

Introduction to the Physics and Chemistry of Low Explosives (Part 1)

by K.L. and B.J. Kosanke

This article is a slight modification of an article originally prepared for the International Association of Bomb Technicians and Investigators. Because much of this same material is of interest to the fireworks community, this article was offered to the PGI Bulletin. However, in order to enhance its usefulness, some additional material was included and other sections were re-written. Because of the length of this paper, it will appear in three parts.

In part, this paper is intended to stand alone as an introduction to the basic physics and chemistry of low explosives (i.e., pyrotechnics). However, this paper is also intended to present information needed in preparation for other papers to follow.

Following the presentation of a few definitions, this paper addresses the basic physics of explosions, chemical combustion, requirements for initiation and propagation, effects of form and confinement, effects of particle size and shape, and sensitivity to accidental ignition.

Occasionally this article includes some tidbits of practical information for the pyrotechnician. These items are indented and in italic-typeface for emphasis.

Initial Definitions

The word "explosion" is widely understood by laypersons and professionals alike, and it would seem that its definition should be almost trivial. However, it is not that simple. A fairly good definition¹ for an explosion is that the necessary and sufficient conditions are:

- 1) That gas is released.
- 2) That energy is released.
- 3) That 1 and 2 occur very rapidly.

By this definition, all three conditions must be met for there to be an explosion. For example, in the case of burning wood, gas is released (carbon dioxide and water vapor) and energy is released, but there certainly is no explosion. Of course, the

reason is that the third condition is not met; the gas and energy are not released "very rapidly."

"Explosive" can be defined by adding one further condition to the three above:

- 1) It must be capable of producing a gas.
- 2) It must be capable of producing energy.
- 3) That 1 and 2 must be produced very rapidly.
- 4) That once initiated, 1, 2, and 3 must be self-sustaining, continuing throughout the mass of material.

Something similar to the above definitions are the ones most often used. However, these are not perfect definitions, and when using these definitions, some degree of caution is necessary. Some limitations of these definitions are discussed later in this paper.

The term "pyrotechnics" is also somewhat difficult to define. In some instances, it is defined as the study of explosives that burn rather than detonate. In other cases, it is defined as the study of materials capable of undergoing a self-sustained chemical reaction producing heat and often gases, but generally at rates less than sufficient to produce an explosion without confinement. For the purposes of this paper, it is the latter definition that will be used.

As one example of the difficulties with the definition of explosives given above, consider pyrotechnic materials. For the most part, these materials react too slowly when unconfined to cause an explosion. Take for example the chemical composition used in making safety matches. When a match is struck, there certainly is no explosion. It is only when such materials are confined that they can be made to function explosively. Further, many of these materials must be highly confined or must be present in very large quantity before they can be made to react explosively. Nonetheless, the US Department of Transportation classifies most of these materials as explosives, whether confined or not, when highly combustible might be a better description. It is important to recognize

that in many instances the legal definition of explosives may not be consistent with the technical definition.

Basic Physics of Explosions

Although very high temperatures (usually exceeding 3000 °C) are produced by explosives, much of the damage is usually the result of pressure. The reason for this can be seen in the defining relationship for pressure (P),

$$P = F/A, \quad (\text{Eq. 1})$$

where F is the force exerted and A is the area on which the force is acting.

By rearranging Equation 1, it is seen that

$$F = P \cdot A, \quad (\text{Eq. 2})$$

which states that the force applied to an object is equal to the pressure acting on the object times the area of the object (i.e., the force experienced is directly proportional to pressure).

All objects are held together by internal cohesive forces. When the external force (pressure) exerted on an object is greater than the cohesive forces holding it together, the object will break apart producing fragments. This is true for all objects, containment vessels, walls, windows, people, etc.

From Newton's Second Law of Motion, it is known that a force applied to an object results in an acceleration (a) of that object. Expressed as an equation,

$$a = F/m, \quad (\text{Eq. 3})$$

where m is the mass of the object.

By substituting equation 2 for F in equation 3

$$a = P \cdot A/m, \quad (\text{Eq. 4})$$

which states that the acceleration of an object is also directly proportional to the pressure applied to it.

