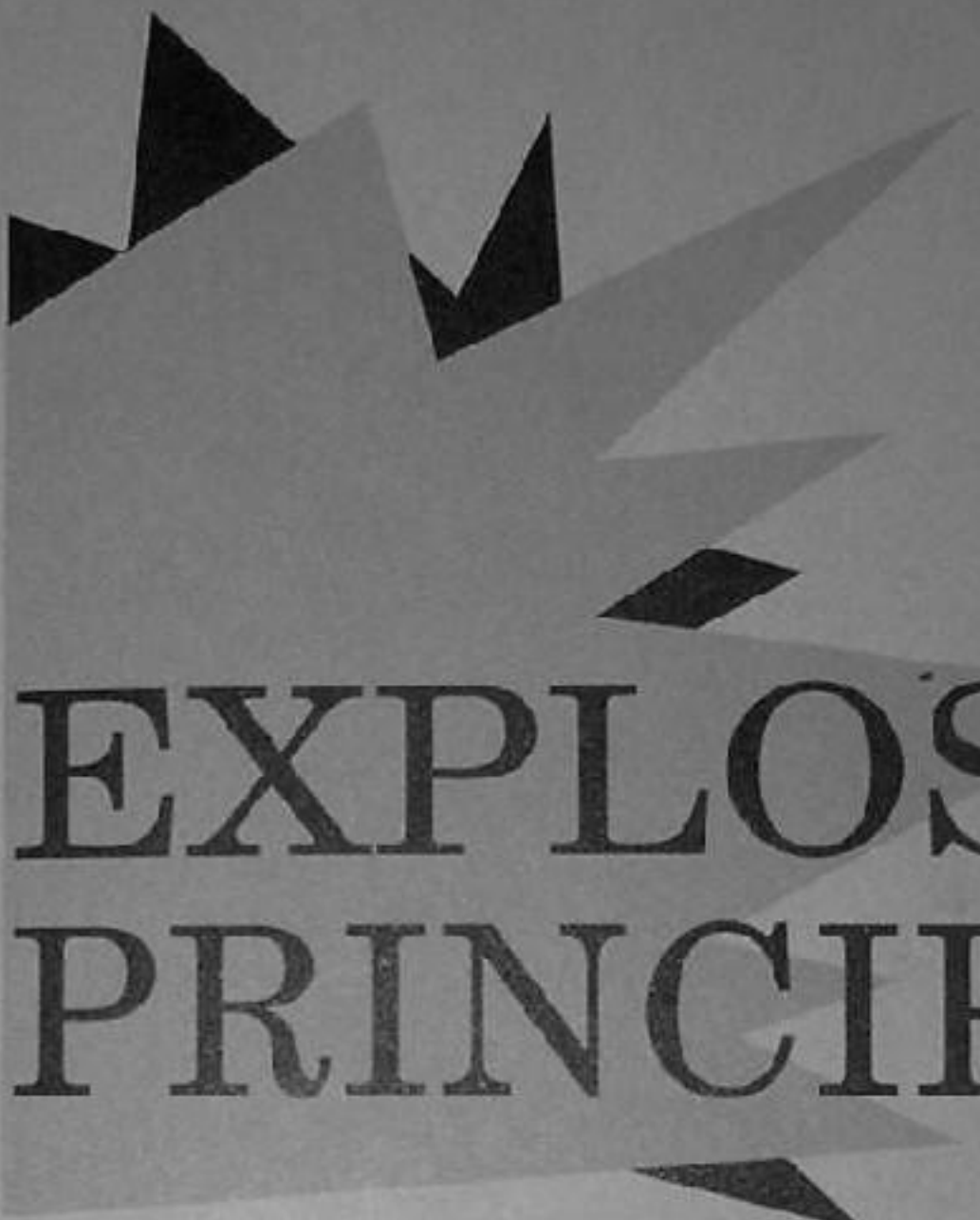




EXPLOSIVE PRINCIPLES

*AN ESSENTIAL
GUIDE TO
UNDERSTANDING
EXPLOSIVES AND
DETONATIONS*

Robert A. Sickler

Explosive Principles:

An Essential Guide to Understanding Explosives and Detonations

by Robert A. Sickler

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CONTENTS

Chapter One

Introduction to Explosives 1

Chapter Two

Physics of Energetic Material Decomposition 5

Chapter Three

Explosive Material Chemistry 17

Chapter Four

Physics of Explosives 23

Chapter Five

Explosive Materials 39

Chapter Six

Testing 53

Conclusion 57

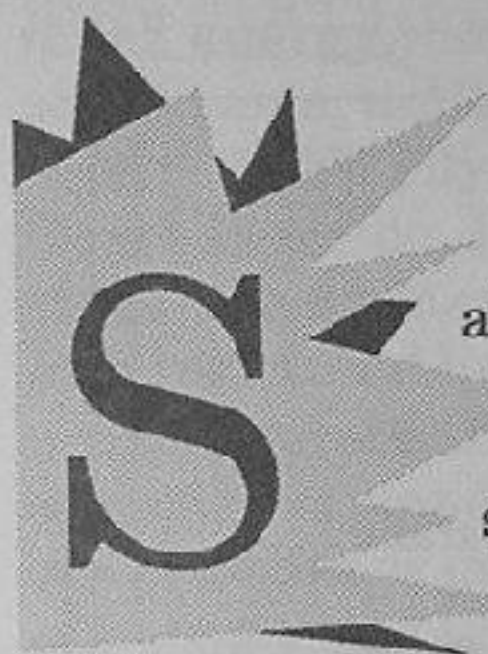
WARNING

The procedures described in this manual and the resulting end products are *extremely dangerous*. Whenever dealing with high explosives, special precautions must be followed in accordance with industry standards for experimentation and production of high explosives. Failure to strictly follow such industry standards may result in harm to life and limb.

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INTRODUCTION TO EXPLOSIVES



Some of the most feared, misused, and least understood substances on the face of the earth are energetic materials. In the broadest sense, energetic materials can cover everything from combustibles to high explosives. One way of defining this wide range of materials is to consider them as stuff (compounds or mixtures of compounds) that undergoes a change or, more accurately, a decomposition which results in the generation of energy. The rate of change can be the slow burning of combustibles or the rapid chemical decomposition of a high-order explosive.

Regardless of the type of energetic material, it cannot undergo a decomposition until sufficient energy has first been added to get the process started (*ignition* or *initiation*). The energy added to the material can be in the form of heat, impact, friction, shock, or any combination of these energy sources (See Fig. 1).

Once a material starts to undergo decomposition, it also begins to change into new material. The new material is said to be in a more stable state, or is less energetic, than the original material. For instance, when a piece of

