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Parallel and Propagative Pyrotechnic Burning

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Introduction

In effect, there are two basic mechanisms for pyrotechnic burning. One, which is primarily burning inward, perpendicular to the burning surface, and one in which accelerated burning along surfaces is most important. These can be termed "parallel" and "propagative" burning, and the same pyrotechnic material can manifest radically different burn rates depending on which type of burning predominates. A theoretical discussion of burn rates and the many factors effecting burn rate is beyond the scope of this article; however, a working knowledge of these two types of burning is useful in understanding the way in which a number of fireworks items function and, on occasion, malfunction. Also, should the need arise to dispose of pyrotechnic materials by burning, a knowledge of these two types of burning, and the potentially dangerous transition that might occur between the two, could be of critical importance.

It must be acknowledged that in the literature there is conflicting usage of the terms describing burn types and that the propellant powder industry uses similar terms in a somewhat different manner. In an attempt to avoid confusion, an appendix has been included to explain the powder industry's use of the terms degressive, neutral, and progressive burning. Also, erosive burning is briefly discussed.

Background

To prepare for the discussion of burn types, it is useful to review a few points from basic pyrotechnic chemistry (for further background, also see Reference 1):

- Pyrotechnic compositions are mixtures of a fuel with an oxidizer; thus burning is possible without the necessity of drawing oxygen from the air.
- Pyrotechnic compositions are called "metastable" because, although they may burn rapidly once ignited, they generally will not spontaneously combust.
- In simple terms, the process of ignition requires the raising of a pyrotechnic composition to its ignition temperature.
- Burning of solidly compacted pyrotechnic composition generally proceeds in an orderly fashion, layer by layer, as shown in Figure 1. The "reacting" layer produces heat, some of which acts to raise the temperature of the "pre-reacting" layer. Once the ignition temperature of the pre-reacting layer is reached, it too begins to burn and passes some of the heat it generates along to the next layer. In that manner, the entire stick of pyrotechnic composition is consumed.

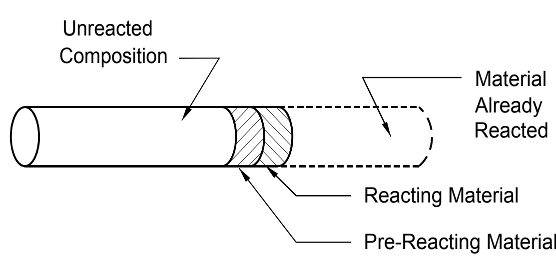

Figure 1. Model of pyrotechnic burning.

Figure 1 illustrates parallel burning (sometimes also called progressive burning), in which burning occurs, layer by "parallel" layer, in an orderly fashion.

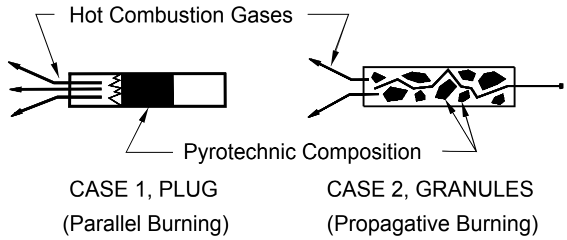

Figure 2. Examples of "parallel" and "propagative" burning.

A comparison between the conditions leading to parallel burning and propagative burning is shown in Figure 2. In Case One, parallel burning, some pyrotechnic composition has been compressed very tightly inside a tube, forming a solid cylinder of material. When that material is ignited at one end, it will burn layer by parallel layer as described above. The burn rate will be relatively slow, because the reaction only takes place on the exposed surface of the plug, and hot combustion gases vent easily through the open end of the tube.

Now consider Case Two, propagative burning, in which granules of pyrotechnic composition are packed rather loosely in a tube. In this instance each granule is a proper mixture of fuel and oxidizer such as might be produced if the cylinder from Case One were crushed into small pieces. During the first instant of burning the first grain, it will be parallel burning, and the hot gases generated will vent through the open end of the tube. However, very soon some of the hot combustion gas will begin to pass into the tube through the small spaces between granules (called "fire paths"). When this occurs, some of the granules farther into the tube receive the energy necessary to ignite. As these additional granules burn, more hot gases are produced, some of which pass still farther into the tube igniting even more granules. In this manner, all the granules of pyrotechnic composition are soon ignited. This type of rapid burning is called propagative, and quickly "propagates" throughout the entire amount of pyrotechnic composition.

