now that quantum theory and general nature of light have been introduced, it is time to be more specific. Among non-scientists, light is generally considered to be only that to which our eyes respond. So one possible definition of light is: those photons of the necessary wave length (or energy, or frequency) to invoke visual sensations. However, most people also know about invisible light as well, infra-red and ultra-violet light. Infra-red photons are longer wave length (less energetic) than visible photons and ultra-violet photons are shorter wave length (more energetic) than visible photons. There are no fundamental differences between infra-red, visible and ultra-violet photons; they just have different wave lengths, and wave lengths are continuous (i.e., there are no wave length gaps between what we call infra-red, visible and ultraviolet photons). Then should our definition of light be made to include infra-red and ultra-violet photons?

The world is full of photons with wave lengths longer than infra-red (micro-waves and radio-waves are examples) as well as photons with wave lengths shorter than ultra-violet (X-rays and gamma rays are examples), see Figure 9. All these photons are fundamentally the same, and we would be justified in calling them all by the same name. However, for the purposes of this paper, we shall define light as only those packets of wave energy (photons) that are usually termed infra-red, visible and ultra-violet light.

## 3.2 The Mechanism of Light Generation in Flames

Quantum theory is basic to our current understanding of physics for other reasons than its explanation of the nature of light. It plays a central role in almost every area of physics. In particular, it is necessary to have an understanding of quantum theory in order to be able to explain the mechanism through which light is generated.

### 3.2.1 More Quantum Theory

One of the major tenets of quantum theory is that "all bound systems are quantized". Bound systems are those that are constrained to stick together in some manner. Some examples of bound systems are electrons whirling about an atom, the moon orbiting the Earth, and a weight swinging at the end of a string. In each case there is some force that holds the system together, electrostatic forces between electrons and the nucleus of an atom, gravity between the Earth and moon, and tension in the string attached to the weight. Quantum theory tells us that each of these bound systems is "quantized". That is, these systems can only have certain allowed amounts of energy; they cannot have just *any* amount. Thus, the range of energy values for bound systems is not continuous; only specifically allowed amounts of energy are

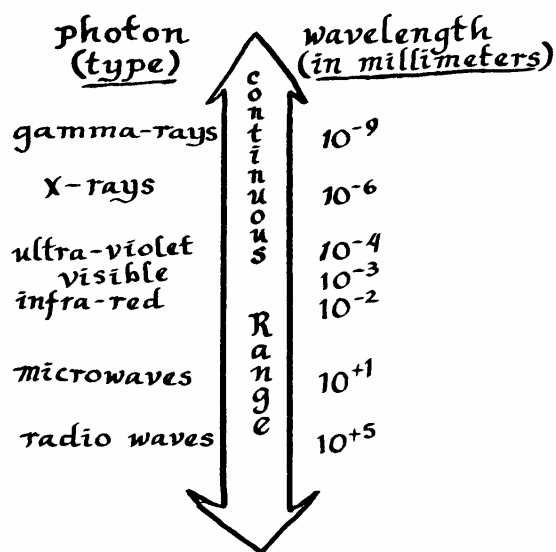


Figure 9. Continuous Range of Photons.

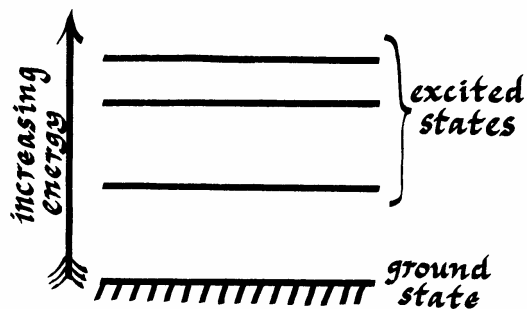


Figure 10. Energy Level Diagram.

possible. It's a little like climbing a ladder: you can stand on any rung you wish, but you can't stand half way in between two rungs. If you try, you will fall to the next lower rung. It is the same way with these bound systems; each can have any of a number of allowed energies but none of the energies in between.

When a bound system has one of these allowed energies, it is said to exist in a particular "energy level". Energy levels are often described using energy level diagrams like the one in Figure 10. The lowest energy level is called the ground state and those with higher energies are called excited states. The system being described in the energy level diagram can have energies corresponding to any of the allowed states but is forbidden to have any of those energies in between. If we try to give the system one of the forbidden energies, the system will accept only enough energy to reach the next lowest allowed state. Bound systems also prefer to exist in the lowest possible energy states. If a system is given enough energy to reach a highly excited state, it will usually give up that energy, dropping to lower energy states.

When systems gain or lose energy, this is called an "energy transition". In energy level diagrams, energy transitions are shown as arrows between the energy levels involved. Figure 11 is the graphic representation of a bound system, originally in an excited state, losing energy through two energy transitions, dropping to the ground state. Note that it is not necessary for the system to pass through each intermediate energy state during an energy transition. In the case of the second transition in Figure 11, the system passes from the second ex-

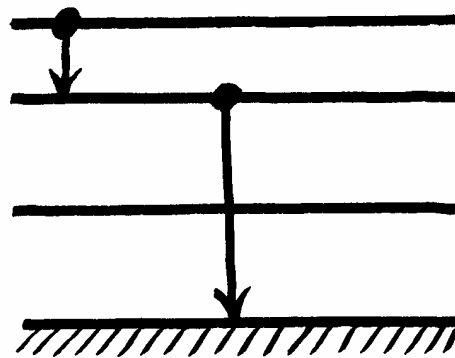


Figure 11. Energy Transitions.

cited state directly to the ground state, without passing through the first excited state.

We have been talking about systems that have "energy"; but just how does that energy manifest itself? The energy can be in the form of motion within the system as in a whirling fan blade (kinetic energy) and it can be in the form of stored energy as in a compressed spring (potential energy).

Consider an example from pyrotechnics, that of a simple wheel as shown in Figure 12. The wheel is a bound system because it is constrained from flying apart by the stick connecting its two drivers. If quantum theory is correct, then the energy of this system must be quantized and can have only certain allowed values. In the case of a wheel, its energy is in the form

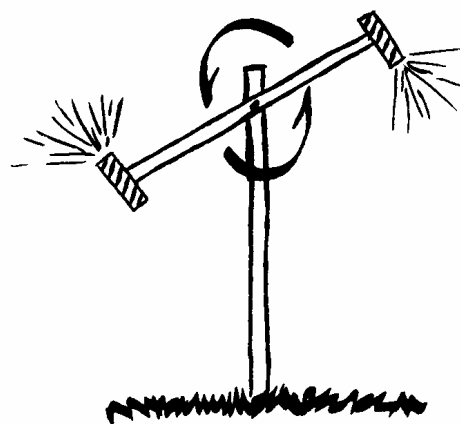


Figure 12. Pinwheel.

of its spinning motion. Thus quantum theory predicts that only certain allowed rates of spinning are possible and that spin rates in between are not possible. This seems to contradict what we observe. In our everyday experience, it appears that the wheel can be made to spin at whatever rate we wish and that the rate of spinning varies continuously, not in steps. Is this observation reconcilable with what we know about quantum theory? Yes it is. It is not that the allowed energies and the steps between them don't exist: it is just that for objects as large as a wheel, the allowed energies are so very close together that we can't observe the steps even with our most sensitive instruments. For example, if the pin-wheel were stationary and a single particle of dust happened to fall on one of the arms, this dust particle supplies the pinwheel with a billion, billion, billion times the energy necessary to step up to the first allowed rate of spin. It's no wonder we can't observe the spin rate steps predicted by quantum theory.

Why bother with quantum theory if you can never hope to observe its effects on those objects in the world about us; why spend time trying to understand it? Well, in the sub-microscopic world of atoms and molecules, the steps between allowed energy levels can be enormous, and quantum effects are *very* observable. It is in this sub-microscopic world that light is generated. In order to understand and work effectively with light generating processes in pyrotechnics, it is necessary to have a general understanding of quantum theory.

### 3.2.2 Atomic Line Spectra

Now consider a more relevant example, that of an atom of hydrogen, Figure 13. The hydrogen atom has a nucleus consisting of a single proton with a positive charge. About this proton is a single orbiting electron with a negative charge. The electron is constrained to orbit the nucleus by electrostatic forces of attraction resulting between opposite charges. Thus the atom of hydrogen is a bound system and its energy states will be quantized. If left alone, the electron in a hydrogen atom resides in the lowest or ground state. As energy is supplied to the atom, the electron can occupy higher excited states, moving to orbits that are farther from the

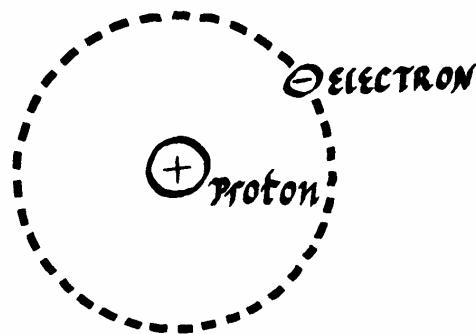


Figure 13. Hydrogen Atom

nucleus. In pyrotechnics, this energy would usually be supplied by chemical reactions in a flame. To give an idea just how large a step exists between hydrogen's ground and first excited states, it would take a flame temperature approximately twice as great as that generated in a typical pyrotechnic flame to supply the energy for this transition. Unlike the fireworks wheel example, quantum effects in the hydrogen atom cannot be ignored!

If a hydrogen atom had been energized to its first excited state, it could absorb additional energy with its electron moving to the second or even higher excited states. The energy required for this second transition is less than that required for the transition from ground to first excited state. However, it is more likely that the hydrogen atom will experience a transition back to its ground state. When this happens, the extra energy will usually be carried off in the form of a light photon. In the energy level diagram of Figure 14, the light photon emitted as the atom decays back to its ground state, is shown as a wavy arrow to the side. The energy of this photon is equal to the energy difference between the two energy levels involved in the transition, i.e., energy is conserved.

If the hydrogen atom above had absorbed additional energy in a transition to its second excited state, it would have been faced with some alternatives regarding its transition back to the ground state. The transition could go directly to the ground state emitting a single higher energy photon, or it could be a two step process, passing through the first excited state, emitting two photons (see Figure 15).

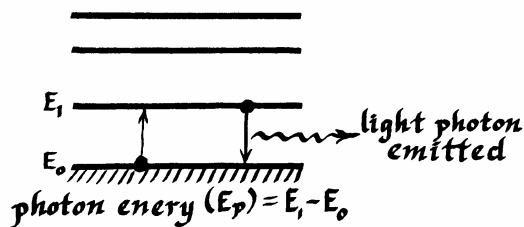


Figure 14. Atomic Light Generation.

With the exception that the energies between allowed energy levels are greater, the example of hydrogen is typical of the first type of light production in pyrotechnics. Atoms absorb energy from a flame, causing electrons to occupy excited states; then the electrons drop back to their ground states generating light photons in the process. In each case, the energy of an emitted photon is exactly equal to the energy difference between the energy levels involved in the transition.

The energy levels of all atoms of a given chemical element have exactly the same set of precise energies. Thus, if a sample containing a large number of atoms of the same chemical element is excited sufficiently for electron transitions to occur, photons will be emitted, but only with certain specific energies. If a graph is made of the number of photons emitted with different energies (see Figure 16), it will be observed that at most energies, zero photons are emitted. Only at a relatively small number of energies are photons observed. These photon energies correspond to the differences between allowed energy states for atoms of that chemical element. Had a different chemical element been used, the graph would appear similar; however, the energies at which photons are observed would be different. These graphs are representations of light spectra emitted by atoms and are usually referred to as "atomic line spectra". They are called line spectra because all of the photons emitted by that chemical element have one of a set of very precise energies, giving the appearance of lines in the graph.

If the excited atoms emit some photons with energies that fall in the range of visible light, then an observer could see the emissions (provided they are intense enough). If these photon

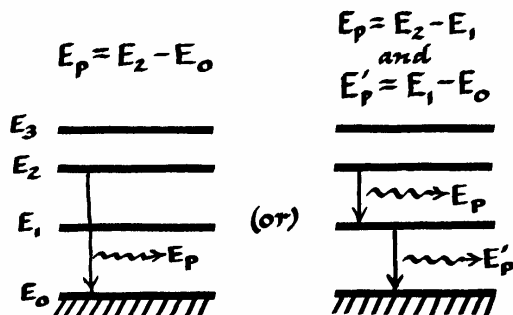


Figure 15. Atomic Transitions.

energies fall predominately in one part of the visible light spectrum, the emitted light appears colored.

The subject of colored light from atoms will be taken up again in the portion of this paper discussing chemistry. However, most useful sources of colored flame in pyrotechnics originate from molecules, not from atoms. It is therefore necessary to continue our discussion of quantum theory with a look at molecules.

### 3.2.3 Molecular Band Spectra

Molecules, like atoms, can be excited and experience electron transitions that result in photon emission. While the mechanism is the same, there is an important difference in the spectrum of photons emitted. The energies of emitted photons in atomic spectra have relatively few values giving rise to lines in the spec-

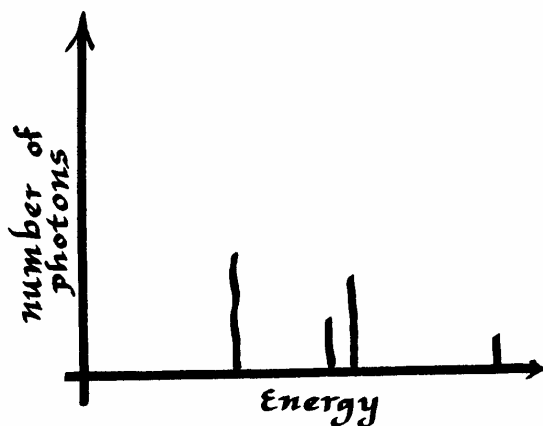


Figure 16. Atomic Line Spectra.

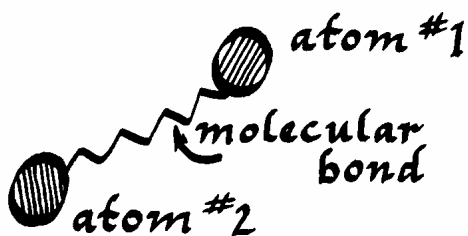


Figure 17. Simple Molecule.

tra; in molecular spectra, the energies of emitted photons have numerous values that cluster in groups giving rise to bands in the spectra.

Like the lines in an atomic spectrum, the bands in a molecular spectrum can be understood from quantum theory. Consider a simple molecule consisting of two atoms bound together. In addition to the electrons being bound to the atoms, the atoms are bound to each other in an arrangement that looks somewhat like the fireworks wheel discussed earlier (Figure 17). Like the wheel, the molecules can rotate. However, unlike the wheel with a rigid framework, the molecule is flexible; it can also bend and stretch, giving rise to vibrations as shown in Figure 18. Because the molecule is a bound system, these rotations and vibrations are quantized and can only take on certain allowed amounts of energy. The molecule can vibrate (or rotate) a little and be in a low energy state, or it can vibrate more vigorously and be in a higher energy state.

Just as an energy level diagram can be drawn showing electron levels, energy level diagrams can also be drawn showing rotational and vibrational levels. However, the spacing between vibrational energy levels is much less than that between electron levels, and the spacing between rotational energy levels is even less than that between vibrational levels.

Like an atom, a molecule must always be in one of its set of allowed electron energy states, the ground state or one of its excited states. In addition, a molecule must also be in one of its set of allowed vibrational states and in one of its set of allowed rotational states. However, the molecule can have any combination of its allowed electron, vibrational and rotational states. The energy of the molecule is the sum of its

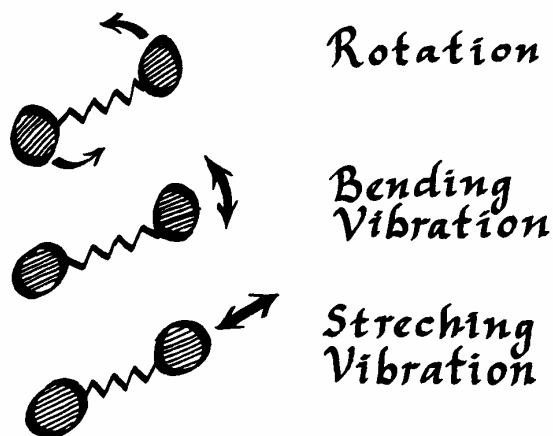


Figure 18. Molecular Motions.

electron energy, plus its vibrational energy, plus its rotational energy. Thus an energy level diagram for a molecule will still have ground and excited electron states with spacings similar to those in an atom, see Figure 19-a. However, independent of its electron energy state, the molecule can exist in any number of vibrational states. Accordingly, added to each electron state in the level diagram will be a set of vibrational levels, each with slightly different energies. Figure 19-b is an attempt to show an exploded view of one electron level, Note that the electron level is broken into a number of closely spaced vibrational levels. Similarly added to each vibrational level is a set of rotational levels. Figure 19-c is an exploded view of a single vibrational level, Note that the vibrational level is further broken down into a set of rotational levels. The net effect is to have groups of very closely spaced energy levels, each group start-

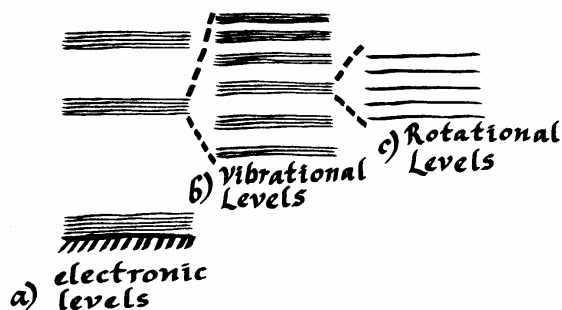


Figure 19. Molecular Energy Levels.

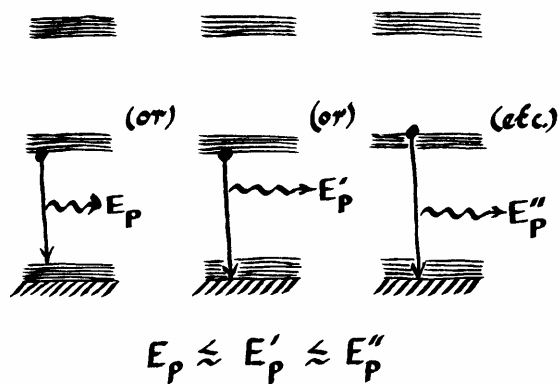


Figure 20. Molecular Transitions.

ing at the energy of an electron level.

When a molecule receives energy and is excited, it can occupy any of the levels in one of these closely spaced groups. Similarly, when the molecule loses energy in a transition back to a lower energy state, the molecule can again occupy any of a large number of energy levels, see Figure 20. The energy of photons given off during such a transition to a lower energy state is still equal to the energy difference between starting and final states. However, because there are numerous, slightly different starting and final energy levels possible for this transition, a very large number of photon energies, differing only very slightly from each other, will be observed. The result is that molecules have band spectra (see Figure 21), while atoms have line spectra.

Just like atomic spectra, if the photon emissions from molecules fall in the range of visible light, they can be seen by an observer. If the emissions fall predominantly in one portion of the visible range, they will appear colored.

### 3.2.4 Continuous Spectra

In their relation to fireworks, the two light generating mechanisms discussed so far have the desirable characteristic of being able to produce intensely colored light. Unfortunately, there are two other light generating mechanisms that operate in flames that have a deleterious effect on color purity. This negative effect results from the generation of light photons with a continuous and wide range of energies throughout the visible spectrum. The effect of these

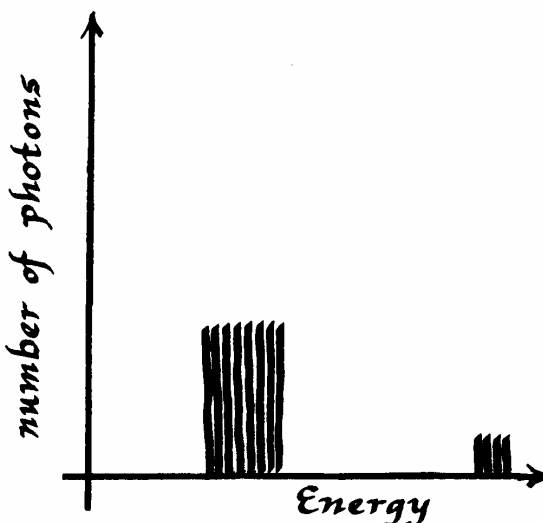


Figure 21. Molecular Band Spectra.

continuous emissions is a washing-out of flame color, possibly ruining an otherwise excellent color effect. (NOTE: A thorough discussion of color is deferred until the next section of this paper. At that time the reason for this washing-out of color will be discussed.)

The first mechanism for generating a continuous spectrum in a flame can be understood using the same energy level diagrams that were used to explain atomic and molecular spectra. When discussing the level diagram for atomic hydrogen, it was mentioned that the separation between first and second excited electron states was less than that between the ground and first excited state. Similarly, the separation between levels continues to decrease as you go higher, until the separations between electron energy levels becomes microscopic at some limiting value. This limiting value is called the "ionization energy" for the atom (or molecule). If the atom acquires enough energy for one of its electrons to exceed this ionization energy, that electron is energetic enough to escape the atom completely, see Figure 22. Ionization of an atom is roughly like a space ship breaking out of Earth orbit. The result is a free electron and an ionized (charged) atom. What was originally a bound atomic system has become unbound and as a result is no longer quantized. Thus a free electron can take on any of the continuous range of energies, shown as the cross-hatched area, in Figure 23.



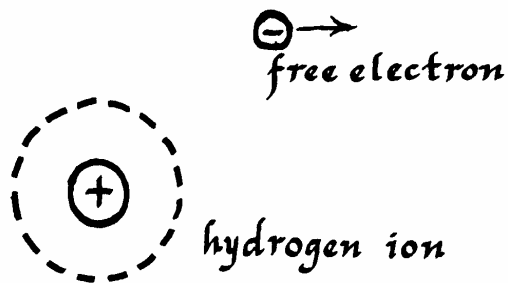


Figure 22. Ionization.

Just as atoms do not normally exist in excited electron states (the first chance they get they undergo transitions back their ground states), free electrons and ions prefer to drop to lower energy states by recombining. Upon recombination, the excess energy is again carried off in the form of photons, but with one important difference: because the free electrons and ions started off as an unbound system, they did not have precisely defined energies before their recombination. Therefore, even though the energies of photons given off will still be the difference between initial (free electron and ion) and final (atom) energies, that energy will not be unique, see Figure 24. The result is not a line or band spectrum but a continuous spectrum of photon energies.

While on the subject of ions, it is worth pointing out that ions are still bound systems for those electrons that remain orbiting the ion's

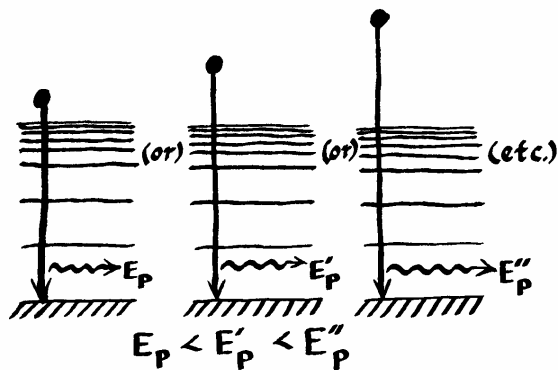


Figure 24. Ion Recombination.

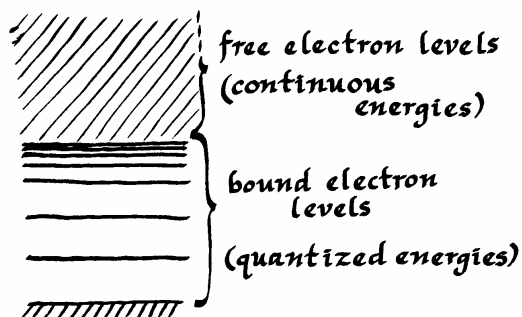


Figure 23. Free-Electron Energy Level.

nucleus. Everything that was said about atoms and molecules still applies to electron transitions within atomic and molecular ions. It is only when ions recombine with free electrons that continuous spectra result, see Figure 25.

The other mechanism by which continuous spectra are generated is incandescence. When any solid or liquid is heated to a high temperature, it will glow (remember black bodies in an earlier section). The object is seen to glow because it is emitting photons that are in the visible range. As the temperature is increased, the object glows brighter and the average energy of the emitted photons increases. In pyrotechnics, smoke particles and other non-vaporized material will incandesce in flames, producing a continuous spectrum, which can seriously wash out color.

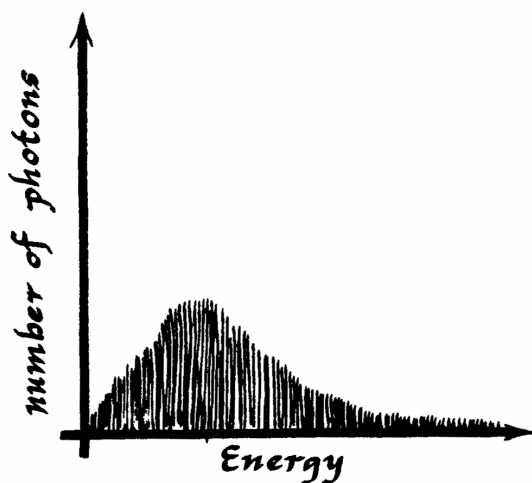


Figure 25. Continuous Spectrum.

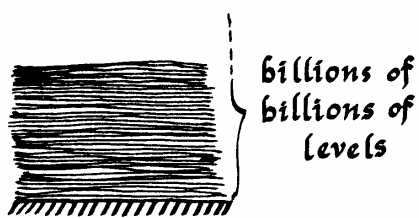


Figure 26. Smoke Energy Levels.

In order to explain the physics of incandescence it would be necessary to introduce another area of quantum theory, called solid state physics. That would be a difficult exercise for the author and reader alike. Because the details of incandescence are not a particularly important topic, solid state physics will not be introduced.

Even the very tiny particles in smoke consist of billions of atoms bound together. When this is the case, it is no longer proper to think of the atoms as individual entities in the solid. It is the solid (or liquid droplet) as a whole that quantum theory treats. The net effect of having a system containing billions of atoms is a complete smearing out of identifiable energy levels for the smoke particle. In a way it is an extreme example of what happened in the molecule above. When we went from one atom to just two atoms in a simple molecule, we caused the introduction of many additional vibrational and rotational levels. When we now consider a smoke particle with billions of atoms bound together, the result is the introduction of billions of billions of additional levels, see Figure 26. When a smoke particle is thermally excited and when there are transitions back to lower states, it can assume any of the myriad of smeared-out states. The result is that the emitted photons can have essentially any energy whatsoever, creating a continuous spectrum.

### 3.3 The Definition, Laws and Measurement of Color

In this section I will only deal with light's wave-like properties. Much of the discussion will concern the wave length of colored light sources. I will also discuss the laws of color mixing and the measurement of color. While recent theories of the perception of color may form a new basis for understanding the classical

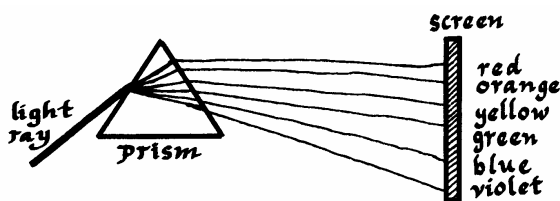


Figure 27. Newton's Observation.

treatments given in this section, the classical approach is still in general agreement with observation and will provide a useful framework from which to discuss colored flames.

#### 3.3.1 The Definition of Color

In the seventeenth century, Newton made the observation that a beam of white light falling on a prism could be made to separate into a continuous series of colors, now called the visible spectrum, see Figure 27. While he was at a loss to explain the physical basis for his observations, his work laid the foundation for understanding color, and he developed the first laws of color mixing.

The colors Newton saw in his experiments ran from violet (bent most by the prism) through blue, green, yellow and orange, to red (bent least). The colors were continuous, there were no gaps and they graded smoothly from one color to the next. If the colored light from the prism is made to fall on a strip of white material, we get a more conventional picture of the color spectrum, see Figure 28. Wiggly lines have been added to the sketch to denote the approximate limits to the various spectral colors. These wiggly lines are artificial and do not appear in a real spectrum. Wave lengths corresponding to the various colors are also included

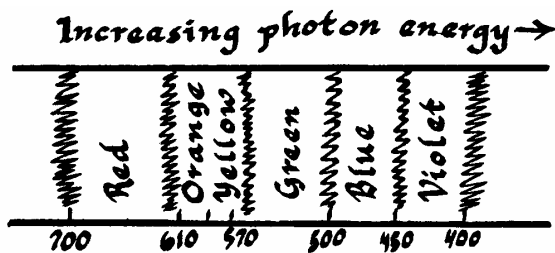


Figure 28. Visible Light Spectrum.

in the figure. The wave lengths are given in nanometers, or billionths of a meter.

It is important to understand what the prism has done. It has not changed white light into colored light; the light that originally appeared white was already a combination of the different colors. What the prism did was to cause each color component of white light to be bent a different amount when passing through it. This caused the various color components to diverge from each other and fall on different parts of the screen. There is no single energy of light photons that will appear white to an observer. Whenever we see something as white, it is because our eyes are receiving the proper combination of colored light to be mentally interpreted as white.

Beyond the short wave length limit of violet and the long wave length of red, Newton observed the spectrum to fall dark. These are the ultra-violet and infrared regions of the light spectrum. It is not that light photons do not fall in these dark regions; it is just that our eyes are not sensitive to light of these wave lengths.

For purposes of this paper, color shall be defined as “those visual sensations produced when viewing any combination of light sources having wave lengths in the visible region of the spectrum”. As such, color is a psychological reaction to a visual stimulus and only exists in the mind of the viewer. This subjective definition was chosen rather than a precise physical definition, because it is possible to produce most color sensations in many different ways, using different combinations of different wave length light. Accordingly, most colors are *not* uniquely quantifiable in the sense of being able to characterize color on a “*unique*” set of physical properties.

The above definition of color must seem rather unsatisfactory. Be patient—the reason for this imprecise definition will become clearer after discussing chromaticity diagrams and the laws of additive color mixing later in this section.

### 3.3.2 Flame Spectra Seen Using a Prism

Newton’s prism was a rudimentary form of today’s visible light spectroscopy, which can be used to analyze a source of colored light by separating it into its color components. It might

be useful to consider what atomic, molecular and continuous spectra would look like with such a spectroscopy. In order to do this effectively, and also tie the discussion to what was presented earlier when discussing quantum theory, it is necessary to make a very important distinction: all photons have definite measurable energies. If they have a single energy that falls in the visible range, they can be seen by an observer and will appear colored. The color they appear depends on their energy. Low energy, visible photons produce a color sensation of red; high energy visible photons produce the color sensation of violet. Photons with energies in between will produce the color sensation corresponding to one of the other colors Newton saw using his prism. These colors are called “spectral colors” and they are special colors, special because for them there is a unique relationship between color and photon energy. However, spectral colors represent only a tiny fraction of all possible colors. For the majority of color sensations, those produced when viewing a combination of different energy photons at the same time, there is no unique relationship between color and photon energy. This is because for all colors that are not spectral colors, the same exact color sensation can be created using an infinite number of combinations of different energy light photons.

Let me summarize that part of what I just said that is important for this section of the discussion. For spectral colors, those special color sensations produced by photons all having the same energy, a unique relationship exists between color and photon energy.

If the light coming from an atomic light source were made to pass into the spectroscopy, photons with different energies (colors) would be separated. If they were projected onto a screen, they would appear as a series of colored lines separated by dark spaces. Figure 29 is an example of what might appear on the screen. Each colored line corresponds to one of the energy lines in the graph in Figure 16. In Figure 16, the length of the line was used to indicate the intensity of that energy photon. In Figure 29, each of the colored lines is equally long, and the intensity of each color line is determined directly by observing its brightness.

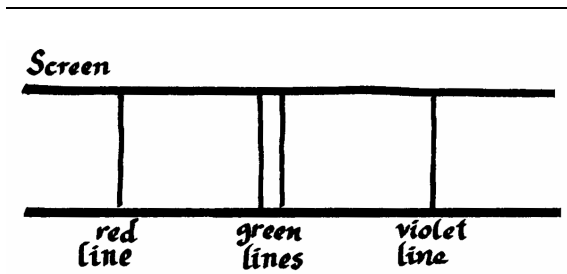


Figure 29. Atomic Line Spectra.

Figure 30 is an example of what might appear if we were observing a molecular source of light. In this case the spectroscopy would produce bands of color with dark regions in between. These colored bands correspond to the bands graphed in Figure 21. If we were to observe an incandescent light source, emitting a continuous spectrum, the spectroscopy would produce something like the visible light spectrum of Figure 28; various colors of light would fall throughout much or all of the color spectrum and there would be no gaps between any of the colors present.

### 3.3.3 Chromaticity Diagrams

Newton found that it was possible to generate a very large number of new colors, including white, by blending sources of the spectral colors: red, green and blue. In order to deal efficiently with this subject of composite colors, it was necessary to find some way of quantifying observations. An obvious possibility was to use a three dimensional graph (this page is a two dimensional surface). The approach would be to represent the colors produced in such a manner on a three dimensional graph in which each of the three axes corresponded to the intensity of one of the three primary colors. If this were done, each of the colors produced would correspond to a point in this three dimensional color space.

Fortunately, a much simpler, two dimensional method was developed to represent spectral and composite colors. This was made possible by the observation that if the brightness of all three primary light sources were varied proportionately, e.g., if the intensities of each source were doubled, then the composite color remains unchanged except for its brightness, which is also doubled. Thus, it is only the frac-

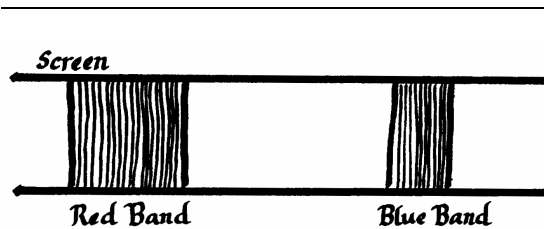


Figure 30. Molecular Band Spectrum.

tional intensity of the three primary colors that determines the composite color. In addition, it is only necessary to specify two of these fractions to completely describe the mixture. For example if a composite color is made using red, green and blue light sources, and you are told that  $1/3$  red and  $1/3$  green light has been used, then because the total must equal one, obviously the amount of blue light being used must also be  $1/3$ . A convenient method to represent color is just to specify two of the three primary color fractions, and this can be done using a graph in just two dimensions. When color fractions are plotted for all colors, the result is what is commonly referred to as a “chromaticity diagram”, see Figure 31.

All possible composite colors fall inside the tongue-shaped color region of the chromaticity diagram. The pure spectral colors fall on the curved line surrounding the composite color region. Spectral wave lengths (in billionths of a meter, called nanometers) have been included for some of the color points along this spectral color line. The colors listed in the chromaticity diagram of Figure 31 are those that a typical observer of the composite colors would call them. The colors grade gradually from one to the next. The lines separating each of the colors have been added as a convenience and serve to indicate the approximate boundary at which our typical observer begins to call the colors by some other name.

The shape and orientation of the color region depend on the choice of three primary colors. If negative fractions of the primary colors are allowed, e.g.,  $3/4$ ,  $3/4$  and  $-1/2$ ) then almost any three different colors make satisfactory primaries. In fact, even if we choose the spectral colors of red, green and blue, it is not possible to make all of the other colors without occasionally using negative amounts of the primary col-

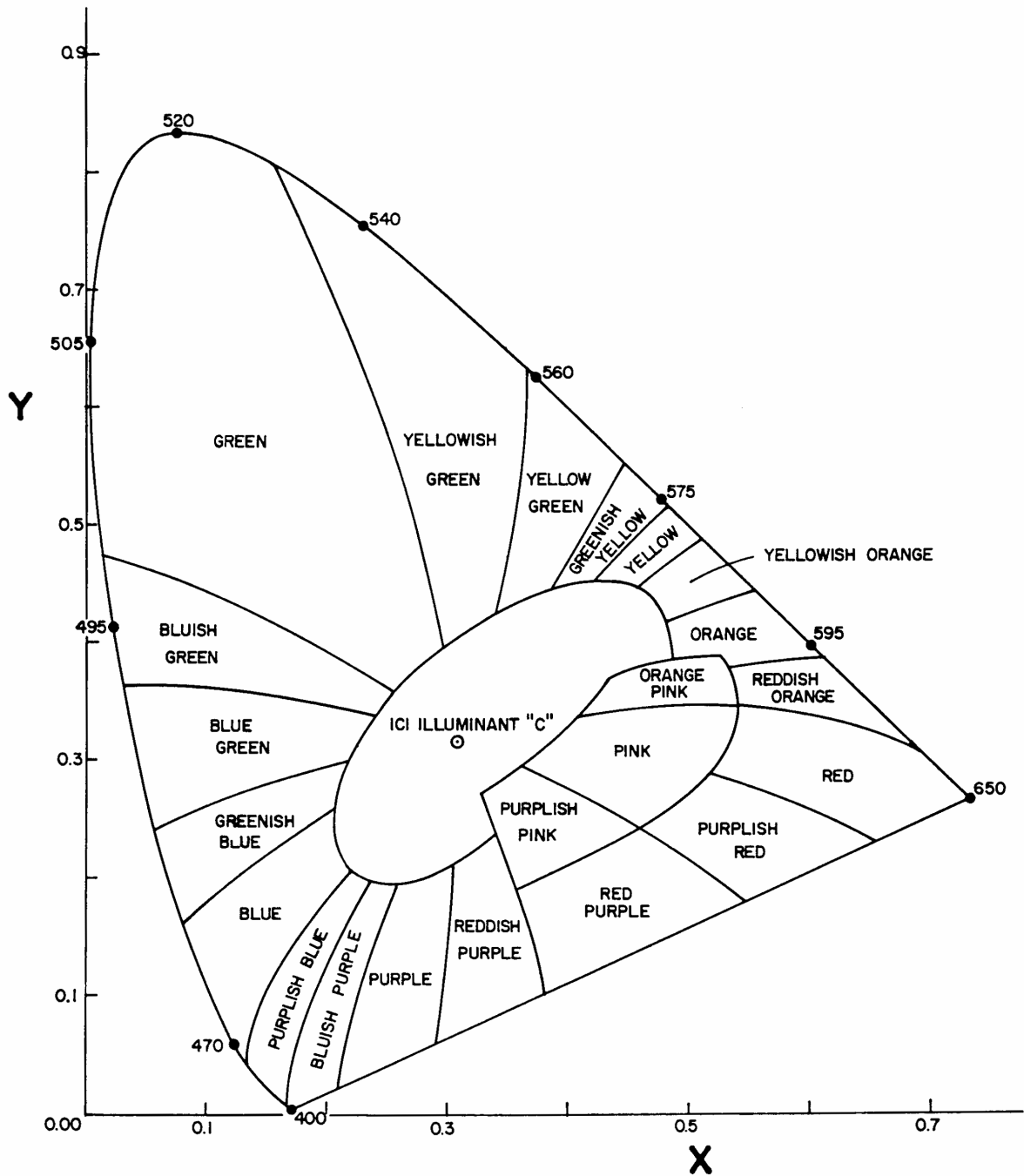


Figure 31. Chromaticity Diagram.

ors. On a mathematical level this is okay, but it is confusing conceptually. How can you use less of a primary color than none at all? That is what a negative amount represents.

In order to eliminate the necessity of negative color fractions and to standardize diagrams, an international commission on illumination

was assembled in 1931. Their solution was to invent three new (unreal) primary colors. Remember, chromaticity diagrams were created just to make it a little easier to deal with the subjective science of color; there is nothing sacred about chromaticity diagrams or the primary colors on which they are based. If three

slightly unreal primary colors will help to make color easier to work with, they should be allowed, providing everyone uses the same primary colors. The chromaticity diagrams in this text are based on these primary colors chosen by the 1931 International Commission on Illumination.

The point near the center of the chromaticity diagram labeled illuminant "C" is the color point for a standard light source called illuminant "C". This standard was chosen because it is a good approximation for average daylight and is now taken as the definition for white light.

### 3.3.4 The Classical Laws of Additive Color Mixing

For the most part, these laws of color mixing were derived as the result of subjective observation using people as scientific measuring instruments. Remember, color is a psychological response to a physical stimulus; it is in your mind and has no physical attributes that can be measured with scientific instruments. In effect, these color mixing laws are just a systematic expression of our everyday observation of color. As such, they have served us well. Recent work by Land (1974) has demonstrated that these simple laws are not always satisfactory. However, these laws will go a long way to help explain color in pyrotechnics and will be very useful when discussing the chemistry of colored flames in the second part of this paper. Therefore they will be discussed here in some detail. In the third part of this paper, we will look beyond these classical laws of color mixing and will discuss some of the very exciting possibilities suggested by Land's work.

As you read the material in this section, you will need to refer to the chromaticity diagrams in the figures. For simplicity in these figures, the color information has been eliminated: thus, you will probably find it necessary to occasionally refer back to Figure 31 for that information.

The first of the classical laws of color mixing simply states that *every color is represented by a definite point in the color region of the chromaticity diagram*. All of the slightly different colors we might call green will have color points falling somewhere near Point "A" in the chromaticity diagram in Figure 32. Similarly,

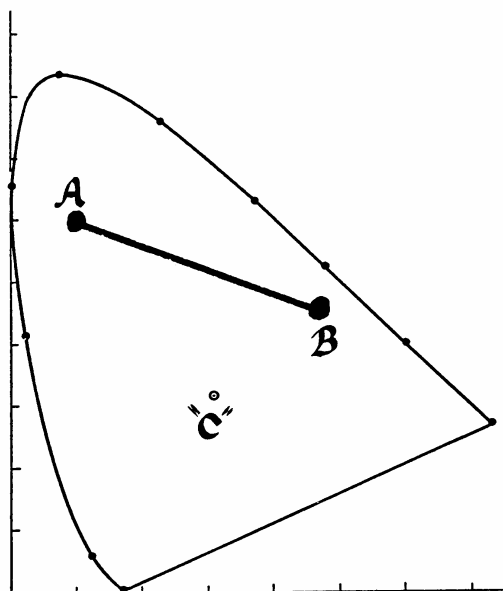


Figure 32. Color Points and Lines.

all light sources we should call yellow have color points somewhere near Point "B".

The second law of color states that *when two color light sources are added together in various proportions, the resulting color points will lie along the line connecting the original color points*. For example, if green and yellow sources of light, Points A and B, are mixed, the resulting color will always lie along the line AB. Depending on the relative amounts of green and yellow used, any color from green, through yellowish green, yellow green and greenish yellow to yellow is possible. However, none of the colors not on the line AB are possible. It is not possible to make blue or red by mixing sources of green and yellow light.

The third law states that *every color, except pure spectral colors, can be made using any of a large number of combinations of color sources, and that those composite colors will appear indistinguishable to an observer*. For example, if it were desired to make white light (illuminant "C"), one possibility would be to mix bluish-green (color Point D in Figure 33) and pink light (color Point E). By varying the relative proportions of the two colors, all the colors along the line DE can be made. Observe that the color point for illuminant "C" falls on this line. Thus white light can be made, using sources of bluish

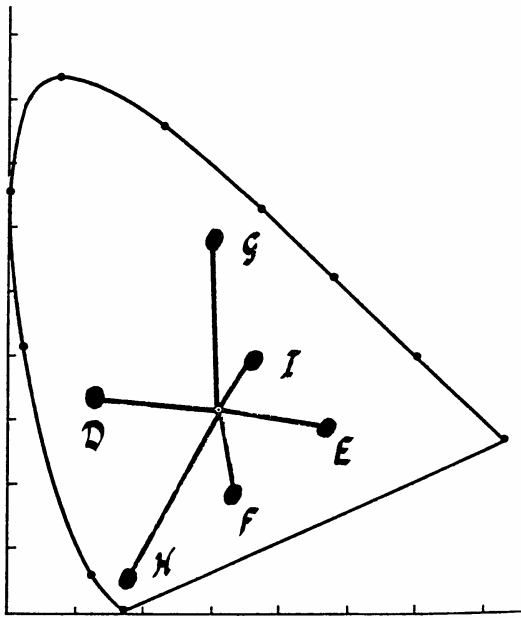


Figure 33. Color Combinations Producing White Light.

green and pink light in the correct proportions. Other possibilities are to mix yellowish green and reddish purple (line FG) or purplish blue and greenish yellow (line HI) in the proper proportions. In fact, the number of possibilities is infinite. If observers, using only their eyes, compared the standard light source, illuminant "C", to each of the three composite sources just described, they would be unable to discern any difference.

As an extension of the third law, if an additional source of colored light is added to a number of different composite sources, each producing the same color point, then the final color points resulting from the combinations will all fall at the same place in the chromaticity diagram and each will appear identical in color. From the illuminant "C" example above, if a source of red light were added to each of the three composite sources resulting in color points at illuminant "C", in every case, the result would be the exact same shade of pink.

Using the laws of color mixing, it is now possible to demonstrate why the spectral colors red, green and blue can be used in combinations to make most, but not all, of the other colors. To do this, first consider a source of spectral

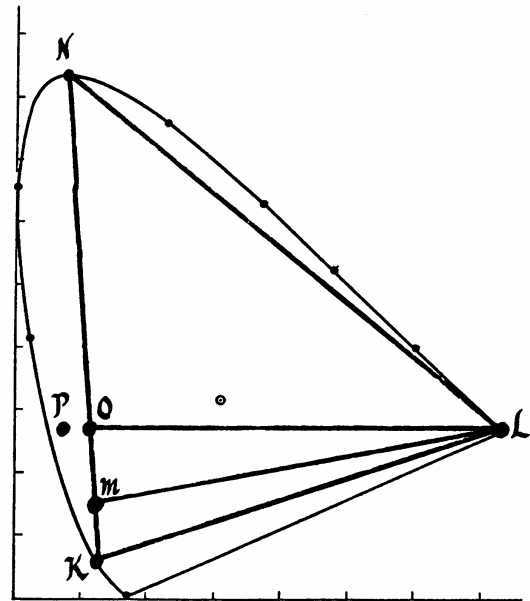


Figure 34. Primary Color Mixing.

blue light, color Point K in Figure 34. If spectral red (color Point L) is added to the blue, any of the colors along the line KL can be made. Next the red is "turned off". If a small amount of spectral green (color Point N) is turned on while the blue is turned down a little, the color Point M, on the line KN, can be reached. If red is again added to the green and blue combination, any of the colors along the line ML can be made. Now, if red is turned off again and a little more blue is replaced by green, color Point O can be reached. If once again red is added, any color along the line OL can be made. If this process is continued, eventually the blue light will be completely replaced with green. When this happens and red is added, any of the colors along the line NL can be made. Thus, it should be clear that all of the colors inside the triangle KNL can be made using combinations of the spectral colors red, blue and green. These colors, inside the triangle KNL, constitute most, but not all, colors in the chromaticity diagram. Consider the color at Point P. The closest you can approach it using blue and green is the color Point O. When red is added, color points along the line OL will be reached. The more red that is added, the closer the composite color points move toward the red color Point L. Thus, adding any red at all takes us farther from the desired color Point P. In order to reach Point P,

it would be necessary to add less than no red at all, i.e., a negative amount of red. From a practical standpoint, this is impossible. The color at Point P is one of those that cannot be made using spectral red, green and blue; similarly, none of the colors outside the triangle KNL can be made using these primary colors.

### 3.3.5 The Measurement of Color

The basis for the measurement of color follows from the third law of color mixing, from something I will call the principle of equivalent color. Even though there are many ways of combining colored light sources to produce the same color sensation, they are all equivalent as seen by an observer. Therefore, a precise physical description of any of those methods producing the color sensation will serve to define the color. For example, we previously described three different combinations that created the color of illuminant "C". If I precisely describe any of these methods, then I have defined the color point for illuminant "C". This process for defining (measuring) color is satisfactory, but would be improved if the method were completely standardized.