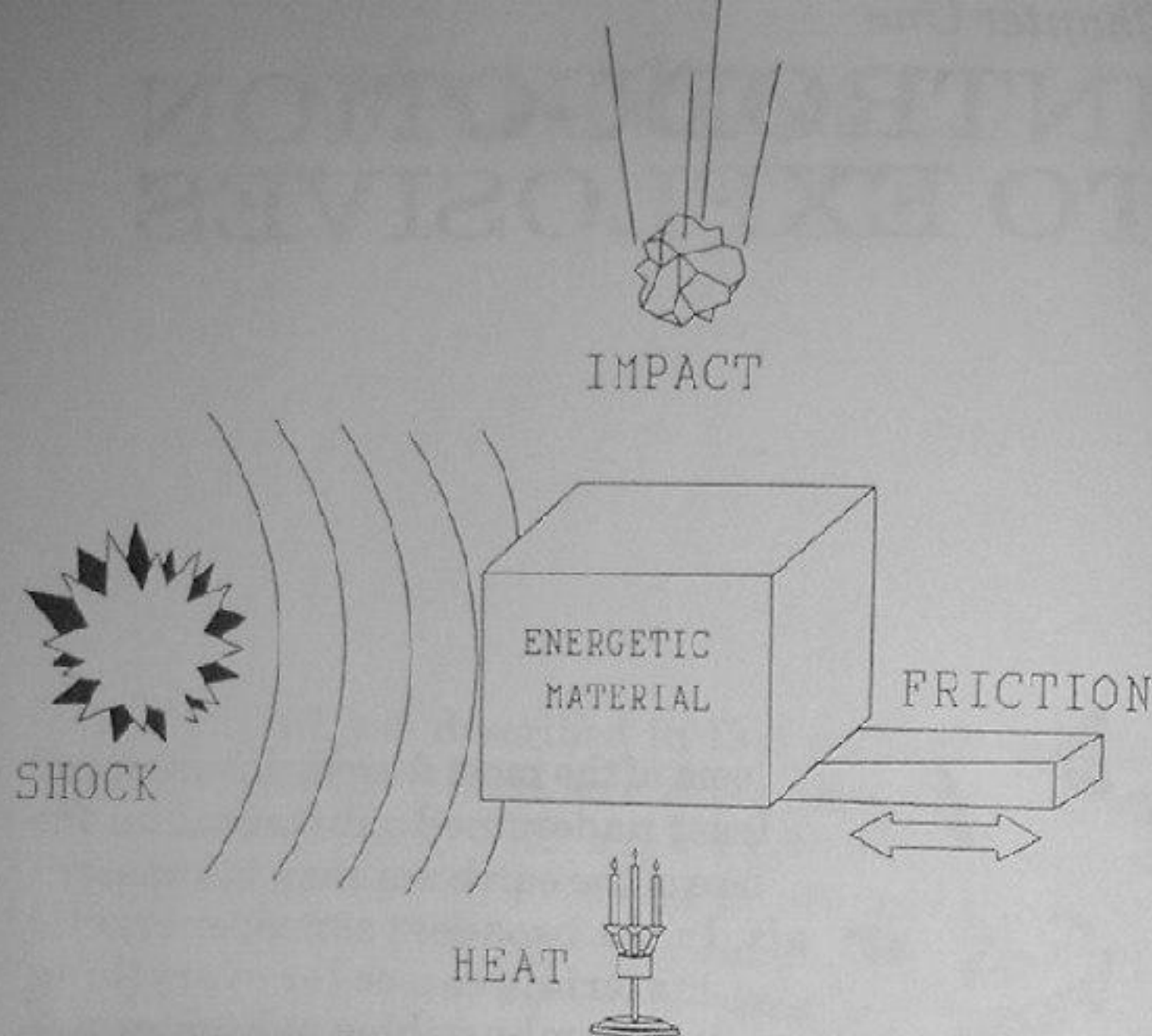


Figure 1. Methods of energetic material initiation.

wood burns it changes into smoke and ashes, which are noncombustible. Therefore, the burning of wood produced nonenergetic material, or a more stable type of stuff.

The same thing happens during the decomposition of explosive materials. The new stuff formed by the decomposition of energetic materials is also a more stable suite of compounds. Of interest to the explosives engineer, the decomposition of an explosive material produces large volumes of gases (kind of like smoke) and minor amounts of residue (kind of like ashes), all of which are accompanied by the release of vast amounts of heat.

This rapid production of gases from the decomposition of an explosive results in the formation of a high-pressure zone in the area where decomposition is taking place. This is an important concept to understand because this generation of pressure is one of the things

we want to put to use. For example, if the energetic material is inside of some closed or partially closed container (a hole in the ground, a building, etc.), then the pressure formed by decomposition could be large enough to push the container apart. Out in the open, the pressure, if built up fast enough, will push against objects and move or destroy them, kind of like a strong wind.

On the other hand, if the decomposition of the energetic material is extremely fast, the area of decomposition is preceded by *shock* or *stress waves* which move out through the surrounding media (while pressure is also being built up in the area of decomposition). Of importance to us is the fact that this shock wave contains so much energy that it will break things around it. The shock wave, unlike pressure, does not push against an object; it actually enters the object and breaks it apart from the inside. It is this combination of pressure and shock-wave generation that makes energetic materials both useful and hazardous.

In the preceding paragraph, the general public's concept of an explosion (decomposition fast enough to generate pressure or pressure and shock) was introduced. In more scientific terms, if the decomposition of energetic material occurs at a rate greater than the speed of sound, the decomposition process is called *detonation*. When an energetic material is capable of undergoing detonation-type decomposition, that energetic material is called a *high explosive*. The actual speed at which the detonation moves (*propagates*) through the energetic material is referred to as the material's *detonation velocity*, and it is often used as a tool for classification of high explosives.

If, on the other hand, the energetic material undergoes decomposition at a rate less than the speed of sound, the decomposition process is called *deflagration* (superfast burning). Energetic materials that decompose through deflagration are referred to as *low explosives*, and they do not generate a shock wave. A general rule of thumb for the dividing line between detonation and

deflagration is a decomposition velocity of about 3,000 feet per second (fps).

If the decomposition rate is very slow, it is referred to as *combustion*, or burning. Combustion is the normal form of decomposition for materials (for the most part nonenergetic) that have been ignited. In most cases of combustion, there is very little, if any, pressure generated. However, as in almost all things, there are exceptions to the rule, and under special conditions both energetic and nonenergetic materials can be made to burn, deflagrate, or detonate.

PHYSICS OF ENERGETIC MATERIAL DECOMPOSITION



Understanding the physical process of an explosion requires a brief look at the physics associated with energetic material decomposition. The key physical parameters associated with this decomposition are heat, pressure, and shock. In this chapter, the interaction and interdependency of these parameters will be discussed.

DEFLAGRATION

Deflagration of energetic materials is an exothermic redox reaction. In more common terms, it is a reaction that, once initiated, generates sufficient energy to sustain the reaction. The actual physics of initiation of energetic materials is very complex and beyond the scope of this text. It is sufficient to know that ignition occurs when an external energy source introduces energy to an energetic material, causing hot spots to form on or in the material.

Figure 2 is a microscopic representation of a near-surface cross section of energetic material. The stippled rectangles represent the general nonhomogenous (made up of more than one type of stuff) and nonisotropic (stuff