In parallel burning, linear burn rates generally range from about 0.01 inch per second [0.025 cm/sec] to about 1 inch per second [2.5 cm/sec]. In propagative burning, the linear burn rate of each individual granule is the same as it would be in parallel burning. However, the linear burn rate along a collection of granules can range to more than 1000 times that for the same material burning in a parallel fashion. For example, a single grain of Black Powder or a solid plug burns progressively at about 0.4 cm/sec; however, a long line of individual grains of the same Black Powder, burns propagatively at about 60 cm/sec, or about 150 times faster.[2] In tests performed by the authors, when Black Powder was compacted tightly into a 3/8-inch internal diameter plastic tube, and ignited on one end, the burn rate was measured to be about 0.5 cm/sec. When an identical tube was filled with the same weight of loose 4FA granular Black Powder and ignited on one end, the burn rate was measured to be about 1000 cm/sec, or about 2000 times faster than when tightly compacted.

Black Match / Quick Match

Black match is generally made by applying a coating of rough powder (hand-mixed meal powder ingredients) bound with dextrin over a collection of thin cotton strings. In the absence of wind, black match burns at a rate[3] of about 1.2 in/sec [3.0 cm/sec]. The burning progresses in a more or less orderly manner along the length of fuse. Except for occasional sparks being propelled ahead, and igniting material farther along, black match can be considered to be an example of primarily parallel burning.

When black match is encased in a thin, loose-fitting layer of paper (match pipe), it becomes quick match, which burns at a rate[3] of about 10 ft/sec [3 m/sec], about 100 times faster than without the paper sheath. Based on what has already been said about burn types, one might expect that the burning of quick match is an example of propagative burning, and this is correct. The mechanism is made more clear in Figure 3, which is based on a description by Shimizu.[4] On the left of the figure it is suggested that the burning of black match produces a flame similar to that of a candle burning without obstruction. On the right, when a barrier is imposed above the candle, obstructing the flame, the flame spreads out along the barrier. Shimizu suggests that, in much the same way,

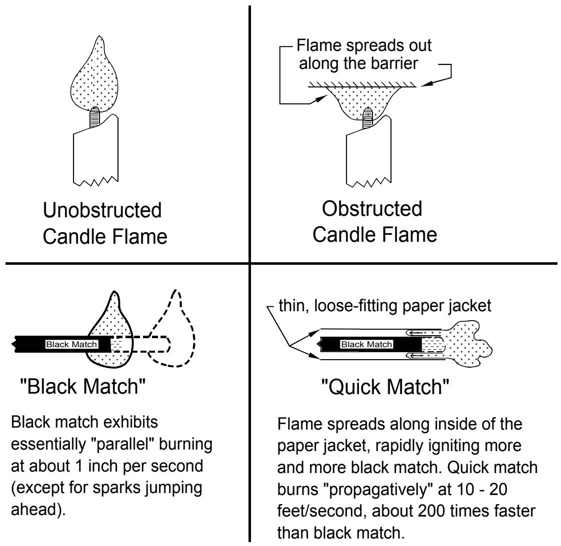

Figure 3. The quick match phenomenon.

the loose paper sheath of quick match acts as a temporary barrier for its flame. When the flame spreads out along the barrier, some passes freely out the open end, but some also passes inside toward unignited composition. When that composition is ignited by the flame, it produces more flame, some of which passes out and some passes still farther inward along the fire path provided by the loose paper wrap, igniting even more composition. In this fashion the linear burn rate of the quick match rapidly accelerates to its high value.

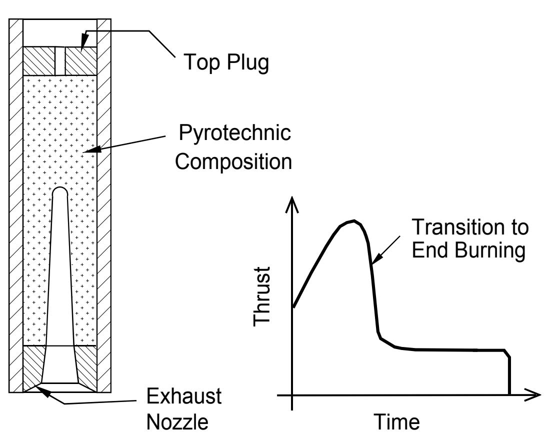

Figure 4. Core burning rocket motor.