Thus the high pressures produced during an explosion have two direct effects, fragmentation and acceleration of those fragments. When fragments, which have been accelerated to high velocity, impact other objects, those objects too, will be damaged and may become secondary projectiles. In all cases the seriousness of the damage at any point and the range over which the damage extends, is a function of the pressure generated dur-

ing the explosion. Figure 1 is a sketch of overpressure versus time for a shock (pressure) wave produced by a typical explosion. (Overpressure is that pressure in excess of atmospheric or ambient pressure.)

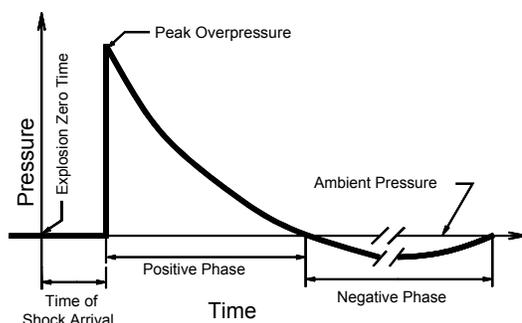


Figure 1. Explosive overpressure versus time.

In part, the pressure generated by an explosion is the result of the gas produced by the explosive chemical reaction. However, this can only begin to explain the very high pressures generated. The other factor responsible for pressure generation is the release of large amounts of thermal energy (i.e., temperatures over 3000 °C are produced). The way in which gas generation and temperature are related to pressure can be seen in the Ideal Gas Law, which can be expressed as:

$$P = n \cdot T (R/V), \quad (\text{Eq. 5})$$

where n is the amount of gas, T is temperature, R is a constant, and V is volume.

Equation 5 states that pressure is proportional to the amount of gas and also to temperature. Thus if the explosive produces both a large quantity of gas and high temperatures, the pressures generated will be very high.

Equation 5 also points out another reason to be cautious using the definitions given for explosion and explosive. It is not absolutely necessary for an explosion to generate both gas and energy (high temperatures), either one may suffice to generate explosive pressures. To illustrate this, consider the example of copper(III) acetylide, Cu_2C_2 . When this material decomposes, the products are copper metal and carbon, neither of which are gases. Nonetheless, its decomposition is surely an explosion.² The reason it acts explosively is that, upon its decomposition, a great amount of energy is produced, which manifests itself by raising all nearby materials to high temperature. These near-

by materials include atmospheric air, which, as a result of being raised to high temperature, produces high pressure causing the explosive effect. Contrary to the standard definitions, this is one of a number of explosives that produce no gaseous products.

References for Part 1

- 1) H.J. Yallop and S.S. Kind, *Explosion Investigation*, The Forensic Science Society and Scottish Academic Press, 1980.
- 2) T.L. Davis, *The Chemistry of Powder and Explosives*, Angriff Press, Reprint of 1943 edition.

Introduction to the Physics and Chemistry of Low Explosives (Part 2)

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Chemical Combustion

The chemical reactions responsible for the explosive production of gas and energy fall into the broad category called combustion. The general chemical equation for combustion is:



Fuels are generally chemical elements, or molecules primarily composed of those elements, that can form very strong chemical bonds with oxygen. Some good fuels are hydrogen (H), carbon (C), phosphorous (P), sulfur (S), and many metals such as, magnesium (Mg), aluminum (Al), titanium (Ti) and zinc (Zn). Many of the most common molecular fuels are organic materials, which consist primarily of two excellent fuels, carbon and hydrogen.

Table 1. Major Combustion Products and Reaction Energies for Typical Combustion Reactions.

Reaction Type	Reactants	Combustion Products	Energy Output	Reference
Wood Burning	Wood Air Oxygen	H ₂ O _(g) CO _{2(g)} Ash _(s)	1.9 kcal/g	Authors
Black Powder	KNO ₃ S C	CO _{2(g)} N _{2(g)} K ₂ SO _{4(s)} K ₂ CO _{3(s)}	0.7 kcal/g	3
Flash Powder	KClO ₄ Al	KCl _(s) Al ₂ O _{3(s)}	1.8 kcal/g	3
Nitroglycerin	C ₃ H ₅ N ₃ O ₉	CO _{2(g)} H ₂ O _(g) N _{2(g)} O _{2(g)}	1.5 kcal/g	4

(g) = gas (s) = solid

The feature that differentiates between pyrotechnic reactions and most other combustion reactions is the nature of the oxidizer. For most combustion reactions, the oxidizer is oxygen in the air. However, for pyrotechnic reactions, the oxidizer is usually present in solid form as a chemical ingredient. This is a very important difference. If pyrotechnic reactions can proceed without the benefit of airborne oxygen, they can proceed even when tightly confined inside containers, thus allowing the possibility of producing explosive results.