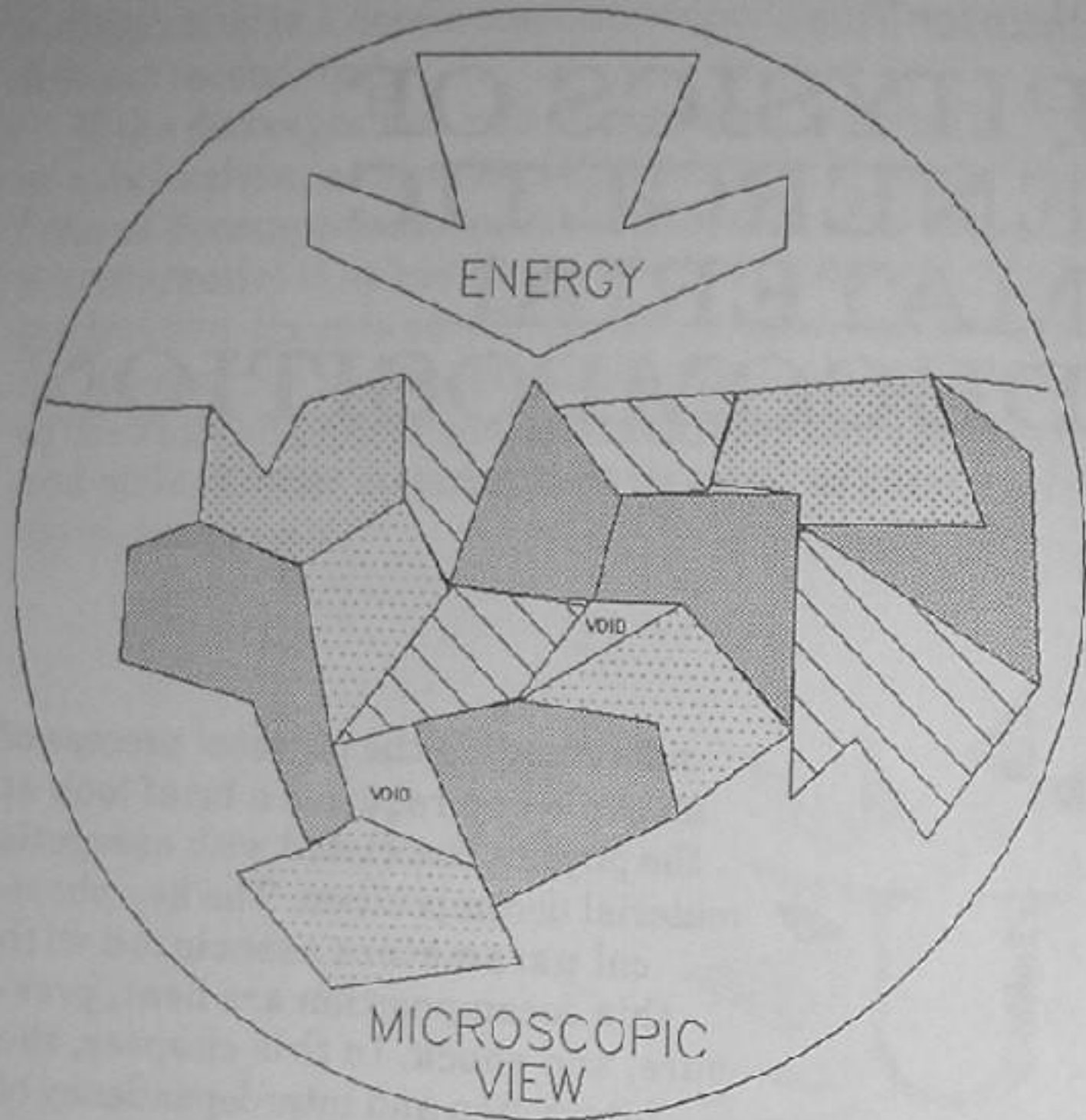


Figure 2. Introduction of energy.

that is not all the same shape or does not lie in the same direction) character of most common energetic materials. The crosshatched blocks represent those sections of material that are most susceptible to the external energy that is being introduced. If the energy was heat, perhaps from an adjacent fire, the crosshatched blocks would be those portions of the material most susceptible to heat energy. Whatever the external source of energy, it is important to recognize that the initial interaction of energy with energetic material may not be a uniform process.

There are three basic methods for turning sensitive areas into hot spots: (1) compression of the explosive

material can cause adiabatic compression of tiny gas bubbles entrapped within the explosive mixture; (2) deformation or movement of the material can cause frictional heating when the surfaces of solid ingredients are rubbed together; and (3) rapidly flowing materials can generate viscous heat as they are forced through the explosive. In most cases of deflagration, there will be more than one hot-spot generation mechanism at work. The resultant hot spot initially is very small (10^{-3} to 10^{-5} cm in diameter, or .001 to .00001 cm) relative to the explosive mixture's overall volume. Although unlikely, if there were no sensitive areas or voids in the explosive mixture, hot spots could not form and thus no explosion would occur. When this does happen (often due to overcompaction), the explosive is considered as being *dead-pressed*.

Once the energetic material has been exposed to external energy and hot spots have been generated, the surface of the material will soon reach temperatures high enough to volatilize it. Generally, this process, called the *induction lag* or *ignition time delay*, occurs in a very short period of time (measured in microseconds). There is no standard lag time for explosive material since the induction lag is dependent on the composition of the explosive mixture. As an example, the liquid, nitroglycerin, begins to vaporize at only 140°F, whereas the solid, sulphur, requires around 500°F to volatilize.

With the deflagration process underway, the energetic material environment takes on a definite layered character (Fig. 3). Because the flame zone is the heat source that perpetuates volatilization of the explosive, it can be viewed as the key layer. The hotter the flame zone, the more rapid the rate of volatilization and thus the more rapid the rate of decomposition. The gases produced by deflagration of the explosive create a pressure zone that expands into the surrounding media. The pressure experienced in this zone is proportional to the rate of deflagration and to the degree of confinement of the energetic material.

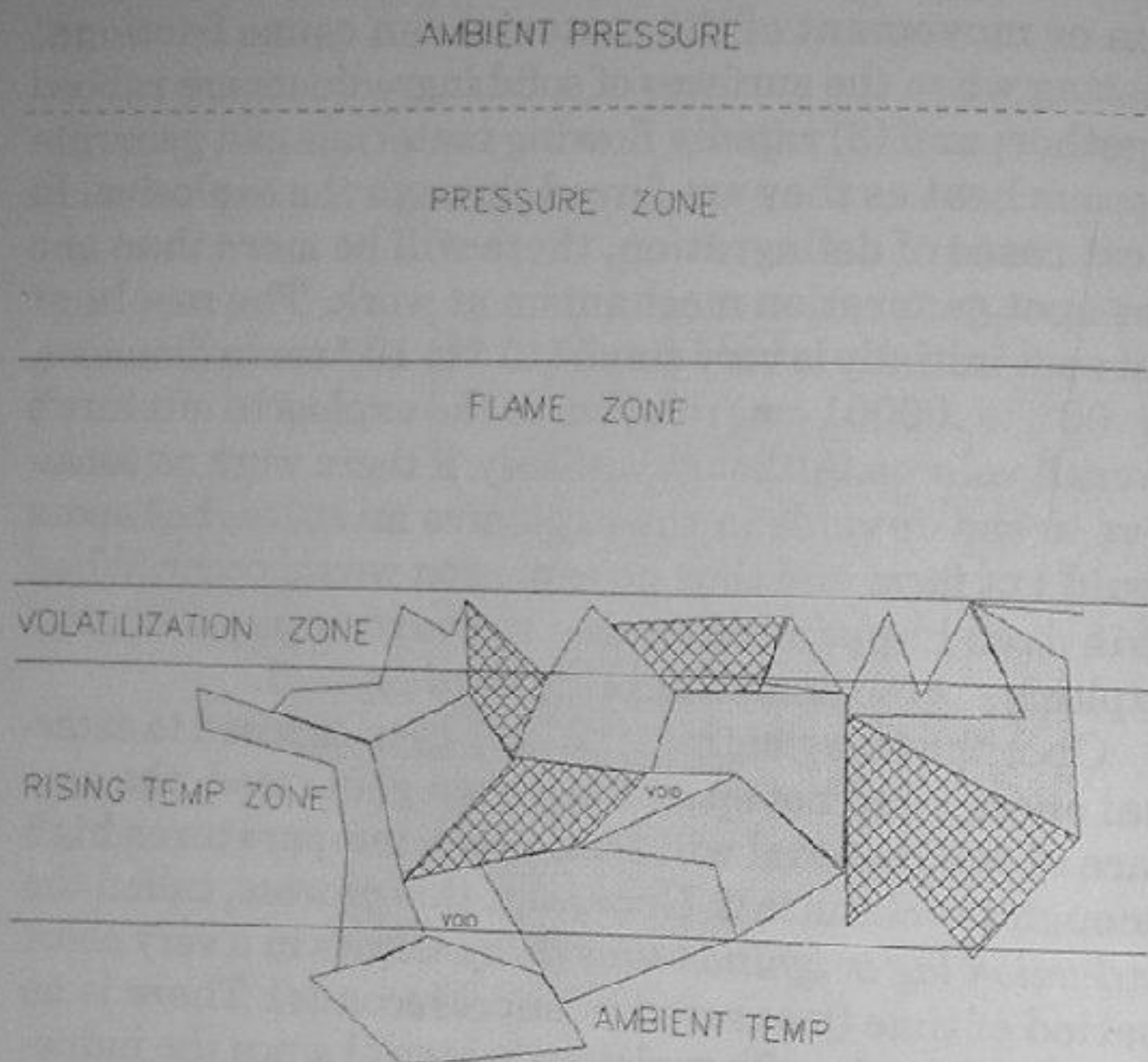


Figure 3. Deflagration zones.