The standard method is based on the observation that most color points on the chromaticity diagram can be reached using a combination of white light (illuminant "C") and one of the spectral colors. For example, the color Point P in Figure 35 can be reached using a combination of white light and the spectral color with a wave length of 490 nanometers. If the wave length of the spectral color and the percentage of the distance along the line from illuminant "C" to the spectral color are specified, then the color point is completely defined. The wave length of the spectral light used is called the "dominant wave length". The percentage of the distance along the line is called "purity". In this example, the dominant wave length of color Point P is 490 nanometers and its purity is 85%.

This standard method of measuring color must be modified slightly if colors in the triangle CKL (Figure 35) are to be treated. These colors (sometimes called nonspectral colors) cannot be made by combining white light and one of the spectral colors. Consider the color Point Q; this color does not have a "dominant" wave length as described above. However, what

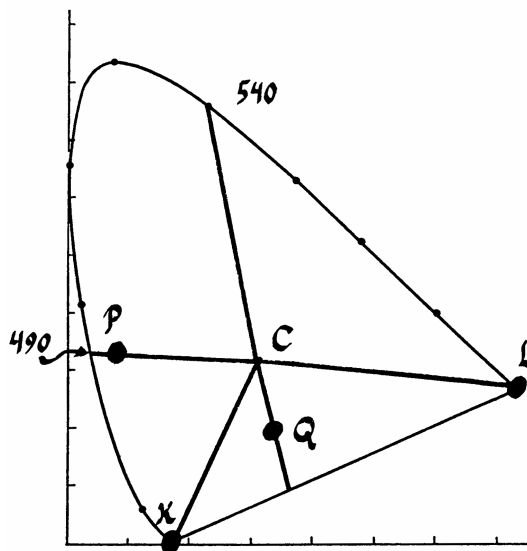


Figure 35. Measurement of Color.

is called its "complementary" wave length can be found by extending the line QC until it intersects the line of spectral colors. In this case, the color Point Q has 540 nanometers as its complementary wave length. In order to indicate that this is the color point's complementary wave length, the prefix C is added, i.e., C-540. The purity of the color is determined as above and is the length of the line CQ, expressed as a percentage of the distance from Point C to the line KL. Thus, the color at Point Q would be measured as having a dominant wave length of C-540 nanometers and a purity of 50%.

Colors are completely defined by specifying their dominant wave length and purity. However, colored light sources have another attribute that must be specified, that of brightness. The brightness of a light source is measured as luminous flux, or for the purposes of this paper, intensity. Light sources in pyrotechnics are completely described using only dominant wave length, purity and intensity. None of the other terms such as hue, saturation, chroma, etc. are necessary (or even useful) in pyrotechnics.

### 3.4 The Physics of Colored Flames, Applied

In this last section, before taking up the chemistry of colored flames, it is appropriate to apply the physics already discussed in pyrotechnics.



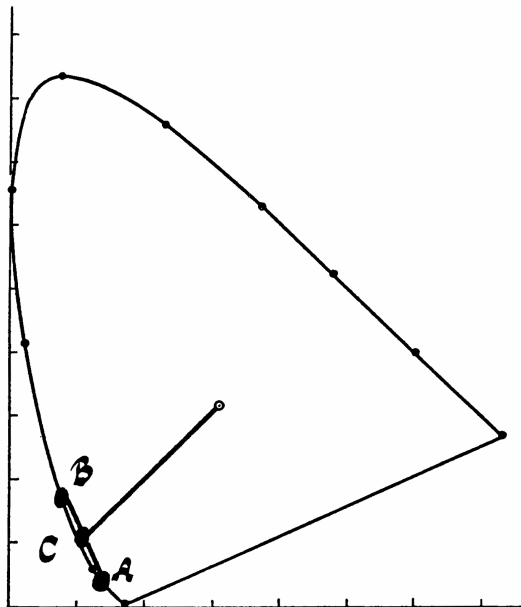


Figure 36. High Purity Example.

In an earlier section of this paper, it was said that atomic line spectra have the desirable characteristic of being able to produce deeply colored flames, and this is true. Consider the hypothetical case of atoms of some chemical element that produce spectra with only one spectral line falling in the visible region. In this case the color point corresponding to electronic transitions in this atom will fall somewhere along the outer edge of the color region of the chromaticity diagram. This spectral color, by definition, has a purity of 100%. If this is the only light source in the flame, the flame will be very deeply colored. The particular color generated will depend on the wave length (energy) of the spectral line. In this example, our spectral line, Point A in the chromaticity diagram in Figure 36, has the dominant wave length of 450 nanometers. Unfortunately, there are two things wrong with this hypothetical case. First, I do not know of any atoms that have only one spectral line falling in the visible region. Second, in a pyrotechnic flame, there will be many different atomic species present, each contributing their own spectral lines.

Let us examine the effect these added spectral lines have on our hypothetical colored flame with 100% purity. We shall start by adding just one additional spectral line, color Point B in Figure 36. This second spectral line has a dominant

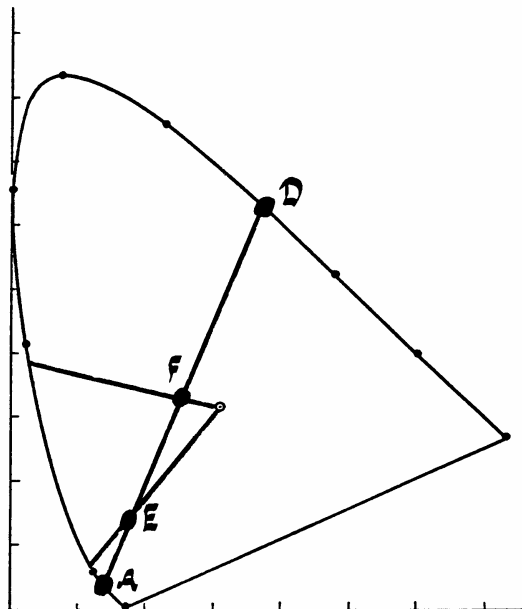


Figure 37. Low Purity Example.

wave length close to that of the first spectral line. The composite color must lie somewhere along the line AB connecting the spectral color points in the chromaticity diagram. The exact position of the composite color will depend on the relative intensity of the two spectral lines. If we assume the intensities are equal, the composite color point will lie at Point C, midway between Points A and B. The composite color will still be very pure, about 97%, in this example. The most noticeable effect will be a slight shift in dominant wave length to a value between that for A and B. To an observer, the effect will be a slight change in color, but the flame will still be seen as an intensely deep color. If, on the other hand, the second spectral line we added had a dominant wave length quite different from the first, then real problems can result. Consider the case where the added spectral line (Point D in Figure 37) has a dominant wave length of 560 nanometers. If this spectral line has only one-tenth the intensity of the first line, the composite color point will fall at Point E. Color Point E has about the same dominant wave length as in the high purity example in Figure 36. However, its purity has dropped to only 70%. There will be a slight change in color to an observer, similar to that in the first example, but the color will appear noticeably washed-out.

Had the second spectral line been equal to the intensity of the first, as it was in the high purity example above, the composite color would have the color Point F. The dominant wave length of this composite color has changed greatly, and its purity is only about 20%. This light source will appear almost pure white to an observer, a devastating loss of flame color.

In the real world, pyrotechnical flames have atomic and ionic species producing a lot more than just two spectral lines. Thus, it is understandable why it is difficult to produce deeply colored pyrotechnic flames. All one can hope for is that the collection of spectral lines produced will tend to predominate in one spectral region, giving reasonably pure colors. In practice, colored pyrotechnic flames have color points falling somewhere inside the shaded doughnut shown in the chromaticity diagram of Figure 38.

Thus far we have discussed atomic line spectra; however, molecular band spectra are much more common in pyrotechnic flames. A molecular band spectrum with just a single band will produce a deeply colored flame just as in the high purity example of Figure 36. Remember that a molecular band is just a collection of closely spaced lines that give the appearance of being a continuous band. On a chromaticity diagram, it is as though there were a large collection of color points in one spectral region. The collection of equally intense color points running from 450 to 480 nanometers, shown in Figure 39, will produce a composite color with the dominant wave length of about 470 nanometers and having about 98% purity. Thus molecular bands can be treated just the way that atomic lines were in the examples above, i.e., a molecular band can be treated as if it were an almost pure spectral line with its dominant wave length about midway through the band. Everything that was said above for atomic line spectra, applies equally to molecular band spectra or to mixtures of atomic and molecular spectra. The important thing to remember is that the wider the molecular band, the less pure (more washed-out) the color will appear.

The next topic to consider is that of continuous spectra. These can be treated as nothing more than extremely wide bands. However, because of the extreme width, there can be a tremendous

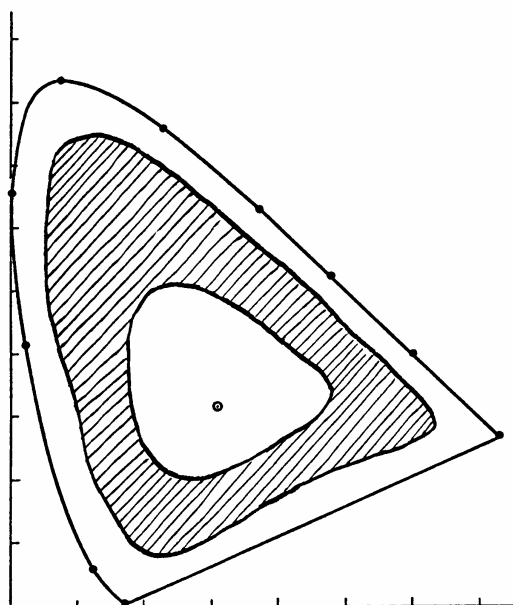


Figure 38. Colored Pyrotechnic Flames.

loss of purity. Consider the example of a continuous spectrum with equal intensity throughout the visible region. This would result in a composite color Point G in Figure 40, not far from the white color point of illuminant "C". If the continuous spectrum is generated as the re-

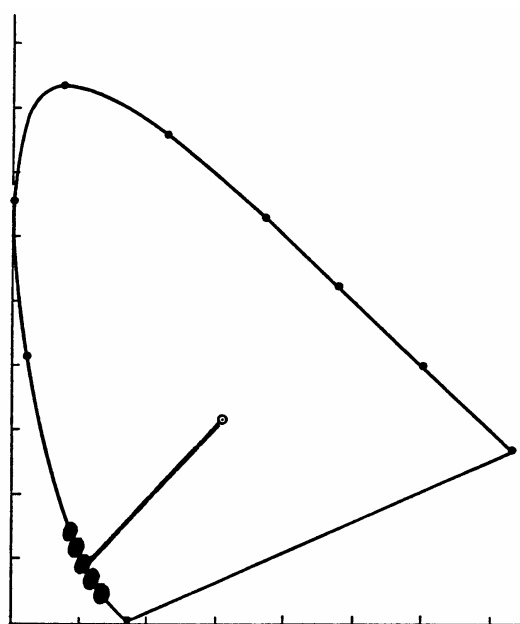


Figure 39. Molecular Band.

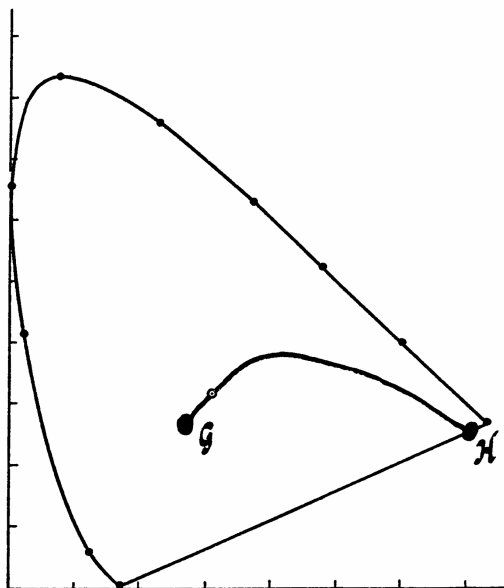


Figure 40. Continuous Spectra.

sult of incandescence, the composite color point would lie somewhere along the line GH. Its position along the line depends on the temperature of the solid or liquid material that is incandescing. It is obvious why sources producing continuous spectra can be so detrimental in pyrotechnic colored flames: they often produce nearly white light, and any white light added to colored flame reduces its purity, appearing as a washing-out of color.

Finally, consider the case of purple colored flames. Any pyrotechnist will tell you that really good purples are very difficult to produce. The reason should be clear after studying a chromaticity diagram. In order to produce a deeply colored purple flame, it is necessary to generate a composite color with its color Point K inside the shaded region shown in the chromaticity diagram in Figure 41. To accomplish this, you need to mix spectral lines from the extreme opposite ends of the color spectrum, Points I and J. Finding the red source is fairly easy but finding an intense violet line (not blue) is tough. An even tougher problem is that the addition of even a small amount of green or yellow will move the composite color point out of the intense purple region with a rapid loss of purity. Suppose we have a source of green light, in our otherwise excellent purple flame, with a

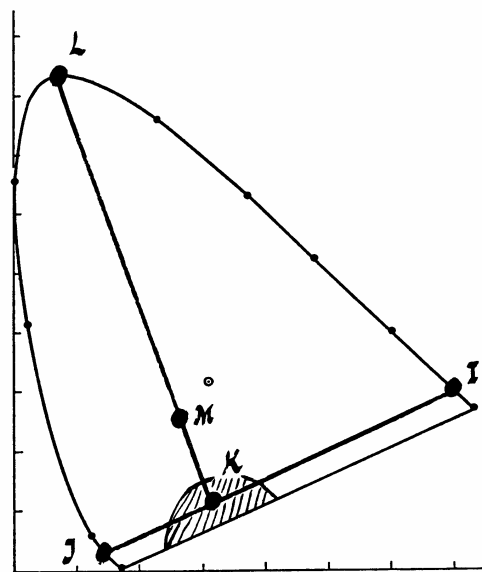


Figure 41. Purple's Tough.

relative intensity only one-fourth that of the purple composite. The result will be the new color Point M. To an observer, this will appear white, a totally washed-out purple. This combined set of requirements, two-thirds violet light plus one-third red light with very little else in the flame, is really tough to achieve. We will take up the subject of purple again at the end of the chemistry section of this paper.

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**END OF PART I**

## Taming Triangle Diagrams

Ken L. Kosanke

### ABSTRACT

A “dialogue” is presented wherein the author demystifies the triangle diagram or trigonometrical graph and shows how it can be a means of discovering hidden relationships between the components of a pyrotechnic composition, finding optimum formulations for a pyrotechnic system, and for summarizing the results of pyrotechnic experiments.

### Introduction

Triangle diagrams are not something new; they have been used for well over a hundred years in many areas of scientific study. They can be a powerful tool used to discover relationships between variables that cannot be seen from a tabular listing. Triangle diagrams can help the pyrotechnist quickly find the optimum formulations and can show at a glance the effects of varying formulations. Should the occasion arise to make a written or oral presentation of your studies, you will find triangle diagrams useful in summarizing your work. They can make it easy to demonstrate how you achieved your results. They can also be used to present the results from many experiments in a very compact form.

The current interest in triangle diagrams among pyrotechnists stems mostly from the writing of T. Shimizu (in Lancaster 1972) and Shimizu (1976, 1980, 1982). Shimizu has obviously found triangle diagrams to be extremely useful in both his pyrotechnic research and in his written descriptions of that work. In this article, it is my intention to provide sufficient understanding of triangle diagrams to allow you to read and comprehend the information contained in them. It is further hoped I will convince you that the use of triangle diagrams in your own experimental work will frequently be of great assistance.

This material is written in a style similar to “Programmed Instruction”. By that I mean this text is more of a dialogue, between you and me, than would normally be the case. I will accomplish this by asking you to work your way through this text instead of just reading it. I will occasionally ask questions requiring short answers. Occasionally, I have even left blanks for your answers. If you have not experienced programmed instruction before, this may seem a little “hokey”, but give it a try. When attempting to learn this type of material (triangle diagrams), programmed instruction will allow you to gain a better understanding in a shorter time. As a check, for your “fill-in-the-blank” answers, I have included answers at the end of the article.

In order to demonstrate that triangle diagrams can make it possible for a pyrotechnist to move faster in developing optimum formulations, consider the hypothetical results listed in Table 1.

**Table 1. Hypothetical Results Obtained from Experimental Formulations.**

Trial No.	Ingredients by Percent				Results
	%A	%B	%C	%D	
1	45	27	18	10	No effect
2	36	36	18	10	Weak effect
3	27	27	36	10	No effect
4	36	49	5	10	No effect
5	18	45	27	10	Weak effect
6	9	45	36	10	No effect
7	18	54	18	10	No effect
8	27	36	27	10	Weak effect
9	—	—	—	10	Best result

In Table 1, “no effect” means that the formulation did not produce the desired effect or result; “weak effect” means the formulation resulted in some of the desired effects but was less than completely successful. Suppose Table 1 was a listing of the results from your experiments, and you are getting a little pessimis-

tic about the results and a little tired of the project. Suppose you decide to give it one last try; what formulation would you compound? Think about it then fill in the values for trial No. 9 in Table 1. (I won't give you my answer now, because you will have a chance to change your answer later in this article.)

Had you been tracking your experimental progress using triangle diagrams, you could answer the above question almost without hesitation. Also, you would probably pick very nearly that formulation that has the best chance of being successful. In fact, if you had been tracking your experiments on a triangle diagram, you would probably have already tried that "best chance" formulation by trial Number 5 or 6.

### Triangle Diagrams

In working up to understanding three component triangle diagrams, consider the more trivial case of working with a two component mixture, having ingredients X and Y. If you wanted to keep track of your progress, you could graph the results using a single line. One end of the line could correspond to 0% X (pure Y) the other end to 100% X (pure X). Then points in between correspond to percentage values from 0% to 100% X (see Figure 1a). A scale has been added to help locate points along the line. In this case, a coarse scale consisting

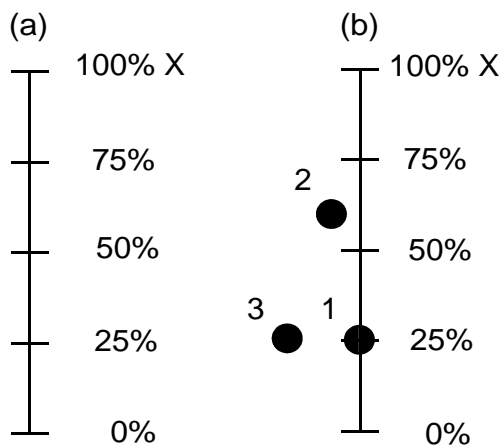


Figure 1. One way of keeping track of experimental results for two component formulations.

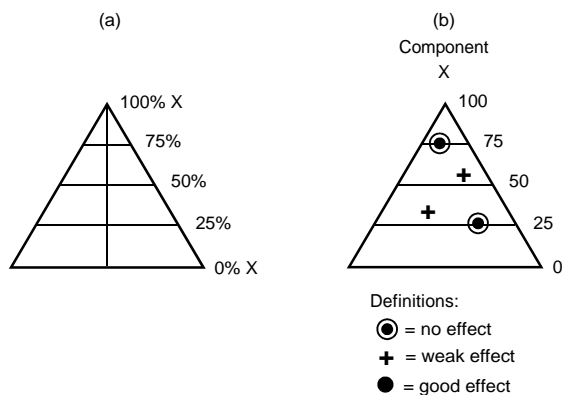


Figure 2. Two component graphs looking a little like triangle diagrams.

of 0, 25, 50, 75, and 100% was used. Obviously, any convenient scale could be used. In Part b of this figure, consider Point 1, it corresponds to a formulation containing 25% of ingredient X (and 75% Y). Similarly, Point 2 corresponds to 60% X. In this case, it was necessary for you to mentally interpolate to determine the percentage of Point 2. It was obviously between 50 and 75%. It appears to be about 2/5 of the distance between 50 and 75% and that corresponds to 60%. Now, in my graph I chose (for reasons to become clear later) not to care how far off to the side the points are located. That is to say, both Point 1 and Point 3 correspond to 25% of ingredient X used in the formulation. It does not make any difference that 1 is on the line and 3 is off to the left at some distance. All points lying at the same height above 0% X have the same value.

In Figure 2a, the scale lines have been widened and a triangular border added, giving the two component graph of Figure 1 more the look of a triangle diagram. Figure 2b has had percent signs and vertical line removed. Again, this was done to achieve the appearance of a triangle diagram. In Figure 2b I have defined three symbols for marking points on the graph. The different symbols indicate varying degrees of success of the two component formulations. There are four points on the graph corresponding to two formulations that exhibited none of the desired effect and two that resulted in a limited success. Starting with the least amount of component X, what are the values, in percent, of X for the four points? (Answers are la, b, c, and d).

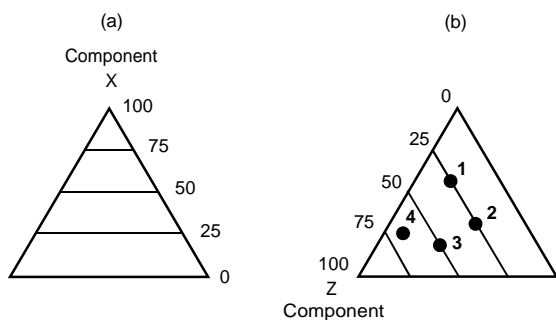


Figure 3. Adding a third component (ingredient) to the mixture and a new scale for measuring it.

Even this very limited information provides a fair idea of the amount of X you should try in your next formulation. The best results so far were achieved with 35% and 60% X; using 25% and 75% X produced no effect. It seems unlikely that trying less than 25% or more than 75% X will produce good results. I would try something in the range from 40% to 50% X. In effect, this would represent splitting the difference between the two formulations that had limited success.

In this two component example, we could have talked about the percentages of ingredient Y just as easily as ingredient X. To do this we would just subtract the percentage of X from 100 to determine the percentage of Y.

In the next example, consider a three component mixture, consisting of ingredients X, Y, and Z. In order to graph mixtures of three components, another scale must be added. This is done in Figures 3 and 4. Figure 3a is simply a two component graph; Figure 3b is the same, but tipped on its side. We read the location of points in Figure 3b for ingredient Z just as we did for ingredient X in Figure 2b. Thus Points 1 and 2 both correspond to 25% of ingredient Z. What are the amounts of ingredient Z for Points 3 and 4? (Answers 2a and b).

Figure 4 is the result of simply overlaying Figures 3a and 3b. Even though this appears considerably more complicated, the only change from 3a and 3b is that 0% and 100% have been dropped from the scales for both ingredients X and Z. This was done partially to avoid confusion in labeling the upper apex of the graph,

Table 2. Three Component Percentages for the Points in Figure 4a.

Point No.	Components		
	%X	%Z	%Y
1	55	25	20
2	35	25	40
3	20	50	30
4	25	65	10

which is both 100% X and also 0% Z. However, the main reason for this change is because that is the way triangle diagrams most often appear in the literature. You can determine for yourself what the value each apex has by reading that scale increasing toward the apex and mentally adding the next value. It is similar for the scale line forming the side of the triangle opposite each apex. For example (as in Figure 4a), if the scale increasing toward the Z component apex reads 25%, 50%, and 75%, then surely the apex must correspond to 100% Z and the line forming the side opposite the apex must be 0% Z.

We have already read the percentages of ingredient Z from Figure 3b. It should still be obvious in Figure 4 that the values are 25%, 25%, 50%, and 65% for Points 1 through 4. Using Figure 4a, what are the percentages of ingredient X? (Answers 3a, b, c, and d). If you are having trouble, here are some rules to help you:

1. Find the apex (point) of the triangle diagram labeled for the ingredient you wish to read. (In this case, the upper one labeled X.)
2. Mentally concentrate on the series of parallel

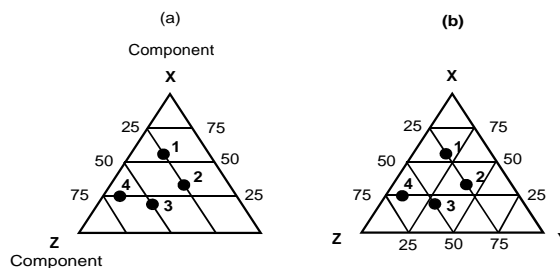


Figure 4. Three component triangle diagram with two and three percentage scales.

lines, starting with the side of the triangle opposite the apex of interest (each line gets shorter as you approach the apex). Refer back to Figure 3a if this gives you trouble.

3. There will be a number indicating a percentage printed at each end of each line. You should use the series of numbers that increase as you approach the apex. (In this case it is the series of numbers on the right, but be careful; the Figure could have just as easily been drawn reversed with the proper scale on the left instead.)
4. Read the percentages for the point of interest from the scale located in Step 3. If necessary, mentally interpolate the distance between two of the parallel lines found in Step 2.

It should now be clear why in Figure 1b, even though Points 1 and 3 both corresponded to 25% X, it was only the distance along the scale from 0% to 100% that was important. That Point 3 was to the left of the scale had to be overlooked. In Figure 4a, both Points 1 and 2 correspond to 25% of ingredient Z, but they indicate different amounts of X.

In a three component mixture it is reasonable to ask for the percentage of all three ingredients. From Figure 4a we have read the percentages of only two. Knowing that percentages must add to 100, the percentages of Y can be calculated. For example, Point 1 has 55% X and 25% Z, thus it must have  $(100 - 55 - 25 = 20)$

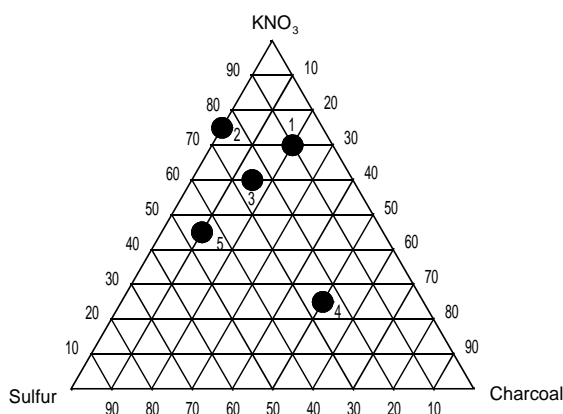


Figure 5. Three component graph for a star prime using black powder ingredients.

20% Y. Table 2 is a listing of percentages for the points on Figure 4a; check to be sure you agree.

Instead of calculating the percentage of the third component, it is normal practice to include an apex and scale lines for each of the three components. This has been done in Figure 4b. Again, the graph was simplified slightly by omitting the word “component”. This is the way you are most likely to see triangle diagrams. Check yourself by reading the Y percentages off the graph and compare with the values in Table 2. If you have trouble, recheck the rules above, this time using the Y apex of the triangle.

As a final exercise before taking up some other aspects of triangle diagrams, consider the triangle diagram in Figure 5. This is a graph for a three component mixture of potassium nitrate, sulfur, and charcoal. In an attempt to confuse you (and simulating the real world) I have reversed (side for side) some of the scales and made them finer. Try filling in the blanks of Table 3. Only through practice will triangle diagrams become understandable and useful. If you follow the rules above, you should not have too much trouble.

Table 3. Tabular Listing of the Data in Figure 5 % of Component.

Point No.	Potassium Nitrate	Charcoal	Sulfur
1	70	20	10
2	75	(4a)___	(4b)___
3	(4c)___	15	(4d)___
4	(4e)___	(4f)___	(4g)___
5	(4h)___	(4i)___	(4j)___

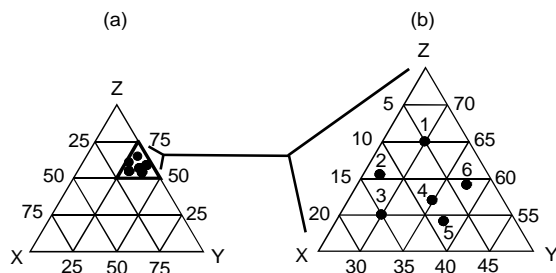


Figure 6. Partial triangle diagrams.

### Partial Triangle Diagrams

Consider the data presented in Figure 6a. Here the data are closely grouped in one part of the graph and are difficult to read. If Figure 6a were redrawn as in Figure 6b, expanding the region of interest, it can be more easily read, interpreted or discussed. What has been done is to take the smaller triangle (heavily out-lined in Figure 6a) formed by the lines for 0% X, 25% Y, and 50% Z, enlarge its size and add finer scale lines. The same general rules (listed earlier) still apply. Thus the percentages for Point 1 are 5% X, 30% Y, and 65% Z. Those for Point 2 are 12% X, 27% Y, and 61% Z. If you don't arrive at these same results, recheck the rules. Fill in the missing values for the other points in Table 4.

Table 4. Tabular Listing of the Data in Figure 6.

Point No.	Components		
	%X	%Y	%Z
1	5	30	65
2	12	27	61
3	15	(5a)___	(5b)___
4	(5c)___	(5d)___	57
5	(5e)___	38	(5f)___
6	(5g)___	(5h)___	(5i)___

### Formulations with Four or More Ingredients

Using two dimensional triangle diagrams (like we have been using) it is only possible to work with three components at a time. One solution to working with four (or more) ingredients is simply to work with various amounts of the three most critical ingredients while holding the other(s) constant. Good candidates for ingredients to be held constant are the binder or the chlorine donor. Having picked the ingredient to be held constant, guess the proper amount to use (e.g., 5% dextrin). Then always using that amount, experiment to determine the amount of the other ingredients that give the best result. Use a triangle diagram to record the mixtures tried and the degree of success achieved. Next, holding the ratios of these three critical ingredients constant, try using slightly more or less of the ingredient originally held constant. Once the optimum amount has been found, check to see if additional small changes in the other three ingredients are necessary. This last step is particularly important if the optimum amount found for the constant ingredient was much different than the amount used in your first series of experiments.

In practice, there are two slightly different procedures that can be followed when working with four components. You can refigure the percentage of the ingredients so that the three components you wish to vary add up to 100%. Then the fourth component (the one being held constant) can be listed as an "additional percentage" above the 100%. For example, the formulation for a star prime consisting of potassium nitrate, charcoal, sulfur, and dextrin could be given as 75% potassium nitrate, 15% charcoal, and 10% sulfur (equaling 100%) plus an additional +5% dextrin. Additional percentages are usually indicated by the use of a plus sign before the number. In order to work with the data from Table 1, the percentages for the four components could be recalculated, listing ingredient D in terms of an additional percentage. Once this was done the formulations and results could be plotted in a triangle diagram like the three component mixtures shown in Figures 4, 5, and 6 above. This is the technique usually followed by Shimizu. If you are used to working with "additional percentages" and custom-



arily record experimental mixtures this way, then I suggest this is the best way to present your results on a triangle diagram. On the other hand, if you tend to work in parts (and not percent) or if you have the total of all your ingredients equal 100%, then there is a little simpler way to go about it. The three components listed on a triangle diagram can be expressed by parts or percentages that do not add to 100%. However they MUST always add to the SAME number in all formulations to be plotted on the same graph; it's all right if all formulations add to 90%, 80%, 10 parts, or 12 parts, etc. The easiest way to work with the data in Table 1 is to have the components in the triangle diagram always add to 90%, with component D held constant at 10%. Figure 7 is a presentation of the data in this manner.

There is another way to treat mixtures of more than three components on a triangle diagram. This technique uses constant concentration mixtures of ingredients in place of pure components. For example, suppose you wish to use potassium perchlorate and red gum as oxidizer and fuel in a color star formulation. First you could experiment with these two components to find an effective ratio of oxidizer to fuel. Having discovered this, you can prepare a supply of the mixture for further experimenting, now treating the mixture as if it were a single (pure) component. On a triangle diagram you could now use as the three components (1) color agent, (2) chlorine donor, and (3) oxidizer–fuel mixture. Further expanding on this example, suppose that you were attempting to derive a purple star formulation, or one requiring a pair of color agents. You could experiment to find a satisfactory ratio of the color agents, one producing the desired color. Next prepare a mixture of the color agents for future experimenting. Then use both the oxidizer–fuel and the color agent mixtures as single components in your final experimenting. Having found the optimum formulation using mixtures as components, it would be a good idea to check to see if the ratios of ingredients used in the original mixtures could be adjusted slightly to further improve the formulation. This would be particularly important if, for example, the chlorine donor or binder can act as a fuel or if flame temperature affects the color generating ability of the two color agents differently.

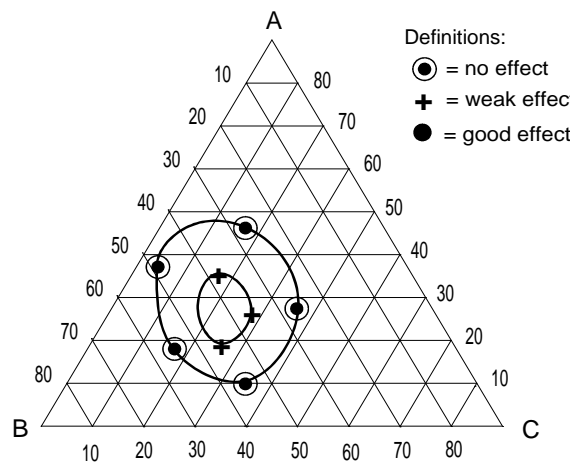


Figure 7. Triangle diagram of the data from Table 1.

Using constant component mixtures of ingredients in triangle diagrams can be a powerful tool. This is because it will allow you to simultaneously work with large numbers of ingredients. In the above example, had you included a binder and a flame deoxidizer as fixed added percentages, you could have been working with seven ingredients on the same triangle diagram.

## Conclusion

In Figure 7, a triangle diagram of data from Table 1, I have used different symbols to identify those formulations that produced either no effect or produced a weak effect. I have also added two roughly circular lines, passing through those points giving similar results. It is likely that new formulations with points falling on or near the circles will provide results similar to the other points on the circles although you can not be certain unless you verify it experimentally. In Figure 7, place a point where you would indicate a mixture containing 45% A, 36% B, and 9% C. This point is roughly on the same circle with those that produced none of the desired result. It is rather likely this mixture would also give none of the desired result. What degree of success would you expect from a mixture containing 35% A, 40% B, and 15% C (answer 6)?

It is possible to think of the circles in Figure 7 as a target or “bull’s eye”. When you look

at it in this way, it should be easy to pick your next formulation, that which has a high probability for success. It makes sense to pick one near the center of the bull's eye, or one having concentrations close to (7a) \_\_\_% A, (7b) \_\_\_% B, and (7c) \_\_\_% C. You might choose to compare these percentages with those you selected earlier and listed at the bottom of Table 1. As the result of being clever (or lucky) your earlier guess might almost exactly equal those percentages you just chose. If this is the case, ask yourself these questions:

1. Did you take longer making up your mind studying Table 1 or Figure 7?
2. After looking at Figure 7, are you more confident of the likelihood of having success with your next trial formulation?
3. Depending on the degree of success of this formulation, if still another attempt is necessary, would you pick your next formulation using Table 1 or Figure 7?

If your original "guess" percentages were more than a few percent from your "informed choice" percentages, the value of the triangle diagram should be obvious.

As useful as triangle diagrams can be in guiding your experimentation, they can be even more useful, if you choose to document your investigations. This is equally true whether you are just writing up results for your own future reference, presenting the data orally to an audience, or writing for publication. You can present a large amount of complex data in a single, easily understandable, triangle diagram. Probably you will also wish to include a table of your results, but it is the triangle diagram that will clearly show the complex relationship between the components and the results produced.

## Acknowledgments

I wish to acknowledge gratefully the comments and suggestions of the editorial staff of Pyrotechnica, especially the extensive suggestions supplied by R. M. Winokur.

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## Answers

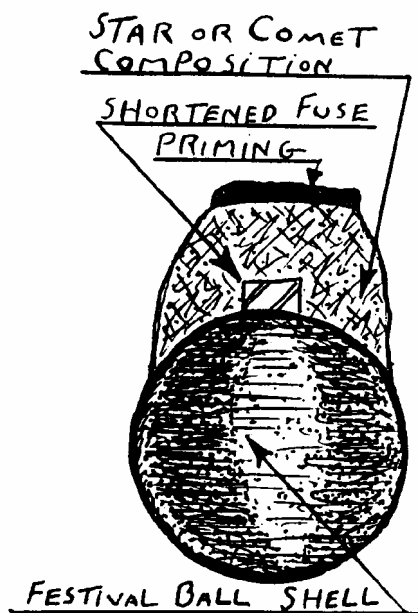
- 1a, b, c, d. (25% X, 35% X, 60% X, and 75% X)
- 2a, b. (50% Z and 65% Z)
- 3a, b, c, d. (55% X, 35% X, 25% X, and 20% X)
- 4a, b, c, d, e. (0% charcoal, 25% sulfur, 60% potassium nitrate, 25% sulfur, 25% potassium nitrate)
- 4f, g, h, i, j. (50% charcoal, 25% sulfur, 45% potassium nitrate, 10% charcoal, 45% sulfur)
- 5a, b, c, d, e. (30% Y, 55% Z, 8% X, 35% Y, 8% X)
- 5f, g, h, i. (54% Z, 3% X, 38% Y, 59% Z)
6. (weak effect or some of the desired result)
- 7a, b, c. (27% A, 41% B, 22% C)

## Festival Ball Comets

Ken Kosanke

Festival ball comets are inexpensive, easy to assemble and produce a nice effect. Before discussing their construction, let me acknowledge that, as far as I know, the basic idea for this firework originated with Bob Winokur.

The device consists of a festival ball shell with comet composition coating the fuse end of the shell. Festival balls are small Class "C" aerial shells, about 1-3/4" in diameter and are usually painted red in color. Unlifted, they cost about \$20.00 per hundred. Kits of 12 lifted shells with a mortar are available for five or six dollars. The small shells have stars of any of several colors and are a fairly effective firework for the price.



To assemble a festival ball comet, first the bundle of Chinese fuse on the festival ball shell is cut off 1/4 to 1/2 inch away from the shell. Next, a small amount of heavily dampened comet composition is molded around the fuse end of the shell (see the illustration to the left). Obvi-

ously, the length of the fuse remaining and the thickness of the comet composition covering the end of the fuse determine the time delay for the shell break. Essentially any comet formulation can be used; however, it is important to substitute gum Arabic as the binder. Gum Arabic bound compositions dry very hard and stick tenaciously to almost any surface, in this case, to the festival ball. With most other binders, there is significant likelihood that the comet will loosen from the festival ball and fall off during the shock of firing from the mortar. The final assembly step is to apply prime to the end of the comet composition. Homemade meal powder (75% potassium nitrate, 15% charcoal and 10% sulfur) bound with nitrocellulose lacquer is quite effective, particularly when a small amount of fine grain black powder (3 or 4 Fg) is sprinkled on the prime while it is still wet. The choice of fast drying nitrocellulose lacquer as binder is not critical.

As a mortar for these small festival ball comets, 1-1/2-inch schedule 20 PVC serves adequately. (Note: 1-1/2 inch schedule 20 PVC has an inside diameter of 1-3/4 inches.) I do not generally advocate the use of PVC mortars; however, I have not had problems using it with light weight festival balls. This past year, we fired more than 500 festival balls from racks of these thin walled PVC mortars, with the loss of only two mortars to cracking. As lift, 1/2 tablespoon of 4FA blasting powder (not 4Fg powder) seems sufficient. Obviously, the festival ball comet should be loaded into the mortar with primed comet end down.

As would be expected, the effect of these devices is an ascending comet ending in a small colored shell break. Festival ball comets can be produced for an out of pocket cost of about 25 cents each. This seems modest considering the effect produced. These devices are particularly effective when fired simultaneously in mass.

# The Physics, Chemistry and Perception of Colored Flames

## Part II

K. L. Kosanke

### 4.0 The Chemistry of Colored Flames

#### 4.1 A Summary of General Chemistry for Colored Flame Production

This paper is intended to benefit readers who do not enjoy a thorough understanding of chemistry. Thus, before dealing with more advanced topics, a discussion of some aspects of general chemistry may be of benefit. Any reader with an understanding of chemical symbols and the Periodic Table, chemical formulas and IUPAC nomenclature, chemical equations, the idea of reversibility and Le Châtelier's Principle, stoichiometry and mole weights should skip ahead to section 4.2.

##### 4.1.1 Chemical Symbols and the Periodic Table

The ancient Greeks believed that all material substances were composed of four basic elements: water, air, earth and fire. This idea, however wrong, showed profound insight. Their theory of basic elements recognized the fact that there are not millions of different fundamental substances, but rather these millions of substances are just different combinations of a few basic elements. This concept, basic elements in different combinations, is what got the whole idea of chemistry started; if you knew the basic elements and how to combine them, you could make anything you wanted.

Eventually, when the scientific method replaced philosophic rationalizing as the manner of conducting research, it became apparent that the Greeks' four elements didn't suffice, and the search was on for the real chemical ele-

ments. By the mid-nineteenth century, most of the elements had been discovered, named and given a shorthand chemical symbol. The name and chemical symbol for those elements most often encountered in pyrotechnics are listed in Table 1. (The utility of these chemical symbols will become increasingly clear as we continue working through this chemistry section.)

Early on, it was observed that there were groups of chemical elements that had similar physical and chemical properties. For example, one group of elements were all soft metals, an-

**Table 1. Element Names and Atomic Symbols Commonly Used in Pyrotechnics.**

Element Name	Atomic Symbol
Aluminum	Al
Antimony	Sb
Arsenic	As
Barium	Ba
Calcium	Ca
Chlorine	Cl
Copper	Cu
Hydrogen	H
Iron	Fe
Lead	Pb
Magnesium	Mg
Mercury	Hg
Nitrogen	N
Oxygen	O
Phosphorus	P
Potassium	K
Silicon	Si
Sodium	Na
Strontium	Sr
Sulfur	S
Titanium	Ti
Zinc	Zn

other group were all gases. Also all members of a group combined with elements of other groups in the same proportion, making compounds that again had similar properties. One of the groups, called alkali metals, consists of lithium, sodium, potassium, rubidium, cesium and francium. If you know something about the chemistry of ONE of these elements, you also know a little about the chemistry of ALL the others. For example, you probably know that sodium combines readily with chlorine to make common table salt, sodium chloride. Because lithium and potassium are members of the same group of elements, you can be reasonably certain that both lithium and potassium combine with chlorine to make lithium chloride and potassium chloride. You can also be reasonably certain that both lithium chloride and potassium chloride will have properties similar to sodium chloride, i.e., all will taste salty, all will be soluble in water and all will form crystals with similar appearance, hardness, and melting points, etc.

Chlorine, too, is a member of a chemical group, called halogens, consisting of fluorine, chlorine, bromine, iodine and astatine. With this information and your knowledge of sodium chloride, you can be rather confident about the existence of sodium fluoride, sodium bromide, potassium fluoride, etc., and you will know something about the properties of these compounds.

A knowledge of chemical groups combined with only a little other chemical knowledge gives you great predictive powers. A knowledge of sodium and chlorine, and the way they combine allows you to speculate on the existence, manner of combining and properties of a large number of compounds, in this case 30 (six alkali metals times five halogens).

It was realized very early in the systematic study of chemistry that the organization of chemical elements into relatively few groups would allow a great simplification of the subject. If all chemical elements could be organized in this fashion, and you learned the way the groups interact with one another, then you could speculate about tens of thousands of possible reactions. This would be a very great simplification indeed.

In 1869 Mendeleev successfully organized all the chemical elements known at the time into a table (in order of increasing mass of the elements), in which the elements fell into the known groups. In fact, he was so successful that he was able to predict the existence of several then unknown elements because of unfilled positions in his table of elements. With only slight modification, Mendeleev's arrangement of chemical elements has become known as the Periodic Table of Elements. It is called "Periodic" Table because, in a listing of chemical elements in order of increasing mass, chemical and physical properties repeat periodically. In essence, what Mendeleev did was to lay out the elements from left to right, as they increased in mass. Each time elements seemed to be repeating properties of earlier elements, he started a new row. Thus the elements lithium, sodium and potassium all came to fall in the same column, because they all behaved similarly.

Today we understand the underlying reason why the Periodic Table appears as it does and why the properties of the elements repeat themselves. The reason is related to the way electrons arrange themselves about the nucleus of the different chemical elements. A discussion of these different electron arrangements and why they exist might be interesting to a few readers, but is beyond the scope of this paper.

Before leaving the subject of the Periodic Table, it is appropriate to spend a little more time to make it a useful tool. Below is a summary of what has already been said about the Periodic Table and some of the additional information contained in it. (A copy of the Periodic Table is included at the end of this article.)

- (A) Each vertical column is representative of a chemical group of elements, with generally similar properties. This includes "physical" properties like melting points, metallic or non-metallic character, crystal structure, etc., as well as "chemical" properties such as tendency to combine with other elements, the relative proportions in which they combine, etc.
- (B) Molecules formed by combining different elements of the same two groups will generally have similar physical properties. Thus, sodium chloride, lithium bromide and po-

tassium fluoride, etc., all are crystalline in nature, all are water soluble and all have rather high melting points.

(C) Some of the information contained in the Periodic Table of Elements is:

- (1) Group number: The number of each chemical group, IA to VIIIA, is printed above the top chemical element in each vertical column.
- (2) Chemical symbol: The shorthand symbol for each of the chemical elements is printed in the center of the square for that element. Also in each square is the name of the element.
- (3) Atomic number: In the upper left hand corner of each square the element's atomic number is printed. This is the number of protons in the nucleus of each atom of that particular chemical element. It also equals the number of electrons orbiting each neutral atom of that chemical element.
- (4) Atomic weight: The atomic weight for each element is printed in the upper right hand corner of each box. Atomic weights are proportional to the weight of one atom of that chemical element.

#### 4.1.2 Chemical Formulas and IUPAC Nomenclature

Using the chemical symbols from the Periodic Table, a systematic chemical shorthand has been developed to describe combinations of chemical elements forming molecules. Use of that shorthand will simplify our discussions as well as shorten this paper significantly. For chemical elements in their natural atomic state, the shorthand notation is just to use the chemical symbol, instead of writing out the full chemical name. Thus, the symbol Na is used in place of the name sodium; Cl is used for chlorine, etc.

In the case of chlorine, the symbol Cl means chlorine atoms; however, chlorine is a diatomic gas under normal conditions. Diatomic means that chlorine molecules consist of pairs of chlorine atoms bound to each other. Instead of writing this as ClCl, it is written Cl<sub>2</sub>. The subscript 2 means that two atoms of chlorine have combined to form a diatomic molecule. All gaseous

elements, except those in group VIIIA, normally exist as diatomic molecules. Some examples are hydrogen (H<sub>2</sub>), oxygen (O<sub>2</sub>), and nitrogen (N<sub>2</sub>).

In general, numeric subscripts are used to indicate when a molecule is composed of more than one atom of the same element. Another familiar molecule is water, H<sub>2</sub>O. Here two atoms of hydrogen and one atom of oxygen are bound together to form a single molecule.

A chemical formula is the shorthand method of describing the type and number of atoms in a compound (molecule). Above, H<sub>2</sub>O, Cl<sub>2</sub>, O<sub>2</sub>, etc., are all chemical formulas.

In order to avoid possible confusion, let me point out that sometimes when people talk about chemical formulas, they are really talking about something quite different. Sometimes recipes are mistakenly called chemical formulas. When someone tells you to mix one part water and one part dirt to make mud, they may be giving the formula for making mud, they have not given you the chemical formula for mud. There is quite a difference, the former is a recipe and the latter is the EXACT way in which atoms combine to form compounds.

At the beginning of this section, I said that elements in their "normal" atomic state are described by using their chemical symbol. This is true, but I should have been more specific and said "in their normal atomic state under standard thermodynamic conditions". Standard thermodynamic conditions are 25 °C and one (1) atmosphere pressure. (This should not be confused with standard temperature and pressure (STP) which is 0 °C and one atmosphere pressure.) The reason to be more specific is that by changing temperature and pressure, the normal state of elements and molecules changes. At 25 °C copper is a solid, above 1100 °C, it is a liquid, and above 2600 °C, it is a gas. When something is in some state other than its standard state, it is indicated by the use of (g), (l) and (s) as subscripts. The parentheses are normally used and g, l and s indicate gases, liquids and solids, respectively. Thus Cu<sub>(l)</sub> indicates we mean liquid copper and Cu<sub>(g)</sub> indicates gaseous copper. Sometimes, in order to make a point or to avoid possible confusion, even an element in its normal room temperature state will have its

state designated using these same symbols. It is not necessary to write  $\text{Cu}_{(s)}$ , but it is OK.