Pyrotechnic oxidizers are generally salts that con-

tain an abundance of easily released oxygen (O). Some good oxidizing salts are potassium nitrate (KNO₃), ammonium perchlorate (NH₄ClO₄), potassium chlorate (KClO₃), and potassium perchlorate (KClO₄).

Combustion products include various materials, many of which are gases, but some of which may be solids. Table 1 lists the major combustion products and reaction energies for some combustion reactions.

In terms of gas producing ability, nitroglycerin is the best, followed very closely by wood burning. In terms of energy production, wood burning is best, followed closely by flash powder. The fact that wood burning has the best combined performance in terms of gas and energy production, and yet obviously does not represent a state of explosion, serves to emphasize the importance of the requirement (see Part I) that the gas and energy must be produced very rapidly for an explosion.

Combustion reactions may be divided into one of three classifications depending on the rate (speed) of the chemical reaction. Table 2 identifies the approximate burn rates associated with each of the three classifications and gives some examples.

There are a number of things about Table 2 that should be discussed further. First, the chemical reactions of all the examples are of the same general nature, combustion. The principal difference is only the speed of the reaction. Second, under the proper conditions any of the listed examples can be made to produce an explosion. Third, explosive mixtures are physical mixtures of different materials (individual particles of fuel and oxidizer), neither of which is normally explosive by itself. Fourth, explosive molecules are chemicals that contain both fuel and oxidizer within the same molecule, which partly explains their very high burn rates. Since the fuel and oxidizer atoms are in very close proximity, it is relatively easy for them to react with explosive speed. In contrast, consider explosive mixtures. In this case even very fine powders, those only about 0.001 inch in diameter, consist of nearly a million billion atoms. Of these, less than one in ten thousand is on the surface of the particles; all the rest are buried inside. For

the most part, it is only the atoms on the surface that are available to react. Those atoms inside have to wait until the ones on the surface have reacted and left, thus exposing the ones further inside. This is the principle reason why explosive mixtures are not capable of the very high reaction rates of most explosive molecules.

Perhaps at this point it is appropriate to discuss the often-used terms, low and high explosives, and also primary explosives. Low explosives, better termed deflagrating explosives, can be considered those that, under optimum conditions, have burn rates less than 6000 feet/second. The choice of 6000 feet/second in the definition is somewhat arbitrary but is alleged to be based on the speed of sound in a more or less typical explosive under standard temperature and pressure conditions. By that definition, all pyrotechnic mixtures would be considered low explosives. However, it must be acknowledged that there are at least three other common definitions of low explosives. According to two of these definitions, some pyrotechnic flash powders have burn characteristics that class them beyond the range of low explosives. (A more complete discussion of this subject is beyond the scope of this paper and will form the basis of a future article by the authors.) High explosives, better termed detonating explosives, can be considered those that have burn rates greater than 6000 feet/second.

Most commercial high explosives are difficult to initiate, which tends to make them safe to handle under ordinary circumstances. Many explosives can be burned or struck with a bullet without detonating. However, there is a subclass of high explosives, called primary explosives, which are

Table 2. Classes of Combustion Reactions.

Combustion Class	Usual Burn Rate Units	Examples
Burning	Inches/Minute	Wood Burning Safety Matches Most Fireworks Unconfined Black Powder Rocket Propellants
Deflagration	Feet/Second	Confined Black Powder Explosive Fireworks Comp. Explosive Mixtures
Detonation	Miles/Second	Dynamite Primary Explosives Explosive Molecules

very sensitive to heat and impact, which tends to make them difficult to handle safely even under the best of conditions. Primary explosives are often used in detonators (caps) for other high explosives.