If the energetic material is unconfined (in other words, it is sitting out in the open), pressure within the pressure zone rapidly drops to the surrounding ambient pressure (atmospheric pressure if you are outdoors). If the energetic material is confined, however, such as in a drill hole or steel pipe, the pressure zone's pressure cannot drop to ambient pressure until it has first risen to a level high enough to overcome the strength of whatever is confining it. As the pressure in the pressure zone increases, it forces the flame zone toward the surface of the energetic material, increasing the rate of heat transfer into the material, which results in an increase in the rate of deflagration.

A good example of deflagration is in the operation of a black powder rifle. To represent unconfined decomposition, a normal load of black powder, approximately 90 grams, is placed on the ground. A lead bullet is placed on the pile of powder and the powder is ignited. Upon ignition a large cloud of gases will be created and a small noise will occur, but the lead bullet will barely be moved. Decomposition took place, but the unconfined pressure zone never reached a level high enough to force the flame zone toward the surface of the black powder.

If, however, the same amount of powder were placed into a rifle and a bullet firmly placed on top of the powder, the energetic material would be confined. Ignition of the powder will produce a considerable noise, and the bullet will be thrown a long distance. What has happened is that the deflagration process remained confined until it had generated a pressure sufficient to move the bullet down the barrel of the gun. This small increase in pressure forced the flame zone closer to the explosive and increased the rate of deflagration. The increased rate of deflagration produced a more powerful release of energy than the decomposition of the unconfined pile of powder.

In the above example, the lead bullet had been secured in the rifle so that it could not be moved, the deflagration process could have become a detonation-type decomposition. Although it is uncommon for a low explosive to experience detonation, it can happen under the proper conditions. In most cases the low explosive must be confined in such a way that the pressure zone's pressure increases to a point where the flame zone is driven into the energetic material. This is referred to as a *convective flame front* and is characterized by the propagation of hot combusive gases through the pores of the explosive.

For example, if a strong pipe is filled with a low explosive and the explosive is ignited at the open end of the pipe, the explosive will start deflagrating. As it is consumed, the flame front moves deeper into the pipe and pressure begins to build up behind it. The pressure

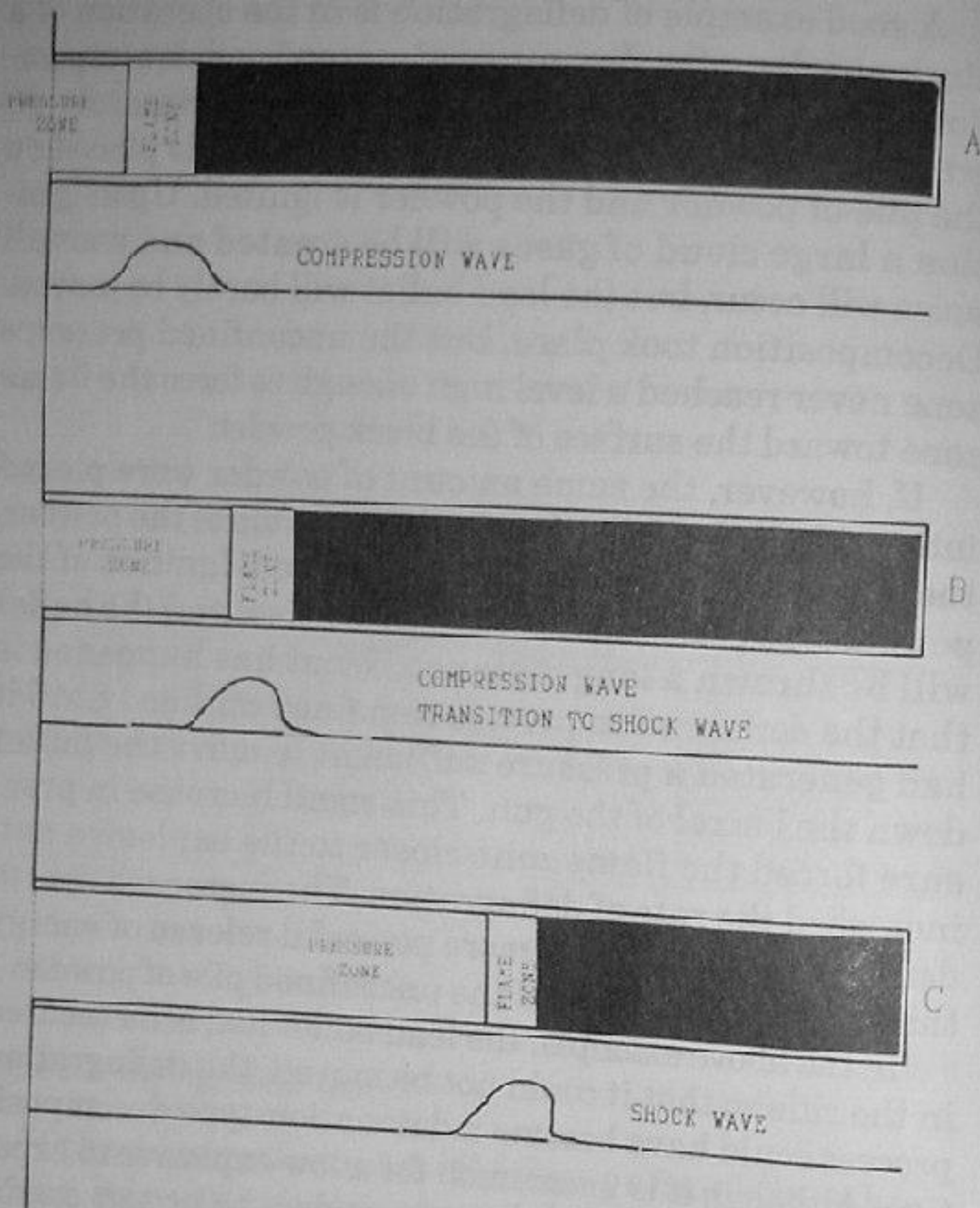


Figure 4. Deflagration to detonation transfer.

buildup occurs because the decomposition gases have a greater distance to travel to get to the open air and because they are being generated at the point of decomposition faster than they can get out of the pipe. This increased pressure behind the flame front acts as a hydraulic ram, forcing hot combustion gases forward and into the explosive material.

This advance of the hot combustive gases increases the internal pressure of the explosive material. Soon a

series of compressive waves of small intensity are produced and travel forward into the material. These waves are characterized by a front and back slope that are almost identical (Fig. 4A). The propagation of compressive waves through the explosive material results in an even more accelerated pressure and temperature buildup. Eventually the rate of buildup reaches a point where the wave's peak amplitude (its top) is accelerated to a speed faster than the leading edge of the wave (Fig. 4B). As the peak of the wave overtakes its leading edge, it no longer is a compressive wave but has become a shock wave, which is characterized by an almost instantaneous pressure rise at its front (Fig. 4C). At this point the explosive material's decomposition is through detonation, which is caused by the shock wave. The phenomenon just described is most often referred to as a *Deflagration to Detonation Transfer* (DDT).

DETONATION

The detonation of an energetic material is a shock-wave initiated, self-propagating process in which the axial compressive effect of a juxtapositioned shock wave produces a change of state in the energetic material. What a mouthful! One way to look at this is to visualize the shock wave as something that slams into the explosive so hard and so fast that the explosive material cannot move out of the way. As a result, the energy that would have moved the material instead causes it to undergo certain changes. This change of state results in an exothermic chemical decomposition (heat is given off). This decomposition then moves through the explosive at a rate proportional to the speed of the shock wave, and it keeps the shock wave moving on in front of it.