Another thing it is necessary to indicate in a chemical formula is whether something is electrically charged, i.e., whether it is a neutral atom or molecule, or an ion (charged). This is accomplished using a superscript plus or minus after the chemical symbol or formula. For example,  $\text{Cl}^-$  indicates a chlorine ion with a charge of minus one;  $\text{Na}^+$  indicates a sodium ion with a plus one charge. If the charge of the ion is more than plus or minus one, a numeral is added before the sign. Thus  $\text{Ca}^{2+}$  indicates a calcium ion with two units of positive charge. Remember from the brief discussion of ionization (in Part I of this paper) that positive ions result when atoms or molecules LOSE one or more of the electrons that orbit them. Similarly, negative ions result when atoms or molecules GAIN one or more orbiting electrons. When writing formulas for ions, it is necessary to use the superscript plus or minus. Atoms don't normally exist as ions, so when writing about neutral atoms or molecules, it is not necessary to indicate their neutrality; however, sometimes to avoid possible confusion, a superscript 0 is used. For example, the chemical symbol  $\text{Cu}^0$  indicates neutral copper atoms.

Sometimes neutral atoms or molecules have an electronic structure that makes them unusually reactive. When this happens, they are usually called "free radicals" and are indicated using a superscript dot (in place of the zero), e.g.,  $\text{Cl}^\cdot$  or  $\text{OH}^\cdot$ . Because free radicals are so reactive, they usually are not found at room temperature, where they quickly combine with other atoms or molecules. However, in pyrotechnic flames, free radicals abound.

The final topic in this section is IUPAC nomenclature. When the International Union of Pure and Applied Chemists (IUPAC) was formed, one of the first tasks undertaken was to standardize the method of naming chemical compounds. Below is a short discussion of some rules of nomenclature.

(A) Molecules composed of a metal and a non-metal, have the metal named first followed by a slightly modified non-metal name. The metal name is pronounced just as it would be for a metal powder. For example, Na in

NaF is "sodium", Cu in CuCl is "copper". The non-metal name has its ending changed to "ide". Thus fluorine in NaF is "fluoride", chlorine in CuCl is "chloride" and oxygen in FeO is "oxide".

When a metal, like copper, is capable of combining in different proportions with the same non-metal elements, like chlorine, it is necessary to be able to distinguish between the different chemical forms. This is accomplished by adding a Roman numeral in parentheses between the metal and non-metal name. The Roman numeral indicates the "valence state" of the metal. (The concept of valence is beyond the scope of this paper; suffice it to say that a metal's valence state determines the ratio in which it will combine with other elements.) Gone are the frequently confusing names for copper such as "cuprous" and "cupric" in the names of CuCl and CuCl<sub>2</sub>, respectively. In the new naming system, CuCl is copper(I) chloride, CuCl<sub>2</sub> is copper(II) chloride. When a metal has only a single valence state possible, it is not necessary to include the Roman numeral. Thus NaF is just sodium fluoride.

- (B) There are several groups of atoms that stick together rather well and often act as if they were just a single element when forming compounds. These ionic functional groups have each been given their own names. Some of these encountered in pyrotechnics are:  $(\text{NO}_3)^-$ , nitrate;  $(\text{ClO}_4)^-$ , perchlorate; and  $(\text{NH}_4)^+$ , ammonium (see Table 2 for a more complete list). Some compounds containing these functional groupings are: NaNO<sub>3</sub>, sodium nitrate; KClO<sub>3</sub>, potassium chlorate; CuSO<sub>4</sub>, copper (II) sulfate; and NH<sub>4</sub>ClO<sub>4</sub>, ammonium perchlorate.
- (C) Complex natural organic molecules continue to be called by their historical names. Sometimes this is because the IUPAC name is very long and complicated; other times, this is because the natural substance is not a single compound, but several compounds in a variable mixture. Thus names like shellac, red gum (accroides), and gum Arabic are proper to use.

**Table 2. Names and Formulas of Functional Ionic Groups Frequently Found in Pyrotechnics.**

Group Name	Chemical Formula
Ammonium	$\text{NH}_4^+$
Carbonate	$\text{CO}_3^{2-}$
Chlorate	$\text{ClO}_3^-$
Hydrogen carbonate (bicarbonate)	$\text{HCO}_3^-$
Nitrate	$\text{NO}_3^-$
Oxalate	$\text{C}_2\text{O}_4^{2-}$
Perchlorate	$\text{ClO}_4^-$
Sulfate	$\text{SO}_4^{2-}$

Occasionally in this paper the prefix “mono” will be used in a chemical name, to indicate that the single atom is present in the compound. This is done to avoid possible confusion. For example, at normal temperatures, strontium always combines with chlorine in the ratio of 1 to 2 to form the solid  $\text{SrCl}_{2(s)}$ . Thus the proper name for the compound is simply strontium chloride. However, when  $\text{SrCl}_2$  is vaporized, the stable molecule is  $\text{SrCl}_{(g)}$ . To avoid confusion,  $\text{SrCl}_{(g)}$  will be called strontium monochloride.

The rules of nomenclature given thus far are a long way from being complete; however, they should help avoid confusion. As a further aid, you can refer to Table 3, which lists a number of the more common chemical names and formulas which are important in a discussion of the chemistry of colored light production.

#### 4.1.3 Chemical Equations

Chemical equations describe chemical reactions, i.e., the way chemicals react to form new chemicals. Instead of telling you that hydrogen and oxygen can combine to form water, it can be done using a chemical equation:



In addition to being shorter and easier to use, it also gives more information. It tells the relative numbers of atoms and/or molecules involved in the reaction, i.e., two molecules of hydrogen combine with one molecule of oxygen to form two molecules of water. The numeral 2 in front of  $\text{H}_2$  and  $\text{H}_2\text{O}$  indicates that 2

**Table 3. Names and Formulas of Chemicals Commonly Used to Produce Colored Flames.**

Oxidizers	
Ammonium perchlorate	$\text{NH}_4\text{ClO}_4$
Barium chlorate <sup>x</sup>	$\text{Ba}(\text{ClO}_3)_2$
Barium nitrate <sup>x</sup>	$\text{Ba}(\text{NO}_3)_2$
Potassium chlorate	$\text{KClO}_3$
Potassium nitrate	$\text{KNO}_3$
Potassium perchlorate	$\text{KClO}_4$
Sodium nitrate <sup>x</sup>	$\text{NaNO}_3$
Strontium nitrate <sup>x</sup>	$\text{Sr}(\text{NO}_3)_2$
Fuels	
Aluminum	Al
Carbon*	C
Magnesium	Mg
Magnalium <sup>xx</sup>	Mg/Al
Red gum (accroides)	Complex
Shellac	Complex
Color Agents**	
Barium sulfate	$\text{BaSO}_4$
Calcium carbonate	$\text{CaCO}_2$
Calcium sulfate	$\text{CaSO}_4$
Copper acetoarsenite	$(\text{CuO})_3\text{As}_2\text{O}_3 \cdot \text{Cu}(\text{C}_2\text{H}_3\text{O}_2)_3$
Copper(II) carbonate, basic	$\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$
Copper(II) chloride	$\text{CuCl}_2$
Copper metal	Cu
Copper(II) oxide	$\text{CuO}$
Copper sulfate	$\text{CuSO}_4$
Sodium hydrogen carbonate	$\text{NaHCO}_3$
Sodium oxalate	$\text{Na}_2\text{C}_2\text{O}_4$
Strontium carbonate	$\text{SrCO}_3$
Strontium sulfate	$\text{SrSO}_4$

Notes:

- x These oxidizers also act as color agents.
- \* Charcoal has the composition 82% C, 13% O, 3% H, and 2% Ash (from Shimizu, 1981).
- \*\* Under high temperature conditions such as in strobe star burning, many of these color agents can also act as oxidizers.
- xx Magnalium is an alloy of magnesium and aluminum, most often in near equal proportions.



molecules are involved in the reaction. The arrow in a chemical equation should be read as “reacts to form”. The starting chemicals are called the REACTANTS, and the chemicals produced are called the PRODUCTS. In the water equation, H<sub>2</sub> and O<sub>2</sub> are the reactants and H<sub>2</sub>O is the product.

To be a proper chemical equation, it must be balanced, just as a mathematical equation must be balanced. In chemical reactions, elements are immutable; they are neither created nor destroyed. Thus there must be an equal number of each type of atom on both sides of the arrow. If I had written the equation

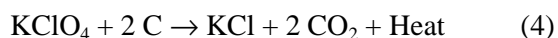


it would be incorrect, since it is not balanced. There are two atoms of hydrogen on each side of the equation, but the left side has two atoms of oxygen while the right side only has one. Note that Equation 1 is balanced.

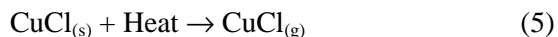
Sometimes, for emphasis, chemical equations will indicate whether heat energy is consumed or generated during a chemical reaction. This could have been indicated in Equation 1 by listing heat as one of the products,



An example from pyrotechnics, complete combustion, where an oxidizer (potassium perchlorate) and a fuel (carbon, i.e., charcoal) combine completely to generate reaction products plus heat, is

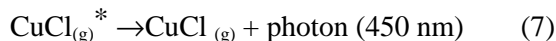
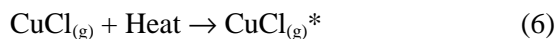


In order for molecules in a pyrotechnic flame to emit their characteristic band spectra, they must first be vaporized; this requires heat energy. Copper(I) chloride, CuCl, has the potential to be a powerful emitter of violet light if it has been vaporized. The chemical equation showing this vaporization is



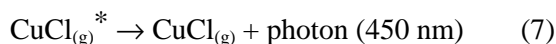
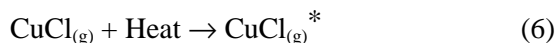
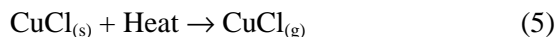
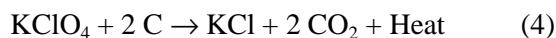
Another thing that can be shown in a chemical equation, to aid in clarity, is when an atom or molecule is in an excited electronic state, capable of emitting a light photon upon de-excitation. This is usually indicated using a superscript asterisk. Decay from an excited state with the emission of a photon can be indicated

by listing the light photon as one of the reaction products. Equations 6 and 7 are examples using CuCl:



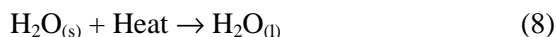
Equation 7 also indicates the wavelength of the emitted photon in nanometers (nm).

As an example of how chemical equations are a useful shorthand, consider the set of equations given above. They represent one possibility for generating violet light. In longhand, the process would be described as: “One molecule of potassium perchlorate reacts with two atoms of carbon to generate one molecule of potassium chloride, two molecules of carbon dioxide and heat. Copper(I) chloride, which is also present in the composition, consumes heat energy and is vaporized; it then consumes additional heat energy and becomes electronically excited. Finally, the excited molecule of copper(I) chloride de-excites generating a violet light photon of wavelength 450 nm.” In the more explicit shorthand of chemical equations this becomes, simply:

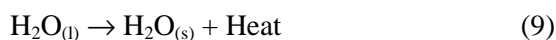


#### 4.1.4 Chemical Reversibility and Le Châtelier's Principle

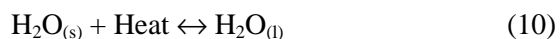
All chemical reactions are reversible to some extent. Thus, if two elements combine to make a compound, this compound has some tendency to decompose back into the two original elements. For reactions involving only a change of state, the idea of reversibility seems natural. For example,



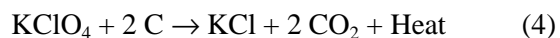
It is an everyday observation that the reverse reaction also takes place, i.e.:



A convenient way to point out that this reaction is reversible, is to use a double-headed arrow in the equation



For most other reactions, the idea of reversibility may be hard to accept. Remember the example of potassium perchlorate reacting with carbon,



It seems inconsistent with common experience to suggest there is a tendency for the reaction products to recombine again to make potassium perchlorate and charcoal. In fact there IS a tendency to do just that, even if the tendency is very slight at room temperature and atmospheric pressure. At high temperatures and pressures, the tendency for the reverse action to occur is increased, though still not great.

As a consequence of chemical reactions always having some tendency to go in both directions, they never go 100% to completion. Some of the reactants are always left over at the end, because some of the products have reacted in a reverse direction to remake some of the reactants. The final amount of reactants and products depends on the relative tendencies for the forward and reverse reactions to occur. If the tendency for the forward reaction to occur is much greater, then almost all the reactants will be consumed. On the other hand, if the reverse reaction has a much greater tendency to occur, then very little of the starting material will be consumed.

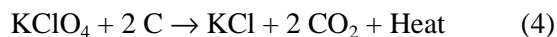
Later in this paper when discussing colored flame production, it will be important to understand the concept of chemical reversibility and something closely related called Le Châtelier's Principle. Le Châtelier's Principle states that when stress is applied to a chemical system in equilibrium, the system will react in such a manner as to relieve that stress. In Equation 4, I said there was a very slight tendency for the reverse reaction to occur, but when the pressure was raised, the tendency of the reverse reaction to occur became greater. This is can be thought of as Le Châtelier's Principle in action. Note that the only gas involved is  $\text{CO}_2$ , one of the products. If we increase the pressure, the only way to relieve the stress of added pressure is for some of the gaseous product to recombine to form the more compact  $\text{KClO}_4$  and carbon, and this is just what happens. Another way to apply stress to a chemical reaction is to increase the

amount of one of the reactants or products. If more of one of the reactants is added, the reaction progresses to the right, using up more of the other reactants and making more of the products. If more charcoal is added, some of the left over  $\text{KClO}_4$  will react with it to generate more of the reaction products. If you add some of one of the reaction products the reaction is pushed to the left, using up some of the other products to remake more of the reactants. Note in Equation 4 that heat energy is one of the products of the reaction. Thus if we apply stress to the reaction by raising the temperature (by adding heat), we would expect that stress would be relieved by some of the reaction products recombining, consuming heat energy, and re-making more of the reactants. This is just what does happen.

The reason it is important to understand Le Châtelier's Principle when attempting to generate good colored flames is that it gives us a way to shift chemical reactions so that they produce more desirable light generating species in colored flames, or so that they produce less undesirable light generating species.

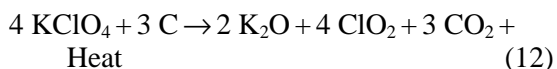
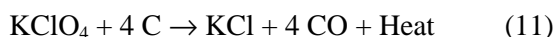
#### 4.1.5 Stoichiometry and Mole Weights

Stoichiometry (pronounced sto-i-key-om'-a-tree) is the detailed study of the ratio in which atoms and molecules combine to form other molecules. Whenever we write a chemical equation that is properly balanced (and expresses reality), it is an exercise in stoichiometry. Equation 4 for the complete combustion of carbon using potassium perchlorate,



is an exact description of one of the ways in which potassium perchlorate and carbon react in a pyrotechnic flame to produce heat. It tells you exactly how many atoms of carbon combine with one molecule of potassium perchlorate. If this were the only way for the reaction to proceed, it would be a relatively simple matter to design pyro-reactions on paper that worked perfectly in practice. Knowing that two atoms of carbon were consumed for each molecule of potassium perchlorate, you could (knowing about molecular weights) calculate the exact weight of potassium perchlorate and carbon to use in a pyro-formulation. Unfortunately,

Equation 4 is only one of the possible ways for the reaction to proceed. Two more equally legitimate possibilities are:



Equation 11 suggests that the proper ratio is four carbon atoms to one potassium perchlorate molecule, not two to one as in Equation 4. Equation 12 suggests that carbon and potassium perchlorate will react three to four. In practice, when formulating, how can you be certain which of the three ratios to use? In fact, none of the ratios are exactly correct. EACH of the reactions occurs and is correct in a stoichiometric sense. The problem is that ALL THREE equations (and others) take place to some extent at the same time in the flame reaction. It's not that stoichiometry doesn't work; it's just that flame reactions are too complex to be represented completely by a single chemical equation. To add to the complexity, the extent to which the various flame reactions occur depend on such additional things as: grain size of the chemicals, degree of compaction of the material, type and amount of color agents and other chemicals added to the formulation, pressure, velocity at which the composition is moving through air (i.e., flame temperature). It is just not possible to write a single equation, no matter how long and complex, that will precisely describe chemical reactions in a typical pyrotechnic flame under all conditions.

In spite of this, stoichiometry can be a great help in developing pyro-chemical formulations. It can provide very good, although only approximate, starting points for amounts of chemicals to use. In addition, stoichiometry can tell you almost exactly how to make substitutions in your formulations.

Stoichiometry (balanced chemical equations) tells in what proportions atoms and molecules react. However, in your pyro-lab, you don't work with individual atoms; you work with grams, ounces or pounds. What is needed to know is how many ounces of this combine with how many ounces of that. The concept of "molecular weights" will let you work with amounts by weight instead of numbers of atoms. To explain molecular weights, it is necessary to de-

fine a new unit, a "mole". A mole is a number, a very big number; it is equal to 602 thousand billion billion atoms ( $6.02 \times 10^{23}$  atoms). This large number is the number of hydrogen atoms in a single gram of atomic hydrogen. Instead of talking about  $6.02 \times 10^{23}$  atoms of hydrogen, one can simply call it a mole of hydrogen. The unit "mole" is used in just the same way as the unit "dozen"; just think of a mole as a "super dozen". In your kitchen you make recipes using individual eggs, but an army cook works in dozens of eggs. Similarly in your pyro-lab, you need to think in terms of moles (super dozens) of atoms.



Equation 1, gave the ratio of hydrogen and oxygen molecules that combine to make water. It told you that two molecules of hydrogen combine with one molecule of oxygen to make two molecules of water. However, it is also true that two dozen hydrogen molecules combine with one dozen oxygen molecules, or that two moles of hydrogen molecules combine with one mole of oxygen molecules. If you want to make water, and want to use precisely the right amount of hydrogen and oxygen, you still need to know how much a mole of hydrogen and a mole of oxygen weigh. Remember from the discussion of the Periodic Table, that one type of information contained on it are atomic weights (the number in the upper right corner of the box for each element). The atomic weight is the weight of one mole of that element in grams. Thus one mole of atomic hydrogen (H) very nearly weighs one gram. However, because hydrogen is a diatomic gas ( $\text{H}_2$ ), the molecular weight of a mole will be twice its atomic weight, or 2 grams per mole of molecules. Similarly for oxygen, with an atomic weight of 16, one mole of molecular oxygen ( $\text{O}_2$ ) weighs 32 grams. From Equation 1 you know that 2 moles of  $\text{H}_2$  combines with one mole of  $\text{O}_2$ . Thus 4 grams of hydrogen gas (2 moles  $\times$  2 grams/mole) combine with 32 grams of oxygen gas (1 mole  $\times$  32 grams/mole).

Since the metric system is not in general use in the US, many people don't formulate using grams as a unit of mass. Well, the above information is still useful and it's not necessary to convert units of weight. The above information indicates that 4 parts by weight hydrogen com-

bine with 32 parts by weight oxygen to make water. The unit of weight can be anything convenient: grams, grains, ounces, pounds, kilos, tons, etc.

As a more relevant example demonstrating molecular weights, consider a problem from pyrotechnics. Suppose you wished to substitute metallic copper powder for copper(II) oxide in a blue star formulation. It is relatively safe to assume that it is only the amount of copper that is important and that the presence of oxide ions has only minor effect on flame color. The first thing needed to be established is how much copper is in copper(II) oxide,  $\text{CuO}$ . The molecular weight of  $\text{CuO}$  is 79 grams/mole (63 grams/mole for copper + 16 grams/mole for oxygen). The fraction of copper in copper(II) oxide is  $63/79$  or about  $4/5$ . Thus every five grams of copper(II) oxide contributes four grams of copper. If the blue formulation called for ten parts copper(II) oxide, you should begin by using eight parts of copper metal ( $10 \text{ parts} \times 4/5$ ).

## 4.2 Pyrochemical Flames for Color Production

### 4.2.1 Definition and Function of Flames in Color Production

The most important characteristic one uses to determine whether something is a flame is the emission of light. Other characteristics such as flickering, giving off heat and apparent chemical nature are far less important. The emission of light is in fact the best criterion to use. It is important to point out that in Figure 42 (a drawing of a typical flame) the principal difference between point B (just inside the flame envelope) and point C (just outside the flame) is that the molecules at point B are emitting visible light and those at point C are not. For the most part, the same kinds of molecules are present at both points, and the temperature at point C is only a little lower than at point B.

Even though the temperature difference between B and C is small, it is sufficient to account for the molecules at point B emitting light while those at point C are not. Remember that energy is required for excitation of electrons from their ground states to excited states, and that light is given off when those electrons fall

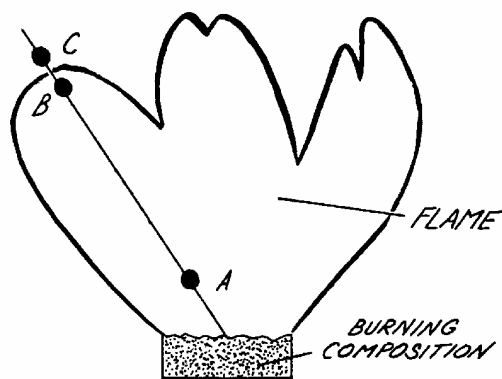


Figure 42. Typical pyrotechnic flame.

back to lower energy states. If the temperature at some point is high enough to cause electron excitations, then the molecules at that point can give off light. At the same point, if the temperature falls lower, such that there is no longer sufficient energy for electronic excitation, no light is given off. Figure 43 is a graph of expected temperatures along the line in Figure 42 on which points A, B and C fall. Included in Figure 43 is a line meant to correspond to the approximate flame temperature necessary for the production of light from the molecules present. At point A, the temperature is well above that value, at point B the temperature is slightly above that value, and at point C, slightly below. The molecular species that are present at point B are also present at point C. As far as light

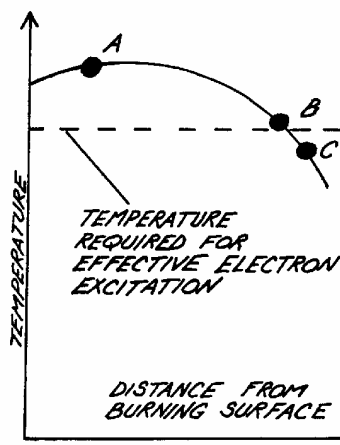
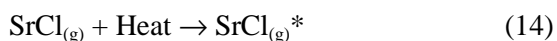
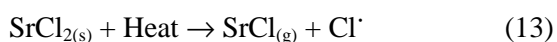


Figure 43. Flame temperature as a function of distance from burning surface.

generation is concerned, the only important difference is temperature and that difference is not great.

Thus an appropriate definition of a flame is that region surrounding a source of chemically generated heat energy where the temperature is sufficient for the emission of visible light.

In the generation of color in pyrotechnics, the flame serves two functions. The first is to supply the heat energy necessary to vaporize the chemical color agent. (Remember only vaporized atoms and molecules can be sources of useful flame color. Solid particles and liquid droplets emit undesirable continuous spectra.) The second function is to supply the heat energy necessary to excite electrons in the color agent in preparation for their decay and consequent emission of light. Using chemical equations for a strontium red flame, the process can be represented as:



#### 4.2.2 The Source of Energy in a Flame

The energy for colored light production is the result of combustion. The general formula for combustion is:



As a starting point in this discussion, it is worth considering how the heat energy of combustion is generated and why different fuels and oxidizers generate differing amounts. When atoms come together to form molecules, chemical bonds form between the atoms. These chemical bonds hold the atoms together as a molecule, and are the result of electronic forces caused by either a transfer or a sharing of electrons between atoms. It requires energy to break chemical bonds and energy is given off when new chemical bonds form. The stronger the bonds, the more energy is required to break them and the more energy is given off upon their formation. The strength of the chemical bond depends on the type and number of atoms forming the molecule.

During a chemical reaction, chemical bonds are broken and new ones are formed. If heat is to be produced during a chemical reaction, then, on the average, the chemical bonds formed must be stronger than those broken. This is the case with combustion, oxidizers and fuels have chemical bonds that are weak when compared with chemical bonds of the reaction products. When various fuels and oxidizers are used, different numbers of bonds will be broken and formed between different kinds of atoms. Thus it should be expected that varying amounts of energy will be produced in these different combustion reactions. The energy released by some common oxidizers reacting with carbon (charcoal) to produce carbon dioxide (CO<sub>2</sub>) is listed in Table 4. Here, the unit kcal (kilocalorie) is used as a measure of the heat produced in the reaction.

In Table 4, note that potassium perchlorate and not potassium chlorate produces the greater amount of heat energy. This is typically true for KClO<sub>4</sub> and is not an isolated result caused by using carbon as the fuel. For the most part, it is the result of KClO<sub>4</sub> containing one additional oxygen atom per molecule in comparison with KClO<sub>3</sub>. The additional oxygen atom is available to form a strong bond with a carbon atom, thereby releasing more energy. The result is that KClO<sub>4</sub> is the more potent generator of heat energy. This may seem to contradict your experience. You may have observed that formulations using KClO<sub>3</sub> are often easier to ignite and

**Table 4. Energy Released by Some Common Oxidizers.**

Oxidizer	Energy Released	
	kcal/mol	kcal/g
KClO <sub>4</sub>	189	1.4
KClO <sub>3</sub>	146	1.2
Sr(NO <sub>3</sub> ) <sub>2</sub>	146	0.7
Ba(NO <sub>3</sub> ) <sub>2</sub>	131	0.5
KNO <sub>3</sub>	42	0.4

Note: In each case the fuel is charcoal and it is oxidized to CO<sub>2</sub>. The results were calculated using data published in Shidlovskiy (1964, p. 24) and Douda (1964, p. 46).

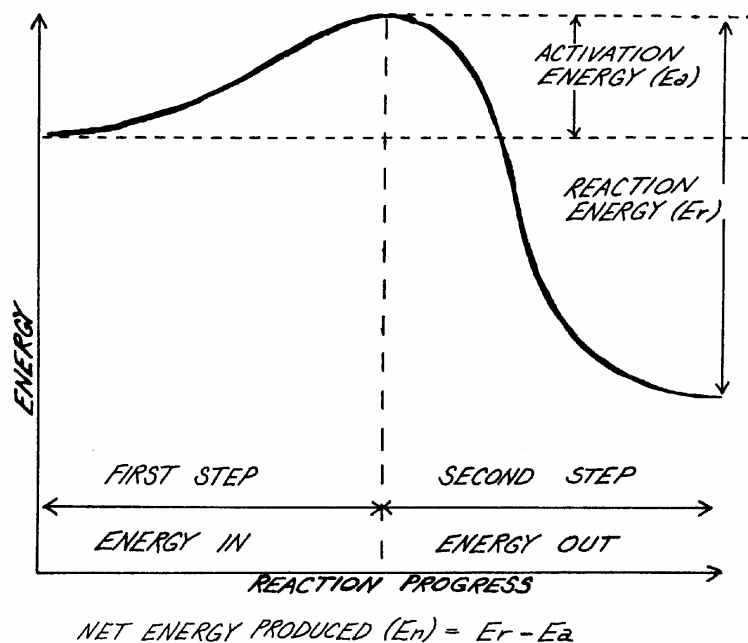


Figure 44. Generalized chemical energy level diagram.

more resistant to being extinguished when moving at high velocities through the air than are formulations using  $KClO_4$ . These observations are accurate (Shimizu, 1981, p. 23) but are not the results of  $KClO_3$  being the better heat producer. This will be discussed below.

Even though a formulation has the ability to generate heat energy, it usually requires an input of energy to begin the process. For example, before a star gives off energy in the combustion process, it is necessary to add heat energy (i.e., to light it). Chemical reactions can usually be broken into these two parts with respect to energy production. It is possible to think of the first step as when old chemical bonds are being broken. This requires energy, called activation energy in Figure 44. In a very real sense, this is an energy barrier that must be surmounted before the reaction can begin. Similarly, the second step can be thought of as when new chemical bonds are being formed. This liberates energy. In terms of the amounts of energy involved, the two steps are mostly unrelated. The activation energy can be large or small and has little effect on the amount of energy produced by the reaction. In Figure 44 the difference between the activation energy (en-

ergy in) and the reaction energy (energy out) is the net energy generated by the reaction. The energies in Table 4 correspond to the net energy generated in Figure 44.

Activation energy is a measure of how difficult it is to initiate a reaction. If the activation energy is large, the reaction is difficult to get started, and is also difficult to keep going. If the activation energy is small, the reaction is easily started and kept going. If the activation energy is zero, the reaction will start spontaneously. Formulations containing potassium chlorate have rather low activation energy barriers to surmount. This has the desirable effect of making these formulations easy to light and they tend to stay lit when moving at high velocities. However, this low energy barrier is also the reason  $KClO_3$  formulations are rather friction and shock sensitive. Similar formulations containing potassium perchlorate have a higher activation energy barrier, but also produce more energy during the reaction. Figure 45 shows chemical energy level diagrams for typical formulations containing  $KClO_3$  and  $KClO_4$ .

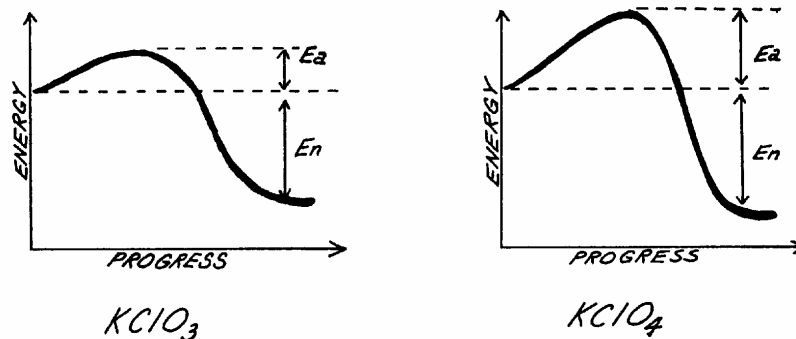


Figure 45. Comparison of  $KClO_3$  and  $KClO_4$  formulations.

### 4.2.3 Flame Temperature in Color Production

For the most part, the flame temperatures produced are a function of the amount of energy released in a chemical reaction. The more energy released during a fixed period of time, the higher the flame temperature. Thus, in Table 5, which is a compilation of flame temperatures taken from Shimizu (1976, p. 74), the order of flame temperatures produced by the different oxidizers should and generally does follow the same order as the amounts of energy produced when reacted with carbon (listed in Table 4).

The amount of energy produced in combustion, and therefore flame temperature, also depends on the fuel chosen. Table 6 is a listing of flame temperatures observed for some non-metal fuels reacting with  $KClO_4$ ,  $NH_4ClO_4$  and  $Ba(ClO_3)_2$ .

Flame temperature has important ramifications in the production of intensely colored flames. Recall that the characteristic most different between points just inside and just outside a flame was that molecules at one point emit light and those at the other point do not. The type and number of molecules at both points are similar; the difference is that inside the flame the temperature is still high enough for visible light production and outside, it is not. For the most part, at temperatures above that which is required for colored light production, the higher the temperature, the greater the amount of light produced. In addition, the relationship between temperature and light produc-

tion is non-linear; a small change in temperature causes a large change in light production. Thus one of the criteria for intensely colored flames is high flame temperature. Another criterion is to have a high concentration of the color generating molecules (atoms) in the flame. Unfortunately, as more color agent is added to a colored flame formulation, more energy must

Table 5. Maximum Flame Temperatures of Oxidizers with Shellac (Data from Shimizu, 1976, p. 74).

Oxidizer	%	Fuel	%	Flame Temp. (°C)
$KClO_4$	74	Shellac	16	2247
$NH_4ClO_4$	76	Shellac	14	2207
$KClO_3$	77	Shellac	13	2177
$KNO_3$	72	Shellac	18	1697

Note: All mixtures contained 10%  $Na_2C_2O_4$ .

Table 6. Flame Temperatures, in Degrees Celsius, of Oxidizers with Various Fuels (Data from Shimizu, 1976, p. 74).

Fuel	$KClO_4$	$NH_4ClO_4$	$Ba(ClO_3)_2$
Pine pitch	2465	2238	2177
Colophony	2322	2092	2237
Shellac	2245	2198	2032
Woodmeal	2057	2025	1688

Note: All mixtures contained 10%  $Na_2C_2O_4$ , necessary to measure flame temperature.

be used to vaporize it. The consumption of this energy lowers flame temperature, lowering light output. Thus a compromise must be struck, as shown in Figure 46, between too little color agent and too low a flame temperature. Obviously fuel/oxidizer combinations that produce high flame temperatures have the advantage of being able to accommodate greater amounts of color agents and are thus capable of producing more vividly colored flames.

Some fuel/oxidizer combinations produce flame temperatures so low as to be virtually useless for the production of colored flames. For example, the only intense color that can be produced using  $\text{KNO}_3$  and non-metal fuels is yellow.

One way to partially overcome the loss of energy taken to vaporize the color agent is to use a color agent that is itself an oxidizer. For example, using  $\text{KClO}_4$  and red gum as the primary source of thermal energy, considerably more strontium can be added to the formulation, without seriously lowering flame temperature, in the form of  $\text{Sr}(\text{NO}_3)_2$  than  $\text{SrCO}_3$ . This is because  $\text{Sr}(\text{NO}_3)_2$  can itself react with red gum to produce additional heat energy.

Another way to increase the amount of color agent in a formulation without lowering flame temperature to a point too low for good color production, is to start with a fuel/oxidizer combination that is capable of producing very high flame temperatures. This can be accomplished using a metal fuel: aluminum, magnalium or magnesium. A comparison of Tables 5 and 6 with Table 7 demonstrates the ability of magnesium to significantly increase flame temperature. In terms of maintaining color purity, mag-

**Table 7. Metal fuel flame temperatures (data from Shimizu, 1976, p. 76).**

Oxidizer	Flame Temp (°C)	Magnesium %
$\text{KClO}_4$	2987	45
$\text{KNO}_3$	2552	60
$\text{Sr}(\text{NO}_3)_2$	2902	45
$\text{Ba}(\text{NO}_3)_2$	2717	45

Note: All mixtures contained either 10% PVC or 10% shellac.

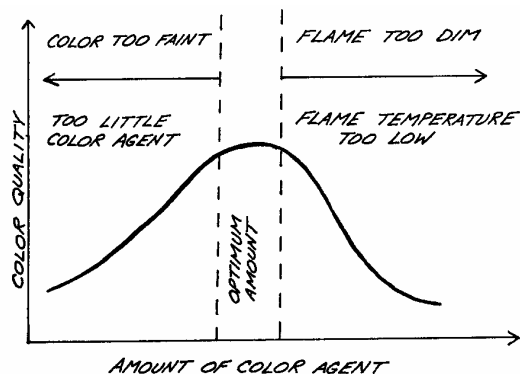


Figure 46. Optimum amount of color.

nesium is the best choice, followed next by magnalium, and then by aluminum. This is because when aluminum is burned, aluminum oxide, a source of white light, is formed. This reduces the purity of the colored flame produced.

Fuel and oxidizer combinations capable of producing high temperatures are important for producing intensely colored flames. However, the very highest flame temperatures are not usually the best. The chemical species responsible for generating intensely colored pyrotechnic flames are almost always molecules. At very high temperatures, these desirable light producing molecules decompose. This is a double-barreled problem; not only does decomposition result in a loss of desirable light emitters, but the products of decomposition are almost always undesirable light sources. This can result in a serious loss of color purity in the flame.

### 4.3 Color Production in Flames

#### 4.3.1 Desirable Color Generating Chemical Species

Table 8 is a list of the metals commonly used to produce colored pyrotechnic flames. Also included are the chemical species actually responsible for the color. Note that in all cases except sodium, it is molecular compounds (not atoms) that are the color generating species. For example, the red color generating species are  $\text{SrOH}$  and  $\text{SrCl}$ . Strontium atoms not only don't produce red light, they interfere with the production of intensely colored red flames; stron-



**Table 8. List of Metals Commonly Used to Generate Colored Pyrotechnic Flames (Basic Data from Douda, 1964).**

Metal	Color	Color Generating Species	Approximate (equivalent) Wavelength (nm)
Strontium	Red	SrCl	630
	Red-orange	SrOH	610
Barium	Green	BaCl	520
	Green	BaOH	weak emitter
Copper	Violet-blue	CuCl	450
	Green	CuOH	540
Calcium	Orange	CaOH	600
	Red-orange	CaCl	610
Sodium	Yellow	Na <sup>0</sup> (atoms)	589

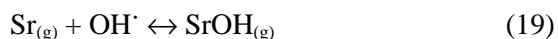
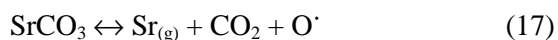
Note: In general, any of the halogens (group VIIA) can be substituted for chlorine in the metal monochlorides.

tium atoms emit a mixture of blue and violet light.

Table 9 is a listing of some other, rarely used, metals that can be used to produce colored pyrotechnic flames. The reason these metals are not used is their generally high cost and technical limitations.

#### 4.3.2 Typical Flame Reactions and Detrimental Color Generating Species

It rarely occurs that color agents added to a formulation are the color generating species listed in Table 8. For example, the source of strontium is usually SrCO<sub>3</sub> or Sr(NO<sub>3</sub>)<sub>2</sub>. Thus it is usually necessary to form the color generating molecules in the flame itself. In general, the mechanism is first to break apart the color agent. Then, by providing a source of the proper non-metal atoms or atom groups, allow the desired chemical species to form. For strontium a simplified version of this can be represented as:



**Table 9. List of Metals Rarely Used to Produce Colored Pyrotechnic Flames (Basic Data from Douda, 1964).**

Metal	Color	Color Generating Species	Approximate (equivalent) Wavelength (nm)
Lithium	Red	Li <sup>0</sup>	650
Rubidium	Red	Rb <sup>0</sup>	630
Cesium	Blue	Cs <sup>0</sup>	460
Boron	Green	BO <sub>2</sub>	530
Thallium	Green	Tl <sup>0</sup>	530

NOTE: Cl<sup>·</sup> and OH<sup>·</sup> are not stable chemical species at room temperature; however, they can be formed and are stable at flame temperatures.

Unfortunately, these reactions are not the only possibilities in a strontium flame. Figure 47 is an attempt to summarize the most important flame reactions for strontium. To some extent all of the reactions in Figure 47 take place. The problem is that strontium monochloride (SrCl) and strontium monohydroxide (SrOH) are the only chemical species that generate good quality red light. The light generating properties of all the others are more or less detrimental (see Table 10).

Because of the production of chemical species that seriously reduce color quality, and in order to optimize the production of useful species, it is necessary to control the reactions taking place in flames.

**Table 10. Partial Listing of Chemical Species, Present in Strontium Red Flames, That Have Undesirable Light Generating Properties.**

Chemical Species	Detrimental Effect
SrCl <sub>(l)</sub> or <sub>(s)</sub>	strong continuous spectrum
SrO	blue-violet color
Sr <sup>+</sup>	violet color and continuous spectrum from ion recombinations
SrO <sub>(s)</sub>	orange color

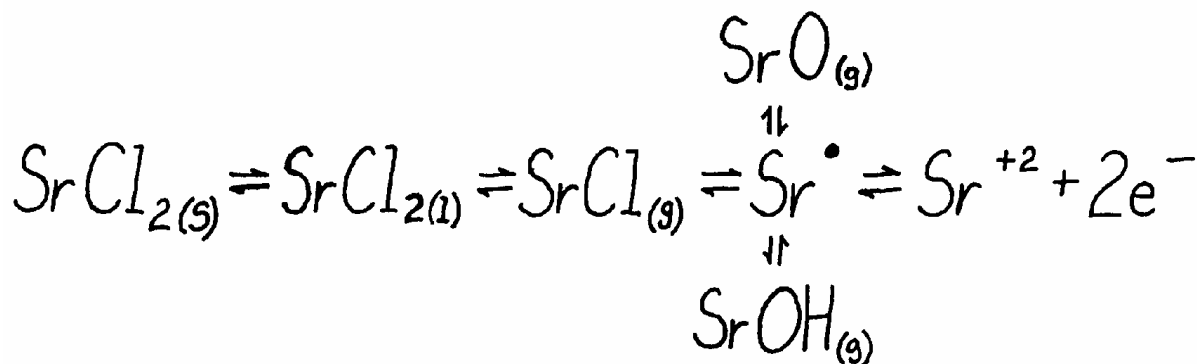
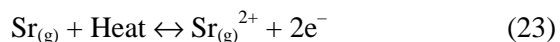
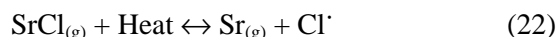
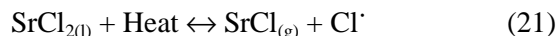
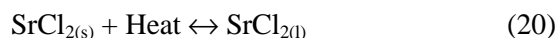


Figure 47. A representation of some of the possible reactions for strontium in a flame (taken from Douda, 1964). NOTE: In order to simplify the figure, some reactants and products are not explicitly shown.

### 4.3.3 Control of Flame Chemistry

As discussed earlier, all chemical reactions are reversible; none go 100% to completion. Thus to some extent all those chemical species shown in Figure 47 will be present in a strontium red flame. However, it is possible to preferentially form more of the desirable color emitting species if Le Châtelier's Principle is cleverly used, i.e., when the proper stresses are applied to the chemical system.

In Figure 47, each step moving to the right requires the input of energy. It is as though heat energy was one of the chemical reactants. This is shown in Equations 20 to 23:



Flame temperature is an approximate measure of heat energy available in a flame, thus you can appreciate the importance of flame temperature. It is  $\text{SrCl}_{(g)}$  that we wish to have present in the flame, not  $\text{SrCl}_{2(s)}$  or  $\text{SrCl}_{2(l)}$ . If flame temperature falls too low, this is equivalent to removing heat (one of the reactants). This is a stress on the reacting system. The stress is relieved by some of the  $\text{SrCl}_{(g)}$  combining with  $\text{Cl}^{\bullet}$ , condensing as liquid  $\text{SrCl}_2$  droplets. With the loss of  $\text{SrCl}_{(g)}$ , the red color generating molecule, the purity of the red flame is reduced. On the other hand, if the temperature rises too high, more of

the  $\text{SrCl}_{(g)}$  decomposes into  $\text{Sr}_{(g)}$  and  $\text{Cl}^{\bullet}$ , again reducing color purity. This high temperature problem is unfortunate because the brightness of a colored flame increases significantly with relatively minor increases in temperature. Thus it would be desirable to have the flame temperature as high as possible.

One way to allow a higher flame temperature, without a loss of  $\text{SrCl}_{(g)}$  by decomposition, is to balance the stress caused by adding heat, by adding more of one of the products,  $\text{Cl}^{\bullet}$  for example. One benefit of using  $\text{KClO}_3$  or  $\text{KClO}_4$  as the oxidizer in this type of colored flame production is their ability to contribute some  $\text{Cl}^{\bullet}$  to the flame. Substantially greater amounts of  $\text{Cl}^{\bullet}$  (or  $\text{HCl}$  which is equivalent) can be added using most any chlorine-rich compound that does not interfere in some way with other aspects of flame chemistry. Among the important properties of these chlorine donors are: a high percentage of chlorine, a low heat of decomposition, and the ability to decompose under conditions present in flames. Table 11 lists a number of chlorine donors commonly used in fireworks and their percentage of chlorine. Other properties to take into consideration when selecting a chlorine donor are toxicity, cost, the ability to act as a fuel, and the ability to consume excess oxygen in a flame.

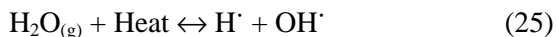
It is worth mentioning that any halogen (i.e., group VIIA element) can be used in place of chlorine. Strontium fluoride,  $\text{SrBr}$  and  $\text{SrI}$  are all useful emitters of red light. However, shifts

**Table 11. Percent Chlorine of Common Chlorine Donors.**

Name	Formula	Chlorine %
Hexachlorobenzene	C <sub>6</sub> Cl <sub>6</sub>	74
Benzene hexachloride	C <sub>6</sub> H <sub>6</sub> Cl <sub>6</sub>	73
Parlon (poly, 2-methyl 1,3 butadiene)	(C <sub>5</sub> H <sub>6</sub> Cl <sub>4</sub> ) <sub>n</sub>	68
Calomel (mercury(I) chloride)	Hg <sub>2</sub> Cl <sub>2</sub>	15
Chlorowax	variable	40–70
PVC (polyvinyl chloride)	C <sub>2</sub> H <sub>3</sub> Cl	57

of dominant wave lengths occur, compared to SrCl, as the result of differing atomic weights and bond strengths.

Another chemical species responsible for strontium red light production is SrOH<sub>(g)</sub>. Strontium monohydroxide is not as desirable a color emitter as SrCl<sub>(g)</sub> because it emits orangish-red light. However, if conditions in the flame are such as to favor SrOH formation, this too would be good. The best way to achieve production of SrOH is to provide a generous supply of hydroxyl radicals (OH<sup>·</sup>). This happens automatically whenever hydrocarbons are present in a color formulation, which is most of the time. Organic resin fuels, most organic chlorine donors and dextrin are all hydrocarbons. When a hydrocarbon reacts with a source of oxygen, water vapor is one of the reaction products. At the temperature of a pyrotechnic flame, some of the water vapor breaks down into H<sup>·</sup> and OH<sup>·</sup> radicals. The process is shown in Equations 24 and 25 for the simplest hydrocarbon, methane (CH<sub>4</sub>).



It is worth noting that B. Douda (private communication) reports only having observed SrOH in relatively low temperature flames, never when metal fuels were used. He conjectures that SrOH is unstable at high temperature.

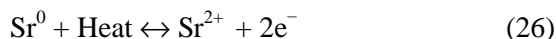
Chlorine donors and hydrocarbons aid in the production of useful red color emitters based on strontium. As such it is appropriate to consider both of them “color enhancers” for strontium

reds. Much of the same is true for barium greens, copper blues and calcium oranges. This is true because in each case the useful color emitters are monochlorides and monohydroxides (see Table 8).

In cases such as sodium yellows or lithium reds, chlorine donors and hydrocarbons do not act as color enhancers. In these cases, it is neutral metal atoms (Na<sup>0</sup> and Li<sup>0</sup>) that are the desirable color generating species. Sodium and lithium monochlorides and monohydroxides are undesirable light emitting species. Thus the addition of chlorine donors or unnecessary hydrocarbons do not enhance the color, they weaken it by consuming desirable species and generating undesirable species. This is not much of a problem for sodium yellow, because sodium is an unusually powerful color emitter and the weakening will not be noticeable. However, for the weaker lithium reds, these so-called color enhancers must be avoided.

I still need to discuss what can be done to further limit production of the undesirable species, Sr<sup>2+</sup> and SrO<sub>(g)</sub>. I intentionally said “further limit” because those things mentioned above that foster increased production of SrCl and SrOH also help limit production of Sr<sup>2+</sup> and SrO. This is because all four are competitors for Sr<sup>0</sup> in the flame. The more SrCl and SrOH made, the less Sr<sup>0</sup> is available to form strontium ions or oxide.

One way to limit strontium ionization,



is to stress the reaction in the reverse direction. This could be done by removing heat energy from the flame, but remember this has the undesirable effect of lowering flame temperature, thereby reducing light output. A better way is to provide a source of free electrons, one of the reaction products. Although this may sound difficult, it is not. In fact you normally provide for this, without realizing it. The introduction of any easily ionizable metal into the flame will supply electrons to the flame. If the metal ionizes more easily than strontium, the electrons thus generated will act to suppress strontium ionization. One such metal is potassium, which may already be present in the flame, if for example KClO<sub>4</sub> or KClO<sub>3</sub> is used as oxidizer in the color formulation. Because of their ability

**Table 12. First Ionization Energies of Metals Usable for Light Generation (From Data Presented in Sargent-Welch's Periodic Table Catalog S18806).**

Metal	First Ionization Energy (kcal/mole)
Copper	178
Calcium	141
Strontium	131
Barium	120
Sodium	119
Potassium	100

to suppress other undesirable ionization in flames, metals such as potassium are sometimes referred to as "ionization buffers". See Table 12 for a listing of ionization energies for potassium and metals commonly used for colored light generation.