Ignition and Propagation

Pyrotechnic compositions generally will not initiate (begin to burn) without the input of some external energy. For example, at room temperature, matches and Black Powder are stable and will not spontaneously begin to burn. However, when the mechanical energy of striking is supplied to the match, it will begin to burn. Similarly, when thermal energy from the match is supplied to the Black Powder, it too will burn. This initiating energy is called activation energy. Following the input of the necessary activation energy the chemical reaction will proceed, normally producing an excess of energy, called heat of reaction. Figure 2 illustrates these energy relationships for a typical combustion reaction.

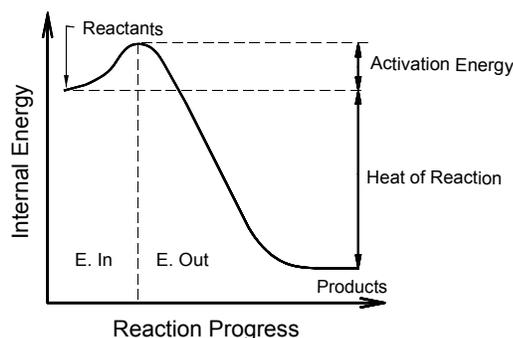


Figure 2. Chemical reaction energy relationships.

It is possible to think of the chemical reaction as proceeding in two distinct steps. First, when energy input is required, the existing weak chemical bonds within the fuel and oxidizer particles are being broken (in preparation for their inter-reaction). Second, when energy production occurs, new stronger chemical bonds are forming between individual fuel and oxidizer atoms as they combine to form the reaction products.

The amount of activation energy needed depends on how strong the chemical bonds are in the fuel and oxidizer. When the bonds are rather weak, only a small amount of energy is necessary.

For example, a mixture of potassium chlorate and red phosphorous has an activation energy barrier so very low that the mechanical action of gentle mixing may be sufficient to initiate a very violent reaction. On the other hand, when the fuel and oxidizer chemical bonds are relatively strong, greater amounts of energy must be supplied to initiate the reaction. For example, a mixture of calcium sulfate (Plaster of Paris) and aluminum has an activation energy barrier so high that a temperature of about a thousand degrees Celsius is required before it will begin to react.

Similarly, the amount of energy produced by the pyrotechnic reaction, the heat of reaction, also depends on the strength of chemical bonds. However, this time it is the strength of chemical bonds formed in the reaction products. The stronger these bonds are, the more energy the reaction produces.

It follows directly that the values for both activation energy and heat of reaction depend on the formulation of the pyrotechnic mixture. With every change in formulation, whether changing the type of ingredients or only changing the percentages of the ingredients, there will be changes in the amount of energy required to initiate the reaction and in the amount of the energy produced by the reaction. This is because in each case the reaction will occur differently; different numbers and/or types of bonds will be broken in the oxidizer and fuel, and different numbers and/or types of bonds will be formed in the reaction products.

It should be noted that there is no simple relationship between the activation energy required and the heat of reaction produced. Some reactions are very easy to start and produce large amounts of energy, while others that are easy to initiate produce very little energy and vice versa.

Once a pyrotechnic reaction starts, it will propagate, providing the reacting material supplies the unreacted composition with the necessary activation energy. This requirement for propagation can be made more clear using Figure 3, which is a model of a rod of reacting pyrotechnic composition. Toward the left in the drawing, the pyrotechnic composition remains in an unreacted state and is at room temperature. Toward the right, the pyrotechnic composition has already reacted and been transformed into combustion products. In between are the two thin disks of material that are of interest. The one labeled "reacting material"

has already received its activation energy, is reacting and producing heat energy. The reacting material is heating the next disk of material, labeled "pre-reacting material." However, much of the heat energy produced by the reacting disk is lost to the surroundings and thus is not available to heat the pre-reacting disk. It is only after the necessary activation energy has been acquired by the pre-reacting material, that it too will begin to react. If this occurs, then it too reacts, producing heat energy, some of which is available to be passed on as the activation energy needed by the next disk of material. In this manner, the reaction will propagate along the rod of pyrotechnic composition. However, if for any reason, the reaction of one disk of material does not provide the needed activation energy for the adjacent disk, the reaction will terminate, leaving all the remaining material completely unreacted.