Although it is the shock wave that moves through the energetic material, another way of viewing detonation is to consider the shock wave as being stationary and the energetic material as being in motion. In this way the shock wave is like a hill and the explosive material like a

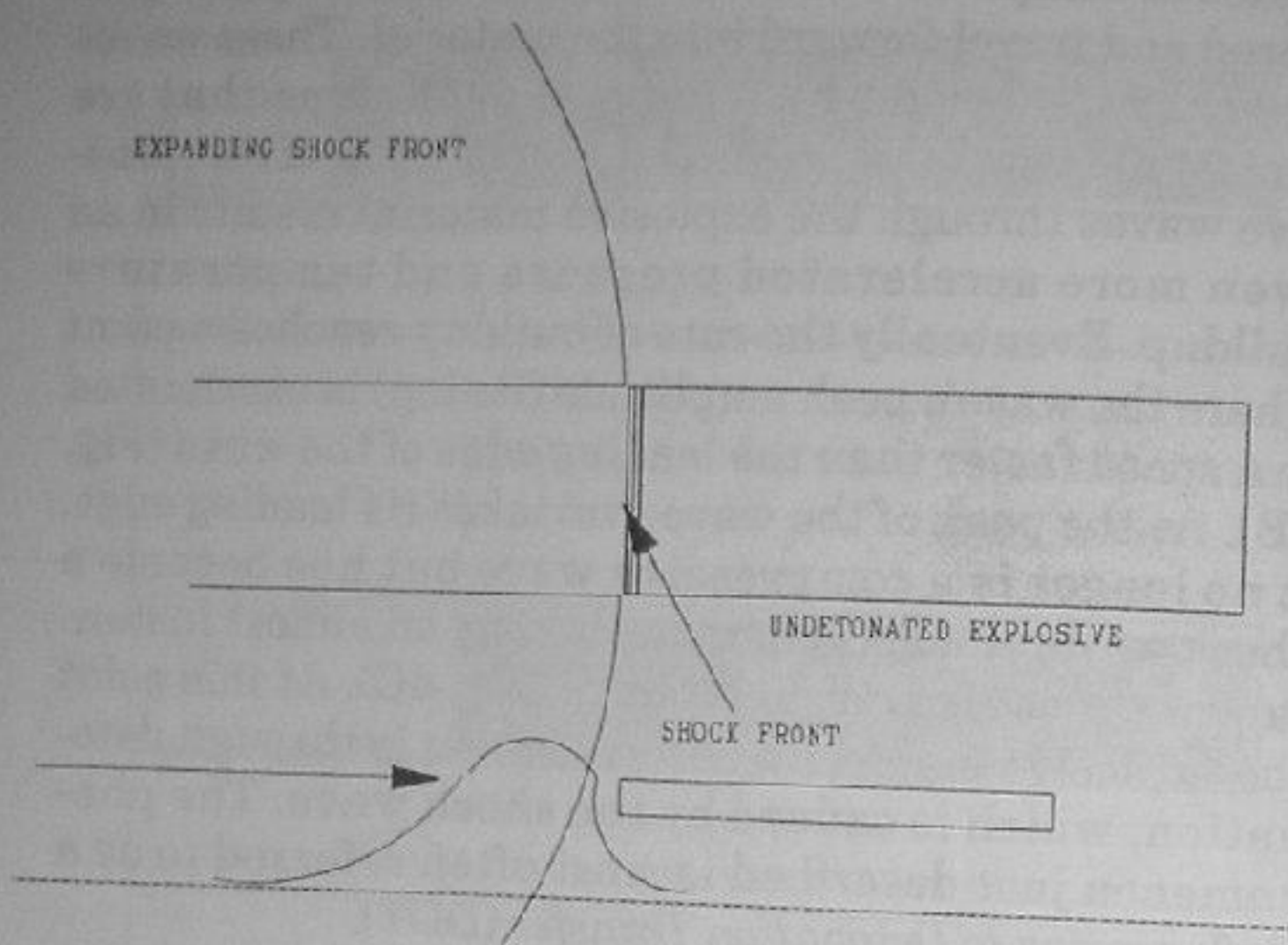


Figure 5. Shock wave.

rod moving toward the hill. If the wave has the shape of a compression wave, as in Figure 4A, it is like a smooth hill that the material can easily pass over, resulting in no detonation. However, if the shock wave is like a hill that has a steep forward side, as in Figure 4C, the material will slam into the cliff instead of passing over the hill. The shock of slamming into the cliff puts energy into the material faster than the material can deform; as a result the explosive begins to undergo chemical decomposition.

Figure 5 illustrates this concept, except that in the illustration the shock wave is moving and the energetic material is stationary. The shock of the face of the wave slamming into the explosive initiates the decomposition process, which then generates enough energy to keep the decomposition process going.

One of the interesting things about nature is that nothing is simple, and that holds true for the detonation process. The example of the hill with the steep front side works, but it does not go into enough detail to really

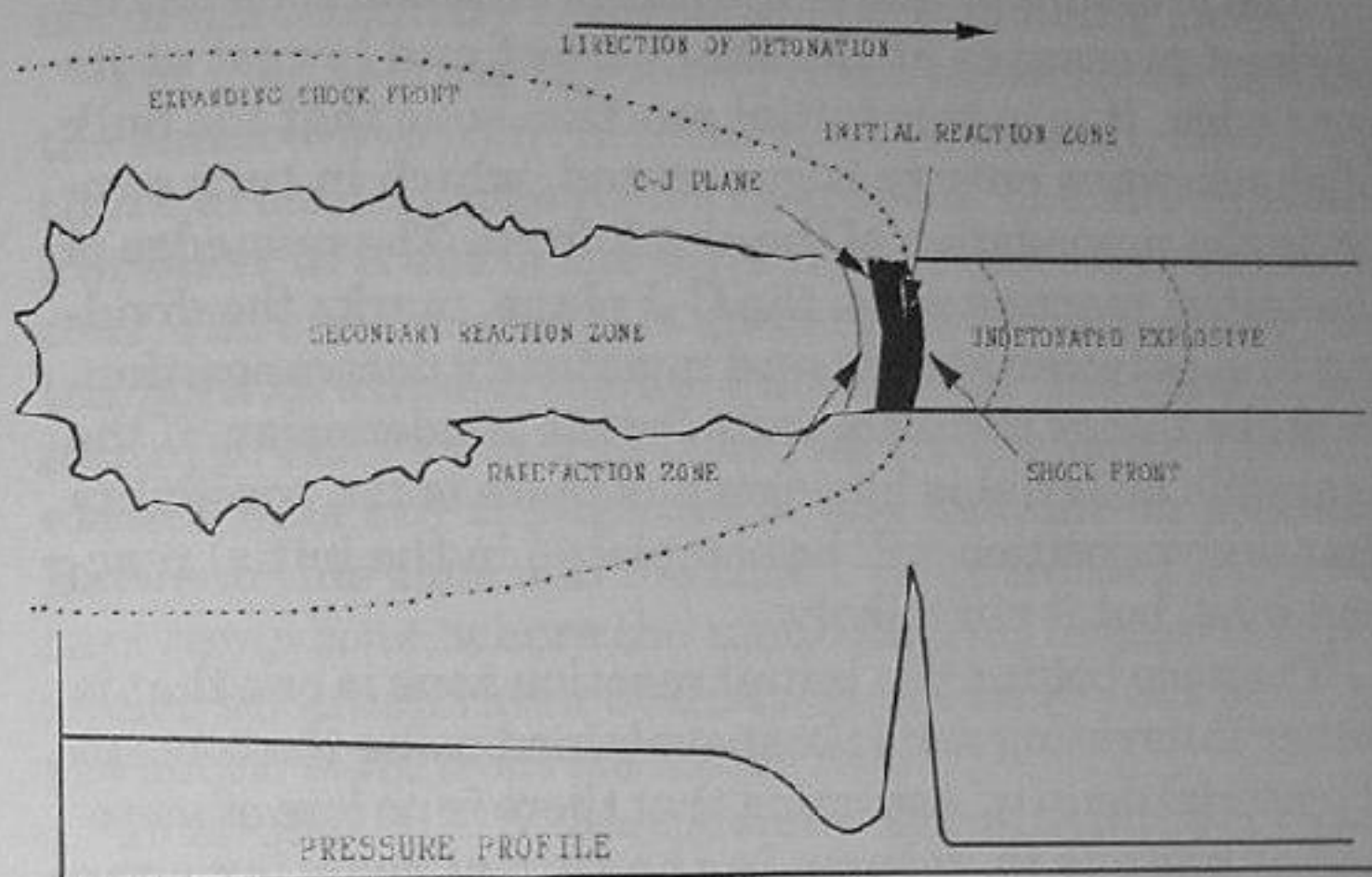


Figure 6. The detonation process.

explain what is happening in the detonation process. To better understand what is happening during decomposition, we will freeze the detonation process in time and view the explosive material as being subdivided into six basic pressure zones. There are those who would argue that a more accurate description of the six zones would be to base their classification on the material density in each zone. For our engineering needs, however, we can view the subdivision as six areas in which the material is undergoing different changes.

