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Pyrotechnic Spark Generation

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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.[1,2]

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.

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

Temperature °C	Descriptive Color(a)	Relative Brightness(b)
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[1] 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.[3] For a general discussion of the physics of colored light production, see an earlier article by one of the authors.[4]

(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[5] and the work of Edwin Land.[6]

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 colors of incandescent light generated, occurs for aluminum particles.[1] 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

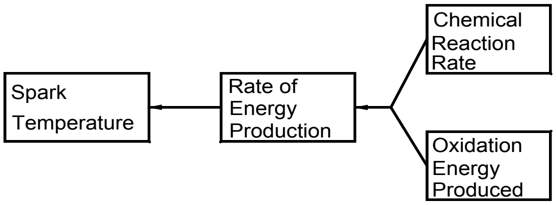

Figure 1. Some factors affecting spark temperature.

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 tabulation 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(a)	Energy Produced(b)
Aluminum	Low	400 (as $Al_{2O}3$)
Charcoal	Moderate	26 (as CO) 94 (as CO_2)
Iron	Moderate	197 (as Fe_2O_3) 267 (as Fe_3O_4)
Magnesium	High	144 (as MgO)
Titanium	Moderate	225 (as TiO_2)

(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.[7]

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.[2] However, the exact mechanism for branching is unclear. Other metals used in fireworks, such as titanium and magnalium, 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.

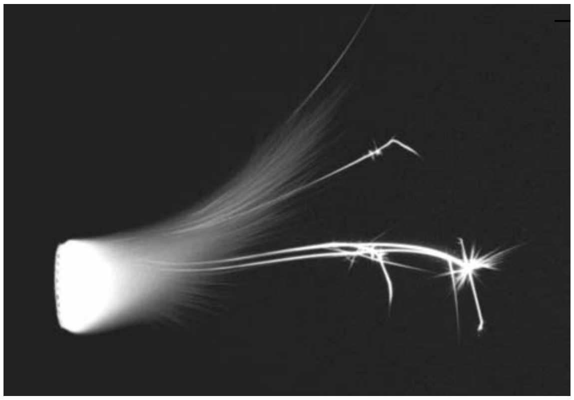

Photo 1. Illustration of terminal spark branching using Fe/Al.

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

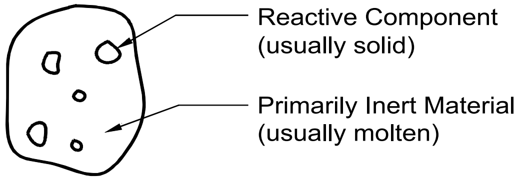

Figure 2. Typical (composite) spark particle.

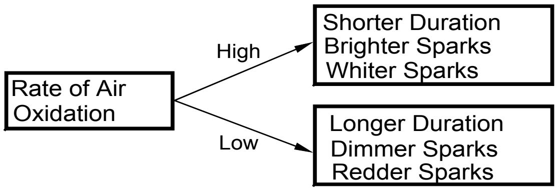

Figure 3. Effect of air oxidation rate on the sparks produced for a given material.

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 material. 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.)

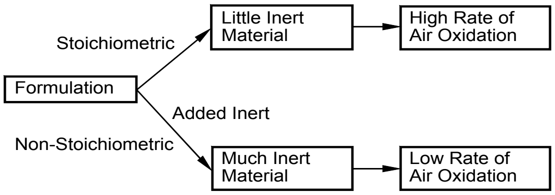

Figure 4. Adjusting the formulation to control the amount of inert material produced, thus varying the rate of air oxidation.

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-

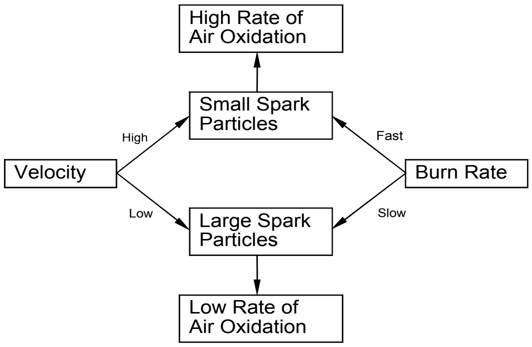

Figure 5. Adjusting velocity and burn rate to control spark particle size, which varies the rate of air oxidation.

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.[1] 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 literally explodes with a flash of light and possibly secondary sparks.[8] 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.[9] 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.

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.[1]

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

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

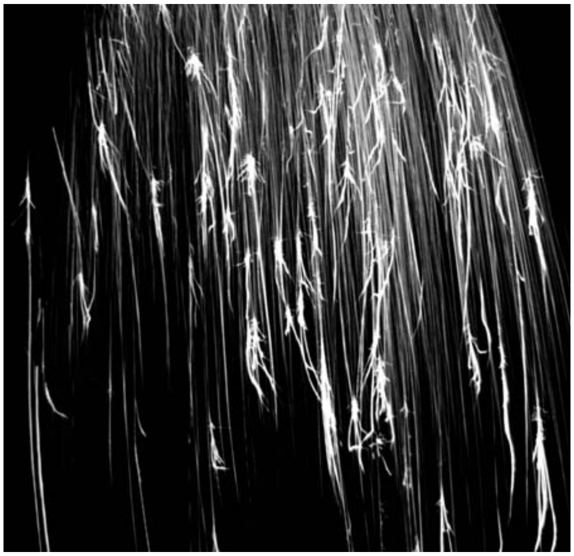

Photo 3. Illustration of a Fe/Al Firefly Effect in a shower of sparks from a suspended ½" comet.

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, magnesium can be used simultaneously as fuel and spark generator, in some applications.[10])

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