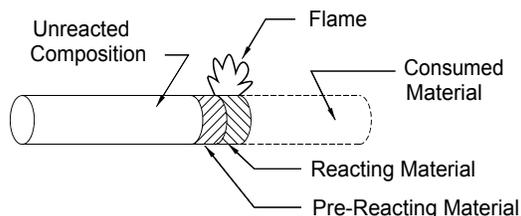


Figure 3. Model of propagating pyrotechnic reaction.

There are many reasons why the propagation of the chemical reaction through a pyrotechnic material may be interrupted; often it is not because the unreacted material is incapable of reacting. Thus, after burning pyrotechnic materials, it should never be assumed that any remaining unreacted material is safe; it is quite possible it has the

Table 3. Mechanisms for Energy Transfer from Reacting to Pre-Reacting Material.

Energy Type	Transfer Mechanism	Efficient Conditions
Thermal	Convection	Many "fire paths" for hot combustion gases to follow.
	Conduction	Use of metal fuels or other materials with high thermal conductivities.
	Radiation	Use of materials that are dark or black in color.
Kinetic	Shock Wave	Compact materials in intimate contact.

same reactive properties as the material that was consumed.

There are three factors that make it more likely that a pyrotechnic reaction will propagate, consuming the total composition. First is if the pyrotechnic composition has a low activation energy barrier, such that the feedback of only a small amount of energy is required. Second is if the heat of reaction is large; obviously the more heat produced by the composition the more likely that each succeeding layer of material will receive its necessary activation energy. Third is if the mechanism of energy transfer within the pyrotechnic composition is highly effective, making the feedback of energy more efficient. Table 3 lists the mechanisms for energy transfer and the conditions that make the transfer more efficient.

References for Part 2

- 3) J.A. Conkling, *The Chemistry of Pyrotechnics*, Marcel Dekker, 1985.
- 4) R. Meyer, *Explosives*, 3ed., VCH Verlagsgesellschaft, 1987.

Introduction to the Physics and Chemistry of Low Explosives (Part 3)

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Effects of Particle Size and Shape

The burn rate of a pyrotechnic mixture is strongly influenced by size and shape of fuel and oxidizer particles (grains) making up the mixture. To better understand why this is the case, consider again some information presented in Part 2 of this article. In large measure, it is only those atoms on the surface of a fuel or oxidizer grain that are ready to participate in a chemical reaction. Atoms buried inside the grain, generally must wait until those on the surface have reacted or have been vaporized before they too can participate in the reaction. Accordingly, the rate of a pyrotechnic reaction depends on the fraction of atoms ready to participate in a reaction, which is the fraction located on the surface of the grains in the mixture, i.e. the surface area to mass ratio of individual particles.

The surface area to mass ratio for a particle depends mostly on the particle's size and to a lesser extent on the particle's shape. Particles that are small and those that are flakes or highly angular have the greatest surface area to mass ratios. Accordingly, pyrotechnic mixtures consisting of particles with those characteristics will tend to have the highest burn rates. The data in Table 4 demonstrates the effect of increasing rate of reaction as a result of decreasing particle size.

There is a second reason why pyrotechnic mixtures consisting of small and angular particles tend to have higher burn rates. When such particles are exposed to high temperatures, the individual atoms, particularly those in any pointed or thin extremities, quickly gain thermal energy, and thus rapidly acquire the activation energy necessary to allow the reaction to proceed.

Even if one has extensive experience with a type of pyrotechnic com-

position, when the materials used in compounding it come from different production lots, or if there is uncertainty about particle size and shape, it cannot be assumed that the composition will perform with previously experienced burn rates.

Effects of Form and Confinement

Any reasonably well-formulated pyrotechnic composition can be made to cause an explosion, even if under normal conditions the material only burns slowly. The main factors affecting the potential for explosive output are the form of the material and, to a much greater extent, the degree of confinement of the material.