The most important subdivision is the area where shock-induced steady decomposition is taking place, referred to as the *initial reaction* or *detonation zone* (Fig. 6). In the illustration the direction of detonation is from left to right; therefore, to the right also means to the front. Thus the initial reaction zone has to its front the *shock-wave front* and to its rear the *C-J plane*. The shock-wave front is that very small portion of the explosive where the detonation wave exists. The C-J plane

(Chapman and Jouquet plane) is that point where the pressure of the initial reaction zone changes drastically.

The pressure profile of the initial reaction zone has its highest pressures at the shock front and lowest at its rear edge. It is in this initial reaction zone that the bulk of shock-wave energy is generated, which in turn supports the propagation of the shock front. The rear edge of the initial reaction zone, the C-J plane, marks the dividing line between steady and nonsteady decomposition. To make things more accurate for the academician, if the energetic material is homogenous there is the possibility that decomposition will be completed in the initial reaction zone, but it ain't likely.

The zone behind the initial reaction zone is one that is rather interesting and is best explained using the concept of material density. Assuming that there is no loss of material or change in volume in the initial reaction zone (remember, you cannot destroy material; you can only change it from one form to another), then the density of the material after detonation must equal the density before and during detonation. From the pressure profile in Figure 6, it is evident that the density of the material in the initial reaction zone is very high. To balance things out, the *rarefaction* zone just behind the initial reaction zone must have a very low density or a very low pressure. Toward the rear of the rarefaction zone the pressure begins to build again until the *secondary reaction zone* is reached, where undetonated material undergoes decomposition.

For many high explosives, the initial shock-induced decomposition will not be uniform, and as a result some of the explosive material will remain undecomposed after the initial reaction zone has passed its location. The material left in this secondary reaction zone may undergo a local detonation or it may experience a form of rapid deflagration. What happens in the secondary reaction zone is largely a function of the strength of the initiating shock wave and the quality and homogeneity of the energetic material. These are key issues for those who wish

to design an explosive train correctly (explained later). Regardless of the decomposition method, the major product of the secondary reaction zone is expanding gases.

For engineering purposes, these three zones behind the shock-wave front are the most important; however, there are also three zones in front of the shock zone. Farthest in front is the *unreacted explosive material zone*. Here the material is undisturbed and is at normal temperature and pressure. Just behind this zone is the *initial pressure buildup zone*, where the material first experiences any change due to the detonation process. Between this zone and the shock-wave front is the *pressure ramp zone*, where the material first begins to experience an accelerated buildup in pressure just prior to the shock-wave front slamming into it.

It is difficult to picture the detonation process. Perhaps one way would be to consider a large, long cylinder of explosive material lying on its side and you are an observer inside it. For this example time will be slowed way down so that as you stand there, you can see, hear, and feel the detonation as it passes your position. At first there is no sound; your only sensation that detonation is taking place off to your left is that pressure begins to build up around you. All of a sudden the pressure jumps sky high, there is a great deal of heat, and everything around you is breaking apart and turning into a vapor or gas. Just as you start to get your bearings, the pressure drops almost as fast as it had risen. Soon you begin to feel the pressure slowly building back up and you can see chunks of explosive material tumbling about like leaves behind a fast-moving car on a country lane. These chunks of material are all in the process of undergoing their own little detonation process or deflagration. At last the pressure begins to drop to normal and, as the dust settles, you realize you have experienced detonation.

Before we leave this discussion on deflagration and detonation, it is necessary to point out that there is no clear division between these two explosive processes. In

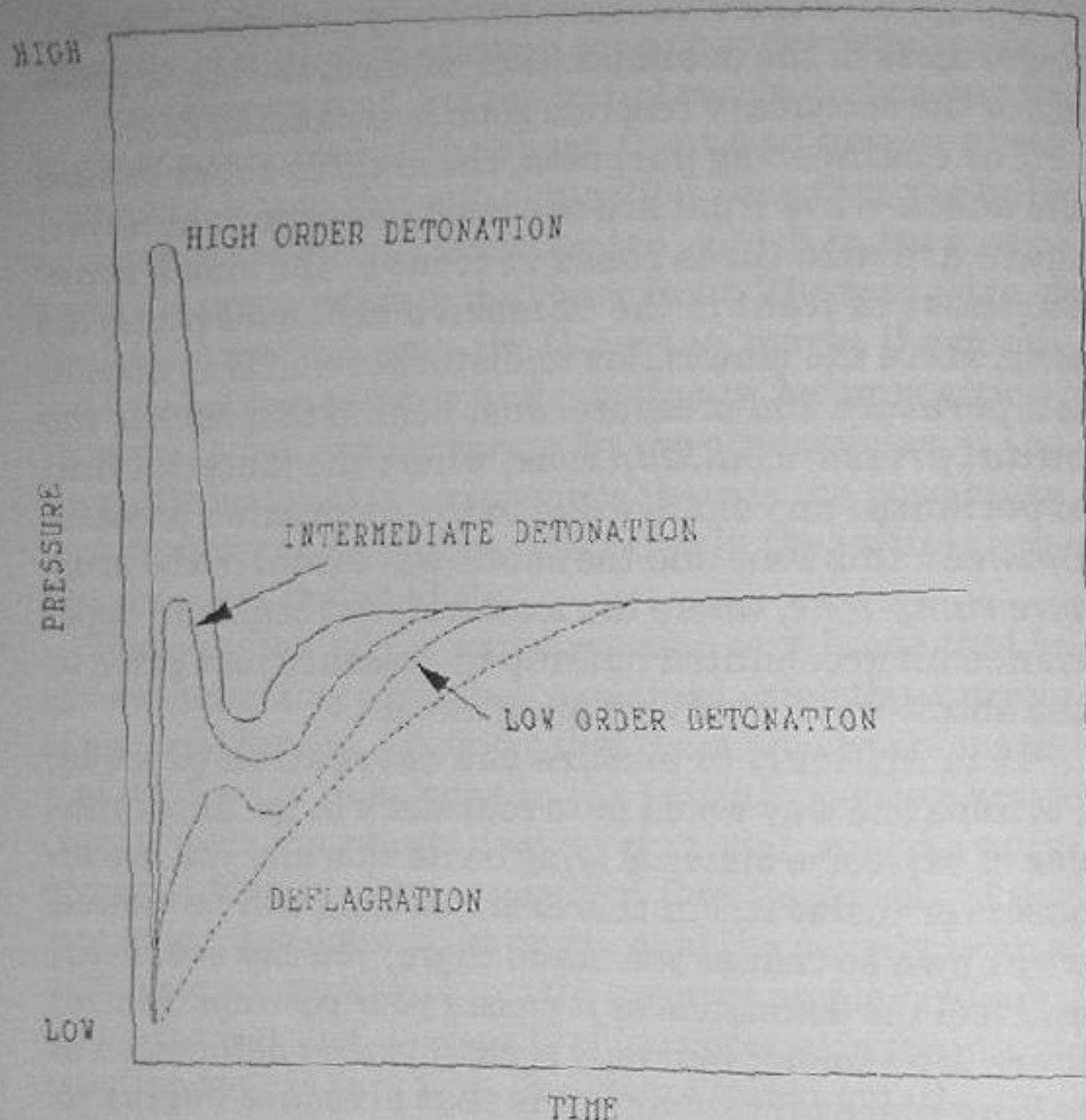
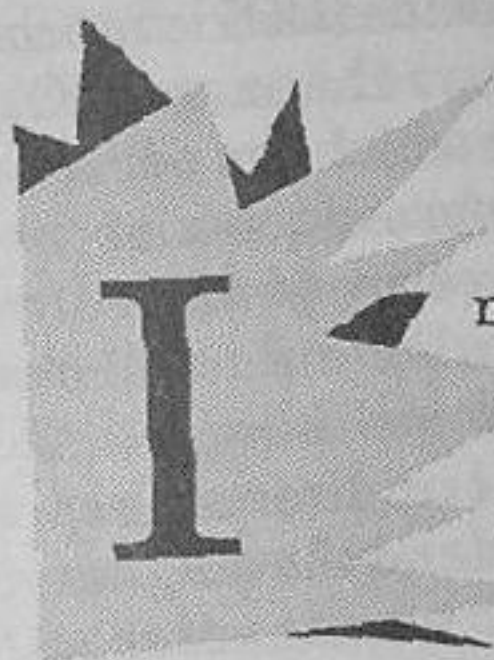