Probably the best way to limit formation of SrO in flames is to limit, as much as practical, the presence of oxygen radicals in the flame. Obviously the first thing to do to accomplish this is *not* to use an excess of oxidizer in the formulation. (Another good reason to do this is that slightly fuel rich flames tend to have larger flame envelopes.) However, even fuel rich flames will pick up additional oxygen from the air, leading to the formation of oxides in the flame tips. For strontium this is not that noticeable, because the formation of SrO produces orange flame tips. On the other hand, in barium greens, this produces yellow flame tips and in copper blues produces pink flame tips. The objectionable production of oxides in flame tips can sometimes be reduced by the use of secondary, slow-reacting fuels that consume the excess oxygen. T. Fish (Fish, 1981) recently discussed this for formulations in which magnesium was the primary (more active) fuel. In that work Fish coined the descriptive term "flame deoxidizing agent" for hexamine (hexamethylenetetramine), his choice as the secondary fuel.

## 4.4 Colored Pyrochemical Flames

### 4.4.1 Red, Green and Orange Flames

In the production of intensely colored flames, using strontium for red and barium for green, exactly the same chemical principles apply. In the discussion above, where strontium was used as the example, barium can be substituted in nearly every sentence and chemical equation where strontium appears. The same is almost true for calcium used to produce orange flames, except that CaOH is the preferred orange color emitting species and not CaCl (see Table 8).

A look at the Periodic Table of elements suggests why the interchangeability of Sr, Ba and Ca in the above discussion should not be a surprise. Calcium, strontium and barium are all group IIA elements, and should be expected to follow the same general chemistry.

### 4.4.2 Blue Flames

The standard blue flame is produced using copper. In general, everything that has been said about strontium red flames also applies to copper blue flames. Only a couple of additional points are worth discussing. For strontium reds, both the monochloride and the monohydroxide emit useful colored light. This is not the case for copper blues. The principal emission bands for CuCl fall in the purplish-blue portion of the spectrum. However, those of CuOH fall mostly in the green portion of the spectrum. Thus for effective blue flames, it is even more important to include a generous source of chlorine. However, the presence of a small amount of CuOH in the flame is useful because its green emissions add to the purplish-blue emissions of CuCl to produce a high purity blue light. This color addition is shown on a chromaticity diagram in Figure 48. (For information on scales, wave lengths and colors for the chromaticity diagram, see Figure 31 from Part I of this paper.)

Because of the suspected loss of CuCl by decomposition at relatively low temperatures, it is probably true that temperatures of blue flames cannot be allowed to range as high as strontium reds. However, some of the notions about low flame temperatures have been improperly stated. For example, a reason often expressed for using stearine in blue formulations is that it lowers

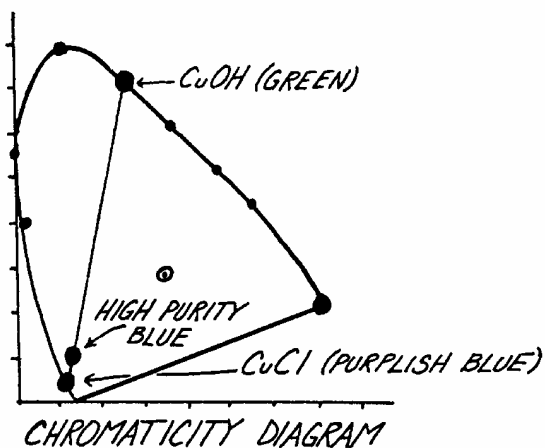


Figure 48. The addition of  $\text{CuOH}$  and  $\text{CuCl}$  emissions in the proper proportion to produce high purity blue light.

flame temperatures. This does not make much sense; a more effective way to lower flame temperature would be to add more copper color agent and/or chlorine donor. Perhaps the beneficial effect of stearine results more from its acting as a flame deoxidizing agent.

#### 4.4.3 Yellow Flames

Yellow is generally thought to be the easiest flame color to produce. The addition of almost any source of sodium will suffice. This is because essentially no attention has to be given to flame temperature, color enhancers, or flame deoxidizing agents, etc. Flame temperatures too low to allow intense production of the other colors can still produce good yellow color. On the other hand, very high flame temperature is not really a problem either. For other color flames, high flame temperatures can result in the loss of desirable color generating species by decomposition. For sodium yellows, it is sodium atoms that are the color generating species; thus there are no molecules to decompose. Ionization will still occur at high flame temperatures, but sodium is so powerful a color source, that this is not much of a problem. Again because it is sodium atoms that emit yellow light, color enhancers are not necessary. Even the formation of oxides at flame tips does not weaken the strong yellow flame color.

There are two factors, however, that make the production of good yellow flames less than trivial. The first is the tendency for double decomposition reactions to occur between water soluble sodium color agents and the oxidizer, when water soluble binders are used. An example of such a double decomposition reaction is:



The problem here is production of  $\text{NaNO}_3$  which is hygroscopic, i.e., tends to pick up moisture from the air. This can result in drying problems, ignition problems and possibly additional decomposition problems with other ingredients because of the retained moisture.

The other area for concern with sodium yellow flames is the use of magnesium or magnalium in the formulation. Again, if the sodium color agent is water soluble and the composition is dampened with water, there is a probability that undesirable reactions will occur, producing potentially dangerous amounts of heat in the mixture. The solution is the same for both problems; either eliminate the use of water soluble binders or use water insoluble sodium color agents. Two such insoluble substances are sodium aluminum fluoride (cryolite) and sodium aluminosulfosilicate (ultramarine), the latter of which requires rather high flame temperatures to be effective.

#### 4.4.4 Purple Flames

In Part I of this paper, the difficulty of producing intensely purple colored flames was discussed. The reason is restated again in the chromaticity diagram in Figure 48, intensely purple colored flames are those whose additive spectral colors produce color points in the shaded region of the chromaticity diagram. The lower the color point falls in the shaded region, the more intensely colored the flame appears. The only way to produce colors in this region is to combine spectral colors from opposite ends of the spectrum (i.e., purple itself is not a "spectral" color). It is commonly believed that high purity purple can result from combining red and blue light. This is not really true, red and violet (purplish-blue) light are the necessary ingredients. Remember from the discussion above that the formation of a small amount of  $\text{CuOH}$  (green) is useful, tempering the purplish-blue

light of CuCl and producing a high purity blue flame (color point A in Figure 49). Similarly, the production of both SrOH (red-orange) along with the preferred SrCl (red) still produces an effective red flame (but with its color point shifted from color point B to C). When these colors (points A and C) are added in the approximate ratio of 4:1, a relatively low purity purple flame results (color point D). When these colors (points A and E) are added in the approximate ratio of 4:1, a relatively high purity purple flame results (color point F). Thus the key to production of high purity purple flames is to foster the production of CuCl and SrCl and limit the production of CuOH and SrOH. This can be accomplished by using fuels and chlorine donors that do not contain hydrogen atoms. Metal powders and carbon are possible fuels. Hexachlorobenzene ( $C_6Cl_6$ ) and mercury(I) chloride ( $Hg_2Cl_2$ ) are possible chlorine donors. Organic binders (hydrocarbons), like dextrin and red gum, should be avoided. For a binder, it might be possible to use hexachlorobenzene, which is soluble in benzene. (Note that benzene is a carcinogen.) B. Douda (private communication) has suggested that high flame temperatures may also aid in the production of good quality purple flame. This is because he believes CuCl and SrCl (the desired color sources) are more stable than the hydroxides at high temperatures.

### Acknowledgments

I wish to gratefully acknowledge the comments and suggestions of R. M. Winokur and other members of the Pyrotechnica staff, and especially the technical comments of B. E. Douda and his colleagues at the US Naval Weapons Support Center (Crane, IN).

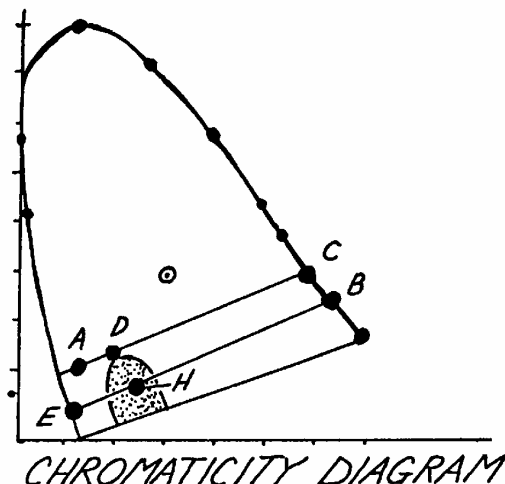


Figure 49. Why a good purple is still tough, but not impossible.

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**END OF PART II**

## An Idea for Small Shows

Ken Kosanke

One problem commonly faced by smaller display operators is the sponsor of an inexpensive show (\$1000 to \$5000) who wants a longer show than he has money for. The obvious solution, slowing down the firing, is usually a poor choice. Some slowing may be practical, but often the sponsor of these small shows wants about twice as much show as they have money. If you slow things down that much, you are guaranteed to disappoint the audience.

Almost all the displays we do are small shows. As the result, we have spent considerable time trying to come up with ways to give more show for the same money. One idea that has worked particularly well, when circumstances allow, is to interrupt the show with a short fireworks demonstration. Two benefits are achieved by doing this. First, during the demonstration relatively inexpensive fireworks are shot at a very slow pace (without boring the audience). In the demonstration described below, only 11 three-inch shells, 1 five-inch shell and a few festival balls are fired over a period of about six minutes. This would seem intolerably slow if it were part of the show, yet as a demonstration of aerial fireworks it is most enjoyable for the audience. Second, after the interruption of the show for the demonstration, relatively small fireworks will again appear impressive to the audience. Generally, as one progresses through the firing of a display, in order to continue to impress the audience, it is necessary to gradually increase the size of shells being fired. However, if the audience's attention is diverted for five or six minutes by the demonstration, subconsciously they "forget" that five minutes earlier it took a relatively large aerial shell to impress them. Thus small shells can again be used in the show, making the show still longer, for the same money and without disappointing the audience.

Before giving the text of the demonstration, a few words of explanation and caution are appropriate. First, in order to do this type of demonstration it is necessary to have someone and

some way to communicate with the audience. In the past we have used both PA equipment (when the audience is seated in bleachers) and local radio broadcasts (when the audience is in parked cars). Second, for the demonstration described below, it is necessary for the audience to have a fairly clear view of the shooting site. Third, our shows are fired (usually electrically) from individually loaded paper tubes above ground; this facilitates the inclusion of ascending flowers and mine effects, but is probably inappropriate for conventionally fired shows. In the text below, when reference is made in parenthesis to a specific size and type aerial shell, that is the point in the demonstration when that shell is fired.

### Fireworks Demonstration

We are going to try something a little different tonight; we are going to spend a few minutes demonstrating and explaining basic aerial fireworks. We are trying this new idea because we think it will be interesting for you and because we believe that your enjoyment of fireworks will be increased when you better understand what you are seeing. If you enjoy this little demonstration, let us know and we may be able to include lesson number two as part of next year's show.

- 1) What you have been seeing tonight are aerial shells, not sky rockets. Sky rockets are unstable which makes them too dangerous and they carry too little payload into the air. As a result, sky rockets have not been used to any great extent in fireworks shows for at least 30 years.
- 2) Aerial shells are fired out of a tube in the ground using a small lifting charge of Black Powder. When the shells are fired, you will notice a flash near the ground as the lifting charge propels the shell into the air. (3" spherical shell) The fire from the lifting charge also lights a time delay fuse which

burns as the aerial shell rises into the air. You may be able to spot a faint trail of sparks from the fuse as it is burning on the way up. (3" canister shell) When the delay fuse burns through the wall of the aerial shell, a second explosive charge is ignited, bursting open the shell and igniting and dispersing the shell's contents. (3" canister shell)

- 3) There are two basic varieties of aerial shells. One type is a cylindrical or canister shell. This type was developed by the Italians and for several hundreds of years was the only type of shell. The shell is basically can shaped with a fuse on one end. Typically, when the shell breaks, the contents are propelled out through one end in a sort of fan shape. (3" canister shell) The other primary type of shell is a spherical or ball shell. These were developed by the Japanese. The shell is ball shaped with the fuse on the bottom. Typically this type of shell breaks much more violently and the contents are propelled out spherically like a giant expanding hollow ball. (3" spherical shell) Look once more to see the difference; first a cylindrical shell (3" canister shell); now a spherical shell (3" canister shell).
- 4) All of the shells fired tonight have been one of these two types. However, to make the shells appear more interesting, most have had a couple of additions. First has been the addition of a few smaller aerial shells fired into the air at the same time from the same tube on the ground. These smaller aerial

shells are sometimes called ascending flowers. (3" spherical shell plus 3 Festival Balls) Second has been the addition of what is called "mine" effects. This is accomplished by adding "stars" to the lifting charge of Black Powder. Stars are chemical formulations that burn with different colors and/or leave a trail of sparks when they burn. The aerial shells you have been watching have been filled with a few of the many different kinds of stars. When these same stars are added to the lifting charge, the result is a firework mine. (3" canister shell plus mine effect) When both ascending flowers and a mine effect are added, the result is considerably more attractive than just a single aerial shell. (3" spherical shell plus festival balls plus mine effect)

- 5) By way of concluding this little demonstration, let's say something about the size of aerial shells. The shells we were firing for the demonstration have all been 3" in diameter, excepting the ascending flowers which were only 1-3/4" in diameter. In the show thus far, we have fired shells of less than 1" in diameter, up to shells that are 6" in diameter. Later in the show we will fire two 8" shells. To give you some idea of the effect size has, first, look at another three-inch shell. This shell is called "Winter Rose". (3" spherical shell) Now let's fire the 5" version of the same "Winter Rose" (5" spherical shell)

Now, let's get back to the show.



# Electrical Firing of Musically Choreographed Aerial Fireworks Displays

K. L. and B. J. Kosanke

## 1.0 Introduction

There are a number of reasons why one might be reluctant to consider abandoning traditional show firing methods in favor of performing electrically fired shows, especially those choreographed to a musical program. One reason is the perceived high cost of performing such shows. Other reasons might be a lack of detailed knowledge about performing such displays or the lack of a full appreciation of the benefits to be gained. It is the purpose of this paper to present detailed information concerning the staging of electrically fired aerial displays choreographed to music. However, in the process we hope to show how high initial costs can be offset in a relatively short time by increased profit. Also we hope it will become clearer that there are other benefits to be gained.

This paper is divided into two major sections. The first discusses electrical firing methods, not from a theoretical orientation, but rather by addressing the practical application of theory. (Note that a comprehensive and well written discussion of theoretical aspects of electric matches, wiring and firing controllers has been authored by Sam Bases.<sup>[1]</sup> The second section addresses details of musically choreographed display design and performance.

This paper will discuss the methods used by the authors for shows priced between \$1,000 and \$20,000. This approach was chosen in part to limit the length of this paper, but mostly because it is only these methods about which the authors have had extensive experience. Certainly it is not intended to imply that these methods are the only approach or even the best approach. However it should at least serve to demonstrate all the important aspects of electrically fired shows choreographed to music. For readers who have not yet begun performing such displays, hopefully, this paper will serve as a starting point from

which their methods can be developed. For readers already performing such displays, this paper may present some alternate ideas that may be of some use.

## 2.0 Electrical Firing, Applied

### 2.1 Basic Requirements

The basic requirements of any method for electrical firing, in order of importance, are safety, reliability, and ease of set-up and firing. A full discussion of these requirements is most appropriate; however, they will only be mentioned at this time. The discussion of these requirements is distributed throughout the paper as this method for electrically firing displays is presented.

### 2.2 Dense-Pack Mortar Trailers

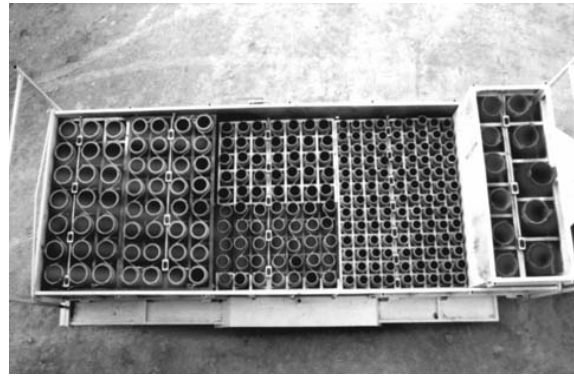
A key concept in this electrical firing method involves the use of "dense-pack" mortar trailers. An example of one of these trailers is shown in Photos 1 and 2. This particular trailer has a bed six by 16 feet, a loaded weight of 7500 pounds, and contains 117 3-inch, 70 4-inch, 32 5-inch, and 21 6-inch paper mortars (note that plastic mortars could have been used). In addition 11 steel mortars, ranging from 7 to 12 inches in diameter, can be placed in a special rack in the front of the trailer. The trailers have the wiring for electrical firing built in, such that final preparation for firing is to simply plug-in the entire trailer. All electrical firing control wiring is in metal conduit to protect the wiring from damage and to shield the wiring from RF transmissions. The mortars are "aimed" by parking the trailer with the tongue pointing away from the fall-out zone, and then using the hydraulic tongue jacks to properly angle the mortars as illustrated in Photo 1. To eliminate any chance of unintentional trailer movement, its wheels and frame are blocked in position (not shown). If for reasons of safety the mortars



*Photo 1. Side view of large "Dense-Pack" mortar trailer raised into possible firing position.*

need to be re-aimed, all 251 mortars can be completely repositioned in only a few minutes by removing the trailer blocks, releasing the tongue jacks, pulling the tongue to one side or the other, then hydraulically raising the tongue again and re-blocking.

The mortars are held in place by a grid-like frame-work made of square tubular steel that loosely surrounds each mortar at its base, mid-point, and near the top. To prevent any chance of a mortar rebounding from its proper position after firing, a piece of elastic cord is woven back and forth between the mortars of each row. (This has the added benefit of slightly cocking the mortars back and forth which helps to disperse the shells in the air.) Because of the close packing of mortars and the lack of complete protection of one mortar from the next, large salutes are normally not fired from the trailers (the use of multiple smaller salutes is discussed below). Thus far, on those few occasions when star shells have exploded and destroyed the paper mortar in which they were loaded, there has never been serious damage to the surrounding mortars and no damage whatever to the rack frame. Further, in terms of safety, it is hard to imagine that it is possible to damage another mortar or the steel frame seriously enough to represent a public safety problem. Even if an adjacent mortar were seriously damaged without the knowledge of the operator, it will still be aimed properly. It is quite possible, if an unfired shell is in the mortar, that it will jam in the mortar and flower-pot when fired, or, if it leaves the mortar, it may have insufficient altitude. However, if normal safety distance requirements have been observed and a properly



*Photo 2. Overhead view of large "Dense-Pack" mortar trailer.*

sized fallout area has been provided, there should be no risk to the public or operator. (Of course the most appropriate action to take if there is any suspicion of possible mortar damage is to interrupt the display to inspect the mortars.)

In addition to safety considerations discussed above, there are two others worth mentioning. Once shells are loaded into mortars, fused and individually covered as described below, the possibility of a careless smoker or stray sparks during a show causing a disastrous mass ignition of shells is eliminated. In addition, since all shells are secured in individual mortars in a small, easily policed area, the likelihood of the theft of shells is greatly reduced.

There are a few other features of this trailer that are worth mentioning. First are the carrying racks on top, which can be used for transporting poles and other set-piece materials to the site, or more importantly, with the aid of three 2 × 4's and two tarps, they can be used to provide a sheltered work place protected from sun and rain. Note that it is only the center support that must be removed from the trailer during the firing. Also shown is a pole with a mercury vapor light on top. This is stored under the trailer until after the show, at which time it and others are easily erected to provide a well-lighted work area during clean-up. On the sides of the trailer is a foot wide platform, for standing on while loading mortars. Electrical firing cables are long, heavy and expensive. The use of sturdy garden hose reels facilitates easy lay out and retrieval of cable and at the same time minimizes damage from twisting, knotting or kinking. (Note that during a show, cable on any



*Photo 3. View of small “Dense-Pack” mortar trailer.*

reel where burning fall-out is possible should be protected by covering or should be removed to a safe place.) Finally there is a metal storage box in front of the trailer, which is useful for transporting and/or protecting trailer blocks, tarps, electrical cords, and other equipment.

Smaller, similarly-constructed trailers are also used (see Photo 3). This trailer has a bed roughly four by six feet and, loaded, weighs 1000 pounds. Its capacity is 32 3 or 4-inch paper mortars plus 20 sets of smaller mortars. For protection of the small mortar sets from accidental damage and sparks (unintentional ignition), each set is placed inside a large diameter plastic tube. The tubes are 8-inch ID with 3/8-inch walls, are slightly longer than the mortar sets, and have a 1½-inch thick wooden plug in the bottom (see Photo 4). To exclude sparks and burning debris from above, each plastic tube is covered with an 8-inch diameter cardboard disc taped over its open end. Typically the small mortar sets will be either four 2½-inch mortars, six 2-inch shell mortars, four 2-inch salute mortars, or twenty 1-inch salute mortars. (The effective use of large numbers of smaller shells and salutes is discussed in Section 3.2 of this paper.) These small trailers can be used singly for very small shows or for modest finales. One or more can be used in conjunction with larger trailers to provide multiple shooting sites. It is also possible to have larger trailers supporting two to four of these small racks. When more than one rack is used on a single trailer, it is possible to spread aerial effects more widely in the sky if the individual racks can be angled (tipped slightly) to opposite sides.

Only 1 and 2-inch salutes are routinely fired from dense-pack trailers. When this is done the mortars are protected from each other using small steel frameworks which are placed inside the 8-inch plastic tubes mentioned above (see Photo 4). Of the relatively few 3-inch salutes used, most are fired from paper tubes staked separately above ground alongside the trailers. On those rare occasions when a 3-inch salute is fired from a trailer, it is arranged for it to be surrounded by empty and/or already-fired mortars. Four-inch, or larger, salutes are not used.

It is suggested that only single-break shells be used in shows fired from dense-pack trailers. There are two reasons for this. The first is related to safety. Single-break shells put less strain on the paper (or plastic) mortars and are less likely to do serious damage to the firing mortar and adjacent mortars in the event of a flowerpot or shell detonation. However, more importantly, in the event of any of the possible shell malfunction modes, multi-break shells offer greater risk



*Photo 4. View of small one and two inch mortar frames and heavy walled plastic tube used to protect adjacent mortar when firing small salutes.*

to public safety than do single-break shells. They also tend to generate more burning fallout because of their heavier construction. The second reason for not using multi-break shells is economic. Multi-break shells in comparison with multiply fired single-break shells cost more and generally offer the audience little by way of added entertainment. When hand firing, multi-break shells do offer the advantage of allowing more breaks to be put into the air in a given amount of time. With electrical firing, it is easy to put up any number of shells in a given time. Further, multiply fired single-break shells can reproduce virtually any effect created by multi-break shells (and many they cannot). When the cost of a multi-break shell is compared with an equivalent number of single-break shells, the multi-break shell usually costs 10 to 20% more and their break sizes are often smaller. However, there is one situation in which multi-break shells are useful. That is when the shells are fired slowly and the audience is close enough and astute enough to see that it is a single shell breaking again and again. Even under these conditions, it is only effective to use a few of these shells during a show, and this can be done with steel mortars outside of the trailers.

By way of demonstrating the effectiveness of dense-pack mortar trailers, consider the following. Over a recent July Fourth season, using these trailers and the methods further described below, four displays were performed in four days, and were performed by the two authors essentially without assistance. These displays consisted of more than 5000 aerial effects and were geographically separated by as much as 250 miles (and several mountain passes).

### 2.3 Chain Firing

As may be seen from careful examination of Photo 2, the electrical wiring and connection terminals only run down the center of each rack section. This is shown more clearly in Figure 1, which is a sketch of the 5-inch mortar rack. Note that while there are eight mortars grouped around one set of electrical firing contacts, there is provision for firing only four electric matches. Of course it is possible to use multiple electric matches attached to one pair of terminals, which would fire shells simultaneously. There are times when this is desired but more often some delay between firing is desired. Fur-

ther, in the case of the 3-inch mortar rack, there are only two firing connection points for every nine mortars. Only occasionally is it desirable to simultaneously fire four or five shells, even in shows approaching \$20,000.

Obviously the system could have been designed with one set of firing contacts for each mortar. However this approach was not chosen for several reasons. The first two, and not very important reasons, are economic. The trailer under discussion has 251 mortars but employs only 87 firing circuits. This reduces the cost and complexity of the trailer wiring, cables, and firing control system. Further, only one-third the number of electric matches need be used. These points were considered but are certainly not the main reason for using this arrangement. The fusing method, to be described below, offers the significant advantage that during a show the operator has an average of three times longer between electrical firings. As a result of having more time, it is less likely that firing errors will occur; there is more time for the operator to observe where fallout is occurring and if people have encroached into unsafe areas; there is more time to critically evaluate the performance (the authors occasionally record such observations on tape during the course of firing a show); sometimes there is even enough time to relax for a moment and enjoy the show!

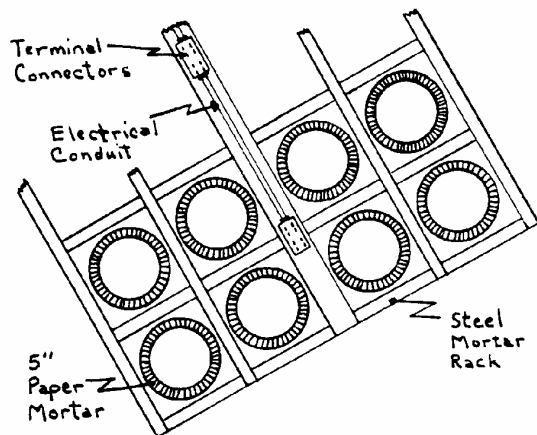


Figure 1. Overhead sketch of a portion of the five-inch dense-pack mortar rack, showing arrangement of mortars and electrical firing contact points.

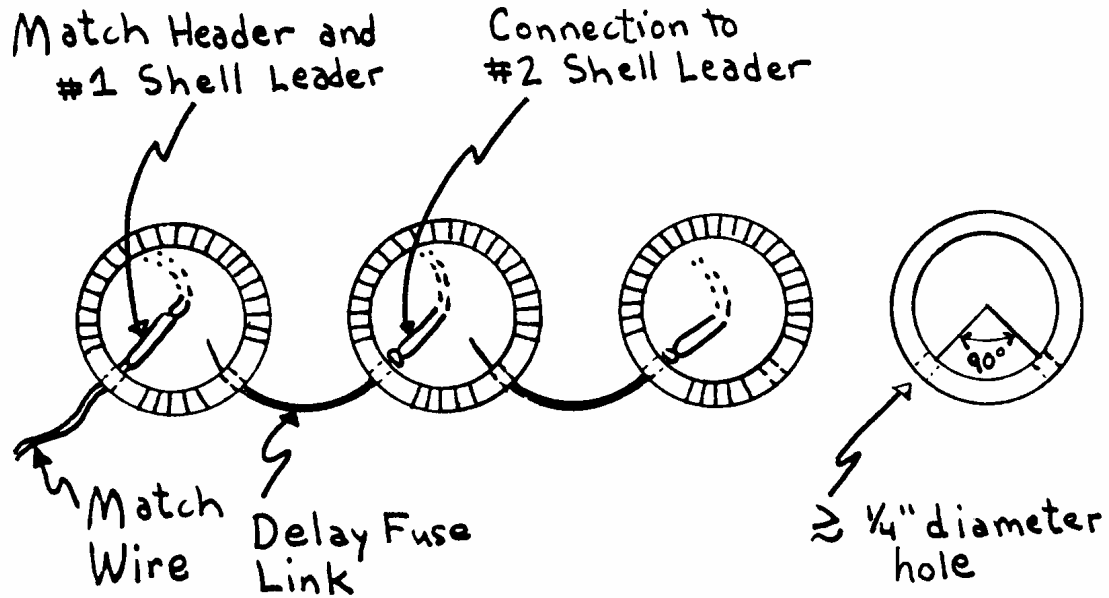


Figure 2. Overhead sketch of mortars chain-fused together, showing match header and delay fuse links. (Note: Heavy rubber bands are used to secure the fuse links but are not shown. See Photo 6.)

The method of firing to be described is referred to as “chain firing”. While the method is quite effective, it is only practical when electrically firing mortars which are securely positioned and are in close proximity to one another. To facilitate chain firing, each mortar must have two small (slightly greater than 1/4-inch) holes approximately one inch down from the top and separated by about 90 degrees of angle (see Figure 2). The first shell in the chain is fired using a “match header” (shown in detail in Figure 3), attached to its shell leader.

Match headers are used for a number of safety, reliability and economic reasons. REGARDING SAFETY: electric matches are both impact and friction sensitive<sup>[2]</sup> and serious accidents have been reported to have resulted from their use. There is concern that an electric match imbedded in the lift or placed relatively unprotected inside a shell leader could ignite if a large shell were dropped on a hard surface or if the electric match leader were pinched between two shells. There is also concern that an unprotected electric match inserted into a shell leader could ignite if jerked out during rough transport or during loading into mortars. Match headers are somewhat protected by the lance

tube used. Also, if pulled free from a shell leader, the electric match will not be rubbed against the black match. REGARDING RELIABILITY: surprisingly, on two occasions it has been observed by the authors that unprimed electric matches that were placed in contact with the black match inside the shell leaders failed to ignite the black match when the electric match ignited. When chain firing, if the electric match fails to launch the shell, not only will that shell be absent from the show, so will all the other shells in the chain. Match headers contain a heavily primed electric match which produces more fire upon ignition. REGARDING ECONOMICS: when assembled from its basic components

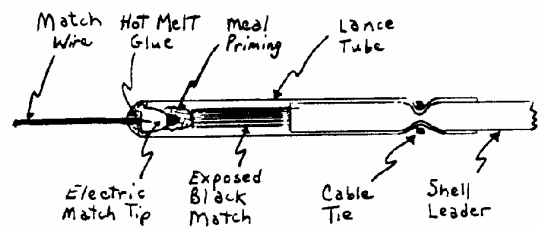


Figure 3. Cut-away sketch of match header attached to shell leader ready for firing.

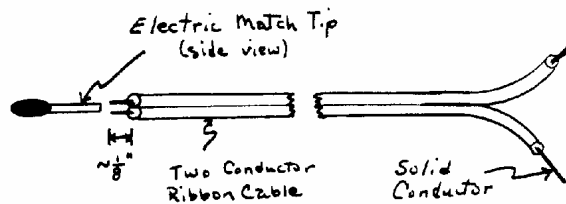


Figure 4. Sketch of two-conductor ribbon cable prepared for soldering to electric match tip.

using personnel paid \$4.50/hour, match headers cost no more than bare electric matches with the same length lead wire. (When 1000 match headers were recently assembled the total cost was approximately \$500.)

The first step in assembling match headers is to attach electrical leads to purchased match tips (Note: bare match tips cost about \$300/1000). After cutting two conductor (22-gauge solid) ribbon cable to the desired length, its ends are stripped of insulation. With ribbon wire (and only a little practice) both wires can be stripped at the same time using a standard side cutting pliers. The end to be connected to firing control points can be stripped to any convenient length and then the two conductors of the ribbon wire can be separated for a short distance to facilitate attachment to firing control points at the time of use. The end to be attached to the match tips is only stripped of about 1/2-inch of insulation and the two conductors should not be separated in any way. The normal separation between the two wires is ideal for attachment to the bare match tips (see Figure 4). In fact, with the proper wire, after the match tip is slid between the two wires, there is sufficient friction to hold the match tip in place while it is soldered to the wires. The soldering operation is accomplished using a 40 watt pencil soldering iron and thin rosin core solder (22-gauge). Note that it is fairly easy to ignite an electric match tip by holding the soldering iron on the match tip too long. However, except for demonstration of this potential problem to an employee the authors never had an ignition of a match tip while soldering. Nevertheless, no more than 100 tips at a time are allowed in the immediate work area and there are no other pyrotechnic materials or other combustibles in the general area when soldering.



Photo 5. "Chain Fusing" components. Shown are: match headers attached to a piece of shell leader; delay fuse link attached to a piece of shell leader; aluminum foil / fiberglass mortar cap, folded to show both its sides; small cable ties and a tensioning tool.

At this time, it is appropriate to shunt the leads of the electric match (match tip soldered to the leads) by simply twisting the stripped wire ends together. Such shunting is effective in reducing the possibility of unintentional ignitions and is required by law in some states. (Regarding safety, it has been reported<sup>[3]</sup> on at least one occasion that the act of separating the leg wires on an electric match is suspected to have resulted in electric match ignition.)

Next the completed electric matches are coated with prime so that additional fire is produced when they are ignited. The prime mix is handmade meal powder in nitrocellulose lacquer. Approximately 25 electric matches at a time are dipped about 3/8-inch into the prime and then hung as a group to dry. When nearly dried, any electric matches that have stuck together can still be easily separated. During the drying time, the lance tubes can be prepared. In order to accommodate the electric match wire, each lance tube is slid over a 1/8-inch rod to partially open its spun-closed end. In the final operation the electric matches are slipped into the lance tubes and a small amount of hot melt glue is injected into the mostly spun-closed end of the lance tube. This makes it almost impossible for the electric match to be pulled through the end of the lance tube, unless enough force is used to destroy the tube.

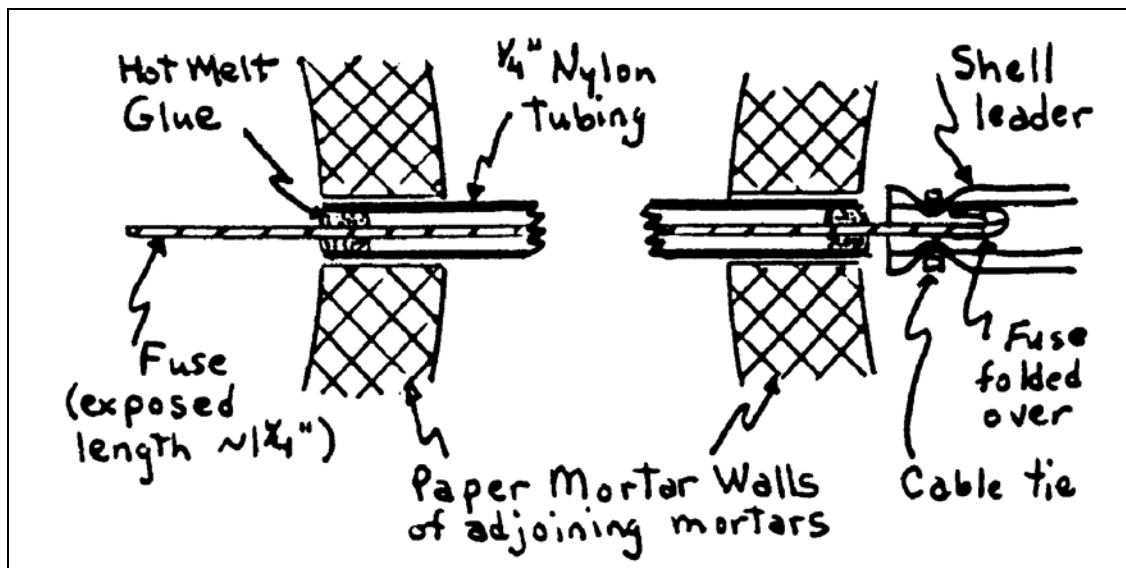


Figure 5. Cut-away sketch of delay fuse link attached to shell leader.

If necessary, the operation of attaching a match header to a shell leader can be carried out well in advance of the date of the show. However, even with the modest protection offered by the lance tube, it is very important to protect electric matched shells from impact and rough treatment, and the shunting of the electric match wires must be maintained.

Attachment of match header to shell leader is accomplished by exposing about three inches of black match at the end of the leader, doubling the black match back on itself by folding, twisting the paper cover at the end of the leader tight against the black match core to minimize its diameter, and sliding the black match and leader into the match header until the black match contacts the primed electric match. Finally the leader is securely held in position using a small cable tie (0.1 by 4-inch tie, which costs about \$15/1000) and a standard tensioning tool. The reason for folding the black match back on itself is to increase the surface area at its end and to expose a fresh (heavily coated) surface of the match. When properly assembled, the match header will be securely attached to the leader; it should be possible (but definitely not recommended) to lift up to a 6-inch oriental shell by the electric match wires. Photo 5 shows a completed match header attached to a piece of shell leader; also shown are cable ties and tensioning tool.

When ready for use, the prepared shell is loaded into its mortar. The match header wires are brought out through one of the mortar's 1/4-inch holes (preferred) or just over the top and connected to the appropriate firing control contacts.

The second and all succeeding shells in the chain are fired using "delay fuse links". In essence these are segments of reliable, easily ignited, and rapidly burning fuse that have been inserted into a protective jacket. The types of fuse well suited for use, in decreasing order of burn rate, are: thermite based Ensign Bickford quarry cord (approximately 18 inches per second), brown Imperial Chemical Industries (ICI) igniter cord (approximately 8 inches per second), white CXA thermalite (approximately 2.2 inches per second), green CXA thermalite (approximately 1.2 inches per second), green Imperial Chemical Industries igniter cord (approximately 0.9 inches per second), and red CXA thermalite (approximately 0.6 inches per second). The protective jacket used in making delay fuse links is 1/4-inch (OD) polyethylene or nylon tubing (cost is about \$3.00/100 feet).

Delay fuse links are made by first cutting pieces of the protective tubing to the proper length, see Table 1 and Figure 5. Note that for each delay fuse type it is the length of the protective tubing and not the total length of the fuse that determines delay time. This is a result of how the delay fuse links are used (discussed

**Table 1. Delay Fuse Link Specifications.**

Delay (Sec.)	Fuse Type/Length (inches)				Relative Quantity	
		Short	Long	Short	Long	
.25	Th	4.0	—	—	8	—
.37	—	—	Th	6.0	—	4
.50	Br	4.0	Th	8.0	4	2
.75	—	—	Br	6.0	—	6
1	—	—	Br	8.0	—	6
2	W	4.0	—	—	2	—
3	—	—	W	6.25	—	2
4	G	4.50	W	8.50	2	2
5	G	5.75	W	10.75	2	1
6	—	—	G	6.75	—	4
7	R	3.75	G	8.25	4	2
8	R	4.25	G	9.50	8	2
9	R	4.75	G	10.75	8	2
10	R	5.25	G	12.0	4	1
11	R	5.75	—	—	4	—
12	—	—	R	6.5	—	2
13	—	—	R	7.0	—	1
14	—	—	R	7.5	—	1

Length: length of fuse contained within the ¼" tubing (i.e., length equals length of tubing).

Symbols used in table:

Th: Ensign Bickford Thermite-based Quarry Cord.

Br: ICI Fast (brown) Igniter Cord.

W: CXA Fuse Fast (white) Igniter Cord.

G: CXA Fuse Medium (green) Igniter Cord.

R: CXA Fuse Slow (red) Igniter Cord.

below). Next, lengths of fuse approximately two inches longer than the tubing are cut and slid into the tubing, with nearly equal amounts of fuse exposed on each end. Finally small amounts of hot melt glue are injected into each end of the tube to immobilize the fuse. It is important to exercise caution in the assembly of these fuse links. Both the operation of cutting the fuse and the operation of hot-melt gluing the fuse have been reported to have resulted in unintentional ignition.<sup>[4]</sup> For these reasons, no more than one roll (100 feet) of fuse is allowed in the immediate work area and no other pyrotechnic compositions or combustibles are allowed in the general area while cutting or gluing delay fuse links. In addition, the person carrying out these operations must be specifically trained how to react in the event of an accident.

Because of the various spacing between different sized mortars, it is useful to have available both long and short fuse links that produce the same time delay. In those cases where it is practical, Table 1 includes specifications for both long and short versions of fuse links. Links shorter than 3½ inches are virtually unusable and those longer than about ten inches tend to be cumbersome. Also included in Table 1 are relative quantities of variously-timed fuse links used in a more or less typical display (Note: the cost of delay fuse links, including labor, averages less than \$25.00/100). (See Photo 5 for a completed delay fuse link attached to a piece of shell leader. Note however, that shell leaders are not attached to delay fuse links until after the shell is loaded into its mortar and the fuse link installed in the wall of the mortar, discussed below.)

Delay fuse links are used by securing one end into one of the small (slightly greater than ¼-inch) holes in the top of the preceding mortar. The other end is secured into a hole in the mortar to be fired. For reasons to become clear below, it is important that the fuse link be held so that the protective tube jacketing the fuse is positioned approximately flush with the inside surface of the mortar. Though it is desirable to have the fuse link fit snugly into the holes, it is not acceptable to rely on friction to hold it properly in place. To assure maintenance of proper position, a large (size 73 or 84) rubber band is used on each end of the link. The rubber bands are quickly installed as follows: as the first end of the fuse link is inserted into the first mortar, it is passed through the center of the rubber band; next pull upward slightly on the rubber band and twist the rubber band half way around (180 degree rotation of end not held by fuse link); next slip the end of the loose rubber band over/around the top of the mortar; the operation is completed by repeating the process for the other end of the fuse link as it is inserted into the next mortar. Photo 6 illustrates the process. The use of rubber bands to secure delay fuse links has been quite successful. The authors have never had a fuse link loosen during a show. On one recent occasion after trailering 250 miles with fuse links pre-loaded, firing the display and returning home, no links came loose. (Note: the operation of pre-loading the variously timed fuse links for



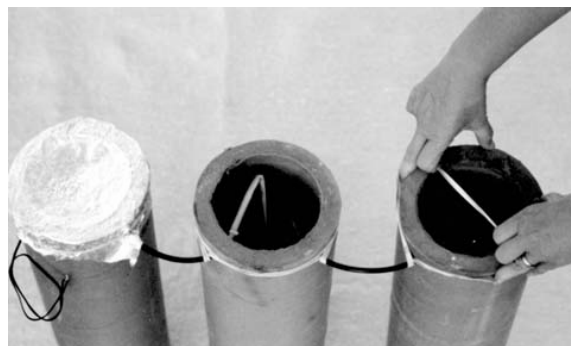
the 251 mortar trailer requires about 1½ hours for two people.)

After installing the fuse link between mortars, the shell to be fired by the link should be temporarily loaded into a nearby empty mortar, but not the one where the shell fusing will take place. The shell is loaded into a mortar so that in the unlikely event of accidental ignition during attachment to the delay link, the shell will fire harmlessly into the air and not remain in the work area and cause injury or ignite other shells. The shell is loaded into a mortar other than the one where it is to be fused because the fusing operation requires placing one's fingers over and slightly into the mortar with the fuse link. In the unlikely event of accidental ignition, the shell will fire harmlessly out of the other mortar and not the one where fingers are at risk.

The shell leader should be cut off just short of exposed black match so that the black match is cut flush with the end of the leader. Attachment is made by bending back a short length (approximately ¼-inch) of fuse at the end of the link, inserting the bent over end of fuse into the shell leader, and securing the coupling with a small cable tie. (See Figure 5.) Some care should be taken to assure that the delay fuse is in contact with the black match in the leader. The fuse end was bent over to facilitate insertion into the shell leader, to generate added fire at that point, and most importantly to reduce the possibility of the fuse link pulling out of the leader. In order to achieve the intended timing, the fuse in the delay link should have been inserted as far as possible into the shell leader. Remember, the delay times were determined by the burn time of the fuse while inside the protective tubing. When the operation of attaching shell leader to delay fuse link has been completed, re-load the shell into its intended mortar. With a little care, the shell will easily fit past the point of attachment with the delay fuse link.

Thus, as you have probably already concluded, a delay fuse link functions by its fuse taking ignition from escaping lift gases of the first shell, continuing to burn inside the protective tubing, and then passing fire to the leader of the next shell. This process is repeated for each shell in the chain.

The final operation in preparing the trailer is to place a protective cover over the mouth of



*Photo 6. Chain fusing method in various stages of the fusing operation.*

each mortar. For this, roughly-cut circles of a special material are formed over the tops of the mortars and held in place with heavy rubber bands (see Photo 6). The special material is Fiberglas cloth that has aluminum foil bonded to it and is highly fire resistant and mostly water-proof (also see Photo 5). This is the same material used by the US Forest Service for small tarps used to protect forest fire fighters in the event they are overrun by fire. When a shell fires, the escaping gases blow the cover clear of the ascending shell. After a show nearly all of the covers (most with rubber bands still attached) will be found in the immediate area and should be retrieved for reuse. Though our use of these covers is also relatively new, it seems that their average service life is at least six shows. These covers are used for two reasons (the importance of the second will become clearer in the next section of this paper). Prepared in the manner described, the dense-pack trailers ready for firing are essentially water-proof and are fallout fire-proof. It is difficult to imagine almost any combination of rain, sparks or burning stars that would necessarily force an interruption of the performance. (Note: the operation of shell loading for the 251-mortar trailer requires about three hours for two people.)

By way of demonstrating the reliability of chain firing, consider the following. Although the authors have used this exact method of chain firing for only their last six shows, there have been only two failures attributable to the methods presented here.

## 2.4 Parasitic Firework Effects

For the purpose of this paper, “parasitic firework effects” are small shells, mine stars and other components that derive their lift energy from other “host” shells. The sizes of parasitic shells usually range from 1¾-inch (festival balls) to 3-inch shells. The quantity and size of mine stars are scaled according to the size of the host shell. Components oftentimes are merely firecrackers, jumping jacks or small bees. (Obviously, when the audience cannot view the mortar area, it is ineffective to use mine and small component effects.) In order to most effectively draw lift energy from other shells, the parasitic effects must be loaded on top of the host shell. When this is the case and the total weight of the parasitic devices is modest in comparison with the weight of the host shell, the host shell’s altitude is not detectably reduced, and the parasitic devices reach ample height. There are a number of reasons why a modest weight of parasitic effects should be expected to be propelled without noticeably affecting the altitude of the host shell. One reason, especially true for spherical shells, is that to some extent parasitic effects are propelled by wasted high velocity lift gases escaping from around the host shell. Another reason is that the greater inertial mass of the combined host shell and parasitic effects means that (without adding more lift powder) higher lift pressures will be manifested throughout the time the host shell is in the mortar. In addition, the higher lift pressure, resulting from the greater inertial mass, acts to speed up the burn rate of the lift powder<sup>[5]</sup> which results in a further increase of lift pressure throughout the period when the host shell is in the mortar and the lift powder is still burning. The effect of higher lift pressure translates into modestly greater carrying capacities for host shells without the use of more lift powder. In some respects this is the same effect that allows a 3-inch cylindrical shell weighing 100% more than a 3-inch spherical shell to be lifted to the same altitude using only 30% more lift powder. It is not intended to imply that parasitic effects can be added without diminishing the height of the host shell. However, when only a modest weight of parasitic effects are added, the height of the host shell is reduced less than might be expected, and the slight reduction in

**Table 2. Parasitic Weights and Relative Points for Host Shells.**

Host Shell (Single Break)			Parasitic Effect
Size (in.)	Approx. Weight (lb)	Point Rating	Typical Total Weight (oz)
3	.5	1	3
4	1.0	2	5
5	2.0	3	8
6	3.5	4	10
7	5.0	6	13
8	8.0	8	16
10	12.0	11	22
12	18.0	14	28

altitude is insufficient to necessitate the addition of more lift powder.

Table 2 includes typical weights of host shells and parasitic firework effects. Acceptable relative weights for parasitic effects range from as much as 1/3 for a 3-inch shell down to 1/10 for a 12-inch shell. In part these varying relative weights correspond to the carrying capacity of the host shell. (Note that because of its low ratio of mass to projected area, a 3-inch shell requires a disproportionately larger lift charge to reach proper altitude. Accordingly, a 3-inch host shell has the greatest relative carrying capacity for parasitic effects.) However, for the most part the varying relative weights for parasitic effects are the result of aesthetic considerations. When a 3-inch shell is properly augmented with parasitic effects, those effects usually weigh about three ounces. For an 8-inch shell, optimum results can be achieved with about 16 ounces of effects.