To illustrate the effect of form on the rate of a pyrotechnic reaction, consider Figure 4. On the left, an amount of pyrotechnic composition has been compressed very tightly into a tube, forming a plug of material. If that material is ignited on one side, it will begin to burn, and that burning will occur relatively slowly. This is because the reaction only takes place on the surface of the plug of composition and the hot combustion gases easily vent through the open end of the tube. As

Table 4. Effect of Particle Size on Performance of a Flare Composition.³

Composition: Component	Percent by Weight	Average Particle Size
Magnesium metal	48	See Table Below
Sodium nitrate	42	34 micrometers
Laminac binder	8	—
Polyvinyl chloride	2	27 micrometers

Magnesium Average Particle Size, Micrometers	Flare Candlepower (1,000 candles)	Flare Burning Rate, inches/ minute
437	130	2.62
322	154	3.01
168	293	5.66
110	285	5.84

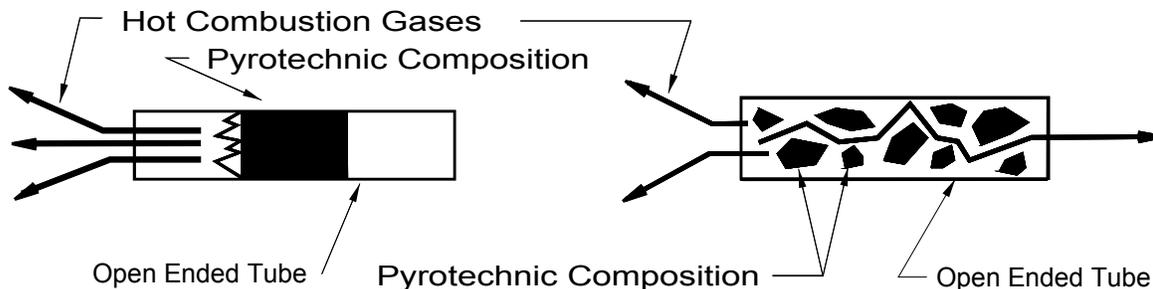


Figure 4. Effect of form on pyrotechnic burning.

was discussed in Part 2, the material just behind the burning surface will not begin to react until it receives the necessary activation energy from the burning surface. Similarly, the material just behind that will not begin to react until the material in front of it burns. Thus the burning is in an orderly fashion, one layer at a time, until finally all the pyrotechnic material has been consumed. Now consider the other case shown in Figure 4, in which granules of pyrotechnic composition are packed rather loosely into a tube. Here each granule is a proper mixture of fuel and oxidizer such as might be produced if the plug in the first case was crushed into several smaller pieces. When burning starts, most of the hot gases generated still vent through the open end of the tube. However, some also pass between the small spaces between the granules (sometimes called fire paths). When this occurs, some of the granules farther into the tube are immediately heated, receiving the activation energy necessary for them to begin to burn. As these additional granules burn, more hot gases are produced, some of which pass farther into the tube heating more granules, which also begin to burn. In this manner, very rapidly all the granules of pyrotechnic composition in the tube are consumed. Of these two cases, it is the second that has a far greater potential for explosion. As a specific example, consider two long, narrow paper tubes filled with equal amounts of Black Powder. However, in one tube the powder has been tightly compacted into a solid plug, while the other tube has been filled with granules. In the first case the device probably will perform somewhat like a weak rocket burning at a rate of about ¼-inch per second. In the second case the device will burst the tube explosively because of a burn rate of about 30 feet per second.

Even if one has vast experience with a pyrotechnic composition in one form, that cannot be

used as a predictor for how the same material will act in another form.

The degree of physical confinement is a very important factor in determining the potentially explosive output of pyrotechnic compositions. One reason is that in most instances unconfined pyrotechnic material burns relatively slow; so slow that in moderately small quantities it usually only represents a flammability hazard. When such material is confined within a vessel of some sort and then ignited, the material will burn producing hot gases. If the gases are produced at a rate greater than they can escape, such as through a fuse hole, then the pressure inside the vessel will rise. If the pressure rises beyond the strength limits of the vessel, it will burst. If the vessel is strong, such that the pressure before rupturing is high, then the bursting will be seen as an explosion. In this case the violence of the explosion directly relates to the strength of the containment vessel and not so much to the pyrotechnic material within it.

Another reason that the degree of confinement is an important consideration is that the rate of the combustion reaction is usually a function of pressure. Equation 7 shows this general relationship.

$$R = A \cdot P^b \quad (\text{Eq. 7})$$

where R is the burn rate for a pyrotechnic composition (in cm/sec), P is the gas pressure on the composition (in atmospheres), and A and b are constants dependent on the pyrotechnic composition.