Figure 7. Explosive pressure curves.

reality, there is a large number of processes that fall between the two end conditions of deflagration and detonation. Figure 7 illustrates this through a plot of pressure versus time. These are the same pressure curves we have been looking at, only this time they are backward. If you move from left to right the detonation curve is like a cliff face and the deflagration curve is like a gentle hillside.

EXPLOSIVE MATERIAL CHEMISTRY

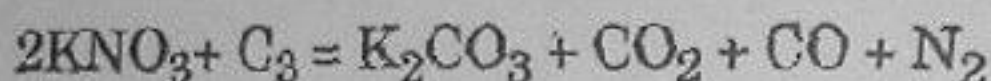


It is important to understand what is happening physically when an energetic material decomposes. To have a more complete picture of the process, however, you must understand what is happening chemically during decomposition. To unveil the secret of explosives, we must go inside the explosive and look at the individual compounds to see how they interact. Close attention must be given to compounds that are present when the decomposition starts, how they break apart into their basic elements, and then how they recombine to form new compounds. The key factor during this chemical process, from an explosives perspective, is the energy that is released.

FUEL-OXIDIZER RELATIONSHIPS

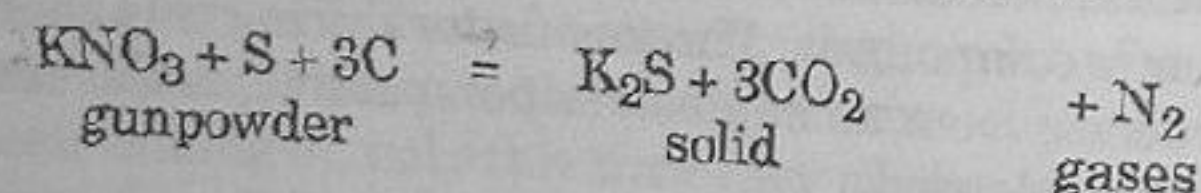
The principal ingredients of explosives are *fuels*, *oxidizers*, and special fuels that make it easier to initiate the material (often called *sensitizers*). Perhaps to an explosives chemist this would be too simplistic a statement, but for an explosives engineer it is accurate enough to explain the basic interaction of explosive ingredients.

Without going into more chemistry than is needed, the interaction of basic explosive ingredients can be illustrated with two of the chemicals found in black gunpowder. The oxidizing chemical in black powder is potassium nitrate (KNO_3) and one of the fuels is carbon (C). In the reaction process, the components of the oxidizer are separated and recombined with the carbon. The chemical equation for this process is as follows:



Because potassium nitrate supplies concentrated oxygen to the carbon, the temperature given off in forming carbon dioxide (CO_2) and carbon monoxide (CO) is much greater than ordinary combustion, where the oxygen (O) is supplied by the air. Also, the rate at which the decomposition takes place is much faster because of the concentrated oxygen, and thus usable pressures are produced.

If we were to add the third chemical found in black powder, sulphur (S), a different decomposition process would take place. The components of the oxidizer are separated and recombined with the carbon and the sulphur. This results in the formation of a small amount of solid residue called potassium sulphite (K_2S), large amounts of the gas carbon dioxide (CO_2), and smaller amounts of the gas nitrogen N_2 . Written in the language of chemists, the decomposition of gunpowder would be as follows:



In this explosive reaction the sulphur acts as a fuel in relationship to the oxidizer, but it also is a sensitizer because of its low ignition temperature (500°F). As a sensitizer the sulphur is the first element in the explosive mixture to ignite, and it does so at a lower energy input than the potassium nitrate and carbon mixture. This means that the sulfur facilitates ignition of the

gunpowder, or makes it more sensitive.

One final thought in this fuel/oxidizer relationship is to point out that oxidization is not moving oxygen atoms between elements. It is true that for most explosive chemical reactions with which the explosives engineer will work, oxygen is the key element in oxidization. In a true chemical sense, however, an oxidizer is something that gains electrons or lowers its oxidization number in a reaction, which means that it does not have to involve oxygen.

ENERGY AND BY-PRODUCTS

All this chemistry is somewhat of a pain, but understanding the basics is vital if correct explosive mixtures are to be formed. For example, in making an explosive, it is important to combine the right amount of oxidizer with the right amount of fuel. One way of looking at this is to take a piece of paper and place it inside of a glass jar with a lid. Now, if you could light the paper (by magic), it would burn until all the air in the jar was gone or until all the paper was burned. If you picked just the right-sized jar and just the right-sized piece of paper, you would have both the air and the paper run out at exactly the same time. If this happened you would have the amount of air and paper in perfect balance.

As in the air and paper example, there is also a relationship between the explosive ingredient's fuel and oxidizer. The optimum ratio is one that provides just enough oxidizer to completely oxidize all the fuel. At this zero-oxygen-balance mixture, the energetic material will decompose with a maximum energy release and a minimum amount of fumes.

If you do not have a balanced explosive mixture, there are two things that can happen. One is a loss of energy; that is to say, you do not get as much bang as you could have gotten if you had a balanced mixture. The second possibility is even worse: not only will you lose power but you will produce a lot of fumes. Many of the fumes resulting from an out-of-balance explosive