In order to maximize the artistic effect, parasitic effects must be properly timed and sized with respect to the host shell. In general, the lowest altitude and smallest effects should occur first, followed by higher and larger effects leading to the break of the host shell, which should be impressively greater than that which preceded it. To illustrate this, consider one possible 6-inch “shell set” (host shell plus parasitic effects). On firing, the shell set produces a massive blue-willow mine effect extending about 150 feet in the air; this is followed shortly by a flurry of eight small purple (festival ball) breaks

at about 250 feet, followed by the massive break of a 6-inch bright red to silver comet chrysanthemum shell at about 600 feet. The synergistic effect of the combination of effects produces a result that is far more aesthetically pleasing than might be expected (particularly when the very modest added cost for the parasitic effects are considered).

There are three reasons for giving the use of parasitic effects serious consideration. The first reason, given above, is aesthetics. Though often seriously under-utilized in displays, mines and ascending effects are attractive in their own right. They also offer variety and utilize an otherwise unused portion of the sky. If nothing else, their use heightens the audience's appreciation of aerial shells by moving the action around in the sky and limiting the boredom which can result during an aerial-shells-only display. Another aesthetic payoff comes in the length of time the effect lasts; the use of a shell set such as the one described above produces a display that lasts about twice as long as would be produced by the large shell alone. Essentially every sponsor of a show wants it to look like one costing two or three times more. For most smaller shows, what is wanted is multiple effects and rapid firing. This would be easy to accomplish if it were not that the show still needs to last sufficiently long. In large measure, the use of parasitic effects affordably achieves the sponsor's aesthetic requirements. However, the most important aesthetic reason for using parasitic effects is that their use increases the perceived beauty of the host shell. As an analogy, consider an example from the cinema, a horror movie. How much impact would the violence of the movie have if it were not for the music setting up the audience by telling them something terrible is about to happen? How much impact would there be if the audience were not first set up by knowing that something was out there somewhere, preparing to do some terrible thing to an unsuspecting person? To a large extent the horror is psychological; horror is mostly the anticipation of violence and not the violent act itself. Without first setting up the audience, the violent act would probably only seem revolting. In a similar way, when host aerial shells are properly set up using parasitic effects, the audience's anticipation of unfolding beauty results in the perception of the host shell

as significantly more beautiful than if fired alone. It is difficult to imagine how effective this can be without actually seeing it.

The second reason to consider using parasitic firework effects is increased profit. One obvious benefit from using this approach is that significantly more fireworks can be put up from the same number of mortars. The dense-pack trailer shown in Photos 1 and 2 will fire a conventional show which would normally be priced at about \$4200 (excluding insurance and choreography). However, when parasitic effects are added, a fair value for the display is about \$5600. In part, the higher price for the display results from the additional fireworks included. However, because the parasitic effects add so much to the favorable impression of the audience and yet cost relatively little, it is acceptable to increase the gross profit on them. (The increased profit can be rationalized as necessary to off-set the fairly high initial costs of firing electrically from dense-pack trailers.) The authors normally work with a gross profit of about 100%, but for parasitic firework effects the gross profit is 200%, and in spite of this, the feedback from sponsors has been very favorable. It's a great day when you can increase your profit and still have delighted sponsors wanting to shake your hand for the great job you did for them!

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

nificant reduction in the number of different types of shells needed in inventory.

Parasitic effects are prepared in advance by loading the mine stars and small shells or components into small (two mil thick) plastic bags and sealing them with PVC tape. A few of the possible assemblages of parasitic effects are shown in Table 3. Large quantities of these pre-bagged items can be stored until needed, during final loading before a show. Also given in the table is a point rating for each of the different assemblages. These are used as an easy way of determining which and how many of each of the assemblages can be loaded on top of any given size host shell. Note that Table 2 includes a point rating for typical host shells; any number and any combination of assemblages can be used as parasitic effects providing their cumulative point total does not exceed the rating for the host shell. For example, for a 5-inch host shell, six festival balls, or two festival balls plus one 2½-inch shell, or one 3-inch shell are all acceptable as parasitic effects.

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

**Table 3. Points for Some Possible Parasitic Effects.**

Points	Description <sup>(a)</sup>
1	2 Festival Balls plus 1 ounce of mine stars
1	4 packs (approximately 70) Firecrackers or Jumping Jacks plus 1 ounce of mine stars
2	1 – 2½" Shell (may include 1 ounce of mine stars)
2	3–1" x 1½" Flash Salutes
3	1 – 2½" Shell plus 3 ounces of mine stars
3	1 – 3" Shell (may include 1 ounce of mine stars)
3	1 – 2" x 2" Crossette Comet
3	6 ounces of 1" x 1" Comets
4	1 – 3" Shell plus 3 ounces of mine stars

Note — all items are heavily primed.

proper ignition of the effects by more completely filling the bag with fire when the host shell is launched.

Parasitic effects are loaded into mortars by simply dropping the filled plastic bags into the mortar after the host shell has been loaded. It is inappropriate and unnecessary to remove the contents from the bags. (This is inappropriate because loose components or stars might jam between the host shell and the mortar wall; unnecessary because the plastic bag will melt away almost instantly when the host shell is fired.)

One word of caution, there is always the possibility that sparks from the firing of one shell will fall into other mortars and unintentionally ignite parasitic effects in those mortars. However, this is prevented by the use of the protective covers mentioned in Section 2.3 above, which provide very effective protection from sparks and even small burning stars.

Certainly the use of parasitic effects in conventionally fired shows is possible (consider ascending flowers and attached comets). However, their use is ideally suited to electrical and chain firing of pre-loaded mortars.

## 2.5 Trailer Pre-Loading

It is fairly obvious that as much work as possible should be completed in advance of the day of the show. In a well designed electrically fired show, whether performed to music or not, the shells and their firing sequence are carefully planned to achieve specific purposes. That is to say, not only are shells selected in advance but also their order of firing, the times between firings, and even which mortar will be used for each firing are predetermined. Accordingly, the shells to be used can and should be marked and pre-packaged in some logical way, well in advance of the show, ready for loading when the time comes. Because the timing of each firing is also known, all necessary delay fuse links should be selected and installed in advance in the proper mortars. In this paper, a display prepared in advance to this state is referred to as "partially pre-loaded". Essentially every show should be at least partially pre-loaded.

Consider the dense-pack trailers used for these performances again for a moment. It is relatively easy for these trailers to meet Department of Transportation requirements for transporting special fireworks. Thus it would be possible on the day of the show to load the display remote from the shooting site and transport it to the site only a few hours before the start of the performance. This would have a number of advantages: security, availability of tools and materials, and personal comfort, to name a few. If the trailers have properly-secured metal tops and are painted with epoxy paint, they would qualify as mobile Type IV magazines. If this were the case, the complete display could be preloaded and stored for days or weeks until being transported to the site on the day of the show. (Arriving at the site in this way is probably safer than with shells loaded in mass in boxes.) In this paper, trailers prepared to this state are referred to as "fully pre-loaded".

Obviously, by arriving on site with partially or fully pre-loaded trailers, a great deal of set up time can be saved; correspondingly, the size of the crew can be reduced. This can have a significant impact on profitability. It is not so much that work is saved, but rather that it can be scheduled in advance at YOUR convenience. When the work is performed in advance, workers can be assigned to perform these tasks dur-

ing periods when they might not otherwise be fully utilized. This corresponds to greater productivity. The more work done in advance, the more shows that can be staged by the same number of workers. More shows mean more opportunity for profit. When a crew is on the road preparing for a show, you are probably providing food and lodging. So if you can send a smaller crew for less time, this means lower expenses. Occasionally shows are lost when problems with local authorities surface on the day of the show or when the weather is inclement. If it only takes an hour on site to set up, even a last minute resolution of problems or a break in the weather may allow a successful performance. (Shows lost at the last minute are costly.)

## 2.6 Firing Control Equipment

As mentioned above in Section 1.0, a theoretical discussion of the construction of electrical firing control equipment has been published elsewhere. The articles by Bases<sup>[1]</sup> should allow most readers with some background in electronics or science to design and construct their own. If the reader does not have such a background, it is likely he can find someone who does. Also there are several sources from which equipment can be purchased. The purpose of this section will be only to express some preferences of the authors and to mention some peripherally related subjects.

Much of the firing control equipment in use fires each item by toggling a switch (assuming the circuits are already armed). This requires some degree of concentration to be certain that the operator's finger(s) are on the right switch(es), and, when in a hurry, it is easy to get the wrong switch. Also, it is difficult to relax between firings when the operator has to keep in mind the number of the next circuit to be fired or has to continuously hold his finger against the next switch so as to be ready to fire it when the time comes. It is thought preferable to have one set of switches used only to arm one or more circuits in advance of firing and a second switch used each time for the actual firing. (For safety reasons, it is preferred that the second switch actually be two switches in series.)

Compatibility between cables, controllers and trailers (or racks) is important. It is preferable to have all cables, controllers and trailers be interchangeable. Arriving at a distant site with the right controller but the wrong cable is at least a problem and possibly a disaster.

Redundancy in design is also desirable. Having two small firing controllers instead of one large one offers more flexibility (allowing use of two firing sites or two simultaneous shows in different towns). However, more importantly, if one controller fails, is damaged or stolen, you will still have one to fire the show, even if it means having to repeatedly plug and unplug different cables into the controller.

Electric generators are frequently used on-site to power lights and music systems, etc. However, unless properly earth-grounded using a rod driven into the ground, they should not be used to power firing control equipment. It is possible for ungrounded generators to build up large static charges. Thus unless care is taken when using a generator, it is possible that a static discharge will accidentally fire some electric matches wired into the display. While ungrounded generators may be used to charge internal batteries in firing control equipment before a show, they should not be connected to the firing equipment during the show.

When firing a show electrically, a low level of light is necessary for the operators to follow the script and operate equipment. The use of any number of light sources is possible; however, the use of part or all of a string of Christmas tree lights can provide low level lighting over a wide area and does not detract from the show.

When firing a conventional show it is often difficult for the operator to be in communication with safety people and others helping to control the show. This might be the result of the operator participating in the firing or just because of the noise and commotion in the area of the mortars. When electrically firing, it is normal to set up the firing control equipment at least 100 feet from the dense-pack trailers, where there is considerably less noise and commotion. After a number of trials of various types of communication equipment, it was concluded that CB transceivers are a good compromise between cost and performance. Be-

cause of the limited power of legal CB equipment, it is felt there is no danger of accidentally firing electric matches. Normally a five-watt base station is used at the firing control site and one-watt portable transceivers (walkie-talkies) are used by persons stationed remote from the firing site. Because the antennas on the portable units are cumbersome and possibly even dangerous at night, the transceivers are normally operated with only the thickest one or two antenna sections extended. This results in a reliable communication range of  $\frac{1}{4}$  to  $\frac{1}{2}$  mile. (Note that because of the low power of these units they are not harmed by operating with antenna detuned by not being fully extended.) By watching for sales, a base station plus four portable units should cost less than \$200. As is true for any communication system, where it is possible that critically important messages may need to be sent, some form of backup is appropriate. Probably the cheapest and still very effective backup is the use of flashlights. When aimed in your direction they can be seen for quite a distance and a pre-arranged flashing signal from any safety person can quickly shut down a display until the potential problem is investigated.

When performing an electrically fired display, particularly one choreographed to music, the sponsor is expecting, and usually willing, to pay for a more professional performance than the typical hand-fired show. There may also be a moderate amount of equipment necessary, such as firing controllers, digital clock timers, sound equipment, communication equipment, and operational lighting. Accordingly, it is appropriate to set up some type of control center from which to operate. This could be nothing more than a table set in the open near the shooting site. This, however, offers little protection for the equipment and operator from wind, rain, dust and errant fireworks; requires a fair amount of set-up time without providing the operating team with a very effective control center; and certainly does not give a sponsor much confidence in the professionalism of the display company. Another possibility is the use of some form of mobile control center, specifically in the form of one of the vehicles used to transport the trailers. Photo 7 is of such a control center in the bed of a pickup truck. Note that the top of the unit is on tracks which allows



*Photo 7. Mobile firing control center in bed of pick-up truck.*

it to be slid forward giving the operators an unobstructed view of the sky and a nearly 360-degree, and slightly elevated, view of the grounds. In addition to the desk for equipment and to work from, there is also a sound equipment rack and a large storage cabinet with a cot on top. Over the front bumper there is an AC generator for large power requirements and built into the engine compartment is an inverter for backup power. Such a control center offers protection of the crew and equipment from weather and dust, and can be set up in minutes. When not being used for a display, all equipment can be removed and the truck used conventionally.

### **3.0 Musical Choreography**

There are essentially three ways in which music can be used to augment a fireworks display. These are differentiated by the degree to which fireworks and music are synchronized. On the one extreme, in what might be called “accompaniment music” shows, the music is used only as background. The fireworks display is designed just as any traditional show and there is not a serious attempt to synchronize the fireworks and musical programs. In this case it is nice to have the musical background, but it adds relatively little to the dramatic impact of the show. At the other extreme, in what might be called “micro-sync” shows, each shell break is precisely timed to break on specific musical cues and there are not two separate programs (fireworks and music) but just one. This can

have a powerful impact on the audience. However, the necessity to account for differing time fuse delays and still achieve synchronization to fractions of a second for rapidly-fired shells makes computerized firing almost a necessity. The third and most common way to use music to augment a fireworks display requires synchronization to about one second. For the most part, the difference between these displays (which might be called “macro-sync” displays) and micro-sync displays is only in the precision of the synchronization. Each individual shell is selected and utilized to fit the musical program. The only difference in shell selection may be a tendency to employ multiple smaller shells in place of large shells. This helps mask the fact that synchronization of music and fireworks is not precise.

It is only the macro-sync technique that will be discussed in this paper. However, most of what is presented is applicable to micro-sync displays as well and much even applies to accompaniment shows.

### **3.1 Music Selection**

Selection of the musical program for the show is not just important, it is critically important. In a properly designed show, proper selection is probably more important than the quality of the fireworks in producing a positive audience reaction. In part, this may be true because audiences are not as offended by poor quality fireworks as are skilled fireworkers. Probably, however, it is because music is a more powerful creator of mood and emotion than are fireworks. Considering its critical importance, one should plan to spend many hours selecting and preparing the music. The musical program should be good enough that if played alone, without fireworks many in the audience would stay just to hear the music and would enjoy the concert.

In terms of audience response, the difference between a good musically-choreographed display and an equally good conventional show is in the height of emotion evoked. To some extent, with a properly designed musical display, it is possible to “wear out” the audience by taking them on an emotional roller coaster ride. In accomplishing this it is the music that is most effective in determining emotional response. Obviously, emotional response is maximized



**Table 4. Examples of Effective Music Taken from Movie Sound Tracks.**

Movie	Song Title	Emotion
Brain Storm	Michael's Gift to Karen	Pensive followed by jubilant
Patton	Winter March	Building sense of forceful resolution
Patton	Patton March	Prideful militarism
Cosmos	Vangelis' Heaven and Hell- Part 1	Ethereal beauty and wonderment
Cosmos	Pachelbel's Canon à 3 or a Ground in D	Optimistic fulfillment and satisfaction
Cosmos	Vangelis' Entendus to les Chiens Aboyer	Reverent joy
Other Side of the Mountain - Part 2	Indian Children's School	Loneliness – sadness
Other Side of the Mountain - Part 2	Love Theme	Joy and fulfillment

when both the music and fireworks are working toward the same end. However, if the moods evoked by the music and fireworks are in opposition, it is the music that will prevail. As an example, consider the same salute barrage fired to the final strains of the “Stars and Stripes Forever” and then again to a portion of Mussorgsky’s “A Night on Bald Mountain”. In the first case the emotional response will be one of prideful patriotic exuberance, in the latter, the response will be one of ominous trepidation. In the first instance the audience will be standing tall (physically), in the latter they will be detectably recoiling, with heads pulled down slightly between their shoulders. The same slowly fired sequence of large spherical shells will create a feeling of beauty and wonderment when viewed to “Abraham’s Theme” from Chariots of Fire, yet will produce a sense of profound sadness when viewed to Barber’s “Adagio for Strings” with a voice over of the news broadcast of President Kennedy’s funeral procession.

Since it is an emotional response that is intended to be produced, motion picture sound tracks are an obvious place to look for effective music; musical sound tracks are added to films to elevate the emotional response of the audience; they are intended to add dramatic impact. Even when these sound tracks draw their musical theme from the classics, they are re-orchestrated. Usually this means condensing around a single theme and heightening its emotional content. As an example, compare the introductory fanfare for Richard Strauss’ “Also Sprach Zarathustra” as played on the classical album versus the rendition from the movie “2001 — A Space

Odyssey”. It is the same music, but very different in emotional impact. Just a slight change in timing and the drama of the fanfare is significantly magnified. Generally during a musically choreographed display, it is desirable to change mood, or at least intensity of mood, every two to four minutes (i.e., between each piece of music). This is another reason to look at movie sound tracks, even for classical themes. The classical piece will generally play for five to 20 minutes, and it is difficult to extract the portions needed. The re-orchestrated version for a movie will invariably shorten the musical theme to a more manageable (useful) length. Table 4 presents a few examples of useful music from movie sound tracks.

Obviously, music can be an effective creator of emotion; however, this is particularly true when the music triggers pre-formed mental images in the listener. Properly staged, the playing of the National Anthem will put a lump in the throats of most of the audience. In this case, while the music is stirring in its own right, it is the mental association with patriotic nationalism that greatly magnifies the emotional response produced. When selecting music for its ability to evoke mental images, it is essential to consider the make-up of the audience. In Georgia, the playing of “Dixie” will put the audience on their feet cheering, like “Yankee Doodle Dandy” never will! Table 5 presents some examples of music producing strong mental images (not all of which produce strong emotion).

Most popular (or popularized) music has some sort of lead-in or introductory passage and often some sort of run-out at its end. This is useful in that it provides a smooth transition



**Table 5. Examples of Music That Is Effective in Creating Mental Images.**

Song	Mental Image or Response
National Anthem	Patriotic nationalism – my country right or wrong
Marine’s Hymn	Militaristic arrogance – potential enemies beware
Dixie	Pride in southern heritage
Battle Hymn of the Republic	Religious patriotism – God is on our side
Auld Lang Syne	New Year’s remembrances
“The Storm”, 4th movement of Beethoven’s 6th	Furious storm building then passing
Olympic Fanfare	Athletic achievement
Stravinsky’s “The Rite of Spring”	Ominous, foreboding, intimidating
Handel’s “Messiah”	Spiritual upwelling

between pieces with differing moods. Generally, no fireworks are shot during these times. The pause in fireworks during the lead-in serves to build the anticipation of the audience; the pause during the run-out gives the audience a moment to relax and contemplate what they have just experienced. The only problem with lead-ins and run-outs is when they are too long; 10 to 15 seconds is great, but 30 seconds begins to be excessive. Another benefit to these short pauses in the fireworks portion of the show is a partial resetting of the audience’s visual perspective. When fireworks are fired more or less continuously, it requires greater and greater expenditures for larger and/or more fancy fireworks to hold the level of the spectators’ interest. Pauses of even 15 to 30 seconds during a display allow the use of slightly fewer or smaller effects without diminishing audience appreciation of the fireworks. However, during a conventional show, pauses of 15 to 30 seconds generally make the audience impatient and thus have a negative impact that seriously offsets any gain from resetting visual perspective. During a musically choreographed display, the same pauses in the fireworks (but not in the music) can add to the entertainment value of the display.

It was mentioned above that the mood, or at least the intensity of the mood, should generally change in a major way between each piece of music. This is true, but it is often desirable to also have at least minor changes of some sort within each piece occur every 30 to 45 seconds. These changes help carry an audience along in building or sustaining emotion. One aspect of Sousa’s “Stars and Stripes Forever” that helps create its rousing exuberance is the contrast between its rousing and delicately quiet pas-

sages. In addition, if the fireworks program follows the music, major changes in the fireworks will only occur when there are changes in the music. If this only happens between pieces of music every two to four minutes, the audience will generally lose interest. One of the few exceptions is for relatively slow firing of large shells when attempting to create a sense of beauty and wonderment. In this case, two to four minutes is the preferred time interval to allow the mood to develop.

The selection of vocal versus instrumental music is of little importance. Each has its strong points. Vocal music can be better in creating mental images whereas instrumental music can be better in creating moods. Similarly, classical, traditional and pop music can each be used effectively. In any case, music should be selected for specific purposes; if the selection accomplishes the purpose, it does not matter what type it is. However, most audiences are diverse, thus a wide variety of music is usually appropriate.

Once the basic selection of songs for a display has been made, one should not consider the task of music selection complete. In most cases there are several, occasionally even hundreds, of renditions of the same song, and they are not all equally suitable for use in a display. Even if one is not very discriminating, many simply will not be acceptable. Remember, the selection of music is critically important to the performance. The difference between mediocre and excellent quality firework items will have less effect on the audience than mediocre versus excellent music. It is important to keep looking until really effective renditions are located.

Although not explicitly stated above, part of the music selection process must be a determination of the sequence in which the music will be played. For the typical display, moderate mood and style changes are appropriate between each piece of music. It is usually inappropriate to put all the rousing or all the classical music selections together as one part of the display.

However, it should be understood that simultaneous radical changes of both mood and style are also undesirable. This makes the show seem disjointed and will not maximize favorable reactions to the display. One example of how to smooth a transition between musical selections can be demonstrated with Neil Diamond's "America". The piece has a classical instrument style lead-in changing to an up-beat pop vocal style. This piece serves well as a bridge after a classical selection. Another way to smooth a transition is to use two pieces of music, significantly different in style and mood, but featuring the same instrumental group, for example, a selection by a Mariachi band followed by a classical trumpet concerto or a pop selection with a brassy sound. When a show is designed such that there are threads of continuity between the pieces of music, the display seems more like a single cohesive performance and the audience's reaction will be more favorable.

The final task in selecting music for a display is the preparation of a high quality audio tape of the various pieces of music. Generally a four second pause between each piece is appropriate. Also, at the start of the tape it is useful to record information describing the tape (e.g., "1986 Labor Day Show for Hillsboro Downs Race Track") and a count down to help queue the tape when used at the display.

### 3.2 Guides to Choreography

In essence, there is really only one rule for effective fireworks with music choreography: The mood created by the music must be the same as that created by the fireworks. In that case, the degree of emotion experienced by the audience will be maximized. When the moods are in conflict, the result is rather bland. Whether the response is instinctive or learned, most people have little difficulty identifying the mood of music: rousing versus tranquil, exuberant versus ominous, etc. However, in prac-

**Table 6. Pleasing, Mood Up-lifting Changes.**

Characteristic	Change
Light Intensity (shells or stars)	Dim to bright
Size (shells only)	Small to large
Altitude (shells only)	Low to high
Tail (shells or stars)	No tail to comet
Color Spectrum (shells or stars)	Cool to warm

tice, the ability to sense or predict the mood produced by fireworks is not nearly so well developed, even among firework people. Accordingly, most of this portion of the paper will be devoted to that subject.

In fireworks, there are some effects that are particularly pleasing and create a mood-uplifting sense.<sup>[6]</sup> Generally these result from changes in light intensity, size, or color; Table 6 summarizes these. For light intensity, it is dim-to-bright that results in a pleasing reaction. This is true for both stars and for shells, i.e., an uplifting mood can be created by a dim-to-bright intensity change for stars in a single shell, and also by firing a pair of shells, the first with low light output followed very shortly by one with high output. In terms of size, it is small to large that produces a pleasing response. Two shells, the first small and the second large, fired with one-half to one second in between will produce a positive reaction. Similarly, but to a much lesser extent, low altitude versus high altitude effects will also accomplish this. With respect to stars, the analog to a change in size is the presence or absence of a tail; here, a change from a simple color to a comet effect produces a pleasing sense. Finally, in terms of color, a cool-to-warm color sequence produces the uplifting response. Cool-to-warm spectral colors start with blue and run through green, yellow, and orange to red, the warmest. In terms of color warmth, the non-spectral color white is very cool and the non-spectral color purple is roughly equivalent to green. By and large, the positive emotion created is magnified when several of the rules of Table 6 are followed at the same time. Imagine a 3-inch dim white peony followed very shortly by a 6-inch bright red chrysanthemum breaking above.

To some extent, an ominous and foreboding response can be produced by breaking the rules in Table 6. For stars in individual shells this is not

**Table 7. Fireworks Used to Evoke Emotional Responses.**

Response	Fireworks Used
Excitement	Rapid random firing of variously-sized shells, both cylindrical and spherical shells, using a variety of colors and effects. If salutes are used, they should be randomly mixed in, or fired in sustained volleys at peaks in the excitement and at its conclusion.
Jubilation	Rapid random firing of similarly sized shells, using only a few colors or effects at a time with all shells either cylindrical or spherical. Colors, effects and types of shells should be changed infrequently or gradually. Shell and star combinations should follow rules of Table 6. Ascending comet effects are particularly effective.
Foreboding	Slow random firing of shell and star combinations that break as many of Table 6 rules as possible, using cylindrical (asymmetrical-breaking) shells. If salutes are used, they should be large. Parasitic effects should be avoided.
Wondrous Beauty	Slow mostly steady firing of shell and star combinations that follow as many of Table 6 rules as possible, using large spherical (symmetrically-breaking) shells. Generally allow each shell to complete its performance before the next is presented. Parasitic effects are particularly effective.
Somber	Slow mostly steady firing of shell and star combinations that frequently break Table 6 rules, using mostly spherical shells. The use of parasitic effects must be avoided.
Prideful/Patriotic	Flights of cylindrical shells (all the same within each flight) with some flights being salute barrages.

easily accomplished unless one makes their own shells. Commercial manufacturers almost invariably follow the rules given above in order to produce a pleasing response. To evoke a negative emotional response in the audience, using purchased shells (not made to specification), usually the only possibility of breaking Table 6 rules is to play one shell against another.

In matching fireworks to music, the colors used, the size of breaks, the symmetry of breaks, the timing and combination of breaks are all important considerations in creating mood and building emotion. Table 7 is a guide outlining some of the ways fireworks can be used to evoke emotional response. However, in using Table 7, be aware that the art of using fireworks for this purpose is still relatively primitive and the content of the table was developed from observations and trials extending only over a few years. The ideas expressed there do work, but others not considered here may work as well or better.

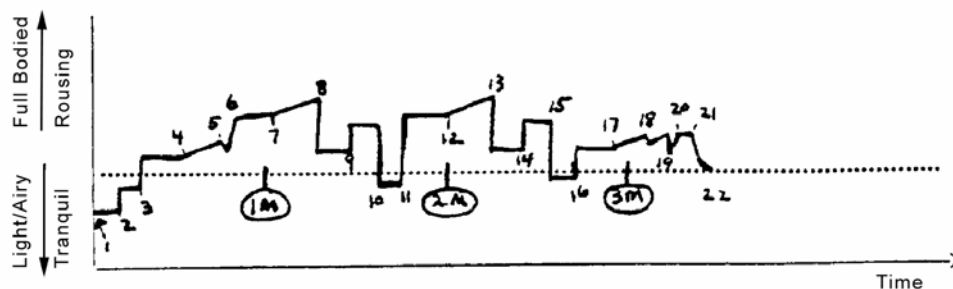
In Table 7 and elsewhere in this paper, shells are occasionally described as being fired randomly. Obviously, in an electrically fired display, nothing happens randomly. What is meant is that the firing should appear to be somewhat

random to the audience. The intervals between firings should not be exactly the same. When these time separations are all the same, the display will appear mechanical as opposed to spontaneous (which is preferred).

In Table 7, the degree of jubilation and excitement created by the fireworks depends mostly on their rate of fire. The higher the rate of fire is, the more the sense of excitement and/or jubilation. The degree of wonderment and beauty created depends mostly on the size of the shells. The larger the spread of the shells is, the greater the sense of wonderment and beauty. Finally, the sense of fullness (heaviness) versus airiness (lightness) created depends on the warmth of star color. The warmer the color is the greater the sense of fullness.

Generally, as a display progresses, larger and larger shells are employed. However, in using Table 7, frequently smaller shells and flights of shells are recommended. The appropriate number of small shells to use is that number which nearly equals the dollar value of the larger shells that they are being substituted for. As an aside, multiple smaller shells are usually more impressive than a single large shell costing the same amount. Consider two 3-inch shells replacing

Song Title <b>Love Theme (Instrumental)</b>	Album Title <b>St. Elmo's Fire</b>	Time <b>3:26</b>
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Change Points

No.	Time	Music Description	General Notes
1	0:00	Lead in	☐ No Fireworks
2	0:08	Lead - augmented	
3	0:15	Theme (Piano)	
4	0:31	Theme (Piano) + Runs	- Runs at (0:31 - 0:35 - 0:39)
5	0:42	Interlude	- No Fireworks
6	0:46	Theme (Full/Heavy Base)	
7	1:02	Theme (Full/Heavy Base) → Runs	- Runs at (1:02 - 1:06 - 1:10)
8	1:16	Theme (Light)	
9	1:27	Theme (Full)	
10	1:36	Lead-in augmented	- No Fireworks
11	1:43	Theme (Sax)	
12	1:59	Theme (Sax) + Runs	- Runs at 2:03 - 2:07

Figure 6. Example of a complete Music Charting Form.

one 4-inch shell or four 4-inch shells replacing a 6-inch shell. (Obviously all shells are assumed to be of equal quality.) However, as a minimum, increased variety can be introduced into displays by substituting multiples of smaller shells for single large shells.

Another guide in matching fireworks to music, independent of the mood of the music, is to consider the sound or feel of the music. Light, airy, higher-pitched music is most effectively matched with cool colors and strobe effects. Heavy, full and lower-pitched music is effectively combined with warm colors and comet effects.

In a musically-choreographed macro-sync display there are not very many uses for large singly-fired salutes. Large salutes can be fired randomly mixed with many rapidly-fired color shells to create a mood of excitement. They can also be used in groups to generate a sense of trepidation. To the contrary, there are many times when volleys of numerous small salutes can be

used. In particular, they are very effective when used to punctuate high points and the conclusion of segments intended to produce a sense of excitement, jubilation or prideful patriotism.

### 3.3 Mechanics of Display Design

Having selected the music for a display while keeping in mind, in a general way, the guidance given above for choreography, the next step is to design the show in detail. This requires several steps, the first of which is to chart each piece of music. It is important to know each piece in detail, including how long each passage of the music plays; how each passage contrasts with other passages in terms of its musical feel (tranquility versus rousing, or lightness versus fullness), and some general ideas of how each passage might be expressed in fireworks. In one way or another it is necessary to chart each piece of music. If this is done somewhat formally, this has the advantage of documenting the information for use again in future shows.

However, more importantly, as the time for the display approaches, for reasons of nervousness or possible better ideas for the show, it is frequently necessary to re-examine the charted information. If the information was poorly recorded, time will often be wasted by having to re-chart many of the musical selections.

Figure 6 is an example of a completed music charting form as used by the authors. The form has three parts: one to identify the source of the music, one to chart the music graphically, and one to record times and descriptions of the various passages. In the graph, time from the start of the music is displayed along the horizontal axis, and the feel of the music is displayed using the vertical axis. Rough indicators for the feel of the music are its sense of lightness, airiness, or tranquility versus a sense of heaviness, fullness, or rousingness. Obviously these qualities are subjective and difficult to quantify. However, this is not really a problem as it is only the approximate feel of each passage and how that compares with adjacent passages that is important. Exactly how tranquil or rousing each passage is, is relatively unimportant, compared with knowing whether the passage is tranquil as opposed to rousing and whether it has more or less of that quality in comparison with the preceding and subsequent passages. Also, while the length of each passage is quite important, it is a waste of effort to attempt to record precise times on the graph. The graph is useful only for visualizing the approximate lengths of the various passages. The detailed time information necessary for display design is recorded in the third part of the form.

The music charted in Figure 6 is the "Love Theme" from the movie *St. Elmo's Fire*. This was chosen because it was quite popular (at the time of writing this paper) and might thus be familiar to the reader (or it should be relatively easy for the reader to obtain a recording). This is important if the reader is having difficulty grasping how the charting is done. Then it will be helpful to recall the music or to listen to the actual music while studying Figure 6. The music begins with a lead-in passage lasting eight seconds before being augmented with another instrumental voice. This augmentation adds to the sense of fullness and appears on the graph as a stepwise increment in that direction (shown as number 2 in the graph in Figure 6). At 15 sec-

onds into the music the main theme of the piece is played featuring the piano, which is again charted as an increase in the fullness of the sound (number 3). At 31 seconds the piano theme continues with a series of three musical runs; the start of each is separated by four seconds. This contributes to a modest building of a sense of spiritual fulfillment and is indicated as a slight ramp-up on the chart (number 4). At 42 seconds there is a brief interlude leading to a repeat of the main theme at 46 seconds. The interlude before the repeat of the theme is shown as a dip followed by a rapid rise on the chart (number 5); the manner in which this is charted is unimportant. It is only intended to show when and how long the interlude lasted. In this case it is shown as a rapid ramp up because the repeated main theme following the interlude has added to it a hard driving bass component. This gives the repeated theme a considerably increased sense of fullness, which needed to be charted in a higher position on the graph (number 6). Had the interlude led to a passage lighter than the piano theme, the interlude would have been charted as a ramp downward. The process of charting continues in a similar manner to the end of the music.

In the lower portion of the charting form, times (to the nearest second) and brief descriptions of passages are recorded along with other notes which may be useful later in designing the display, e.g., the timing of the musical runs is recorded. Note that those times when no fireworks will be shot are also indicated in this area, e.g., during the lead-in.

Having completed charting the music for the display, the next task is to design the fireworks part of the program. In doing this, use the charted music information and the choreographic guidelines presented in Section 3.2. For example, when expressing excitement or jubilation, the rate at which shells are fired should generally follow the levels graphed on the charting form. Similarly, when expressing wonderment and beauty, the warmth of star color should generally follow the graphed levels. However, it would be a mistake not to also consider what the music "says" to you; close your eyes while listening to the music and let your imagination express itself. Hopefully you have already done this in a general way during the process of selecting the music; now detail must

PROGRAM QUEUE LOG			SHOW:	DATE:
			G.J. Chamber of Commerce	1986
Tape No.	Circuit No.	Time	Effect	Notes
— Love Theme: St. Elmo's Fire 3.26				
		0:00	Music Start	No Fireworks
	R12	0:15	6-4" Silver Sets	Random (Ave. 3 sec.)
	G41	0:31	3x3-3" Silver Sets	Flights at 0+4+4 Sec.
		0:42	Interlude	No Fireworks
	R22	0:46	6-4" Red Sets	Random (Ave. 3 sec.)
	G42	1:02	3x3-3" Red Sets	Flights at 0+4+4 sec
	R11	1:16	4-4" Blue+Silver Sets	Random (Ave. 3 sec.)
	R12	1:27	4-4" Blue+Green Sets	Random (Ave. 2 sec.)
		1:36	Interlude	No Fireworks
	R32	1:43	6-4" Red+Silver Sets	Random (Ave. 3 sec.)
	G43	1:59	3x3-3" Silver Sets	Flights at 0+4+4 Sec.
	R			2 Sec.

Figure 7. Example of a completed Program Cue Log.

must be added. When the display design is fairly well in mind, it must be transferred to paper. This is done using some sort of "Program Cue Log", like the example shown in Figure 7. At this time only the three columns on the right are completed. First, the times from the music charting form are entered. Next a description of the fireworks effect for each segment of music is added. In Figure 7, shells are described as "sets". This is a shell of the size listed plus parasitic effects like those described in Table 3. Further, when Figure 7 lists "3 x 3" as the number of shells, this is meant to be three groups of three shell sets. In the final column of Figure 7 to be completed at this time, fusing instructions or other notes may be recorded. For example, at 15 seconds a series of six 4-inch silver shell sets will be fired to appear somewhat random with an average of three seconds between each firing. It is important to record this firing (delay fusing) information because the effect created will be different for random appearing firing, equally spaced firing, firing as a flight, or simultaneous firing.

By comparing the descriptions of the fireworks being used in Figure 7 with the descriptions of the music given in Figure 6, some idea of how Section 3.2 guidelines are implemented may be gained. For example, when the main theme is first introduced at 15 seconds and then

repeated with more fullness at 46 seconds, star color changed from cool to warm. Each time musical runs were added to the main theme (e.g., at 31 and 62 seconds) this was mimicked by the fireworks through the use of smaller shell flights.

The next step in display design is the assignment of each shell to a specific mortar. The process that will be discussed here will be for dense-pack mortar trailers using delay fuse links, but in many ways it is analogous to what would be done for mortars positioned more traditionally. In any event, one cannot wait until the day of the show to physically lay out the arrangement of mortars and wiring; the process just takes too long and mistakes can be costly in terms of both time and personal energy. It is appropriate to map out mortars and wiring well in advance of the show. Figure 8 is a stylized map of the 4-inch mortar rack in the dense-pack trailer shown in Photos 1 and 2. The map has been filled out to record fusing and shell loading instructions. In the example above, the first shell series for the St. Elmo's Fire Love Theme is a series of six 4-inch silver shell sets fired in a manner appearing somewhat random with an average time interval of about three seconds. On the map, this is recorded in the upper left hand area.

# 4" Rack (all circuits Red)

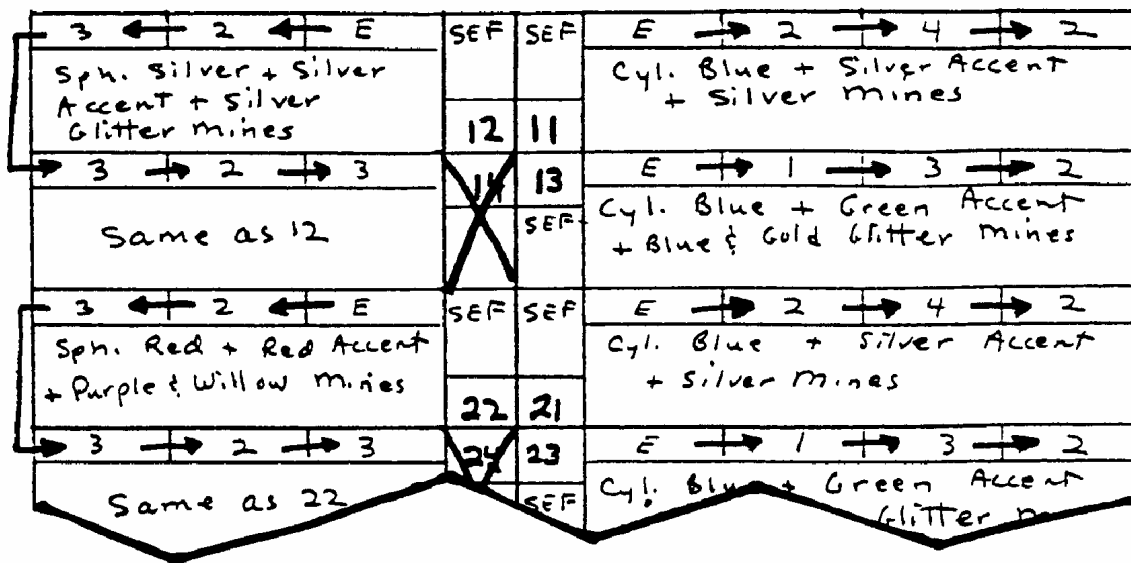


Figure 8. Example of a Trailer Loading Map for the four-inch mortar section of the large "Dense-Pack" mortar trailer.

The 4-inch rack has its electrical firing contact points running down the middle of the rack with three mortar positions to the left and four mortar positions to the right of each set of contact points. In Figure 8, the series of electrical contact points is shown as the vertical band of boxes running from top to bottom about half way across the map. Contact points are grouped in sets of four; in Figure 8 the numbers 11, 12, 13 and 14 correspond to the first set of contact points. The first series of shells for St. Elmo's Fire is fired by circuit number 12. Above the small box for contact points number 12 is another slightly larger box that can be used for recording some brief notes; here the letters "SEF" have been written to denote that this is one of the circuits that will be fired during the music from St. Elmo's Fire. To the left of these two small boxes is the area used to record fusing and shell information for the first three mortars.

Fusing information is noted in the three small rectangular boxes. The "E" in the rightmost of these boxes, next to the electrical contact point for circuit number 12, indicates that the first mortar is to be fired electrically. The

arrow pointing left indicates that the first mortar is used as the ignition source to chain fire the next mortar. The "2" in the second box indicates that the time delay of the fuse link for the second shell is two seconds. Similarly the next arrow pointing to the "3" indicates that the second shell is to be the ignition source for a three second delay link to the third shell.

The design of the display calls for the firing of six 4-inch shells. The remaining chain of three shells could be fired electrically; however, it is easier and cheaper, and firing errors are less likely if the last three shell firings are just made a continuation of the first chain of three. In Figure 8 this is shown as an arrow down the edge of the rack map to a second set of three small rectangular boxes, with additional arrows indicating continued chaining and numbers indicating delay times for the delay links. Because both sets of three mortars to the left of the electrical firing points 12 and 14 have been fired using a single electrical ignition, initiated by circuit number 12, the second circuit, number 14, is crossed out, indicating that it will not be used.



The show design calls for the firing of the first six shells to occur with three second average random firing. This was accomplished by the use of delay fuse links of slightly different delay times that roughly average three seconds.

In the larger rectangular areas, below the series of small boxes for fusing instructions, descriptions of the shells and parasitic effects are listed. In the case above, all six shells and effects are identical and only a single description need be used. Accordingly, for the above example, spherical silver display shells with silver parasitic accent shells and silver glitter mines are identified. If each shell set were to be different, separate descriptions for the shells would have been written below each of the small boxes used for fusing instructions.

At this point an additional piece of information needs to be entered on the Program Cue Log, Figure 7. That is the circuit number for firing the first shell series. In this case it is circuit 12 (the "R" in Figure 7 is a special designation peculiar to the authors' electrical firing controller).

The process of selecting, charting, choreographing and mapping is continued for each piece of music until the display design is complete. In actual practice, it is often effective to start at the two ends of a show and work toward the middle. The reason for this is that one usually has a good idea of what percent of the show budget must be spent on the finale for it to be effective; also one usually knows at what pace the show should begin. Then the process is only to fill in the middle in some logically consistent way without running out of money.

As a final comment concerning show design, it is appropriate to remember that usually, for various reasons, not all spectators will be able to hear the musical program. It is appropriate to consider these spectators too when designing the display. For the most part this just means that long periods of dark sky and prolonged repetition should usually be avoided even if that fits well with the musical program.

### 3.4 Mechanics of Pre-Production

Having completed the detailed design of the display including the layout of the mortars and wiring, the next step is to prepare to take the show on the road. Remembering that there is always too much to do at the last minute, as much work as possible should be done in advance. There are three areas in which advance work can be done: mortar preparation, shell set preparation, and general preparation.

Mortars should be cleaned, inspected and loaded into the trailers, and all required delay fuse links should be installed as early as convenient. It is appropriate to have on hand an abundant supply of variously-timed delay fuse links. The authors use a large case for storage of pre-made fuse links. The case is fitted with a large number of bins into which delay links are loaded. Thus a large number of delay links, organized by their delay times, can be kept ready for use in the chain-fusing operation. Using two people to read fusing instructions from the mortar rack map, select the proper fuse link and install it, results in speedy installation (more than 150 per hour) with essentially zero errors.

Again using the mortar rack map, the shells for the show can be readied. It is effective to prepare, as groups, shell sets just as they will be used in the display. Thus, from the example above, one such group would be six 4-inch silver spherical shells with their plastic bags of silver accent shells and silver glitter mines. As shells are withdrawn from inventory, any that will be fired electrically can have match headers attached to their leaders provided the electric matches are shunted and care is taken to protect them from rough treatment. Those shells that will be chain fired should have their leaders trimmed to remove the exposed black match (or other delay materials normal for shells intended to be manually fired). When a shell set series has been assembled and readied, it can be loaded into a large plastic bag marked to indicate the set of mortars into which they will be loaded. This is usually accomplished by marking the bag with the appropriate electrical firing circuit number. (Even when all the shells in a group are not identical, usually they are not individually marked. Rather, the group of shells is loaded at the shooting site according to the descriptions on the rack map.) Several bags of



shell sets are then loaded into a box marked to indicate the contents. The marking should be clear and easy to interpret, as there will not be time to re-sort things on the day of the display.

Another preparation that can be made in advance is to complete a checklist of those many items that will need to be taken to the display. This is more important than it might seem; musically-choreographed shows fired electrically are considerably more complex and require considerably more equipment (primary and backup) than conventionally-fired displays. The general type of items that should be considered for the checklist include: safety equipment, such as fire extinguishers, warning signs and ear protection; electrical firing equipment, such as cables, hand tools and testers; musical program equipment, such as the program tape, backup tape and reproduction equipment; fireworks, checked item by item from a complete program inventory; program equipment, such as the completed program cue log and stop watch; crowd control equipment, such as flashlights, radios and barriers; personal comfort items, such as sun screen and salt tablets; general display equipment, such as racks, lumber and tools; business items, such as the display contract, permits and proof of insurance. The list of needed equipment can grow to be very long and the probability of forgetting one or more important items is too great not to use a checklist. In addition to just preparing a checklist, as much as practical, the equipment should start to be accumulated several days in advance, ready for final loading.

Other general preparation tasks include making travel preparations such as vehicle inspection and any needed repair, and making lodging arrangements. Also arrangements for support services such as security and clean-up should be finalized.

### **3.5 Music Reproduction**

In Section 3.1, the importance of effective music selection was emphasized. However, even the greatest selection of music will add little emotional impact if its reproduction is of poor quality. The sound needs to be loud enough to be easily heard during the show over the noise of the crowd and over most of the fireworks. The sound needs to be full-bodied, with good

bass response (50–200 Hz) and reasonable high frequency response (2k–10k Hz). The importance for amply loud and high-fidelity sound cannot be overstated. If this cannot be accomplished, don't even bother trying to put on a musically-choreographed display, it simply will not be worth the time and expense!

There are two basic ways to handle music reproduction: broadcast over a radio station or use high-fidelity PA systems. To large extent, which way is best is determined by site and type of display. If the audience is widely dispersed, e.g., across an entire metropolitan area, a radio broadcast is the only possibility. This has the advantage of requiring less equipment on the part of the display operator and is fairly easy to arrange. Depending on the size and popularity of the display, most radio stations will at least seriously consider doing such a broadcast. Probably the greatest disadvantage is the problem of publicity; if spectators don't know that there will be a musical accompaniment, remember to be near or bring a radio, and know what station to tune to, they will be left out. Another problem can be arranging to get the audio signal to the station. Obviously the easiest is to give the radio station a copy of the music program tape. However, this results in a loss of control over its playback. This may not be critical but requires at least some sort of two-way communication link with the radio station. There is always the potential for the display to be delayed or interrupted by an equipment failure or safety problem. Should this occur, coordination with the station to interrupt, delay or restart the musical program is essential. It is simply unacceptable to allow one to be put into the position of having to choose between overlooking an unsafe condition and aborting the musical portion of the show, because one cannot communicate with the radio station. An alternative to giving the station the program tape is to use one's own playback equipment and send an audio feed to the station. This is not trivial but can be arranged particularly if the station is doing a remote broadcast from the shooting site and can accept the audio signal. In that case, only a long audio cable is needed.

If the audience is confined to one or two relatively small areas (such as a grandstand), it is effective to use high fidelity sound reproduction equipment positioned just for the benefit of

the audience. Nearly any high power amplifier(s) will be sufficient, as essentially all modern equipment has good frequency response. The problem with the amplifier will be to get sufficient power output. To be heard effectively and have sufficient bass response, music reproduction requires considerably more power than normal voice PA systems. To be heard equally well, high quality (not loud) music requires five to ten times the audio power needed for voice. Power requirements for even a small crowd will be several hundred watts; larger crowds may require several thousand watts of power. Speakers are another problem. As not only do they have to be able to handle the large power, they need good frequency response. Normal PA speakers, that may be available at the site, are simply inadequate. They almost never have acceptable low frequency response. Unless speaker response extends well below 100 Hz, the music will sound thin and will not be very effective. To make the musical program as effective as possible, an equalizer can be used to balance and temper the frequency response of the system for the acoustics of the site. As a minimum, if an audio spectrum analyzer cannot be used, several parts of the program should be previewed with the listener positioned where the crowd will be and the frequency equalizer adjusted for a pleasing sound.