As an example of the effect of pressure on burn rate, consider the case of sporting grade Black Powder. For Black Powder,⁵ A = 1.21 and b = 0.24. Using these constants, and converting to

inch/second, Black Powder would have the pressure dependent burn rate as indicated in Table 5.

Table 5. Predicted Pressure Dependence of the Burn Rate for Black Powder.³

Pressure (atm)	Pressure (psia)	Linear Burn Rate (in/sec)
1	14.7	0.48
2	29.4	0.56
5	73.5	0.70
10	147	0.83
20	294	0.98
30	441	1.07

One result of burn rate being pressure dependent is that pressures inside a containment vessel rise faster than might be expected, and this can have an effect on explosive output. It was stated above that the burst strength of a containment vessel largely determines the explosive potential for a device. While this is true, the burst strength of the vessel depends, to some extent on the rate of pressure rise within it. When the rate of pressure rise is very great, the "effective" burst strength of the vessel is greater because of inertial-like effects. Even though the vessel may be in the process of bursting, the tendency for objects at rest to remain at rest, acts to hold the vessel together slightly longer. This allows the pressure within the vessel to continue to rise to higher values and increases the explosive output beyond what might have been predicted.

Even if one has much experience with a pyrotechnic composition in one degree of confinement, that cannot be used as a predictor for how the same material will act if the level of confinement changes.

The inertial effect discussed above is also the reason that many pyrotechnic compositions, when present in large amounts, can cause an explosion even when unconfined. When there is a large mass of pyrotechnic material, the material itself and its reaction products tend to act as a containment vessel because of their inertial resistance. In these situations the minimum weight of material necessary for an unconfined explosion is sometimes called the critical mass for the pyrotechnic composition.

When disposing of pyrotechnic materials it is appropriate to test materials in small quantities before disposing of larger quantities. However, one cannot use the performance of a small amount of a pyrotechnic composition as an absolute predictor for how the same material will react in larger quantities.

As a final note, such unconfined explosions are often incorrectly called a detonation or described as "going off high order." By the definitions adopted in this article they are actually inertially confined deflagrations.

Sensitivity to Accidental Ignition Stimulus

It was discussed above that there is an activation energy barrier that must be surmounted before a combustion reaction will be initiated. It is fortunate that this barrier exists. If it did not, the forests would spontaneously burst into flame, all pyrotechnic materials would spontaneously burn, all high explosives would spontaneously explode, and biologic life could not exist. All chemical reactions that are energetically favored would occur immediately and then nothing else would happen forever more. It is the activation energy barrier that allows chemical energy to be stored for future release, and it is the height of that barrier which determines how easy it is to stimulate the release of that energy. A major problem in dealing with pyrotechnic (low explosive) compositions is that they generally have rather low activation energy barriers.

Great care must be exercised when handling pyrotechnic compositions because often only a modestly energetic stimulus is necessary to start the pyrotechnic reaction. (This is in contrast with most commercial high explosives for which a greater ignition stimulus is required.)

There are three basic types of stimuli that can supply the energy needed to initiate pyrotechnic reactions:

- 1) Thermal — Elevated Temperatures,
- 2) Mechanical — Impact or Friction, and
- 3) Electrical — Electrostatic Discharge.

The height of the activation energy barrier is an accurate measure of the amount of energy needed to initiate a reaction. However, the mechanisms through which each of the above stimuli operate are significantly different. As a result, the

effectiveness of the energy transfer for each of the stimuli depends heavily on the characteristics of the pyrotechnic composition involved. Thus, even if one knows the relative height of the activation energy barrier, it is often not possible to predict accurately how easily the material will be initiated by the different stimuli. For this reason, the sensitivity of pyrotechnic compositions is generally reported separately, as auto-ignition temperature, impact sensitivity, friction sensitivity, and electrostatic sensitivity.

Unless all four of these sensitivities are known to be low (hard to initiate a reaction) for a particular pyrotechnic material, great caution is appropriate when handling the material.

References

- (3) J.A. Conkling, *The Chemistry of Pyrotechnics*, Marcel Dekker, 1985.
- (5) A.A. Shidlovskiy, *Principles of Pyrotechnics*, Mashinostroyeniye Press, 1964.