Rockets

The quick match example is an instance when propagative burning is desired to achieve the intended pyrotechnic result. An example of undesired propagative burning can occasionally be found in rockets. Figure 4 is a sketch of a core burn rocket. Once ignited, the thrust and internal pressure of the rocket is roughly proportional to the area of the burning surface. Because of the large open core, produced by a spindle during manufacture, the area of burning surface and thrust starts out at a large value. As parallel burning proceeds the area of burning surface and thrust increases as the diameter of the open core increases further. For a normally performing rocket, burning proceeds until all the composition in the lower portion of the rocket motor has been consumed, but some composition still remains in the upper portion of the motor. At this point, the area of burning surface and thrust fall to a low value, which remains constant until finally the rocket burns out, having consumed all its propellant. However, if during the time its thrust and internal pressure are increasing, the yield strength of the rocket casing is exceeded, the casing will begin to bulge. When this happens, as illustrated in Figure 5, cracks develop in the rocket composition and between the composition and the casing. The parallel burning will now become propagative along the fire paths provided by the cracks. In this manner, the area of burning surface increases, and along with it, internal rocket pressure. The rise in pressure causes further bulging, more cracking, increased area of burning and still higher internal pressure. In this manner, the burst strength of the rocket casing

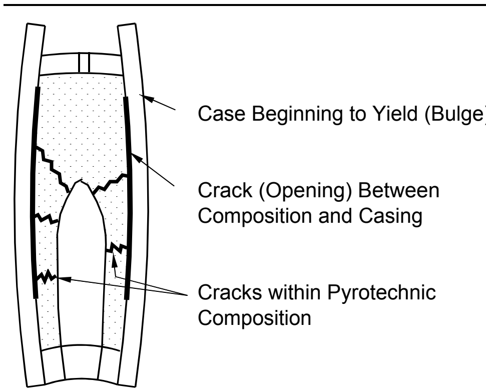

Figure 5. Rocket case failure mechanism.

is quickly exceeded and the rocket motor explodes. (This example is just one way in which cracks can develop in rocket propellants. Other ways are gas production as a result of chemical reactions during storage and shrinkage upon drying when overly moist composition is used.)

Disposal by Burning

On those occasions when it becomes necessary to dispose of pyrotechnic materials by burning, a knowledge of burn types can have important safety ramifications. In parallel burning, linear burn rates are mostly independent of the amount of material present. Thus, a test burn of a small amount of parallel burning material, will usually be a good indicator of how a larger amount of the same material will behave. In propagative burning, linear burn rates can be very dependent on the amount of material present. Thus, a test burn of a small amount of material, capable of burning propagatively, may offer little indication of how a larger amount of that material will behave.

Obviously, then, in planning for disposal by burning, it is important to know which type of burning will predominate and whether a transition from parallel to propagative burning is possible or likely. Unfortunately, that is not absolutely predictable; however, for the following two classes of materials, some generalizations can be stated.

1) A Single Solid Mass of Composition (not often found in fireworks manufacturing, e.g.,a large solid rocket fuel casting):

   - The burning will begin as parallel burning and will continue as such.
   - The duration of burn will be approximately proportional to physical size (i.e., an item twice as large in all physical dimensions will burn about twice as long).
   - The fire output from the burn will be approximately proportional to surface area, the square of physical size (i.e., an item twice as large in all physical dimensions will produce roughly four times the volume of fire throughout the burn).
   - With most materials, it is unlikely that there will be a transition to propagative burning or that the burning will somehow accelerate to an explosion. (Some materials, capable of detonation, may do so when burned in large quantity due to local over-heating, e.g. dynamite.)