If high fidelity PA equipment is used to broadcast the music, the listener has no control of the sound level. Those with control generally will not be in the audience and will have difficulty in setting the proper level. Guesses made during the day, at what level will be effective, will probably miss the mark at least to some extent. For the display to be really effective, the sound level must be nearly as loud as comfort will allow. To complicate things, in the loud environment of the display, the audience's tolerance (desire) for loud sounds will increase as the display proceeds. Accordingly it is desirable to station someone in the audience with a two-way radio to give instructions for setting the audio level during the display. (Note that this same person can also perform a safety watch for debris falling into the crowd or for shells breaking over the audience.)

### 3.6 Show Performances

There are significant differences between setup and performance of electrically fired displays and hand-fired shows. However, beyond what was presented in Section 2 of this paper that discussion is beyond the scope of this article. (See reference 1 for such a discussion.) The addition of a musically choreographed program to an electrically fired display does not change the setup, electrical wiring, mortar distance to spectators, etc. One difference may be the need for AC power on site for tape playback equipment. If a high output audio system is used, the power requirements may be considerable (4 to 5 kW).

It is very useful to have two people firing the musically programmed display, one to throw the switches and one to read the program and stop watch or tape counter. The use of chain fusing and parasitic effects significantly reduces the number of electrical firings and does make it possible for a single person to control a show, but this is clearly not desirable. With only one person, any small problem will be magnified and could seriously diminish the effectiveness or safety of the display.

If the display crew has control of the tape playback equipment, the tape counter on the tape deck can be used to indicate firing times during the display. The Program Cue Log (Figure 7) should then have the appropriate tape counter numbers entered into the leftmost column. If the display crew does not have control of the tape playback equipment, or if they prefer not to use the tape counter for program cues, some form of stop watch or digital timer can be used.

During the display it is necessary to be able to receive input (by radio) from safety people stationed to monitor the fallout and crowd areas. It is necessary for the person doing the firing and the person reading the script to hear each other clearly. It is important to be able to hear the musical program particularly if it becomes necessary to improvise or adjust because of some technical problem. All these important communications taking place in the high noise environment of a display may present problems. One solution is to use an intercom system like that used in helicopters, with headphones and microphones for the two operators and additional inputs for the communications radio and the music program. In Section 2.3, it was men-

tioned that it is occasionally desired to record one's comments and observations during the show performance. With this type of intercom system it is relatively easy to include an output signal for a tape recorder. If this is done, there will be a complete record of the show and all comments and observations. This also includes all reports from safety monitors, which may be helpful if ever there is an accident.

#### 4.0 Conclusion

By way of conclusion, it is perhaps worth restating that the added expense of hardware needed to fire musical aerial displays electrically from trailers can be offset by the increased profit in a relatively short time.

Some specific examples are:

- Such displays require a considerably smaller work force on the day of the show. This results in a savings in salary and per diem expenses per show and also allows more shows to be staged with the same size work force.
- The use of personnel during marginally-productive periods well in advance of shows can represent a savings of labor costs.
- The use of parasitic effects gives the sponsor a more effective show and reduces the number of mortars needed, both of which translate into more profit.
- Shooter and spectator safety are increased in these shows. Even with full insurance coverage, accidents are very costly.
- The use of chain firing can improve a show by reducing errors caused by having to rapidly fire effects. It also saves electric matches and allows the use of less cable and firing control equipment with fewer circuits, all of which can translate into savings.
- Sponsors now increasingly expect and are willing to pay for truly effective and professionally-performed displays. (Note that this may also be an effective way for small operators to compete with a larger company's ship-shows.)
- There are a number of tax advantages (ACRS depreciation, investment credits and Section

179 expensed equipment) that can significantly reduce the effective costs of the equipment.

Considering all aspects, the authors estimate that the cost of equipment will be recaptured after about six displays.

#### 5.0 Acknowledgments

As is so often true, most of the ideas presented in this paper are borrowed from others, and relatively few are original. Unfortunately, there is uncertainty regarding who contributed which ideas over the years. With a general apology, however, some of those who have contributed personally or through their writing to the development of the methods presented in this paper are Takeo Shimizu, Ken Nixon, Robert Winokur, Sam Bases, Tom DeWille, and Bill Ofca.

The authors also wish to thank all those who assisted in the editing of this work. In particular the special efforts of Ken Nixon and John Bergman are appreciated.

Finally, the authors wish to acknowledge the efforts of the staff of PYROTECHNICA especially those of its publisher Robert Cardwell.

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## Sizzling Colored Comets

K. L. Kosanke

The sizzling colored comets described in this article have brilliantly colored heads, have short white tails and produce a sound much like frying bacon. They are very simple modifications of standard potassium perchlorate color compositions, are inexpensive and are relatively easy to make. These sizzling colored comets are suitable for use as comet stars in shells or for use as single large comets.

Presented below are standard formulations for blue, purple and red stars. The blue and purple formulations are taken from T Shimizu's excellent article in *Pyrotechnica VI*. The red formulation is analogous to those presented by Shimizu. The formulations all use potassium perchlorate as oxidizer, red gum (Accroides resin) as the primary fuel, and dextrin as the water soluble binder. The only modification of these formulations, to turn them into sizzling color comets, is the addition of 10 to 20% of 20–50 mesh atomized magnesium. Varying the percentage of coarse magnesium has the effect of increasing the density of the tail and the sound level produced. The addition of unprotected magnesium makes it inappropriate to use water to activate dextrin as the binder. Instead, alcohol, denatured ethanol or methanol (with proper ventilation), should be used to activate red gum as the binder.

The dampened composition is fairly sticky, and while cutting stars is possible it is not easy; making pumped stars is preferred by the author. On drying, the stars/comets are quite water resistant and priming can be easily accomplished by dipping them into a water-slurry of home-made meal powder containing 5% dextrin. To make the stars/comets easy to handle while the wet prime is drying, they can be sprinkled with dry meal powder or rolled in a bowl that is partially filled with dry meal powder.

It is somewhat difficult to judge the color of these comets when burned on the ground. In part this is because they will be surrounded by a

number of bright white sparks which are not propelled very far from the star. However, the main reason is that one's eyes do not perceive color well when over-powered by the high light intensity produced by these stars. Tests should be made with the stars/comets in motion and at a distance of at least a few hundred feet.

The comet stars function very much as one would expect. When the star burns, the large particles of magnesium are partially consumed within the flame envelope. This has the effect of raising the flame temperature which in turn results in increased light output. Because the composition is fuel rich from the addition of magnesium the size of the flame envelope is greater making the star appear slightly larger. Because the magnesium particles are large and rounded, only their outer surface is consumed inside the flame envelope. The burning particles appear white, in the absence of a color agent and chlorine donor, and form the tail of the comet. (Readers wishing additional information on the subjects of chemical color production in stars, flame temperature, etc. are referred to a paper on those subjects that appeared in *Pyrotechnica IX*). The mechanism of generation for the sizzling sound produced by these comet stars is not fully understood.

<b>Standard Color Formulations (parts by wt.)</b>			
Chemical	Blue	Purple	Red
Potassium perchlorate	64	64	64
Parlon	14	13	10
Red gum	9.5	9.5	10
Copper carbonate	13	5	—
Strontium carbonate	—	8	13
Dextrin	5	5	5
(bound using water)			
<b>Additions to Make Sizzling Color Comets:</b>			
Magnesium 20–50 mesh, atomized	15	15	15
(bound using alcohol)			

## HDPE Mortars for Electrically Fired Displays

K. L. Kosanke

When firing by hand, the problems of steel mortars can easily be over-looked. However, even for relatively small electrically fired displays, steel mortars and the usual alternatives (paper and PVC mortars) have limitations that are difficult to cope with.

Steel mortars are heavy; when several hundred may be needed for a show, their weight can easily exceed 5000 pounds. This may necessitate the use of a large truck and must certainly be seen as undesirable by the crew that will need to handle them several times. Service life is long, but high initial cost (about \$1/pound) is another problem. Finally, even though steel mortars are quite strong, there is the possibility that a shell detonation may cause the production of dangerous mortar debris.

Paper mortars are lighter (about 1/3 the weight), cheaper (about 1/4 the cost) and produce less dangerous debris than steel mortars. However, the service life of paper mortars is generally quite short; probably about ten firings on average. Spiral tubes soon tend to have inner wraps peeling up which can bind a shell. All paper mortars will delaminate inner wraps if the mortars are even slightly damp when fired. Even treated paper mortars can be ruined by a single exposure to rain.

PVC mortars weigh and cost about the same as paper mortars. They are water proof and thus have a service life longer than paper. However, because the strength is less than steel mortars, so is their service life. The real problem with PVC mortars results from the combination of their only modest strength and the mechanism of their typical failure. Often a flowerpot and certainly a shell detonation will result in their destruction. Because PVC is relatively brittle, mortars—over-stressed in this manner—fracture and fragment. In addition, the fragments will usually have sharp edges and be pointed. This high velocity debris has the potential to do significant damage to nearby mortars and people.

A plastic mortar that retains all the good characteristics of PVC (low weight, modest cost, long service life) and eliminates the fragmentation problem would be near ideal. What is needed is a plastic that is strong, inexpensive and ductile. For the mortars to have sufficient strength requires a tensile strength approximately equal to that of PVC. For the mortars to be inexpensive requires not only a low base material cost but also that large amounts of pipe with the proper characteristics are already being produced commercially. Ductility is important because it results in a stress failure mode that might be described as bursting rather than fragmenting. Figure 1 is a series of sketches comparing the failure of less ductile (brittle) and ductile plastic mortars. Although fragments are still possible with ductile materials, often none will be produced. Also if any fragments are produced, they will have been stretched thin and will thus meet with greater air resistance, and will be slowed to harmless velocities sooner. Finally, if the material is somewhat flexible, fragments will tend to bend rather than penetrate on impact.

There are a number of promising plastics worth considering, but the one with the best overall characteristics is high density polyethylene (HDPE). This is basically the same material used to make plastic milk bottles; however, it is significantly stronger and is normally black in color (as used by the pipe industry). Table 1 is a subjective comparison of characteristics of steel, paper, PVC and HDPE mortars. As can be seen HDPE has characteristics that make it highly suitable for use as mortars in electrically fired displays. HDPE pipe is available in 2, 3, 4, 5, and 6 inch ID

In Table 1 note that HDPE's strength is listed as greater than PVC. This was done even though the tensile strength of PVC is reported as exceeding HDPE. When I initially considered HDPE, I assumed I would need to have special extrusion dies made and produce the pipe my-

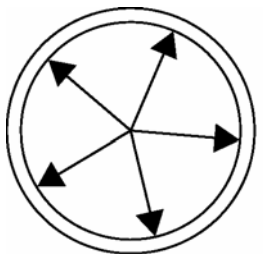
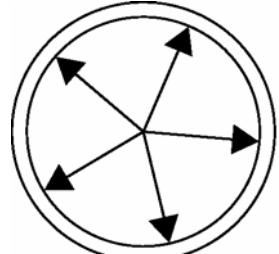
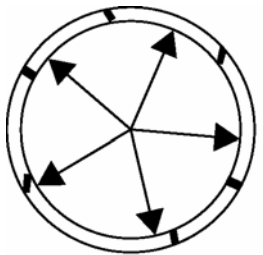
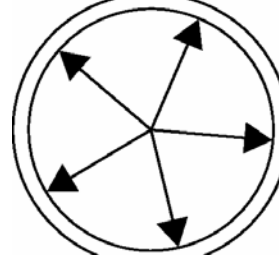
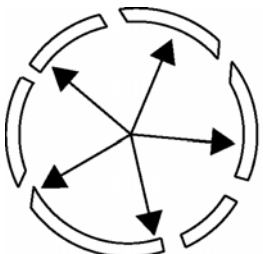
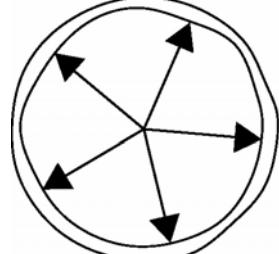
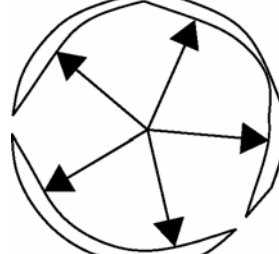
PVC — Less Ductile Mortar		HDPE — More Ductile Mortar	
Condition	Sketch (cross section)	Condition	Sketch (cross section)
High internal pressure.		High internal pressure.	
Rapid increase in pressure exceeds capacity. Pipe expands but fractures develop as elastic limit is soon exceeded.		Rapid increase in pressure exceeds capacity. Pipe expands and strength is reduced as diameter increases and wall thickness decreases.	
Many sharp high velocity fragments are generated.		Very high pressure continues. Elastic limit is exceeded and thin areas develop in mortar wall as it is stretched.	
		Very high pressure continues. Wall continues to be stretched thin until one or more tears develop venting pressure. Few if any fragments are produced.	

Figure 1. Comparison of failure modes of PVC and HDPE mortars.

self. Commercially produced pipe had wall thicknesses and pressure ratings that seemed inadequate for use as mortars. However, during early tests to determine the necessary wall thicknesses, I was pleasantly surprised by the unexpectedly high apparent strength of HDPE. Mortars made of HDPE pipe, with pressure ratings of only about  $\frac{1}{2}$  those for PVC mortars, consistently were capable of withstanding equal or greater stress than PVC mortars. The reason for this seems to be related to their differing failure

modes, and the nature of tests performed to determine pressure ratings.

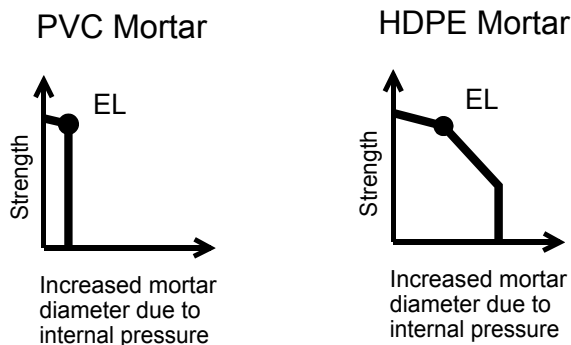
Figure 2 shows the approximate relationship between mortar strength and increases in mortar diameter due to internal pressure. The first portion of the graphs, when strengths are nearly constant, is characterized as elastic expansion of the mortars. Mortar strength falls slightly in this region because as it expands there is a slightly larger surface being exposed to the internal pressure. Mortars not stressed (stretched) further than their elastic limits (points EL in Figure 2) will

**Table 1. Comparison of Characteristics of Steel, Paper, PVC and HDPE Mortars**

Mortar Type	Weight	Cost	Strength	Number of Fragments If Over-stressed	Danger of Fragments
Steel	High	High	High	Few	High
Paper	Low	Modest	Low	Few	Low
PVC	Low	Modest	Low	Many	Moderate
HDPE	Low	Modest	Moderate	Few	Low

regain their original diameter when the stress (pressure) is removed. Also they will not have suffered any permanent loss of strength. For PVC mortars the elastic limit is reached quite soon, and fracturing and fragmentation occur when the elastic limit is exceeded. This results in the strength of the mortar falling essentially instantly to zero. For HDPE mortars, the elastic flexing region is larger than for PVC. Also, when the elastic limit is exceeded, the mortar does not fracture, rather there is a flow (inelastic stretching) of the material. However, unlike the elastic flexing region, now the mortar will no longer return to its original diameter if the stress is removed, and there will be a permanent reduction in its strength. The loss in strength is the result of the pipe walls stretching permanently thinner. In this region of irreversible stretching the strength of the mortar falls more rapidly, but not instantly as it did for the PVC mortar. Finally, after continued stretching, the mortar tears open and its strength falls to zero.

Pressure ratings for plastic pipe are a fraction (usually  $\frac{1}{2}$  to  $\frac{1}{4}$ ) the maximum pressure



*Figure 2. Approximate relationship between mortar strength and increases in mortar diameter due to internal pressure*

they can withstand for very long lengths of time when heated to their maximum operating temperatures. If the pipe material is elastic and deforms somewhat easily (desirable properties of mortars and mortar fragments), it may not stand up to pressure well over long periods of time. This is because as pressure is applied the pipe slowly expands a little; this causes the wall to stretch slightly thinner and exposes slightly more surface area to the pressure (i.e. the effective strength of the pipe is reduced). If the pressure is maintained, the pipe stretches further and weakens more. The process may continue until the pipe bursts. This does not mean that the pipe will not be able to successfully withstand a very short (fraction of a second) exposure to pressures many times greater than would burst the same pipe if sustained for many hundreds of hours. In comparison, a pipe that is more brittle, essentially unyielding under the effect of pressure, might withstand considerably higher pressures, until it fails catastrophically by shattering.

In a mortar, high lift pressures are sustained for only a small fraction of a second and are not uniform along the length of the mortar (i.e., they are high only below the shell being propelled). This sudden and non-uniform application of pressure may be considerably more stressful for a more brittle material like PVC than for one that is more ductile like HDPE. At any rate, this appears to be the case in practice, HDPE mortars (with rated pressures only  $\frac{1}{2}$  those of PVC) demonstrate equivalent or even superior strength in comparison with PVC mortars.



**Table 2. Summary of Initial Tests with HDPE Mortars.**

Test	Results
Destructive test: Salute in a short mortar at about 90 °F.	Mortar was turned completely inside out and several tears occurred at the end of the mortar where the salute was positioned. However, it appeared that no fragments left the mortar and the split ends of the mortars were thinned by stretching so that they were relatively flexible. Also, although the mortar was unsupported and above ground, it came to rest only three feet from its starting position.
Destructive test: Salute exploded in a short mortar cooled to about 15 °F.	The mortar was turned completely inside out and a small number of pieces were torn from it. However, the pieces were all stretched quite thin resulting in their being relatively flexible and having large surface areas in comparison to their weight. It seemed likely that a person, if struck by a piece, might receive an abrasion but a serious puncture wound seemed unlikely. Also it was difficult to imagine that adjacent mortars could have been damaged by mortar fragments.
Rapid fire test: Five 4" canister shells with normal lift plus five 50% over-lifted were fired from the same mortar in approximately 5 minutes. The final shell flowerpotted.	The mortar successfully withstood the test even though the temperature of the outside of the mortar — measured after the test — rose to over 150 °F.
Rapid fire test: Five 4" canister shells 100% over-lifted were fired in 3 minutes. The fifth shell flowerpotted.	The mortar successfully withstood the test.
Strength test: One 4" shell 200% over-lifted was fired from one of the above mortars.	The mortar successfully withstood the test.
Strength test: One 6" spherical shell with normal lift and one 6" canister shell 50% over-lifted were fired.	The mortar successfully withstood the test.
Durability test: Ten additional normally lifted 4" canister shells fired from each of mortars used in the rapid fire tests.	Inspection of inner mortar surfaces revealed a moderate build-up of Black Powder combustion products. After mortars were washed, inspection of inner mortar wall surface revealed essentially no deterioration.
Final 4" test: Ten Additional 4" canister shells, each 200% over-lifted, were fired in 6 minutes from a mortar cooled to 30 °F.	The mortar successfully withstood the test. (Note, the mortar had previously been used to successfully fire 20 shells.) There were no visible signs of mortar deterioration.

Table 2 summarizes the initial tests that were performed on HDPE mortars. As a result of these initial tests, it seems clear that HDPE mortars have both sufficient strength and service life to be used successfully as mortars for electrically fired shows. In addition, their failure mode strongly suggests they represent considerably less hazard to people and adjacent mortars that do PVC mortars. Accordingly, we

have decided to replace 100% of our paper mortars (about 800) with ones made of HDPE.

Note that because HDPE mortars are quite resilient, it is possible to plug the mortars with wooden plugs stapled in place. Pre-drilling or screwing is not necessary as is the case with PVC mortars.

In conclusion we (Kosanke Services, Inc.) offer to share the experience we have gained with HDPE mortars with anyone wishing further information (phone 970-245-0692). This

includes an offer to supply a limited number of test mortars for evaluation and a list of specifications and sources for HDPE pipe with the proper characteristics.

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## Economics of Plastic Shell Construction

K. L. Kosanke

### Introduction

One hears a number of reasons why some manufacturers are reluctant to seriously consider the use of plastic shells. Among these are a feeling that it would somehow represent a betrayal of tradition and aesthetic values; the problem of long lasting debris; that it requires the learning and application of significantly different techniques, which translates into development costs. I understand all of these reactions quite well; I felt and expressed them myself in the past. It was a slow and sometimes trying metamorphosis from the position I expressed in the past to the one I now take.

About seven years ago I reached the conclusion that traditional paper and string shell construction, after having served the industry so well for so long, had essentially reached the end of commercial viability in this country. Certainly the technique produced excellent results but labor costs would soon make it impossible to continue to use these methods. My initial efforts to find an economic alternative were relatively minor deviations from traditional methods, such as the elimination of stringing. We made a small machine that wrapped pasted paper on traditionally formed shell cans. This eventually produced shells that performed well but resulted in only insignificant savings of assembly time. Our next efforts, which spanned several years, focused on the use of multiple pre-made paper components, inner and outer tubes with disks held in place using paper rings. This resulted in useful savings of assembly times, but shell performance was too unpredictable and the cost of the paper components consumed most of the savings from reduced assembly times. Next we worked for a while with paper tubes with plastic end caps. This produced better results than the all paper version, but the cost was higher and there were some operational difficulties associated with gluing on the second end cap.

During this same time frame we started using all plastic 2" canister shells and breaking them with loose sodium benzoate / potassium perchlorate whistle mix. The results were surprisingly good and assembly times were very short. By this time the extreme aversion I initially felt toward plastic shells had been replaced by a strong desire to have larger diameter all plastic canister shells available for our use in manufacturing. Unfortunately, none were available. After another year of wishing that someone would manufacture such shell casings, we decided to take the initiative. We took what we had learned and designed the RAP (Rapid Assembly Plastic) Shell. We are convinced that plastic will eventually replace paper/string shell making in the US. The reason we feel this way is simply a matter of economics. True, plastic shells must perform well in order to replace paper/string shell construction, but they do. True, plastic shell construction requires applying some new techniques, but they are easily learned and taught to employees. True, in order to learn to optimize

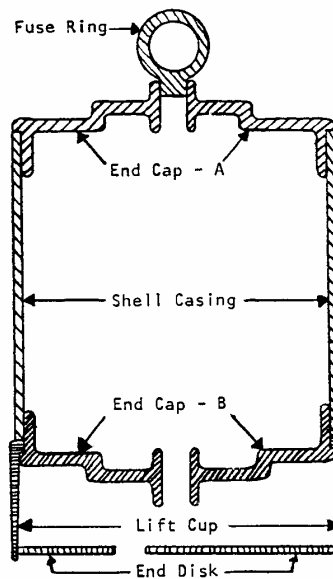


Figure 1. RAP shell components.

**Table 1 Shell Assembly Time Comparison.**

Relative shell assembly times assembling 1000 hard breaking canister shells with comet tail, including lifting and finishing.

Task Description	Time (sec.)		Explanation
	Paper	Plastic	
Preparation of materials (summation of preparation times).	20	13	Fewer materials to prepare and assumes all pieces are precut.
Time fusing, including cross matching.	20	17	Fuse held more securely and larger surface facilitates more rapid gluing.
Case forming, including chipboard lining and attachment of end disk.	30	5	Case already formed and lining not required.
Contents Loading.	25	15	Exact filling and compacting are unnecessary.
Second end closing.	10	5	Paper pleating not necessary.
Stringing shell.	80	0	Not necessary.
Pasting-in and paste wraps.	60	0	Not necessary.
Removal to storage for drying, turning and retrieval after drying.	20	0	Not necessary.
Comet formation and attachment.	35	20	Comet formed already attached to shell.
Leader attachment, final wrap, lifting and tie off ends.	40	20	Lift cup already formed, leader held in place automatically.

the performance of plastic shells, it will require the investment of some time and effort, but this investment is rapidly repaid. Plastic shells will largely replace traditional shells made in this country simply because not making the conversion will make the present difficult competitive situation impossible in the future.

To assist readers who may not be familiar with plastic shells such as RAP shells, Figures 1 and 2 have been included. Figure 1 shows the way in which RAP Shell components fit together, and Figure 2 is of a typically completed RAP Shell.

**Assembly Time Comparison**

Table 1 is a comparison between estimated times for assembling conventional paper/string shells and RAP shells (or similar all plastic shells). The shells are assumed to be single, hard breaking three or four-inch shells with a comet attached. It was assumed that 1000 shells would be made; however, times will not be much different for assembling 100 or 10,000 shells. The times are intended to be those for reasonably experienced personnel with reasonable motiva-

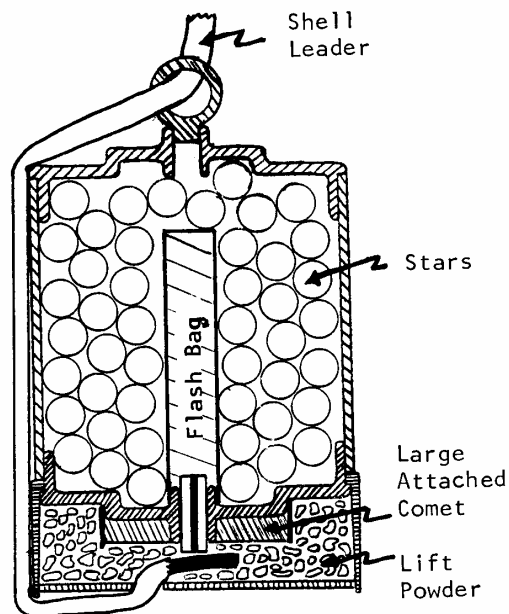


Figure 2. Typically completed RAP shell.

tion and are assembly times that workers would be expected to be able to maintain day after day throughout a prolonged production period.

As can be seen from Table 1, the time savings resulting for plastic shell assembly will amount to about 255 seconds (4.25 minutes) per shell. Most of this results from elimination of case forming, stringing, pasting-in, addition of a paste wrap, and the necessity for drying. However, times required for many of the other operations are also reduced as the result of simplified assembly processes, such as elimination of the necessity for careful contents loading and tying-off the shell ends after leader and lift have been added.

### Labor Cost Savings

To convert these time savings into cost savings, consider the information in Table 2. First are estimates of base hourly labor rates for assembly workers. Three rates are given, the lowest being minimum wage. Next are estimates of burden rates, the multiplier for base hourly rates that will account for additional employer costs for unemployment insurance, FICA, workman's compensation insurance, etc. The lowest assumes a combined federal and state unemployment rate of 3%, FICA of 7% and workman's compensation rate of 18%. Finally are facility overhead rates, the multiplier for hourly rates that will account for employee benefits (such as vacations, sick leave, training, work clothing, production and safety equipment, etc.), breaks (such as scheduled breaks, calls to nature, wash times before lunch and quitting, etc.), and facility costs (such as heat, light, laundry, maintenance, security, rent, management supervision, office expenses, etc.). The lowest rate assumes there are no employee benefits at all, that employees

**Table 2 Labor Costs.**

	Lowest	Average	High
Base hourly rate	\$3.35	\$4.25	\$5.00
Burden rate (Fed. & State Unemployment, FICA, Workman's Comp., etc.)	1.3	1.3	1.8
Facility overhead rates (Benefits, Breaks, Utilities, Set-up time, etc.)	1.3	1.4	1.6
Resultant hourly rate	\$3.66	\$8.92	\$14.80
Resultant cost/min.	\$0.09	\$0.15	\$0.24
Plastic shell cost savings	\$0.38	\$0.64	\$1.02

are productively occupied 50 minutes each hour and facility costs are zero except for supervision which is at a rate of one supervisor per 18 production workers. The result is that actual labor costs probably range between about \$5.65 and \$14.40 per hour and averages approximately \$8.90. Accordingly, if plastic shell assembly techniques save 4.25 minutes per shell as compared with conventional paper/string shell methods, there will be a savings of labor costs of from about \$0.38 to \$1.02 per shell and an average savings of approximately \$0.64 per shell.

### Comparison of Material Costs

Table 3 presents estimated costs for pre-cut components needed to assemble conventional paper/string, shells (three and four-inch). Because costs vary substantially depending on quantity, information has been presented assuming one hundred, one thousand and ten thousand shells will be made.

**Table 3 Estimated Costs for Precut Paper Shell Components.**

Items	Cost Per Unit for Production Runs of Quantity Shown					
	100 Shells		1000 Shells		10000 Shells	
	3"	4"	3"	4"	3"	4"
3 end disks	\$0.15	\$0.18	\$0.12	\$0.14	\$0.06	\$0.08
Shell case(60#) and Chip liner	0.12	0.20	0.06	0.12	0.05	0.10
Paste, String, Paste Wrap & Final Wrap	0.10	0.15	0.07	0.11	0.03	0.08
Totals	\$0.37	\$0.53	\$0.25	\$0.37	\$0.16	\$0.26

**Table 4 Component Costs for Paper vs. Plastic.**

Type	3"			4"		
	100	1000	10000	100	1000	10000
Paper	0.37	0.25	0.16	0.33	0.37	0.26
Plastic	0.60	0.44	0.41	0.71	0.53	0.31
Difference	0.23	0.19	0.23	0.18	0.18	0.25

Table 4 is a comparison of the costs for paper and plastic components. On average, the plastic components cost approximately \$0.21 more than do the paper components. Accordingly, this reduced the cost savings for plastic shell construction to a range from \$0.16 to 0.81 per shell and averaging about \$0.43 per shell.

### Other Cost Considerations

There are a few other savings that can be realized for manufacturers using all plastic shells. First, if the shells have a lift cup, such as RAP Shells do, that functions something like the wad in a shot gun shell, then significantly less lift powder is required. Our tests suggest that three and four-inch RAP Shells can be propelled to adequate heights using only 0.6 and 1.1 ounces of lift powder, respectively. This is a savings of 0.4 and 0.9 ounce compared with conventional shells. Assuming a delivered price of \$2.00 per pound for Black Powder, this corresponds to an additional savings of \$0.05 and \$0.11, respectively for three and four-inch shells.

Current BATF requirements are that all in-process shells be removed to a magazine (or a secured building meeting the distance requirements of a magazine) at the end of every work day. All plastic shells can easily be completed and boxed, ready for shipment on the same day. Thus the requirement for magazine storage at the end of every day is no problem at all. For conventional paper/string shells, the necessity of shell drying is incompatible with storage in magazines for finished products. Thus it is necessary to have available another highly secured building exclusively used for drying. Clearly

there are costs associated with the necessity for this additional building, to say nothing of the energy costs for heating the drying building. Because of the time of year when most shells are made and OSHA/BATF safety requirements on the type of heating equipment that must be used, both the cost of the heating equipment and the energy cost of shell drying are certainly significant. The combined costs for shell drying probably average at least \$0.05 per shell.

Because of the uniformity of plastic components and the simplicity of their assembly, it is fairly certain that significant additional time (cost) savings may be possible by the use of assembly line, semi-automated or automated assembly techniques. However, because these savings are speculative at this time, they will not be included in this discussion.

Accordingly, the saving in lift powder and eliminating the cost of drying, increases the cost savings of all plastic shell construction about \$0.13 on average. Thus the savings should run from \$0.29 to \$0.94 per shell and will average about \$0.56 per shell.

### Conclusion

Shell manufacturers are reluctant to give information on their profits. However, it is certain that the net profit is less than \$0.50 per shell (small single break shells). Even if profits were this great, the conversion to all plastic shells would still represent a two fold-increase in profit. This increase in profitability is simply too great to be ignored; there will be increasing economic pressure to make the conversion to plastic shells.

## An Evaluation of "Pyro-Flake" Titanium for Use in Fireworks

K. L. Kosanke

Kosanke Services, Inc., Pyrotechnic Consultants

Several months ago, our company was approached by the Suisman Titanium Corporation. They told us that they were considering introducing some new titanium products specifically intended for the fireworks trade, and that their materials would be priced below that of titanium sponge. They asked whether we would perform an evaluation of their "Pyro-Flake" titanium and make recommendations concerning the introduction of their products to the fireworks trade. We performed that study, and one of our recommendations was that a condensed report of our study be published. This article is that condensed report and was in part subsidized by Suisman Titanium. However, Suisman Titanium has asked us to be completely candid, and they have not exerted any editorial control over the content of this article.

### Material Description

As its name suggests, Pyro-Flake titanium materials are flakes of titanium metal; this is in contrast with traditionally used titanium sponge which is granular. The flaked material has two dimensions (length and width) that are roughly equal, but its third dimension (thickness) is substantially less. The first Photo is of 20–40 mesh Pyro-Flake titanium. We were asked to evaluate both pure titanium flakes as well as flakes made of a common aerospace alloy (90% titanium, 6% aluminum, and 4% vanadium).

### Ignition and Burn Characteristics Test

Some of the first tests we performed were intended to discover how easily the two types of flaked titanium ignited in comparison with sponge. Also, during these tests, observations were made of relative spark color, intensity, and

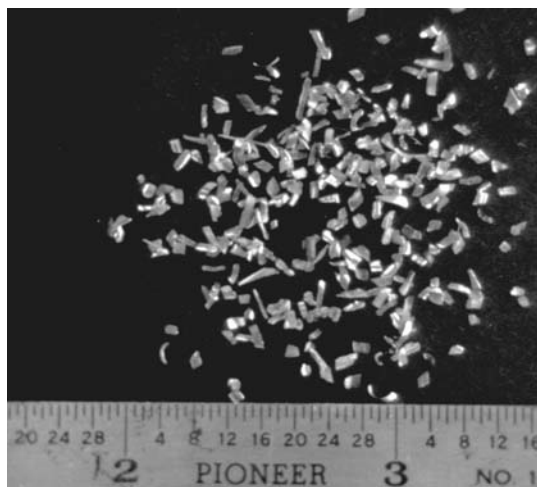


Photo 1. 20–40 mesh Pyro-Flake titanium.

duration as well as the sound produced during burning. In these tests, 16 small tubes ( $\frac{1}{2}$ " ID  $\times$   $1\frac{1}{2}$ " long) were loaded with  $\frac{1}{4}$  tsp. of 4 Fg Black Powder and  $\frac{1}{4}$  teaspoon of various types and mesh sizes of titanium. The tubes were individually raised to a height of 15 feet, fired with the aid of an electric match, photographed (time exposure), and personal observations of the effects were recorded. The test results are summarized below:

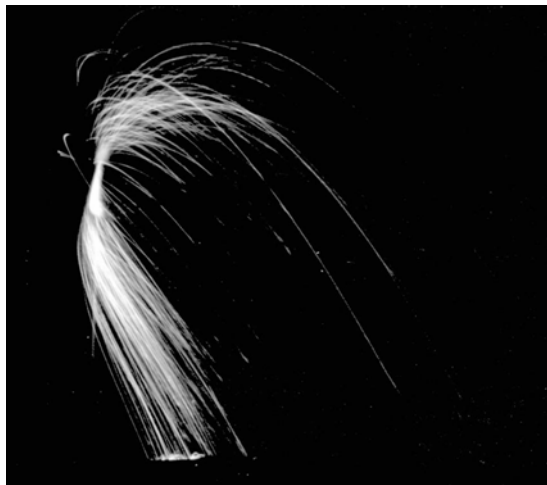
- 1) In all tests, both the pure and 90-6-4 flakes produced roughly an equivalent number of sparks, with probably a slight advantage to the 90-6-4 flakes. More significantly, however, both types of flakes produced considerably more sparks than did the same mesh size of sponge. The difference was most clearly seen for the 10–20 mesh materials which are shown in Photos 2, 3 and 4.



*Photo 2. Ignition test, 10–20 mesh sponge.*

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- 2) There were no discernible differences in spark color or intensity for any of the types of titanium. Similarly, there were no discernible differences in the crackling sound produced by the splitting of the burning particles near the end of their paths.
- 3) Judging from the percentage of sparks hitting the ground, it was felt that sponge and pure flakes (of the same mesh size) had durations that were equivalent. However, the 90-6-4 flakes had durations approximately 10 to 20 percent longer than the pure material.



*Photo 3. Ignition test, 10–20 mesh Pyro-Flake (pure).*

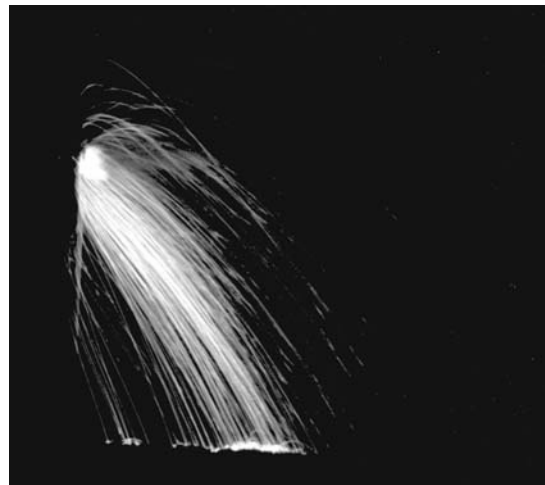
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- 4) In these tests, it is not known for certain why the flake materials generated abundantly more sparks than did the sponge. Two possibilities came to mind, perhaps the flake material is more easily ignited, or more likely, there are an increased number of titanium particles per unit weight in the flake material.

Clearly the flake material significantly outperformed the sponge and, to a lesser extent, the 90-6-4 flakes outperformed the pure titanium flakes.

### **Salute Performance Test**

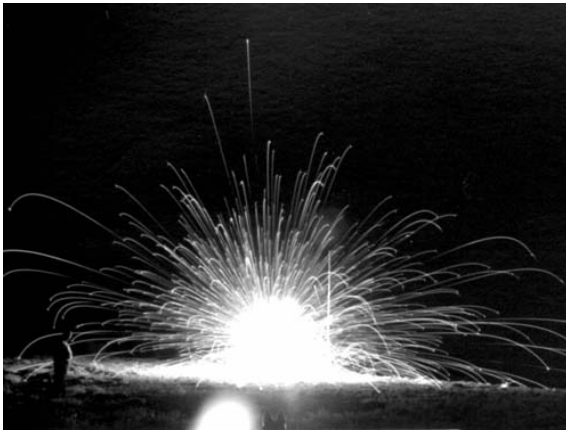
The next series of tests were performed to discover the relative effectiveness of flake and sponge material when used in salutes. The tests employed 32 salutes made with somewhat larger tubes (1" ID × 3" long). Each tube was loaded with 1 tablespoon of flash powder (70% potassium perchlorate and 30% German dark aluminum) and ¼ teaspoon of titanium. In the first half of the tests, the salutes were suspended 5 feet above the ground, fired with the aid of an electric match, and photographed (time exposure). The second half of the tests employed salutes of similar construction; however, in this case, a subjective rating of performance was sought from two observers. In these tests, in order to assure objectivity, no one involved knew which salutes contained the various types of titanium. In order



*Photo 4. Ignition test, 10–20 mesh Pyro-Flake (90-6-4).*

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*Photo 5. Salute, 20–40 mesh sponge.*

to aid the observers in evaluating the sparks produced, a small shadow shield was erected in order to block the bright flash of the exploding salutes. The results of both test series are summarized below:

- 1) In all tests, the salutes containing sponge spread sparks farther than did those containing flaked titanium. As an example, see Photos 5 and 6, which are of salutes containing 20–40 mesh material.
- 2) Even though it was felt that it was possible that the flaked titanium salutes containing the 90-6-4 titanium had sparks that persisted slightly longer than did those from sponge, the sponge titanium salutes were consistently rated by the observers as being more impressive.
- 3) The distance traveled by typical sparks was largely independent of whether the salutes used sponge or flakes. It is primarily in the distance traveled by the longest sparks where the difference occurred. For flaked titanium the typical length of travel was about the same as the maximum distance traveled. Further, the travel distance for sparks from salutes with 10–20 mesh flakes is very nearly the same as for those containing 20–40 mesh flakes.

It is felt that the shape of the flaked titanium results in their limited spark travel distances. It would be expected that the low mass flakes would suffer large aerodynamic drag, in comparison to sponge, when propelled at high velocities.



*Photo 6. Salute, 20–40 mesh Pyro-Flake (90-6-4).*

The result was clear that sponge significantly out performed flaked material when used in salutes. (Note: We have been told by Suisman Titanium that they hope to add thicker flake titanium to their product line, and expect it will compete favorably with sponge in salutes.) There is, however, an area where the more predictable, though more limited, spark travel distances for the flaked titanium may be a definite advantage. That is in producing stage and special effects where it is the stray long traveling spark that can cause serious problems.

### **Fountain Performance Test**

The next series of tests were performed to evaluate the relative effectiveness of sponge and flaked titanium when used in fountains. Ten test fountains were rammed in fairly large tubes (1" ID × 5" long) and were choked with a 3/8" hole. The fountain composition was 88% hand-made meal prime (75% potassium nitrate, 15% air float charcoal, 10% sulfur and + 5% dextrin) and 12% titanium. (Prime composition containing dextrin was used because it was already on hand, and it was felt that the presence of a small amount of dextrin would not affect the test results.) One at a time and in pairs, the fountains were burned at a height of four feet and photographed (1/60 sec.). The test results are summarized below:

- 1) In all tests the flaked titanium significantly out performed sponge in terms of the number of sparks produced. This was particularly



Photo 7. Fountain test, 10–20 mesh sponge.

evident for the 10–20 mesh materials, see Photos 7 and 8.

- 5) As in the ignition tests discussed earlier, there is some question as to why these results were obtained. However, the reason is probably less important than the result.
- 6) From these tests, it was concluded that flaked titanium significantly out performs sponge when used in fountains.

### Comet Performance Test

The last series of tests were performed to evaluate the relative effectiveness of flaked and sponge titanium when used in comets. For these tests, 16 large box comets were prepared by pressing composition into tubes (1" ID × 1" long). Dry-pressed box comets were used in order to save time by eliminating the need to dry conventionally made comets. The composition used for the comets was the same as used in the fountain tests above. The comets were test fired and photographed (time exposure). The test results are summarized below:

- 1) For the comets made with 10–20 mesh material, those made with sponge had a rather sparse tail in comparison to those made with flaked titanium.
- 2) For the comets made with 20–40 mesh material, the increase in the number of sparks produced by the flake titanium was less obvious. However, the flaked titanium did produce a slightly denser tail, and the



Photo 8. Fountain test, 10–20 mesh Pyro-Flake (90-6-4).

produce a slightly denser tail, and the tail persisted longer, see Photos 9 and 10.

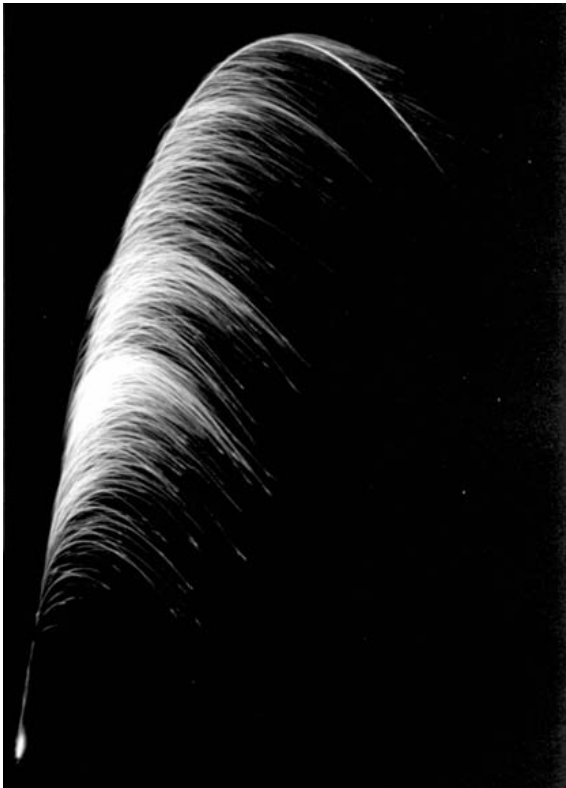
From these tests, it was concluded that flaked titanium noticeably out performed sponge of the same mesh size when used to make comets.

### Conclusion

From the tests performed it was concluded that the Pyro-Flake titanium products supplied by Suisman Titanium Corporation significantly out performed titanium sponge in all applications except in salutes. It was further concluded that between the two types of flaked titanium the 90-6-4 alloy's performance consistently equaled or marginally surpassed that of the pure titanium flakes.

Based on the performance advantage (in addition to the cost advantage mentioned above), we recommended that Suisman Titanium proceed with their introduction of their 10–20 and 20–40 mesh Pyro-Flake titanium (90-6-4 alloy) to the fireworks trade. In addition, we recommended that they consider producing two other products. The first is a thicker 10–20 mesh flake that might equal or surpass the performance of sponge when used in salutes. The second is a – 40 mesh material for use in small comet stars.

We were recently told by Suisman Titanium that they would begin marketing their 10–20 and 20–40 mesh Pyro-Flake products (90-6-4 alloy) about November 1, 1987. They also indicated



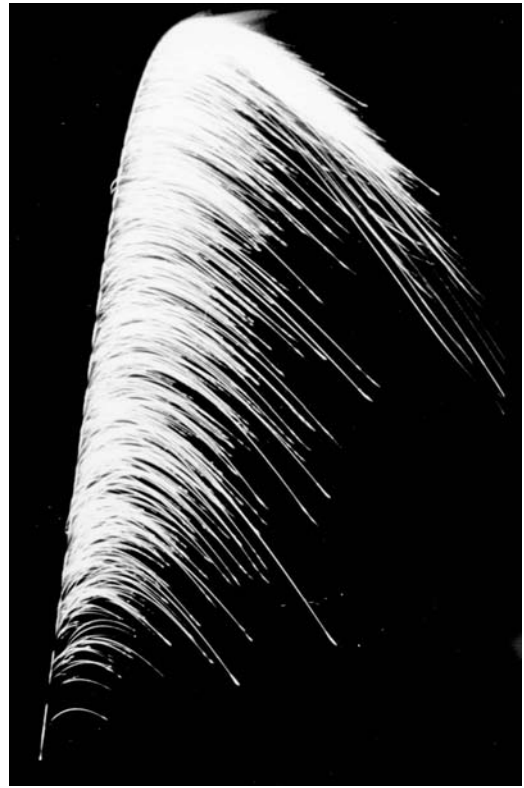
*Photo 9. Comet test, 20–40 mesh sponge.*

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that they were considering making some additions to their Pyro-Flake product line in 1988.

### **Postscript**

Since these tests were performed, Suisman Titanium has modified their Pyro-Flake materials slightly. They are now somewhat thinner flakes than were originally tested. As was confirmed in a brief series of tests, this has the effect of further increasing the number of sparks produced per unit weight, but at the cost of producing sparks with a shorter duration. It is felt that this is an effective compromise for a number of reasons. Sparks from fountains of such



*Photo 10. Comet test, 20–40 mesh Pyro-Flake (90-6-4).*

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long duration that they fall to the ground and continue to burn is a waste of material and represents an added safety concern. For comets, it is true that their attractiveness is enhanced when the duration of sparks is sufficient that a long tail is produced. However, when burning times are excessive, the lingering death of an ever more emaciated tail is quit unattractive. The thinner Pyro-Flake material does seem to generate sparks of sufficient duration. Thus, because more sparks are produced, the cost effectiveness of Pyro-Flake titanium should be even greater.

## RAP\* Shell Assembly Techniques

K. L. Kosanke

### (\* RAP stands for Rapid Assembly Plastic)

We have had a high degree of success using RAP Shells. Assembly times are a small fraction of what is required for Italian style construction and nicely symmetric breaks can be achieved when the proper techniques are employed. This article is a summary of successful methods used by us and reported to us by others. However, no attempt will be made to give detailed step by step instructions, nor will the information in our "Guide-lines for Assembling RAP Shells" [Copy follows.] be repeated here. While the information presented below is particularly relevant for RAP Shell assembly, much also applies to assembling other types of plastic and plastic/paper shells as well. To assist those readers who may not be familiar with RAP Shells, two figures have been included. Figure 1 shows the various RAP Shell compo-

nents and how they are assembled, and Figure 2 shows a typically completed RAP Shell.

### Solvent Bonding

It is certainly possible to apply the solvent for bonding the plastic components with a wool dauber. However, high quality breaks can not be reliably attained in this way. It appears that only by dipping one of the components into the solvent before assembling can high quality breaks be reliability achieved. Dipping is usually accomplished by filling a shallow tray with about 1/2 inch of solvent. Then one or more of the components are placed in the tray so that the surface where bonding is to be achieved becomes wetted by the solvent and starts to dissolve. The length of time the components should remain in the solvent depends on the

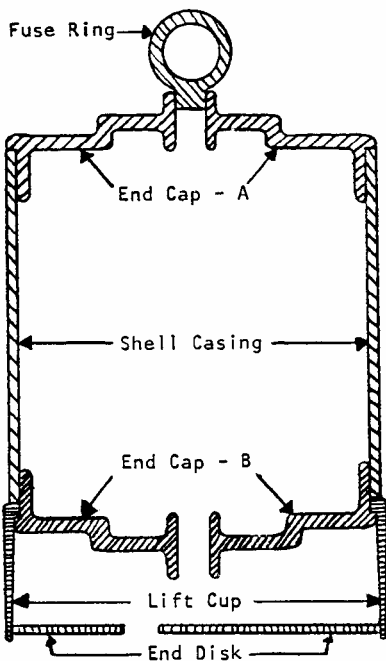


Figure 1. RAP shell showing component.

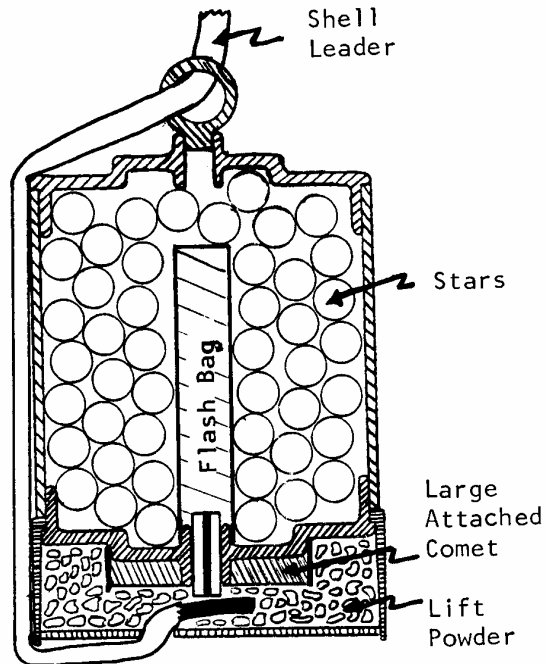


Figure 2. Typically completed RAP shell.

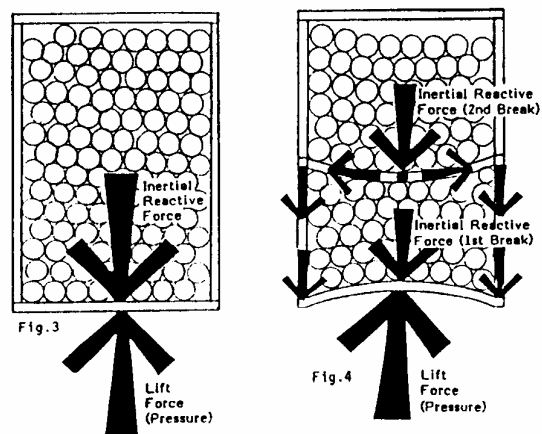
temperature and on the type of solvent used. (For methylene chloride, about 15 seconds is usually sufficient.) The dipping method has the added advantage of being easier and faster when assembly line techniques are employed. The disadvantage is that a larger quantity of solvent is initially required to fill the tray used for dipping. With a solvent such as methylene chloride, the rate at which solvent is used when dipping is not much greater than with the dauber. This is because methylene chloride vapor is about 3 times denser than air. Thus after the tray fills with vapor, relatively little continues to evaporate.

### Caution When Using Thickened Methylene Chloride (TMC)

In the past we recommended the use of TMC when attaching the ring on the top of the shell that holds the quick match leader. (TMC is made by dissolving about 10% by weight of scrap polystyrene in methylene chloride, such that it becomes thick like a heavy syrup.) However, one person has reported having an unfortunate accident when using TMC. On opening the container of TMC the contents effervesced, frothing up to overflow the container (much like what sometimes happens with soda pop). When this happened his hands were covered with TMC. The methylene chloride caused a burning irritation of his skin, which was made worse by having to peel dried polystyrene from his hands after the solvent had evaporated. We have seen TMC effervesce slightly at times, though we have not had it froth up. We still use TMC but are more careful in its use.

### Break Charge

Only through the use of high energy break charges have symmetric and broad spreading RAP Shell breaks been reliably achieved. Flash composition, whistle mix and perchlorate H3 powder have all been reported to generate high quality breaks of shells containing stars. Black Powder and pulverone have only been useful in breaking RAP Shells containing small self-propelled components. Formulations used in flash bags need to be slower and drossier than would be used to make salutes. (Guidance on the use of flash bags can be taken from the



Figures 3 and 4. Forces on shell.

Oglesby article appearing in AFN #52.) Whistle mix (70% potassium perchlorate and 30% sodium benzoate) produces breaks as effective as with flash bags when the whistle mix was contained in a larger version of a flash bag in the center of the shell. When whistle mix is used but is dumped in loose, good breaks are obtained but not as reliably as when it is contained in a centrally located bag. Perchlorate H3 powder (70% potassium perchlorate and 30% airfloat charcoal) either granulated or heavily coated on rice hulls produces good breaks also.

### Contents Loading and Break Symmetry

Because RAP Shells do not derive their strength from the careful loading of their contents, the stars and/or components can be dumped in loose. It is not necessary to attempt to consolidate them or even to fill the shell completely. However, it may be possible to achieve improved break patterns when care was taken to fill the shells completely full. Improved breaks may be more easily obtained when the length of the shell casings is equal to the diameter of the shell. (This also saves on the use of stars.) Finally, as with other types of shells, break symmetry is improved when the stars are loaded around a centrally positioned break charge.

## Multibreak Shells

Some have reported the successful launch of multibreak shells (2 and 3 break color shells and color/color/report shells). However, I can not recommend this. In a conventional shell, much of the compressive strength of the shell is derived from the careful packing of its components. This is not the case for RAP Shells where the strength is derived primarily from its plastic case. On the one hand this has the advantage of not requiring careful packing of the shells. On the other hand it means that RAP Shells will not function very well to launch additional breaks. The reason for this will become more clear by examination of Figures 3 and 4. Figure 3 is a sketch of a single break shell being propelled upward inside a mortar. There is a large upward force created by the high lift gas pressure. This force is exerted uniformly across the bottom end of the shell, but to simplify the drawing and help illustrate the multibreak problem it is shown as a single large upward arrow. This lift force is opposed by an inertial reactive force (Newton's Third Law of Motion) in a downward direction. In essence this force is created by the stars' inertia (if at rest, the tendency to remain at rest) in reaction to the acceleration they are undergoing. These two forces are both acting on the lower end cap of the shell and to large measure, as far as the end cap is concerned, they balance each other. (They do not completely balance because there is also a small outward component of the inertial reactive force that is coupled to the shell wall by friction. However for the purpose of this discussion, this can be ignored.) Thus, for a single break shell, since the end cap has almost completely balanced forces applied to it, there is relatively little stress on it. Accordingly, the end cap can easily survive the lifting process. Figure 4 is a sketch of a two break shell being propelled upward inside a mortar. In this case the forces on the end caps are definitely not balanced. The inertial reactive force from the first break stars acting downward on the lower end cap only balances about half of the upward lift force acting on the end cap. In addition, the inertial reactive force of the stars in the second break is not properly balanced across the middle end cap. The stars push downward across the entire cap but are not opposed by a balancing lift force. It is the shell wall of the first

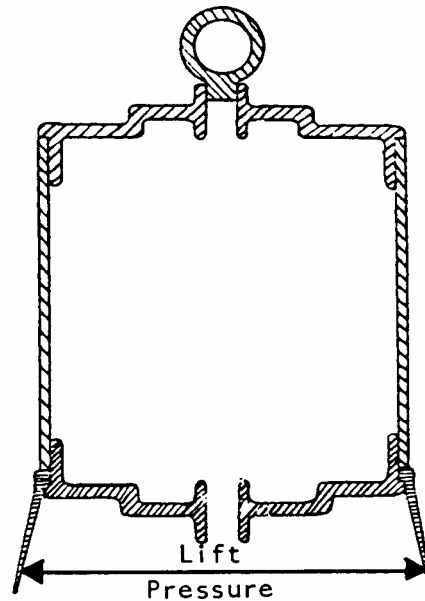


Figure 5. Lift cup expanding.

break that communicates the inertial reactive force from the second break downward to encounter the lift force. The net result is that the bottom end cap experiences an unbalanced force in the upward direction and the middle end cap experiences an unbalanced force in the downward direction. Accordingly, much more strain is experienced by the end caps and there is a much greater chance of their breaking. RAP Shells were designed for a single break shell to have a good chance of surviving being 200% over lifted (three times the normal lift). However, they are not intended or designed to operate as multibreak shells.

## Lift Powder

Because of the design of the RAP Shell lift cup, less lift powder can be used than is necessary for conventional shells. (See Figure 5 to see how the lift cup expands to close the space between the shell and mortar, much the same way as the wadding acts in a shotgun shell.) We use 0.6 and 1.1 ounce of powder to lift 3-inch and 4-inch shells, respectively, which contrasts with 1.0 and 2.0 ounces for conventional cylindrical shells. Also there is no difference in the lift achieved when using 2F powder as com-

pared with using 4F powder. (Normally small shells are propelled more efficiently with 4F powder.) This means that there is no cost advantage in using 4F powder, and the more gentle 2F powder can be used. Some hobbyists, for whom it is difficult to obtain commercial Black Powder, have reported success using granulated perchlorate H3 powder. Also success has been reported using granulated handmade meal powder (75% potassium nitrate, 15% air-float charcoal, 10% sulfur, and +5% dextrin) mixed with a small amount of sporting grade Black Powder (to speed up the burn of the handmade powder).

### **No RAP Salutes**

We have had reports of people using RAP Shells to make salutes. We strongly recommend against this practice. While RAP Shells are made of high impact polystyrene, they are still somewhat brittle and when shattered (broken explosively) sharp fragments will be produced.

### **Caution with Paper Mortars**

In our testing of randomly selected normally lifted RAP Shells we have test fired hundreds of RAP shells, and have never experienced a flowerpot (shell failure inside the mortar). However, when using RAP Shells in our commercial displays we observed several percent of the shells to flowerpot. This was puzzling because it was the same shells that never failed

during tests, that occasionally failed during displays. The problem was traced to our paper mortars, which had seen a moderate amount of use and were slightly torn on the inside surface. They were still successfully launching spherical shells but were causing cylindrical shells to occasionally jam when fired from them. (In our testing only steel and high density polyethylene mortars, with smooth interiors, were used.) RAP Shells do have a rounded upper edge, but no where near so rounded as a spherical shell. Thus, if paper mortars are to be used successfully, they must be inspected and damaged mortars must not be used.

### **Conclusion**

I have been surprised by how quickly and effectively people have learned the new technology of plastic shell construction. RAP Shells can be assembled in a small fraction of the time required for paper/string shells and they can be made to perform approximately as well. I am certain that, of the shells made in this country, plastic shells will become the most frequently made shells in the future. Hobbyists can easily make effective shells and professionals can increase their narrow profit margins. In fact, because of improved fire safety (the lack of burning fall-out) some countries (e.g., France) are reported to have banned the use of any aerial shell NOT made entirely of plastic.

## **Destructive Testing and Field Experience with HDPE Mortars**

Ken Kosanke

In an earlier article on High Density Polyethylene (HDPE) mortars, results from an initial series of tests were published (*Pyrotechnics Guild Int'l. Bulletin*, No. 54, p 5). Those results will not be repeated here. This article continues by presenting the results from an additional test, a summary of the author's field experience since the first article, and comments on HDPE mortar use in England by Rev. Ron Lancaster.

### **Destructive Mortar Tests**

Three tests were performed in which a 22" long 3" diameter HDPE mortar (SDR = 13.5, resin type PE3408) was staked above ground and a 3" salute was exploded in the bottom of the mortar. Approximate determinations were made of: 1) the percent weight loss of the mortar due to fragments leaving the mortar, 2) the radius and area through which fragments were found to have been propelled, and 3) the shape and weight of typical fragments. In the three tests, the mortars were at three different temperatures (5, 40, and 80 °F); however, no temperature dependence was observed in these very limited tests. On average, 6% of the mortar's weight was lost as fragments (not counting the loss of the wooden mortar plug). The fragments were found to have been propelled to a maximum distance of approximately 100 feet, which corresponds to an area of about 30,000 square feet. A typical fragment was stretched to about 1/3 its original thickness, was roughly leaf-like in appearance, and weighed about 1/2 ounce. Judging from the shape and weight of the fragments, it is estimated the serious injury to a properly clothed and positioned shooter, even if struck by one of the few fragments, was unlikely.

As a comparison, two similar tests were performed using 24" long 3" diameter PVC mortars (Sch. 40). In this case, nearly the same range of mortar temperatures were used (10 and

80 °F). As above, no temperature dependence was observed. On average, 80% of the mortar's weight was lost as fragments. Those fragments were found to have been propelled to a maximum diameter of approximately 175 feet, which corresponds to an area of about 100,000 square feet. A typical fragment retained its original thickness, had sharp edges and jagged points, and weighed one or two ounces. Judging from the shape and weight of the fragments it is estimated that serious injury to a properly clothed and positioned shooter was likely if struck by any of the large number of fragments.

The stretching thin of HDPE mortar fragments causes them to be slowed more rapidly after being thrust into the air from a bursting mortar (they are more like a feather than a rock). However, this stretching has an additional safety benefit. The mechanical energy that is consumed in thinly stretching the fragment is, in the process, converted into thermal energy, raising the temperature of the fragments. Calculations suggest that the stretching will result in a temperature rise of about 40 °F. The HDPE fragments are somewhat flexible to begin with, but they become more flexible as their temperature rises.

From these limited tests, it seems fairly clear that HDPE mortars present less danger to nearby persons and equipment in the event of a shell detonation within them, than PVC mortars similarly stressed.

### **Limited Field Experience**

During the recent season, HDPE mortars were used by the author on four displays in which approximately 800 three to six inch shells were fired. (The equipment used to fire the shows positions the mortars in very close proximity to each other in steel racks. The so-called dense-pack set-up was described in a



paper appearing in *Pyrotechnica XI*.) Although several flower pots were observed to have occurred, only two mortars were damaged. In one case the plug blew out and the bottom of the mortar split for about three inches. In the other case, the plug blew out and a bulge occurred about half way up the mortar. In neither case were any fragments generated (except for the mortar plugs) and there was absolutely no damage to the rack or to adjacent mortars.

### **Lancaster's Comments**

The following is an abridged quote from a recent letter from Rev. Ron Lancaster, a noted author and pyrotechnician.

“I notice that you were asking a question about polyethylene mortars and really do know quite a bit about this and think I can say that I have pioneered the use of these materials in this country. ... Quite near to us we have one of the two principal manufacturers of high density polyethylene pipe and I bought material from them over ten years ago and can say that we are

still using the original tubes that we bought from them then. We have many hundreds of these now and we buy a few more each year. ... So far we have never had a serious accident with any of them and I have often wondered what would happen if, for example, a three-inch salute went in such a tube. It did, in fact, happen last year and it burst roughly half-way up the tube and I am happy to say that it ‘belled’ the tube in the centre ... and at one point the heat was sufficient to actually melt the plastic in the bell portion to let the gas come out. This piece of information was really quite useful to us and really I was quite gratified to see what had happened. ...

I think that you will find that these mortars are very useful indeed and much superior to paper.

With every good wish,

Yours sincerely,

Ron Lancaster

P.S. Needless to say we never use PVC.”

## Understanding Product Liability

Ken Kosanke

During the past couple years, in the course of assisting attorneys as an expert witness, I have come to learn a little about product liability. Because this subject is so important to our industry and because product liability laws are not well understood by many of us, I have decided to share with you what I have learned. However, it is important that you understand that I am not an attorney, that my experience in this area is not vast, and that product liability laws are state statutes which vary significantly from state to state. At best, the material presented in this article should only serve to provoke a thorough discussion of the subject with your attorney.

Until relatively recently, an injured party had only two avenues through which to seek compensation from a manufacturer. Those are Breach of Warranty and Negligence. Breach of warranty can involve either an expressed warranty or warranty of merchantability. An example of breach of an expressed warranty would be if a manufacturer sold fountains that were marked "30-second Silver Fountain" and the fountains only burned for 15 seconds. In this instance the fountain fails to meet a stated specification. An example of breach of warranty of merchantability would be if a manufacturer sold aerial shells which had no time fuse whatever installed. In this instance the aerial shells fail to contain a key component implicitly assumed to be there. While breach of warranty is an avenue through which compensation can be sought: 1) judgments are generally relatively small; 2) this is an area that is fairly well understood by business people; and 3) most people would probably agree that compensation was appropriate (just or fair). For these reasons, breach of warranty will not be discussed further.

The second avenue through which an injured party could seek compensation was negligence. In order for a manufacturer to lose such a product liability suit, he had to be proven negligent

in one of five areas. Those areas were: failure of design, failure of materials, failure to test, failure to warn, and failure to direct. Thus if a manufacturer had conducted himself "responsibly", he was essentially certain of winning any product liability suit brought against his company. (By responsibly I mean that he was thorough and conscientious in his design of the product, that proper and high quality materials were used in the manufacture of the product, that the finished product was completely and repeatedly tested, that users were properly warned about known hazards associated with the use of the product, and that appropriate instructions were given for the safe use of the product. It is also meant that proper documentation of each of these functions was assembled and maintained.) If a manufacturer was negligent and that resulted in personal injury, few would argue that the injured party does not deserve to receive compensation from the manufacturer. For the most part, disagreements only arose over exactly what constitutes negligence (how much testing or how exhaustive a warning, etc. is required) and what dollar value of compensation is appropriate. While further discussion of this is appropriate, that will be deferred until later.

As you can imagine, it was not easy to win a product liability judgment against a manufacturer when negligence had to be demonstrated. Even when the manufacturer was negligent it was not an easy matter to assemble a case to prove that to a jury. Because it was so difficult (and costly) to win a product liability judgment, some felt the old laws were unfair to the consumer. In large part, this was the rationale for changing product liability laws to make it easier for plaintiffs to win their cases. Present product liability laws have added a third avenue through which compensation can be sought; that is Strict Product Liability. In order to win a case under strict product liability, in essence, only two questions need to be answered affirma-

tively. The first is, was the plaintiff injured by the product? The second is, did the product contain a defect at the time of the sale? The big difference is that with strict product liability it is no longer necessary that the manufacturer have acted negligently in order for an injured party to win compensation. A manufacturer could have literally done everything that is humanly possible as regards manufacturing a safe and effective product and still be liable for large product liability awards. This is true, even if the consumer contributed in a major way to causing the accident.

On the surface the second question above seems reasonable and may be felt by some to offer protection to a prudent manufacturer. However, it is important to consider some of the kinds of things that could constitute a product defect. It is true that the defect can be something that is obviously wrong with the product, but it could also be things such as:

- directions that are confusing because they contain too many big words or possibly were only too long to expect a consumer to take the time to read them;
- warnings that were not worded strongly enough such that a user did not take them seriously enough, such as only warning that a firework emits a shower of sparks and not specifically stating that serious personal injury is likely to result if one's body part is held over the item when it discharges;
- directions or warnings that do not sufficiently address all the possible ways in which a product might be used or misused, or, on the other hand, warnings that are too specific and thus plant ideas for possible misuse;
- packaging that offers insufficient protection such that, during rough handling by a consumer, the product may become damaged;
- a hazard that is unknown and unimaginable at the time of manufacture and only became evident many years later, such as asbestos caused cancer;
- a product design that does not sufficiently preclude modification by the consumer, such as safety guards that are merely bolted on a machine and thus could be removed by a careless user.

In large measure, in our courts today, if someone is injured while using a product, it is taken as prima facie evidence that the product was defective and unreasonably dangerous. Thus the second question above can become largely rhetorical in nature, and in many cases it is only the first question (was the plaintiff injured by the product) that must be answered in the affirmative.

Now, with strict product liability, it is almost trivially easy for an injured plaintiff to win a product liability suit. What is more, this seems to have been the clear intent of state legislators in revising their product liability laws. To most of us who have been brought up to believe that punishment is appropriate (fair or just) when someone has done something wrong, strict product liability laws seem inherently unfair and unjust. Advocates for strict product liability argue that we are looking at it all wrong. They argue that consumers were being injured and that too often there was no adequate means for their compensation for those injuries and resulting economic losses. They argue that the intent was to provide consumers with "product accident insurance". They argue that the appropriate provider of that insurance is the manufacturer who can simply add the cost of the insurance to the selling price of the product. I cannot say that I agree with this rationale, but at least now I understand how strict product liability has become the law of the land when on the surface it seems so blatantly unfair to manufacturers.

Above I said that negligence on the part of the manufacturer is no longer necessary in order to win product liability verdicts. This is true, but it is still a very important consideration in establishing the amount of the judgment awarded plaintiffs, in particular, punitive damages. Obviously, when negligence can be demonstrated or at least is suspected by juries, awards often increase astronomically. This is an important area in which your efforts can significantly reduce your product liability losses in the event a suit is filed. Take actions to prove you have acted responsibly, document those actions and keep the records. Have your product designs reviewed (in writing) by an unbiased professional outside your organization. Establish written requirements or performance specifications for the raw materials you use. Perform docu-

mented tests of those materials either before they are used in your manufacturing or after they are part of a completed product and are tested by noting the performance of the product. Performance tests of products should demonstrate that specific acceptance limits are met (e.g., 3" shells all reach at least  $x$  feet in altitude, break no sooner than  $y$  seconds after launch and no later than  $z$  seconds, etc.). Also performance testing should include tests that stress the product greater than is expected during normal use (i.e. is there a sufficient safety margin?). Directions and warnings should be reviewed in writing for completeness and accuracy. Remember, doing all this may not keep you from losing a case under strict product liability, but it will certainly help to limit your losses.

What has been said up to this point is generally true in all states. However, there are a number of other points worth discussing that vary significantly from state to state.

Most states assign the responsibility for injuries resulting from a product to each of those who contributed to the product reaching the customer. The word product includes not only tangible items, like step ladders and fireworks, but also intangible items like an architect's design. Those who contribute to the product reaching the consumer include the manufacturer or importer, the wholesaler and the retailer, but also may be interpreted to include the supplier of raw materials to the manufacturer and on occasion even the delivery man. (Unless noted to the contrary, throughout this article, the word manufacturer is intended to include any of those persons or entities that participated in placing a product in the hands of the consumer.)

Most states subscribe to the notion of "comparative fault". That is to say, there is a recognition that the plaintiff may have acted in a manner that contributed to the accident or injury. If that is shown to be the case, the final judgment awarded is reduced in the same proportion as the plaintiff is responsible. Even if the plaintiff is found to be 90% at fault, the manufacturer will still lose the case, but the amount of the judgment is reduced by 90%. (Note that even 10% of a typical judgment might bankrupt a small uninsured manufacturer.)

Many states still subscribe to the notion of "joint and several liability". That is to say, each

defendant can be held totally liable, independent of the extent to which they contributed to the accident or injury. This is the so-called "deep pockets" theory, don't sue the people most at fault, sue the ones with the best insurance and largest assets (the ones with the deepest pockets). Happily this is being changed in some states so that the judgment is passed to the defendants in proportion to the extent to which they contributed to the problem.

Some states limit liability to only the actual manufacturer (or importer of a foreign product) and to no one else (except under special limited circumstances). This is quite a relief to wholesalers, retailers and all others involved. It also eliminates secondary and tertiary law suits, where a sued retailer sues his wholesaler, who sues the manufacturer, each attempting to recoup their loss. When these additional law suits are eliminated, everyone is better off financially (except attorneys).

Most state statutes require that the product involved be "unreasonably dangerous" in order for a suit to be won. On the surface this sounds appropriate and might be interpreted by a manufacturer to offer some protection from claims because of his belief that his product was not unreasonably dangerous. However, in practice, there is essentially no protection whatever. For the most part, unless the product has a history of causing injuries, it is only that one specific device that caused the injury that need be found to be unreasonably dangerous. And, by practical definition in our courts *any* product that injures someone *is* unreasonably dangerous.

In very few states (if any) is there relief for a manufacturer who follows "industry standards" in making the product, and only a few states offer any protection to a manufacturer that either uses "state-of-the-art" techniques or meets federal (or the state's) codes or standards. In most states meeting industry standards, using state of the art techniques and following government codes and standards offer no protection whatever. The area where this often comes up is in labeling. Meeting the consumer product safety commission labeling requirements offers essentially no protection from a manufacturer being found negligent for failing to properly warn and instruct users of fireworks.

In some states, shelf life is considered. For example in Colorado if ten years have elapsed between the time of manufacture and the injury, the product is assumed not to have been defective at the time of manufacture and the manufacturer is free of responsibility.

Some states are moving to limit the amount of non-economic damages, such as “pain and suffering” and “loss of consort” (no longer having a loved one with whom to interact with in the manner prior to the accident). One limit being considered in some states is \$250,000. That is still a lot of money if you are the one paying it, but it is a step in the right direction. However, remember that economic damages (medical costs and up to a lifetime of earnings) can still amount to millions.

As a manufacturer, if you check your state laws and find they are more friendly to manu-

facturers than most other states, don't for a minute think you are off the hook. You may have wholesalers in other states, who have retailers in still other states, who may in turn have customers in still other states, who may use the product in still other states. If there is a suit filed it can be in any of these various states and you can bet it will be filed in the state most advantageous to the plaintiff.

Product liability problems can put you out of business. I recommend that you seek legal advice from your attorney and talk with your insurance agent *before* you have a claim against you. There are at least a few things you can do, in advance, to limit your risks.

I would like to express my appreciation to attorney Kim Orwoll for his personal comments on this article.

## Japanese Shell Break Radii

K. L. and B. J. Kosanke

(Derived from data provided by Dr. T. Shimizu, private communication)

The National Fire Protection Association, Technical Committee on Pyrotechnics is in the process of revising *NFPA-1123, Code for the Outdoor Display of Fireworks* (formerly called *Public Display of Fireworks*). In preparation for considering the appropriate separation distances between spectators and mortar placements and between spectators and fall-out areas, it seemed that it would be helpful to know how great the break radius was for hard-breaking spherical shells. Thus an attempt was made to collect that data. It was also felt that the data would be of general interest to the pyro-community; it was in that belief that this article was prepared.

The assistance of T. Shimizu was sought in the hopes that he had already compiled this information. He graciously responded with a set of unpublished data recorded at the 1965 PL Fireworks Festival, during which shells manufactured by Hosoya, Marutamaya-Ogatsu, Ikebun, Fujiwara, and Aoki were fired. Break radii for approximately 280 shells ranging from 4 to 20 Suns (4.8 to 23.9 inches) were determined photographically, and the results presented graphically. Dr. Shimizu had drawn a curve on the graph indicating the approximate maximum radii as a function of shell size. We added a second curve approximating the typical radii observed for the shells. The table below is a listing of the typical and maximum shell radii (to the nearest 5 feet), which were determined from the Shimizu data.

During discussions with a number of knowledgeable pyrotechnists, concern was expressed that because of the stature of the PL Fireworks Festival in Japan, it was possible that the shells were of a superior quality compared with those exported to this country. Thus the Shimizu data could indicate larger break radii than would be observed for imported Japanese shells. PGI President, C. Hill suggested that some confirmatory tests be performed. He made the offer

**Table of Typical and Maximum Shell Break Radii.**

Nominal Shell Diameter	Shell Break Radius (feet)		Approximate Number of Observations
	Typical	Maximum	
3	130	215	0 (a)
4	170	270	0 (a)
5	210	330	120
6	255	380	50
7	295	430	75
8	330	470	22 (b)
10	415	540	4 (b)
12	490	595	12 (b)
16	630	690	1 (c)
24	805	820	2 (c)

- (a) The smallest shells for which there were data were approximately 5 inch. The results for 3 and 4-inch shells were estimated by extrapolation of the curves through zero.
- (b) For shells of approximately 8, 10 and 12 inches all were observed to break with roughly the same radii; however, smooth curves were drawn through the data for all shell sizes.
- (c) Because of a very limited number of observations for shells greater than 12 inches, the data must be considered to be of limited reliability.

that the PGI would underwrite the cost of the shells and photo-processing, if we would volunteer the labor to layout the test range and perform the tests. Those tests were performed in October, and the results are reported below.

A test range, consisting of two large supported poles and a number of distance markers, was laid-out on a remote portion of our property. Two 35 mm cameras with standard 55 mm focal-length lenses were set-up perpendicular to the line of markers and at a distance of approximately 1400 feet. To establish the scale of the photographs, each camera was used to photograph the range during daylight. That evening a series of 20 aerial shells were electrically ig-

**Data Table for Shell Burst Radii Tests.**

Test/ Photo No.	Shell Size (in.)	Shell Description	Shell Weight (lb.) <sup>(a)</sup>	Break Radius (feet)
1	8	Onda - Brocade Gold	5.3	290
2	8	Onda - Reddish Gamboge to Red, Green and Blue	5.7	400
3	6	Onda - Twinkling Diadem	2.2	265
4	6	Onda - Golden Diadem to Flash w/ Red Pistil	2.2	345
5	5	Onda - Reddish Gam. to Green and Flickering	1.3	215
6	5	Ogatsu - Glittering Silver to Red and Blue	1.5	210
7	5	Ogatsu - 3002 "weak willow effect"	1.1	120
8	5	Onda - Green w/ Encircling Dews	1.4	165
9	5	Onda - Spangled Chrysanthemum	1.7	230
10	4	Onda - Variegated Colored Peony	0.8	215
11	4	Ogatsu - Blue to Silver	0.7	115
12	4	Ogatsu - Blue to Silver	0.7	85
13	4	Ogatsu - Red Chrysanthemum	0.7	160
14	4	Onda - Glittering Silver to Blue	0.9	185
15	3	Onda - Green Peony	0.3	75
16	3	Onda - Brocade Red Chrysanthemum	0.3	110
17	3	Onda - Brocade Red Chrysanthemum	0.3	105
18	3	Onda - Blue Peony	0.3	95
19	3	Onda - Brocade Red Chrysanthemum	0.3	115
20	3	Onda - Brocade Red Chrysanthemum	0.3	100

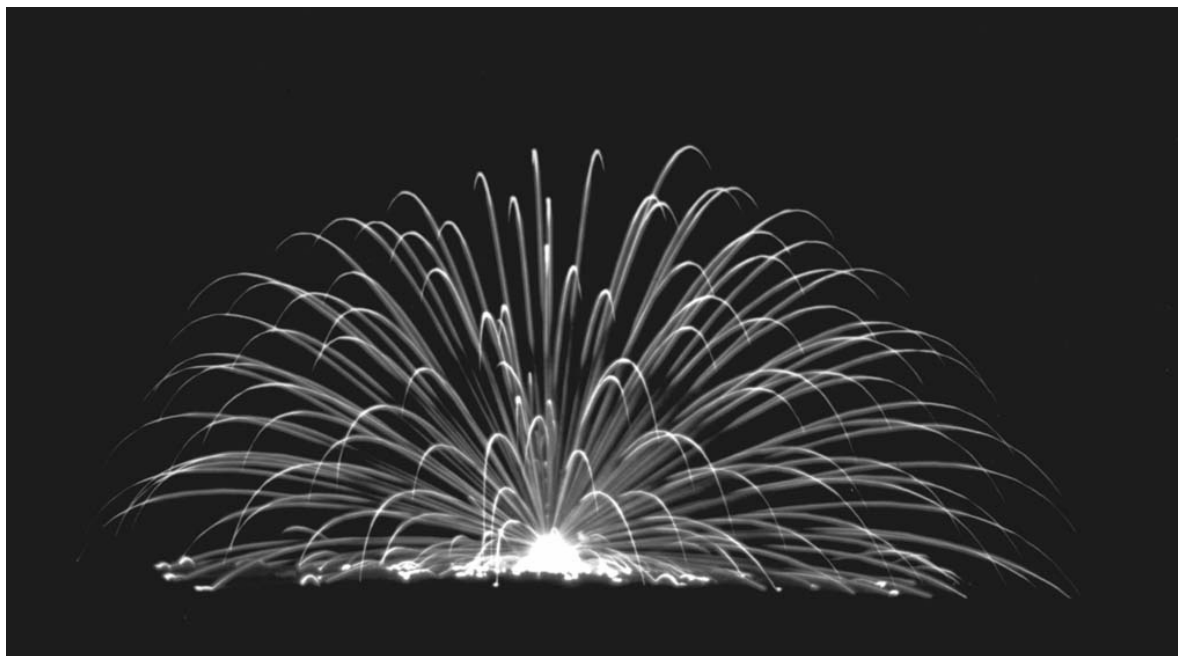
(a) Weights are for unlifted shells.

nited while being suspended approximately 14 feet above the ground on a cable strung between the two poles. The shells were all of Japanese manufacture (Onda and Ogatsu) and ranged from 3 to 8 inches in size. Each shell was photographed (time exposure) as it burst. The Photo below is an example of the results obtained. It is of an 8 inch Onda-Reddish Gamboge to Red, Green and Blue shell which broke with a radius of 400 feet (total spread of 800 feet). The table below presents the results of the series of tests.

Of the 14 shells larger than 3 inches, 7 broke harder than the typical from the Shimizu data, 1 exactly equaled the typical, and 6 broke weaker. The 3-inch shells all broke weaker than the typical radii suggested by the Shimizu data. However, it should be remembered that the 3 inch data was obtained by extrapolation, since no shells as small as that were actually measured by Shimizu. Finally, even though a couple of shells approached the maximums observed by Shimizu, none exceeded those maximums.

In conclusion, considering the limited number of tests performed, it is felt that the Shimizu data is representative of the typical and maximum break radii for hard breaking spherical shells imported into this country from Japan.

The authors wish to gratefully acknowledge the financial assistance of the PGI, the manual assistance of Ken Benkert and Tom Miller, and most especially the data provided by Takeo Shimizu.



*Photo of the burst of an 8" Onda - Reddish Gamboge to Red, Green and Blue shell. Break radius was 400 feet (total spread of 800 feet).*

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An earlier version appeared in *Pyrotechnics Guild International Bulletin*, No. 62 (1988).

## **CMC Its Properties and Uses**

Ken Kosanke

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CMC, as it is commonly called, is more properly referred to as Sodium Carboxymethylcellulose (carboxy-methyl-cellulose). In the food industry it is also frequently referred to as cellulose gum.

CMC is colorless, odorless, tasteless, and non-toxic. It is somewhat hygroscopic and dissolves readily in water. It is highly thixotropic (That is to say, it is a very effective thickening agent, like corn starch except much more effective. It is used in the food industry to thicken things such as low-cal pancake syrup.) For a good grade of CMC the use of only 1, 2 or 3% will turn water into a slimy liquid, a thick goo or gelatin, respectively. CMC is also an unusually effective adhesive.

In pyrotechnics, CMC has two important uses. Because CMC is so effective as an adhesive even in relatively small amounts (1 to 2%), it

makes an excellent binder in situations when the presence of 4 to 6% binder can adversely affect the performance of a composition. For example, in strobe compositions the presence of a high percentage of binder tends to cause the composition to burn continuously as opposed to strobing. The use of CMC in low percentages often improves and makes it easier to control strobe performance. Because CMC is so effective as a thixotropic agent even in relatively small amounts (1 to 2%), it makes an excellent additive when trying to maintain formulations in suspension. For example, in priming or in the manufacture of black match there is always the difficulty of keeping the meal powder ingredients from settling to the bottom of the container during use. The use of CMC in low percentages easily thickens the suspension to the point where essentially no settling occurs.



## Reduction of Aerial Shell Ignition Failures

by K.L. and B.J. Kosanke

A shell ignition failure means there will be a live dud in the fallout area after a display. If that dud is not retrieved, is found by a member of the public, and that person is subsequently injured as the result of mishandling the dud shell, an insurance claim against the shooter and manufacturer will almost certainly result. This article presents a discussion of one method which can result in a significant reduction of the number of shell ignition failures.

For the purposes of this article, an ignition failure is any cause or series of causes that results in fire failing to be passed from burning lift gases to the pyrotechnic contents of the shell via a fuse or similar device. This includes: the fuse failing to take fire from the burning lift gases, the fuse failing to burn continuously, and the fuse failing to successfully transfer fire to the shell's contents. Each of these general causes can be further broken down into a number of more specific causes. However, it is not the purpose of this short article to present a discussion of the relative merits of priming vs. cross-matching, cutting fuse perpendicular vs. cutting it at an angle, using fuse vs. using spolettes, etc. Those are important considerations, but, because of the many variations in technique, each of which can affect the results achieved, that discussion is beyond the scope of this article. This article discusses a simple technique that is routinely utilized in many fields of endeavor when it is necessary to reduce failure rates. The technique is redundancy, in this case the use of two time fuses on an aerial shell. This is not a new idea; it has been used in this country and abroad for many years, but is not commonly done. With manufacturers under increased products liability pressure and with many amateurs seeking short-cuts to priming and cross matching, perhaps this approach is worth further consideration. This is because the reduction in the rate of ignition failures may be considerably greater than might be expected. To understand why this can be the case, it is first necessary to delve a little into Probability Theory.

Probabilities are expressed as numbers ranging from zero (0) to one (1). If the probability of something happening is zero, then it will never happen, ever. On the other hand, if the probability is one, then it will happen every time, always. Obviously, for most things, the probability is some where in between. A probability of 0.5 (or 1/2) means it will happen one-half of the time (one out of two times). A probability of 0.75 (or 3/4) means it will happen three quarters of the time (three times out of four).

If the probability of something happening is  $P$ , then the probability of it not happening is  $(1 - P)$ . In the last case above, when the probability of an event happening was 0.75, the probability of it not happening is  $(1.00 - 0.75)$ , which is 0.25.

If the probability of one thing happening is  $P_1$  and the probability of a second thing happening is  $P_2$ , then the probability of both things happening is  $(P_1 \times P_2)$ . Take as example coin a flipping. When flipping single coin, the probability of getting "heads" is 0.50. When flipping two coins, the probability that both will be heads is  $(0.50 \times 0.50)$ , which is 0.25.

In order to apply probability theory to the problem of aerial shell ignition failure, it is first necessary to establish the probability of experiencing an ignition failure when using a single time fuse under a fixed set of conditions. A mediocre performance might be considered to be one in which 1 out of 100 shells is a dud, which corresponds to a probability of 0.01. A good performance might be considered to be one in which 1 out of 1000 shells is a dud, a probability of 0.001. Perhaps the very best that is achievable is when 1 out of 10000 shells is a dud, a probability of 0.0001. Now consider the case where the same technique is employed that resulted in a mediocre probability of ignition failure of 0.01 for a single time fuse, except that a second identically prepared fuse is used in addition. In this case, the probability of both fuses failing to ignite the shell is  $(0.01 \times 0.01)$  which equals 0.0001, and that is a 100 fold reduction in the probability of ignition

failure, and is the same as had been defined above as the very lowest failure rate achievable.

In addition to the little extra time and the very little extra expense associated with using two time fuses, are there any other costs? The answer is yes; there is an increased probability of shell failure due to fire leaks from the presence of the second fuse. Again, in order to determine the increased probability of fire leaks resulting from the use of a second time fuse, it is first necessary to establish the probability of a fire leak occurring around a single fuse. A mediocre performance in this area also probably corresponds to a failure rate of 1 out of 100, a probability of 0.01. If this is the probability of a fire leak occurring around a fuse, then the probability of no fire leak occurring is  $(1.00 - 0.01)$ , which is 0.99. If two fuses are used, the probability that there will be no fire leak around either fuse is  $(0.99 \times 0.99)$ , which is 0.98; which corresponds to a failure rate of  $(1.00 - 0.98)$ , which is 0.02, a 2 fold increase in the rate of rate of failure.

At this point, the question is whether it is an effective trade-off to achieve a 100 fold reduction of ignition failures at the expense of a 2 fold increase in fire leaks around fuses. However, be-

fore considering this, it is appropriate to point out that there are other ways besides leaks around time fuses that fire can leak into the contents of an aerial shell. Thus it should not be assumed that, because there is a 2 fold increase in the number of fire leaks around the time fuses, there will also be a 2 fold increase in the number of fire leaks from other sources. That is to say, there will not be a 2-fold increase in the number of "flowerpots" experienced as a result of using two time fuses. Further, if chlorate based stars are not used, if the shell is not a salute, and proper firing safety practices are followed, the consequences of the fire leak is likely to be a rather harmless flowerpot. All things considered, a number of manufacturers seem to have concluded that it is an effective trade off, particularly for larger shells. The authors have seen oriental shells with 3 time fuses and have heard of shells with 4 fuses.

(Note: Kosanke Services, Inc. has offered two-hole end disks for aerial shells for about 8 years. From time to time, the question has been asked as to why. In part, this article is in response to those questions.)

## Determination of Aerial Shell Burst Altitudes

K. L. Kosanke

One type of fireworks data generally only guessed at is the altitudes of aerial shells at the time of their burst. In addition to addressing general curiosity, this data is often necessary when designing major aerial displays. Frequently it is important to know fairly accurately at what altitudes the various shells will appear. The rule-of-thumb, that shells break at about 100 feet per shell inch, may be a handy guide but is only very approximate and does not address

differences between shell types and manufacturers. J. G. Taylor (*Pyrotechnica X*) published a theoretical paper which discussed a triangulation method for measuring the height of an explosion in the air. The paper was elegant in its mathematical approach, but may have been somewhat lacking in terms of practicality. The method suggested in this article is less elegant but is also quite practical.

The suggested method is basically the same

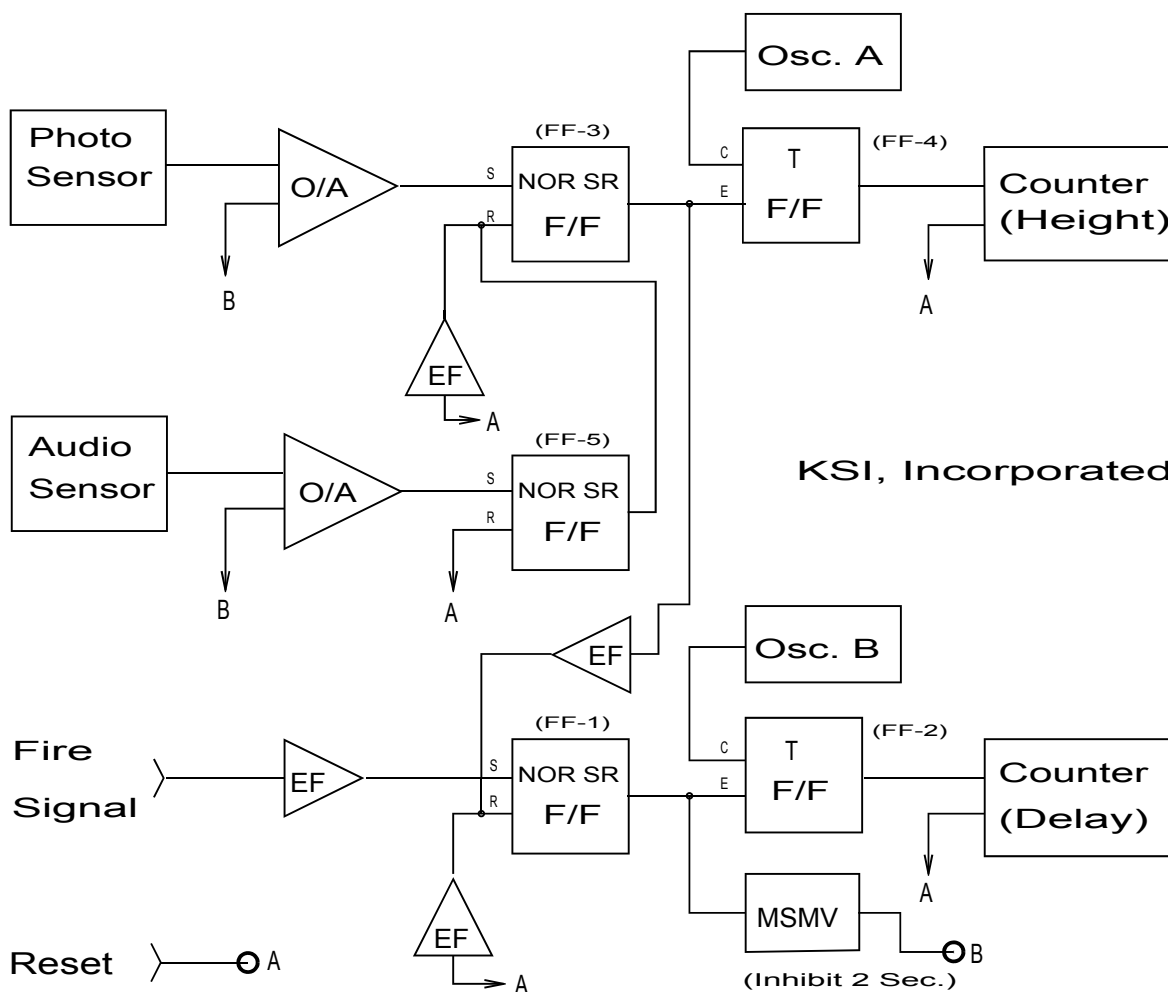


Figure 1. Aerial burst height and delay timer.

one used when people determine the approximate distance to a stroke of lightning by counting the seconds between seeing the flash and hearing the thunder. (The approximate distance in miles equals the time difference in seconds divided by five.) The basis for the method arises from the fact that speed of propagation of light is very high (984,000,000 feet/sec) while that for sound is slow by comparison (1090 feet/sec). In essence, it can be assumed that the flash of light arrives instantaneously, while it takes about 1 second/1000 feet (about 5 seconds/mile) for the sound of the thunder to arrive. The situation is identical for a bursting aerial shell, except that the distances are usually significantly less. If a pair of upward directed sensors (one photo and one audio) is stationed near a vertically firing mortar, and they are used to control the start and stop of a clock timer reading in milliseconds, then the time recorded will approximately equal the altitude of the burst in feet. There are a number of improvements that can be made, but this illustrates the concept.

The block circuit diagram in Figure 1 is one possibility for assembling the electronics to accomplish this measurement. It is certainly not the only way to accomplish the task, and may not even be the best way, but it will serve to illustrate the approach. It also includes circuitry for determining the time between mortar firing and shell burst, another important number needed when designing complex displays. Below is a discussion of how the circuit operates.

The electrical firing signal that is applied to the electric match of the shell in the mortar, is also fed to the measuring unit, shown as "fire signal" in the diagram. This signal is passed through an emitter follower as a safety measure, thus making certain the measuring unit cannot accidentally cause the discharge of the shell. The fire signal is then passed along to a NOR SR (Set/Reset) Flip-Flop (FF-1) which results in its switching to the ON state. The output of this flip-flop is in turn passed to a T (Toggle) Flip-Flop (FF-2), which then responds by allowing clock timing pulses from oscillator B to pass along to a pulse counter. Thus this (delay) counter starts recording clock pulses as soon as the electric match on the shell is energized. The clock pulse counting continues until the shell bursts at altitude. The mechanism by which the shell burst halts the counting of clock pulses is

as follows. When the shell bursts, it is witnessed by an increase in the light level from the burst and/or the appearance of stars. This increase in light level is detected by a photo sensor, whose electrical output is amplified using an operational amplifier. The amplified photo signal is fed to a NOR SR Flip-Flop (FF-3), which responds by switching to the ON state. The output of this flip-flop is passed via an emitter follower (for isolation) down to the other input to the fire signal flip-flop (FF-1), which now responds by switching OFF. This in turn results in the interruption of oscillator B clock pulses passing through the T Flip-Flop (FF-2) to the delay counter. The total number of pulses recorded on the delay counter is proportional to the time elapsing between firing the shell and its burst at altitude. Because T Flip-Flops have the characteristic of dividing clock pulses by a factor of two, if oscillator B has an accurate frequency of 2.00 kHz, the counter will record delay time in milliseconds.