2) A Collection (Pile) of Many Granules of Composition (e.g., granulated Black Powder or fireworks stars):

   - There may be a very brief period of parallel burning, but almost immediately, a transition to propagative burning will occur.
   - The duration of the burn will be nearly independent of the amount of material and will be roughly the same length of time as is required to burn a single granule[5].
   - The fire output from the burn will be approximately proportional to the total mass of material, which equals the cube of the physical size of the pile of material (i.e., a pile twice as large will produce roughly eight times the volume of fire).
   - It is possible that the parallel burning

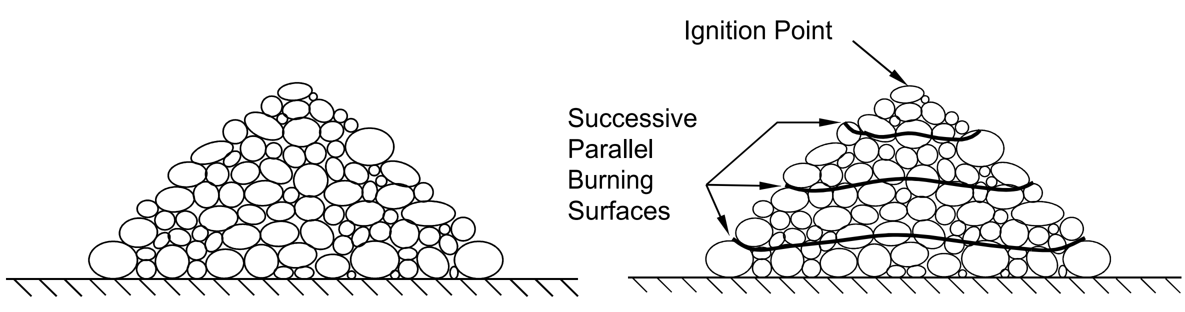

Figure 6. Loose pile of fine powder experiencing parallel burning.

will accelerate to an explosion, but generally only for larger amounts of material.

There is a third general class of pyrotechnic materials, for which predictions about output upon burning are even less reliable. That third class consists of loose, fine-grained, pyrotechnic compositions such as raw star composition. Generally the individual grains will be the components of a pyrotechnic composition (i.e., individual grains of fuel and oxidizer). However, each small grain could also be a complete pyrotechnic in itself such as commercial meal powder. Figure 6 is a representation of how a small pile of such material might appear in cross-section. One important characteristic of the material shown is that it has a wide range of particle sizes (in actuality, this is almost always the case). The smaller particles tend to plug the gaps between the larger ones, thus tending to fill in the fire paths and blocking the penetration of hot gasses when the material is burned. In many cases, such loose powders, once started, will experience parallel burning in a relatively mild fashion. This is illustrated in the right half of Figure 6, where the material is ignited at the top of the pile and then burns downward, as shown by the burning surfaces at three subsequent times during the burning process. In such an instance, the rate of burning does increase somewhat as a result of the increasing burning surface area of the pile; however, it does not become propagative.

At any time during the parallel burning of such a pile of loose composition, there exists the possibility that there will be a transition to propagative burning. This is most likely to occur if the material is disturbed in any way while burning; or the area of burning becomes the least bit confined, perhaps by nothing more than the weight of slag produced during the burning. No matter what the cause, whenever there is a significant penetration of hot combustion gases into the pile, a transition to propagative burning will almost certainly occur. The mechanism for this is illustrated in Figure 7. The pile is ignited on top and first experiences parallel burning as shown. However, as soon as there is penetration of combustion gasses, more material becomes ignited, resulting in a slight rise in local pressure. If the pressure rise is sufficient to separate the loose grains of material, thus opening more fire paths, there will be further penetration of combustion gas, leading to an even greater spread of ignition, still higher local pressure and even greater fire penetration. Very soon all remaining material is consumed, and at a potentially explosive rate. Predictions concerning the likelihood of a transition from parallel to propagative burning are generally not possible for fine-grained pyrotechnic powders. However, some very general guidance can still be given for this third class of material.

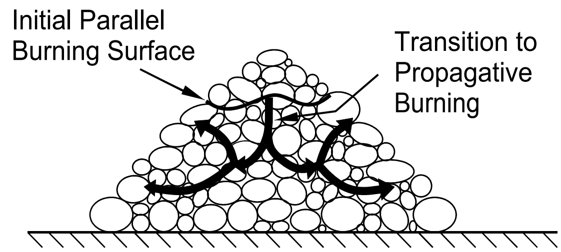

Figure 7. Loose pile of fine powder with a transition to propagative burning.