The process of determining the altitude of the burst begins as described above by the detection of the light from the shell burst. In addition to the output from the NOR SR Flip-Flop (FF-3) being passed down to turn off the delay counter, it is also fed to a T Flip-Flop (FF-4) which then allows clock pulses from oscillator A to pass on to another counter. Thus this (height) counter starts recording clock pulses as soon as the light from the shell burst is detected. The pulse counting continues until the sound of the shell burst is also detected. The mechanism by which the sound of the shell burst halts the pulse counting is as follows. The sound from the burst is detected by the audio sensor, whose output is amplified using an operational amplifier. The amplified audio signal is fed to a NOR SR Flip-Flop (FF-5), which responds by toggling to the ON state. This output is fed up to the other input of the Photo NOR SR Flip-Flop (FF-3), which now responds by toggling OFF. This in turn results in the interruption of oscillator A pulses passing through the T Flip-Flop (FF-4) to the height counter. The total number of pulses recorded on the height counter is proportional to the time between arrival of the light and sound of the shell burst, which is proportional to the altitude of the bursting shell. Because T Flip-Flops have the characteristic of dividing oscillator pulses by

two, and because sound travels at 1090 feet per second (dry air at STP), if oscillator A has an accurate frequency of 2.18 kHz, the counter will record the altitude of the shell burst in feet. Because aerial shells are never fired in dry air, at 760 mm Hg pressure and 0 °C, it is appropriate that oscillator A be capable of being trimmed, so as to be able to calibrate the unit to properly record in feet under the conditions of use.

There remain two aspects of the circuit that have not been discussed. The first is an “inhibit” function provided by a MonoStable MultiVibrator (MSMV) which is triggered by the output of the fire signal NOR SR Flip-Flop (FF-1). This MSMV provides a blocking signal (lasting about 2 seconds) to the operational amplifiers of both the Photo and audio sensors. The purpose of this is to avoid having the Photo and audio sensors mistakenly respond to the firing of the shell from the mortar rather than its burst at altitude. The second aspect is a reset signal (A) and a couple of emitter followers (for isolation) that allow the counters and flip-flops to be reset in preparation for another shell firing.

There are a number of alternatives that might be considered in the circuit design. For example, in place of the visible light Photo sensor, an infrared (IR) Photo sensor could be used. This would offer the potential for use of the instrument during daylight. Also, in place of emitter followers for isolation, opto-isolators (or even in some cases, just diodes) could be used.

The accuracy of the unit will be affected by a number of factors, but none will result in major errors. For example, the spin of a shell will cause its trajectory to curve, resulting in the shell not bursting directly overhead. For typically curving shells this will result in an error of about 1% in measured altitude. Similarly, small lateral displacement errors can result from wind effects. Finally, small errors will result from

changes in the speed of sound due to differing atmospheric conditions. However, all these errors are likely to be much smaller than the differences in performance of supposedly identical shells and thus can probably be ignored. An occasional problem is the likelihood that some shells will confuse the unit, resulting in significant errors. For example, a shell-of-shells may not burst with sufficient initial light output for the Photo sensor to detect the burst. Similarly a poka shell may not break with sufficient sound output for the audio sensor to detect the burst. Most problems of this type could be eliminated by adjusting the sensitivity of the sensors, if in fact it is necessary to make measurements for these types of shells.

Calibration of the altitude measuring unit can be accomplished using small salutes at known distances on the ground. The trimming circuit of oscillator A can be adjusted to achieve correct distance measurements. As an alternative, a calibration curve, relating height counter readings and known distances to ground salutes, can be established for the unit. If there is concern regarding the accuracy of the delay timer, that can be checked by simply using a stopwatch.

Although lab work has demonstrated that this approach is practical, there has not been time to assemble or test a prototype instrument. (Also, the author has only limited knowledge of electrical engineering.) It is estimated that the material cost for this unit will be about \$200. (Thanks in large measure to Tom Dewille’s suggestion of a marvelous pulse counter with LCD readout costing only \$35.) This article is presented in the hope that a reader will have the time knowledge and inclination to successfully turn this concept into a piece of practical hardware.

The author gratefully acknowledges the editorial comments of Sam Bases and John Bergman in the preparation of this article.

## Pyrotechnic Spark Generation

K. L. and B. J. Kosanke

The intentional production of sparks in fireworks contributes significantly to the beauty and spectacle of displays. However, in comparison to the time and effort devoted to generating improved color formulations, relatively little attention has been directed toward the possibilities for new and improved spark generation. This article is offered in the hope that a review of pyrotechnic spark generation might stimulate increased effort in this area. It is acknowledged that this article draws significantly on the published works of Takeo Shimizu.<sup>[1,2]</sup>

### Background

In the simplest terms, a spark is a tiny piece of glowing material. Any liquid or solid particle will emit light (incandesce) when heated to a sufficiently high temperature. Both the color and the brightness of the emitted light are dependent on the temperature of the particle. For a theoretically perfect particle (a so-called black body emitter), the dependence of color and brightness on temperature are shown in Table 1 below.

Thus, ideally behaving incandescent particles can range in appearance from only dimly visible orangish-red through dazzling white. For the most part, bright orangish-red sparks or dim white sparks are not possible. This is literally true for sparks that are the same size, with equal surface areas. However, for sparks at a distance, which appear as point sources of light, the brightness will depend on the size of the incandescent particle. Larger particles, with greater surface area but still appearing as a point of light, will look slightly brighter. For example, a 0.85 mm diameter particle (20 mesh) compared with a 0.42 mm diameter particle (40 mesh) presents 400% more surface area to a long distance viewer, but will only appear about 60% brighter.

While no incandescent particle is truly ideal in its performance, most are close and will therefore behave nearly as indicated in Table 1. One notable exception, in terms of the possible col-

**Table 1. Color and Relative Brightness of a Black Body Emitter as a Function of Temperature.**

Temperature °C	Descriptive Color <sup>(a)</sup>	Relative Brightness <sup>(b)</sup>
500	Orangish Red	1
850	Reddish Orange	3
1500	Orange	5
2200	Yellowish Orange	7
3000	White	8

- (a) The different colors reported by Shimizu<sup>[1]</sup> for sparks of various temperatures are a manifestation of Wein's displacement law, which states that the wavelength of maximum intensity for black body radiation is inversely proportional to absolute temperature. For a more thorough discussion of this phenomenon consult a university level general physics text.<sup>[3]</sup> For a general discussion of the physics of colored light production, see an earlier article by one of the authors.<sup>[4]</sup>
- (b) The relative brightness values reported were derived from the Planck radiation formula, and the assertion that the eye perceives the brightness of point light sources (as seen against a completely dark background) in a logarithmic fashion. For a more thorough discussion of these phenomena consult a university level modern physics text<sup>[5]</sup> and the work of Edwin Land.<sup>[6]</sup>

ors of incandescent light generated, occurs for aluminum particles.<sup>[1]</sup> Aluminum sparks can deviate slightly from the normal colors for sparks. In addition to those listed, aluminum can also produce yellow sparks. From personal observation, it seems that iron too has this capability.

Based on the above discussion, it might seem that useful pyrotechnic sparks could be generated by merely introducing inert particles into a flame. There, they would be heated to high temperature and would leave the flame glowing brightly. In practice, however, this does not work

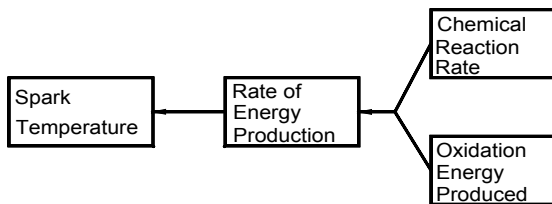


Figure 1. Some factors affecting spark temperature.

at all well. The reason is that spark particles in fireworks are generally quite small in size, ranging from about 10 mesh (2.0 mm) to perhaps 100 mesh (0.15 mm). Such small particles have relatively low mass to surface area ratios. In turn, this means the particles cool very rapidly upon leaving the flame, and fade rapidly to invisibility. For example, when relatively inert particles such as high temperature stainless steel particles are used in a fountain (which is the type of firework best suited for raising such particles to high temperatures), the particles remain visible for only a few feet after leaving the flame. Their rapid loss of brightness leaves the viewer with more of a feeling of sadness than joy.

For fireworks sparks to perform long enough to be aesthetically useful, it is necessary that there be some mechanism through which they can sustain their necessary high temperatures after leaving the flame. This requires that thermal energy be generated by the particles. The mechanism for this is through air oxidation (burning) of the particle (or at least one component of a composite particle). In the process of burning, heat is generated as reactive material is converted into inert products. Thus a spark particle can remain incandescent only slightly longer than its supply of reactive material lasts.

As was discussed above, spark color and brightness are functions of temperature. The temperature of a spark depends, among other things, on the rate of energy production during air oxidation. In turn, the rate of energy production depends on the rate by which the oxidation reaction proceeds and on the amount of energy produced during oxidation (see Figure 1).

The rate of a chemical reaction is a function of activation energy, the energy that must be supplied to initiate the chemical reaction. Unfortunately, the authors do not know of a tabu-

lation of activation energies for the oxidation of commonly used spark generating materials. However, activation energies are somewhat related to the common notion of reactivity (ease of ignition) of materials. Thus, in Table 2, subjective estimates of reactivities have been listed as a guide to predict relative reaction rates for air oxidation of spark particles. Also shown in Table 2 are the energies produced during oxidation of the various materials.

Table 2. Estimates of Reactivity and Energy Production for the Oxidation of Commonly used Spark Generating Materials.

Material	Reactivity <sup>(a)</sup>	Energy Produced <sup>(b)</sup>
Aluminum	Low	400 (as Al <sub>2</sub> O <sub>3</sub> )
Charcoal	Moderate	26 (as CO) 94 (as CO <sub>2</sub> )
Iron	Moderate	197 (as Fe <sub>2</sub> O <sub>3</sub> ) 267 (as Fe <sub>3</sub> O <sub>4</sub> )
Magnesium	High	144 (as MgO)
Titanium	Moderate	225 (as TiO <sub>2</sub> )

(a) Reactivity is considered only in the sense of ease of ignition in a typical pyrotechnic composition, and not in terms of stability in a chemical formulation.

(b) Values are reported in units of kcal/mole.<sup>[7]</sup>

Based on the information in Table 2, it is not possible to precisely predict the colors (temperatures) of the sparks produced; however, some things are apparent. For example, charcoal sparks are orange primarily because of the low amount of energy produced during oxidation and not because of a lack of reactivity. This is contrasted with aluminum sparks which are white primarily because of the very large amount of energy produced and not because it is highly reactive.

### Single Component Spark Particles

The simplest, although rather uncommon, type of sparks in fireworks is single component particles. Here, relatively large particles of reactive material (from 10 to perhaps 80 mesh) are used. The particles, after being heated by a burning pyrotechnic composition, continue to burn after they leave the flame and fall through the air. In this case very little if any of the inert

reaction products from the burning pyrotechnic composition remains attached to the particle. The spark particle continues to be visible until it is completely consumed. While few if any sparks are truly single component sparks; there are examples of mostly single component particles. Probably the best known example of nearly single component spark particles is titanium sparks ignited by flash composition.

With single component particles, the duration of the spark effect is a function of particle size and burn rate. Large slow burning particles simply last longer before they are completely consumed. Because burn rates of materials generally can not be adjusted by the pyrotechnist, the duration of single component sparks is usually adjusted by the selection of appropriately sized particles. However, there is a complication, particle size also affects ignitability, with large particles being harder to ignite. Thus, in most cases complete freedom to control spark duration by adjusting particle size does not exist and compromises must be made.

The most interesting, if not well understood, aspect of some single component particles is their ability to violently break apart into a number of smaller particles during their burning. This produces a most attractive effect, providing the observer is close enough to be able to see the smaller, often less brilliant, and shorter lived sparks. Perhaps the best example of spark branching occurs with burning cast iron particles. Near the end of their burning, most of the particles break into smaller spark particles, many of which break into even smaller sparks, producing beautiful lacy balls of sparks. It is apparent that carbon in the cast iron plays an important role in the process, with carbon contents of 0.7 to 0.8% producing the best spark branching.<sup>[2]</sup> However, the exact mechanism for branching is unclear. Other metals used in fireworks, such as titanium and magalium, produce branching sparks. However, to date none rival cast iron in either the number or the beauty of the branching sparks produced. Photo 1 illustrates terminal branching behavior for Ferro/Aluminum alloy, a newly available pyrotechnic material. Here, grains of 40–60 mesh Fe/Al were dropped into a gas flame as a test of their ignition and branching capabilities.

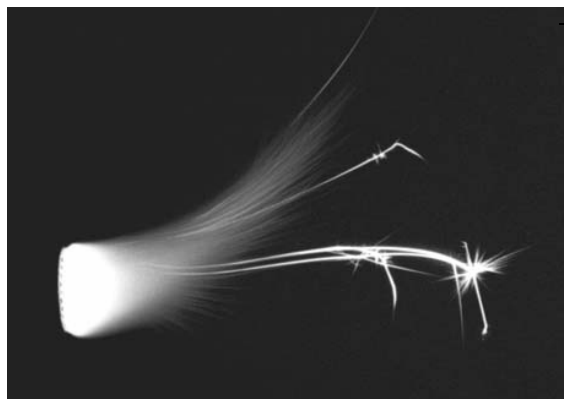


Photo 1. Illustration of terminal spark branching using Fe/Al.

### Composite Spark Particles

The vast majority of fireworks sparks are composites of both reactive and inert material. In many cases, the amount of inert material is significantly greater than the amount of reactive material. Figure 2 is a sketch of a typical composite spark particle, consisting of bits of reactive material surrounded by molten, mostly inert, material.

The size of a composite spark particle is about the same as for single component spark particles (perhaps 10 to 80 mesh). However, as suggested in Figure 2, often the bits of reactive material are much smaller (perhaps 60 to –325 mesh). In addition to the bits of reactive material the molten dross surrounding them may also be partially reactive. The role of the reactive material is the same as it was in the single component spark. Through air oxidation or chemical reaction with other materials in the composite spark particle, the reactive material provides the energy to maintain the particle at high enough temperatures to be visible. One role of the molten dross is to hold the smaller bits of material

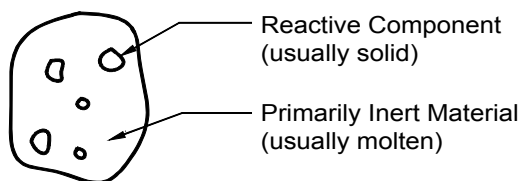


Figure 2. Typical (composite) spark particle.



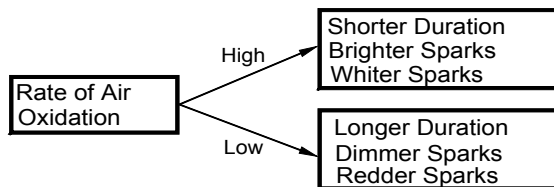


Figure 3. Effect of air oxidation rate on the sparks produced for a given material.

together and, in most cases, to retard the rate at which reactive material is consumed.

Controlling the rate at which the reactive material is consumed is important for two reasons. First, this is the mechanism through which the duration of the spark effect is regulated (long versus short spark tails). Many of the reactive materials used to generate sparks would be consumed much too quickly to be useful, if their rates of consumption could not be retarded. For example, even 36 mesh charcoal, about the largest size practical for use in fireworks, when ignited by a gas flame is completely consumed in less than a second. If it were not possible to significantly reduce its rate of air oxidation, charcoal tail effects would all be of very short duration. The charcoal tail effects would also be sparse, because the use of large mesh material means that many fewer sparks would be generated for a given amount of material. The second reason for controlling the rate at which reactive material is consumed is that this is the mechanism through which the rate of energy production, and thus spark color and brightness, is regulated. Charcoal particles ignited by a gas flame burn bright yellowish-orange and not dim reddish orange as normally seen in fireworks. (See Figure 3.)

The way in which the molten (mostly inert) material in a composite spark acts to retard the air oxidation of the reactive material is by restricting the contact between the reactive material and the air. The molten material mostly surrounds the reactive bits of material, thus limiting their exposure to the air and thereby reducing their rate of consumption.

There are two mechanisms by which the air oxidation rate of the reactive material in a composite spark particle can be controlled. The first is by adjusting the relative amount of inert ma-

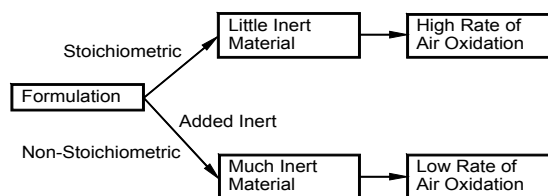


Figure 4. Adjusting the formulation to control the amount of inert material produced, thus varying the rate of air oxidation.

terial. With more inert material, the reactive component will be better protected and will have less contact with air oxygen. The inert material is partly the residue from the burning pyrotechnic composition. To some extent, the amount of this residue can be controlled by adjusting the relative amounts of ingredients. Of course, larger amounts of residue can also be generated by adding inert material to the composition, such as very small amounts of clay. (See Figure 4.)

The second mechanism by which the air oxidation rate can be controlled is by adjusting the size of the composite spark particles produced. By varying the size of the particle, its surface area to volume ratio is changed. The availability of oxygen to the particle is a function of the amount of surface area exposed to the air, whereas the amount of reactive material is a function of the volume of the particle. Thus, for larger particles, with smaller surface to volume ratios, there is proportionally less opportunity for the reactive material to be oxidized. To a large extent, the size of composite spark particles produced is determined by both the speed of the air flowing past the burning pyrotechnic composition and by the ferocity with which the composition burns. The size of the resulting particles will be larger when the speed of the air flow is low. This is controlled by varying the velocity at which the burning pyrotechnic composition is propelled through the air. Similarly, the size of the resulting particles will be large when the burn rate of the pyrotechnic composition is low. This can be controlled by the addition of various ingredients to the formulation being used. For example, commercial meal powder will act to speed up the burn rate of Black Powder formulations; conversely, adding certain other materials or making the composi-

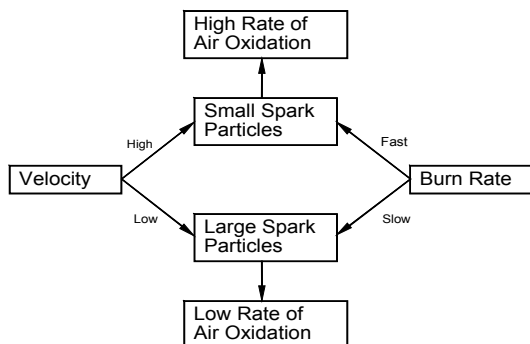


Figure 5. Adjusting velocity and burn rate to control spark particle size, which varies the rate of air oxidation.

tion non-stoichiometric will slow the burn rate. (See Figure 5.)

As an example of compound sparks, consider the sparks produced by a charcoal rich black powder formulation such as the one listed in Table 3. Table 4 lists the major components forming the composite spark particles produced when the composition is burned.<sup>[1]</sup> In this case, the potassium polysulfide reacts with oxygen in the air and produces thermal energy, sulfur dioxide and potassium sulfate. The sulfur dioxide is a gas and is lost from the spark particle; however, the potassium sulfate remains, adding to the amount of inert material. The residual charcoal also reacts with oxygen in the air and produces thermal energy and carbon dioxide, which is a gas and is lost from the spark particle.

For the most part, composite sparks do not generate interesting terminal effects such as branching. However, there are two very notable exceptions to this rule. The first is glitter effects, where an incandescent dross particle lit-

Table 3. Charcoal Spark Forming Black Powder Formulation.

Ingredient	Parts by Weight
Potassium nitrate	75
Charcoal, air float	15
Charcoal, 80 mesh	10
Sulfur	10
Dextrin	5

Table 4. The Major Components in Charcoal Composite Spark Particles.<sup>[1]</sup>

Material	Nature — State
Potassium sulfate ( $K_2SO_4$ )	Inert — Molten
Potassium carbonate ( $K_2CO_3$ )	Inert — Molten or Solid
Potassium polysulfide ( $K_2S_x$ )	Reactive — Molten
Charcoal (carbon)	Reactive — Solid

erally explodes with a flash of light and possibly secondary sparks.<sup>[8]</sup> The second is “firefly” effects (also called transition effects), where after some time has elapsed, an incandescent particle significantly changes its color and increases in brightness.<sup>[9]</sup> Both of these effects are thoroughly covered elsewhere in the literature and will not be addressed here except for their demonstration in Photos 2 and 3, where ferro-aluminum was used as the reactive material.

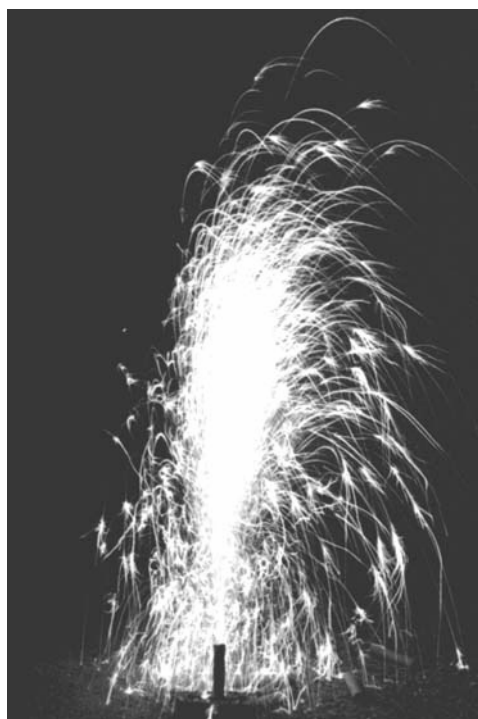


Photo 2. illustration of a Fe/Al Glitter Effect produced by a 3/4" fountain.

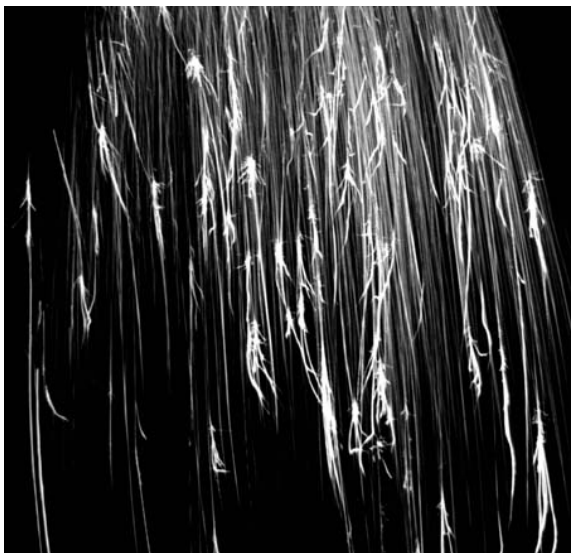


Photo 3. Illustration of a Fe/Al Firefly Effect in a shower of sparks from a suspended 1/2" comet.

### Other Considerations

Before leaving the subject of spark generation, there are two important properties of spark generating materials that must be mentioned. The reactive material being used must be easily ignited (for a single component spark) and must easily undergo air oxidation; however, it must be relatively unreactive with respect to the other ingredients in the pyrotechnic formulation. If this is not the case, there is the possibility of spontaneous ignition or the likelihood that much of the reactive material will be consumed through slow oxidation (corrosion) during storage. Cast iron is notable for this problem and requires a protective coating before it is practical for use in fireworks. Similarly, magnesium often needs to be protected before it can be used. The other important property is that the spark generating material must not be vaporized (at least not completely vaporized) when heated by the pyrotechnic flame. If it is, it will be lost and will be unavailable for spark generation. Thus, the boiling point for the material is an important consideration. This property works against magnesium (BP = 1090 °C) in attempting to use it to generate sparks, but is desirable when using magnesium as a high temperature fuel. (Note that very large, 20 to 50 mesh, mag-

nesium can be used simultaneously as fuel and spark generator, in some applications.<sup>[10]</sup>)

### Acknowledgments

The authors wish to gratefully acknowledge the technical and editorial assistance of John Bergman and Robert Winokur. The authors also wish to thank Galt Alloys, Inc. for permission to use the above photographs, which were originally prepared as part of a study evaluating the potential of Fe/Al for use in manufacturing fireworks.

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## Further Information about HDPE Mortars

K. L. Kosanke

Someone recently raised the question as to whether there could be potential problems with high density polyethylene (HDPE) mortars from contact with detergents and from exposure to sunlight. This article was drafted in response to a request to address those concerns and also to present an update on the status of acceptance of HDPE mortars by display companies and regulatory agencies.

With respect to HDPE and contact with detergents, it was suggested that some detergents may be capable of attacking HDPE. I knew of no such detergent and after checking with an expert in the field, Mr. David Tebeau of AFD, Inc., I still do not know of any such detergents. I do not feel there is any reason to avoid contact between HDPE and detergents; in fact most liquid detergents are packaged in polyethylene containers.

With respect to HDPE and exposure to sunlight, it was suggested that sunlight is capable of degrading the performance characteristics of HDPE. Specifically, it was suggested that while HDPE worked fine in England, problems related to sun damage might be encountered if it were used in the Middle East. First, as background, that component of sunlight that has the potential for damaging polyethylene is ultraviolet light. It should be noted that the transmission of ultraviolet light is mostly unaffected by cloud cover, and the ultraviolet exposure in both England and the Middle East will be much the same. While it is true that ultraviolet light will degrade unpigmented polyethylene, the material manufactured as general purpose pipe is strongly pigmented with carbon black to protect it from such degradation. The HDPE pipe used by the natural gas companies is only weakly pigmented with an orange colorant, yet the standard is to allow its use after 2 years of continuous exposure to sunlight. I would estimate that even a continuous 20 year exposure

of pigmented HDPE mortars would not be a problem.

With respect to the acceptance of HDPE by the fireworks industry, of the approximately 75 people that have provided feedback regarding HDPE mortars, only two have expressed significantly negative opinions.

The first, and most strongly voiced negative reaction, was from the owner of a display company that has recently invested very heavily in new steel mortars. His principal objection was that HDPE was not as strong as steel. This is true, but irrelevant providing HDPE has sufficient strength with the proper wall thickness. It is perhaps worth noting that many fireworks experts feel that a mortar should be only modestly stronger than is necessary to successfully launch the shells for which it was intended. This is because an overly strong mortar can contribute to the magnitude of the explosion in the event of a shell detonation within the mortar. It would be preferred if the gases produced by the detonating shell were safely vented at lower pressures from mortars that rupture without fragmenting. Another objection from this individual was because of his belief that the properties of HDPE varied significantly from batch to batch, which could make mortars unpredictable. This is not true, he is misinterpreting the data. There are several different HDPE resin types and their properties do vary significantly from one resin type to another; however, for a given resin type there is essentially no variation between batches. (Note that the preferred resin type is PE3408.)

The second negative reaction was from a co-operator of a display company who experienced difficulty in loading some types of shells into HDPE mortars. This was the result of the pipe used to make the mortars having an internal diameter less than called for in its specification. This can certainly be a problem as it is a some-

what common practice in the HDPE pipe industry. The industry controls the outside diameter of the pipe very closely, because of the method used to extrude the pipe. Then, in order to be certain that pressure ratings are met, there is a tendency to extrude the pipe with walls a little too thick, just to be on the safe side. The result is that the pipe is produced having an ID less than expected. This is not a problem for the vast majority of HDPE pipe users, but certainly can be a problem for users in the fireworks display industry. Thus when purchasing HDPE pipe it can be important to exactly specify the ID and wall thickness that must be met.

Finally, with respect to the acceptance of HDPE by regulatory agencies, their reaction has been cautiously positive. Both New York and

California, which have extensive state codes for fireworks displays, are allowing the use of HDPE mortars, at least on a trial basis while more field data is collected. The National Fire Protection Association, in their revision to the code for displays, will be including HDPE as an acceptable mortar type. However, the wording which had described HDPE (and paper) mortars as “generally considered not capable of producing dangerous flying debris” has been dropped. It was felt that this wording might cause some state regulators to become overly concerned regarding the use of steel mortars for displays.

All indications are that HDPE will be, or perhaps already is, the material of choice for display fireworks mortars.

## The Use of Titanium in Pyrotechnics

K. L. Kosanke

Titanium is a very effective generator of white (silver) sparks when used in the manufacture of fireworks. This is because of three of its properties: it ignites easily and burns readily in air, it has a high boiling point, and it is corrosion resistant. Because of this unique combination of desirable properties, the use of titanium in fireworks is generally easy, relatively safe<sup>(a)</sup> and very effective. Before discussing the ways in which titanium is used in fireworks and giving some sample formulations, it is useful to discuss why the properties mentioned above are so important for a pyrotechnic spark generator.

Except for smoke items, flame temperatures in fireworks range from about 1700 °C for black powder compositions, through about 2300 °C for typical color formulations, to perhaps more than 3000 °C for some metal fuel color formulations.<sup>[1]</sup> It is important that a material intended to produce sparks in fireworks ignites easily at these temperatures and that it be capable of continued burning in air after leaving the flame. Particles merely heated to high temperature but not ignited may leave the flame glowing brightly but will fade to invisibility very quickly as they rapidly cool.

In most instances, it is important that a material intended to produce sparks in fireworks have a high boiling point. This is because particles that are vaporized in a flame will not be available to produce trailing sparks, which are incandescent solid or liquid particles. Also, in colored flames, the chemistry is complex and easily interfered with.<sup>[2]</sup> Particles that vaporize in such a flame are likely to alter that chemistry, with the result of weakening or destroying the flame's color. Often it is impossible to reformulate such a composition to again produce strong colors. However, it is preferable that the addition of spark-producing particles does not require such reformulation.

It is important that a material intended to produce sparks in fireworks be corrosion resistant, or at least capable of being easily protected against corrosion. If the other materials in a formulation chemically attack the spark-generating material, it may no longer be present in sufficient quantity to produce effective sparks when the firework is used. Thus the useful shelf life of the item will be limited. More important, the corrosion process generates heat, which may be sufficient to cause spontaneous ignition of the composition.

Table 1 rates the metals most commonly used in fireworks for these three important properties. As can be seen in Table 1, titanium's set of properties is the best of any of the listed metals. It ignites easily, has a high boiling point, and is highly corrosion resistant. This makes titanium the easiest spark generating material to use, and it can be used to produce attractive sparks in more types of formulations than any of the other metals. Titanium can be added to most pyrotechnic formulations without significantly altering the performance of the composition except for the additional production of white (silver) sparks<sup>(d)</sup>. Tables 2a, 2b, and 2c give examples demonstrating how easily titanium can be used to produce sparks by simply adding 10 to 20% of it to standard (non-sparking) formulations.

**Table 1. Some Properties of Metals Commonly Used in Fireworks.**

Metal	Ease of Ignition <sup>(b)</sup>	Boiling Point <sup>(3)</sup>	Corrosion Resistance <sup>(b)</sup>
Aluminum	Hard	2467°C	Moderate
Iron	Easy	2750°C	Low
Magnalium (50:50)	Moderate	(c)	Moderate
Magnesium	Easy	1090°C	Low
Titanium	Easy	3287°C	High
Zinc	Moderate	907°C	Moderate

**Table 2a. Examples Demonstrating the Conversions of Non-Sparking Formulations to Silver Sparking Ones.**

Ingredient	Parts by weight			
	Flash Salute	Silver Flash	Whistle	Silver Whistle
Potassium perchlorate	70	70	70	70
Aluminum (German dark)	30	30	—	—
Sodium benzoate	—	—	30	30
Titanium <sup>(e)(f)</sup>	—	15	—	10
Reference	5	—	6	—

**Table 2b. Examples Demonstrating the Conversions of Non-Sparking Formulations to Silver Sparking Ones.**

Ingredient	Parts by weight			
	Wheel Driver	Silver Wheel	Red Fire	Silver & Red
Potassium nitrate	75	75	—	—
Charcoal (air float)	15	15	—	—
Sulfur	10	10	—	—
Potassium perchlorate	—	—	66	66
Strontium carbonate	—	—	20	20
Accaroid resin <sup>(g)</sup>	—	—	14	14
Titanium <sup>(e)(f)</sup>	—	20	—	15
Reference	—	—	5	—

**Table 2c. Examples Demonstrating the Conversions of Non-Sparking Formulations to Silver Sparking Ones.**

Ingredient	Parts by weight			
	Blue Star	Silver & Blue	Bright Green	Bright Silver & Red Fire
Potassium perchlorate	61	61	16	16
Copper carbonate	12	12	—	—
Parlon	13	13	—	—
Accroides resin	9	9	—	—
Rice starch <sup>(h)</sup>	5	5	<sup>(i)</sup>	<sup>(i)</sup>
Barium nitrate	—	—	42	42
Magnesium <sup>(j)</sup>	—	—	25	25
Polyvinyl chloride	—	—	15	15
Lamp black	—	—	2	2
Titanium <sup>(e)(f)</sup>	—	10	—	20
Reference	(6)	—	(6)	—

In addition to the many ways titanium can be used by simply adding it to standard non-sparking formulations, there are two other applications that should be addressed. The first is

a very attractive sparkler that generates an abundance of white sparks that seem to flow in long-lived cascades from the end of the sparkler. The second is sparking primes that some

**Table 3. Examples of Other Uses for Titanium in Fireworks.**

Ingredient	Parts by weight		
	Titanium Sparkler	Sparking Prime	Sparking Hot Prime
Potassium perchlorate	100	—	70
Titanium	100 <sup>(k)</sup>	15 <sup>(l)</sup> (m)	15 <sup>(l)</sup> (m)
Dextrin	45	—	—
Hydroxypropylguar <sup>(n)</sup>	5	—	—
Potassium nitrate	—	75	—
Charcoal (air float)	—	15	20
Sulfur	—	10	—
Accroides resin	—	—	10
Potassium dichromate	—	—	2
Reference	8	—	—

have used successfully in place of cross-matching inside aerial shells. Table 3 gives formulations for these applications.

In addition to a few unique uses, titanium has the ability to produce white (silver) sparks in most standard (non-sparking) formulations without the necessity of altering the basic formulation. Thus it may not be an exaggeration to proclaim titanium as the most versatile and easiest to use pyrotechnic material in fireworks today.

The author gratefully wishes to acknowledge the technical and editorial assistance of John Bergman, Bob Winokur, and John Conkling.

### Notes

- (a) The use of titanium metal in pyrotechnic formulations is relatively safe, particularly in regard to adverse chemical reactions. However, titanium metal powders finer than about 240 mesh are quite susceptible to accidental ignition by static electricity, and the presence of an oxidizer only aggravates this situation. Thus caution is appropriate when using titanium finer than 100 mesh, particularly when it is possible that the material contains titanium finer than about 240 mesh. Titanium metal powders finer than about 325 mesh can be almost pyrophoric (spontaneously burn in air). Material this fine must be handled with extreme caution.
- (b) Ease of ignition and degree of corrosion resistance are given in subjective terms.

This is because the author is not aware of a reference that appropriately quantifies them. The information presented is based on the general observations of the author and reviewers.

- (c) The exact boiling point of 50:50 magnalium could not be found in the literature. However, based on information supplied by Reade Metal, Inc., its boiling point is probably in the range from 1200–1500 °C.
- (d) Strobe formulations and many glitter formulations<sup>[9]</sup> are the most notable exceptions to this rule. Also, regarding spark color, it must be noted that titanium sparks can appear yellowish in some formulations.
- (e) The titanium used can be either granular sponge or flakes, both work satisfactorily. However, granular sponge does work somewhat better in salutes while flake material works better in most other applications.<sup>[4]</sup>
- (f) The particle size of the titanium used in these formulations generally falls into one of three ranges; –10 to +20 mesh, –20 to +40 mesh, and –40 mesh. The choice of particle size is dependent on the desired duration of the sparks to be produced by the firework. Coarse material produces longer-lived sparks. However, for a given weight of titanium, there are many more particles in the finer material, and the number of sparks produced is roughly proportional to the number of particles. Thus, the choice of titanium particle size involves a tradeoff be-



tween producing a modest number of long-lived sparks and producing many more short-lived sparks. In general, the size of the titanium is scaled approximately to the size of the fireworks item. For example, a large gerb (1 to 2") probably would use -10 to +20 mesh titanium, while a medium gerb (½ to 1") probably would use -20 to +40 mesh titanium, and a small gerb (<½") probably would use -40 mesh titanium.

- (g) Acaroid resin is also known as red gum and accroides resin.
- (h) It is satisfactory to use dextrin in place of soluble glutinous rice starch.
- (i) Binding of the star should be accomplished using a non-aqueous binding system such as nitrocellulose-acetone. As an alternative, Parlon can be substituted for PVC, and the Parlon solvated using acetone and methylethylketone.<sup>[7]</sup>
- (j) The magnesium called for is 60 mesh material coated with linseed oil.
- (k) The titanium called for in the sparkler formulation is only identified as "mixed fines". This probably equates to -100 mesh material although slightly coarser material might also be used effectively. Remembering the caution in note (a) above, it might be prudent to sieve the -100 mesh titanium with a 240 mesh screen and dispose of any material finer than 240 mesh.
- (l) The titanium used in the sparking primes should be no coarser than -40 mesh; -100 mesh works well.
- (m) A dextrin—water binding system could be used but this can result in long-lasting moisture accumulation in the powder train of the time fuse. Thus, it is generally pre-

ferred to use the nitrocellulose-acetone binding system with primes.

- (n) Most likely CMC (sodium carboxymethylcellulose) can be used in place of hydroxylpropylguar in this formulation.

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## Recommended Lift Charge Amounts

B. J. and K. L. Kosanke

One of the most frequently asked questions is “How much lift powder do I need for my shell?”. Unfortunately, the answer is not an easy one. The first reason is a lack of consensus regarding the optimum height to which various sized shells should be propelled. Of course, it is a requirement that burning components must not fall to the ground, but that is where the consensus ends. For a 3-inch shell, is 250 feet high enough or is 450 feet required? The second reason is that after deciding on the proper height, there are still a large number of other variables that determine the needed weight of lift powder. Among the variables are:

- Shell Type (cylindrical or spherical),
- Shell Weight,
- Shell Size (diameter),
- Shell Length (for canister shells),
- Lift Powder Grain Size,
- Lift Powder Quality (if it is not a commercial grade),
- Mortar Length,
- Loading Space (volume between bottom of mortar and shell), and
- Shell Clearance in Mortar.

Our typical response is to refer the questioner to what others have reported and to recommend the use of these suggestions as a starting point from which further adjustments can be made as found to be necessary during testing.

Basically, there are two ways in which authors have reported their recommendations regarding shell lift. One is the weight of lift per weight of shell. The other is weight of lift per shell size.

### Lift vs. Shell Weight

As regards the weight of lift per weight of shell, there are at least three recommendations. The Westech<sup>[1]</sup> literature advises 1/5 ounce of black rifle powder for every ounce of shell weight, with the caution that actual weight must be determined by experimentation [Authors’ note: Caution is advised because this is higher than the other recommendations by a factor of at least 3]. Fulcanelli<sup>[2]</sup> also provides a rule of thumb — 1 ounce of 2FA for each pound of shell weight up to ten pounds, then 1/2 ounce for each pound over ten pounds. Fulcanelli also notes that with very large shells, such factors as the fit of the shell in the mortar, the mortar length, and the length of the shell, assume more importance than for smaller shells. A *PGI Bulletin* Question and Answer article<sup>[3]</sup> presented a

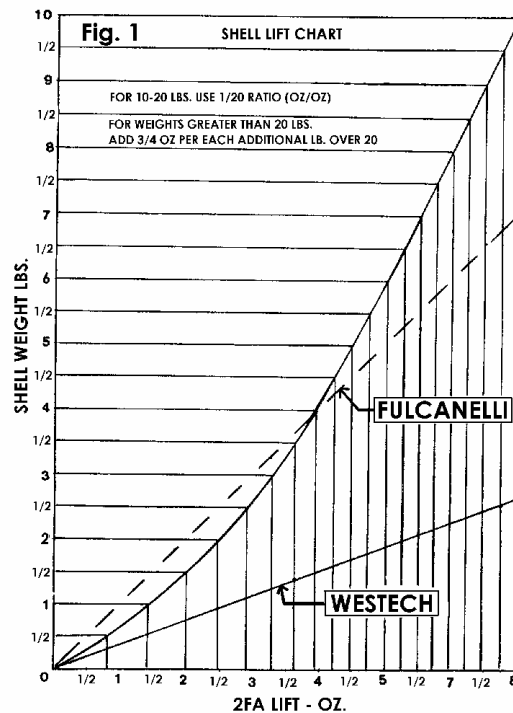


Figure 1. Shell lift chart.

**Table 1. Recommended Lift for Spherical Shells.**

Shell Size (in)	Shimizu (2Fg–3Fg) <sup>a</sup> (oz)	Shimizu Shell Weight (lb)	Lancaster (Cannon Powder) (oz)	Bleser (2Fg) (oz)	Tenge (2FA) (oz)	Weingart (Unknown Powder) (oz)
2	—	—	—	0.3	—	—
3	—	—	—	0.6	0.75	—
4	—	—	2	0.9	1.5	1.5
5	1.3–1.6	.9–1.4	—	1.6	2.5	—
6	2.6–3.0	2.5–3.3	—	2.8	3.5	3.5
7	3.9–4.6	4.4–5.7	—	—	—	—
8	—	—	9	—	6	—
8.5	6.0–6.7	7	—	—	—	—
10	8.5–9.9	7.7–11.7	—	—	—	14
12	15.9–17.6	18.3–20.3	—	—	—	—
24	145.5–172.	132.–149.	—	—	—	—

(a) This does not mean 2 Fg or 3 Fg but rather Shimizu reports using Black Powder with a wide particle size range, which encompasses the particle sizes of both 2 Fg and 3 Fg.

chart of shell weight in pounds versus 2 FA lift in ounces. Figure 1 is a reproduction of that chart with added lines for Fulcanelli and Westech weight ratios. Of these, the authors feel that the graph from the *PGI Bulletin* probably represents the best starting point.

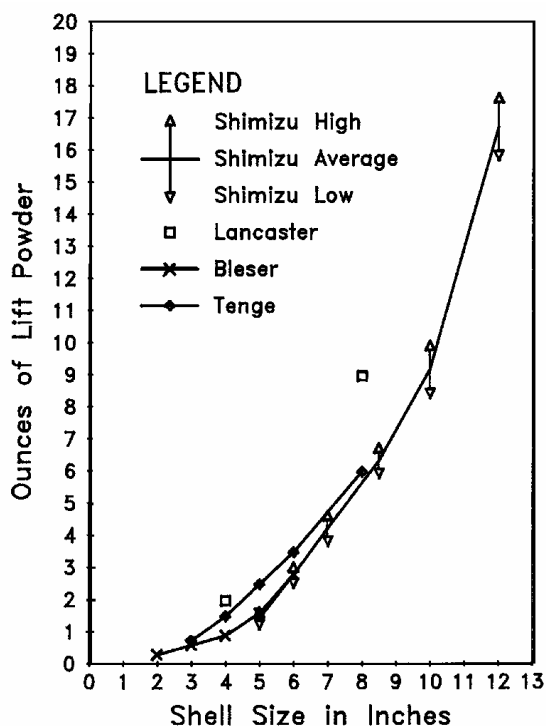


Figure 2. Spherical shell lift chart.

### Lift vs. Shell Size — Spherical

With regard to weight of lift vs. spherical shell size, Table 1 presents the recommendations of Shimizu,<sup>[4]</sup> Lancaster,<sup>[5]</sup> Bleser,<sup>[6]</sup> Tenge,<sup>[7]</sup> and Weingart.<sup>[8]</sup> Only Shimizu provided shell weight data. These same data are presented graphically in Figure 2.

### Lift vs. Shell Size — Cylindrical

Cylindrical or canister shells are more difficult to deal with because: the shell length can vary greatly; the contents of the shell can be high density (stars with Black Powder burst), low density (flash powder), or anywhere between; and the shells can be single or multi-break. Nonetheless Tables 2 and 3 provide suggestions for one- and two-break cylindrical shell lifts from Tenge, Fulcanelli, and Freeman.<sup>[9]</sup> The data are presented graphically in Figures 3 and 4. All references suggest using 2FA powder.

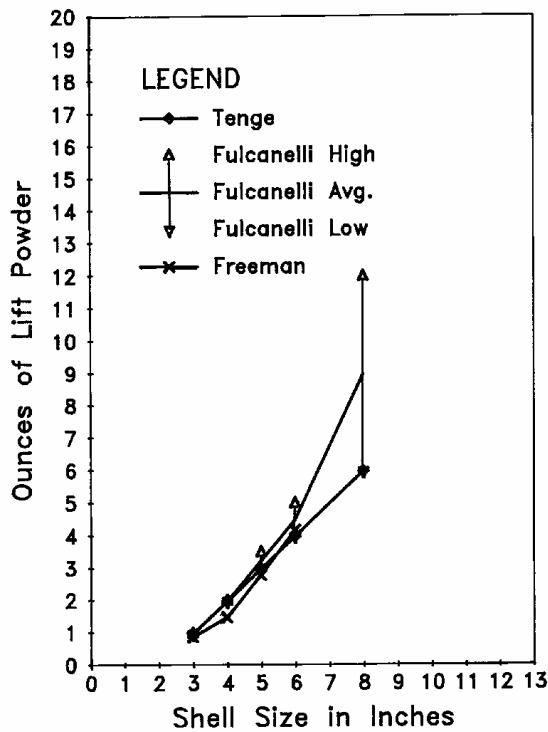
Freeman also offers a chart of estimated shell weights and lift amounts for multi-break 4-inch shells. See Table 4.

For long multi-break shells Freeman notes that the mortar lengths should be at least half again the shell length. For example, a shell 32 inches long should be fired from a mortar at least 48 inches long.

**Table 2. Recommended Lift for 1-Break Cylindrical Shells.**

Shell Size (in.)	Tenge 1-break (oz.)	Fulcanelli 1-break (oz.)	Freeman 1-break (oz.)
3	1	1	.9
4	2	2	1.5
5	3	3-3.5	2.8
6	4	4-5	4.2
8	6	6-12	-

Because of all the many factors mentioned in the introduction, you should only use these tables as starting guidelines; you **MUST** experiment to determine the correct amount of lift for your particular shells.

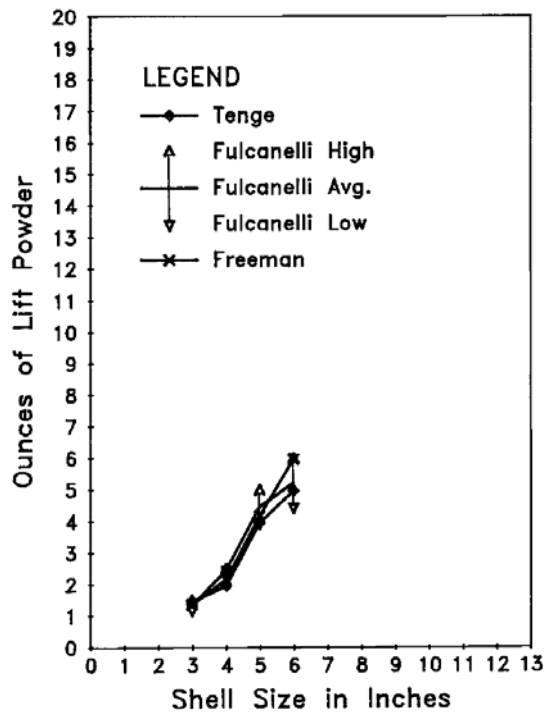


*Figure 3. Lift weights for cylindrical 1-break shells.*

**Table 3. Recommended Lift for 2-Break Cylindrical Shells.**

Shell Size (in.)	Tenge 2-break (oz.) <sup>b</sup>	Fulcanelli 2-break (oz.)	Freeman 2-break (oz.)
3	1.5	1.25-1.5	1.4
4	2	2.5	2.2
5	4	4.0-5.0	4.2
6	4-5.5	4.5-6	6

(b) Specifically color and report, or larger single break component shells.



*Figure 4. Lift weights for cylindrical 2-break shells.*

**Table 4. Weight Ratio for Multi-Break 4-Inch Shell.**

Number of Breaks	Estimate of Shell Wt. in lb.	Recommended Lift in oz.
1	1.2	1.5
2	2.4	2.2
3	3.6	2.8
4	4.8	3.4
5	6.0	4.0
7	8.4	5.0
8	9.6	5.5

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