3) A Loose Pile of Very Fine Powder (e.g., blended pyrotechnic powders awaiting final processing or flash powder):

   - It is not possible to predict with certainty whether the burning will undergo a transition to propagative burning, or whether it will remain parallel throughout the burn. However, it becomes more likely there will be a transition to propagative burning when: large amounts of material are present, the material is of a type that produces a large percentage of gaseous combustion products, or the material burns very rapidly even when it is undergoing parallel burning.
   - Based on a small test burn, it is not possible to predict with certainty how long a larger burn will last or the fire output of that burn. If the burning remains parallel, it could scale up as predicted above. However, at any instant it might undergo a transition to propagative burning and accelerate catastrophically.
   - These materials present the greatest danger of unexpected explosive output.

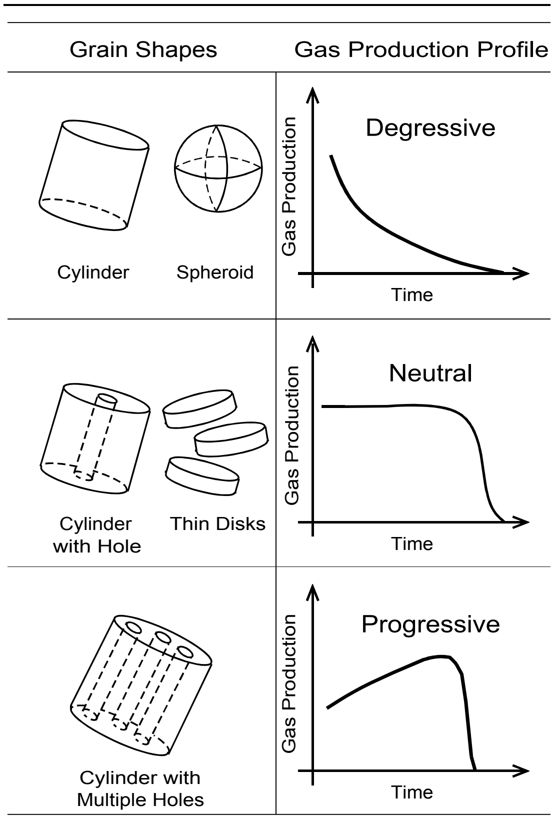

Figure A–1. Propellant powder burning.

Appendix: Propellant Burning[6,7]

In the terms used in this article, each individual grain of propellant powder experiences parallel burning, but a collection of propellant powder grains burns propagatively, with fire rapidly spreading across the surfaces of all the grains. The amount of propellant gas produced per unit time is proportional to the surface area of the burning powder grains at the time. The propellant powder industry uses the terms degressive (also regressive), neutral (also steady), and progressive to describe the time dependent production of propellant gas by their powders. The use of these terms can be explained by considering some typical powder shapes. For powder grains that are solid particles, such as cylinders or spheroids as shown at the upper left of Figure A–1, as each grain burns, it becomes smaller and its surface area decreases. Thus the surface area of a burning collection of grains, and the rate of gas production, decreases with time as the individual grains become smaller and smaller. Shown in the upper right of Figure A–1 is a curve of gas production as a function of time illustrating the decreasing rate of gas produced by a collection of solid powder grains. Propellant powders, which generate such a decreasing curve, are called "degressive."

In the case of propellant grains that are either thin disks or cylinders with an axial hole, roughly the same rate of gas production occurs throughout the period of their burning. This is illustrated in the middle of Figure A–1. For these particle shapes the surface area remains roughly constant as the individual grains are consumed during burning. Propellant powders producing an approximately constant gas production curve are called "neutral."

In the case of propellant grains that have multiple lateral holes, an increasing rate of gas production occurs throughout the period of their burning. This is because the surface area of each grain increases during burning. Propellant powders producing gas at an increasing rate are called "progressive."

Another term used in discussing propellant powders is "erosive" burning. This term is used to describe a situation when burning rate is accelerated because of the passage of jets of hot gases across a burning surface. Consider a propellant grain with an axial hole, as the grain burns along the interior of the hole, gas is produced, which exits by jetting out through the ends of the core hole. Because of this jet of hot gas, across the burning surface inside the hole, the rate of energy transfer to unburned propellant is increased. This manifests itself as an increased rate of inward (parallel) burning, beyond what would occur without the jet of gas.

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