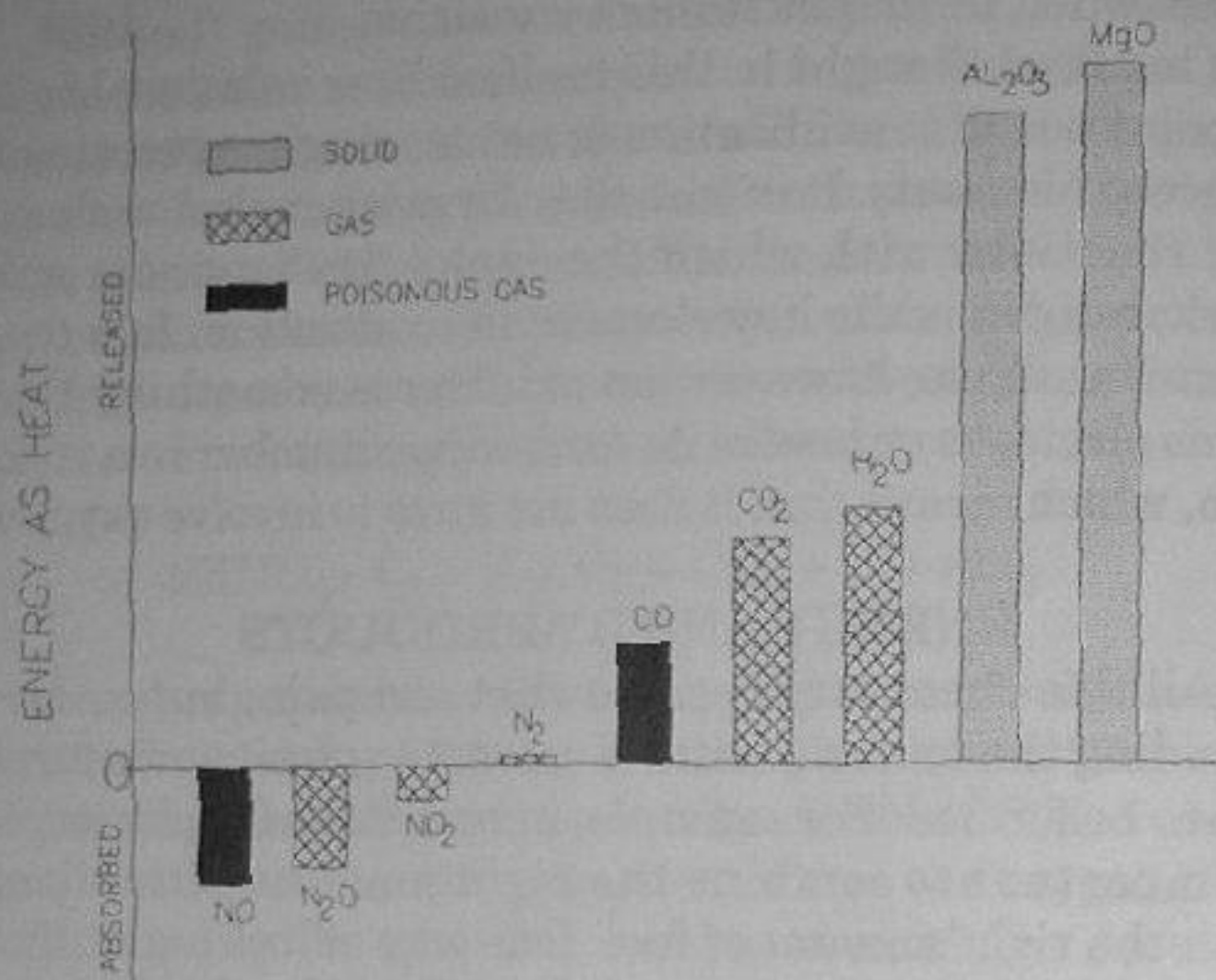


Figure 8. Relative energy released in detonation.

mixture can be hazardous to your health.

If it were possible to form an energetic material from pure elements of fuel and oxidizer, a zero-oxygen-balance mixture would be easy to obtain. This is not the case, however. For example, the most common oxidizers used in commercial explosives are ammonium nitrate, sodium nitrate, and calcium nitrate, all of which have the oxidizer element oxygen (O) combined with other elements. When an energetic material containing these oxidizers undergoes decomposition, some of the oxygen is used up in production of energy robbing compounds such as NO, N₂O, and NO₂. As was said earlier, this results in an overall reduction in energy release and often in the production of toxic fumes.

The common commercial high-explosive oxidizer, ammonium nitrate (AN), in combination with the fuel, fuel oil (CH₂), or in combination with the sensitizing fuel, aluminum (Al), can be used to demonstrate energy-release relationships. Equations 1 through 3 below show

the reduction in energy release as you deviate from the zero-oxygen-balance condition.

Equation 1 is for a zero-oxygen-balanced mixture and provides a reference energy release of about 3.8k joules (the k stands for *kilo* and represents 1,000). Equation 2 is for a fuel-rich or excess-fuel condition and shows a 0.5k joule per gram reduction in energy release. Equation 3 is for an oxidizer-rich condition (too much oxidizer), which has a 0.1k joule per gram reduction in energy release. This indicates that if one were to make an ammonium nitrate fuel oil (ANFO) explosive, it would be better to err on the side of too much oxidizer (ammonium nitrate or fertilizer) than too much fuel (fuel oil).

<u>EQUATION</u>	<u>COMPOUND</u>	<u>ENG-REL/GRAM</u>
<i>zero-oxygen-balance</i>		
(1)	94.5% oxidizer to 5.5% fuel $3\text{NH}_4\text{NO}_3 + \text{CH}_2 \rightarrow 7\text{H}_2\text{O} + \text{CO}_2 + 3\text{N}_2$	3,891 joules
<i>fuel rich</i>		
(2)	92.0% oxidizer to 8.0% fuel $2\text{NH}_4\text{NO}_3 + \text{CH}_2 \rightarrow 5\text{H}_2\text{O} + \text{CO} + 2\text{N}_2$	3,389 joules
<i>oxidizer rich</i>		
(3)	96.6% oxidizer to 3.4% fuel $5\text{NH}_4\text{NO}_3 + \text{CH}_2 \rightarrow 11\text{H}_2\text{O} + \text{CO}_2 + 4\text{N}_2 + 2\text{NO}$	2,510 joules
<i>with sensitizing fuel</i>		
(4)	81.6% AN to 18.4% Al $3\text{NH}_4\text{NO}_3 + 2\text{Al} \rightarrow 6\text{H}_2\text{O} + \text{Al}_2\text{O}_3 + 3\text{N}_2$	6,778 joules

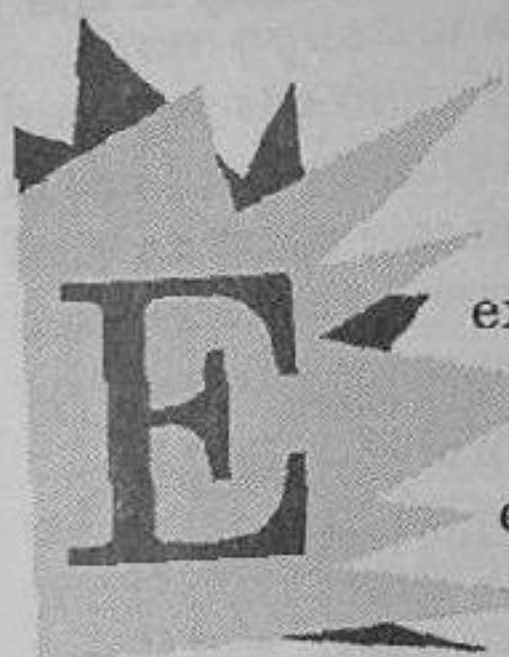
The last equation in our review of energy release for the explosive ANFO incorporates the addition of a special fuel or sensitizer, aluminum (Al). With the addition of aluminum there is a 5k joule increase in energy released. Although aluminum would not be used as the sole fuel, it and/or magnesium are added to an energetic-

material mixture to increase energy release.

In working with basic explosive materials where zero-oxygen-balance is easily controlled, the most common elements associated with energetic materials are oxygen (O), nitrogen (N), hydrogen (H), carbon (C), aluminum (Al), and magnesium (Mg). Of course these elements will be components of a compound made up of other elements. In the decomposition of an energetic material that contains the elements O, N, H, and C, the gaseous products of detonation would be H_2O , CO_2 , and N_2 . For energetic materials that contain Al and Mg as sensitizing fuels, decomposition will form stable solid compounds of their oxides.

A graphical representation of this difference in energy release, by common products of decomposition of energetic materials, is shown in Figure 8. The energy-robbing nitrogen-oxygen compound bars are drawn below the horizontal axis to represent the fact that they absorb heat (energy) rather than release it. The two large bars on the right side of the chart illustrate the energy-release increase resulting from the use of special sensitizing fuels (Al and Mg). It is not important to fully understand the chemistry of what is happening. What is important is to understand the relationship between fuels, oxidizers, and sensitizers.

PHYSICS OF EXPLOSIVES



Explosives are compounds and mixtures of compounds, each of which has its own unique properties. The explosives engineer must understand the physical attributes of various explosives if he is to match the explosive with the mission. The explosive that most efficiently blows a stump out of the ground will not efficiently cut the steel rail of a railroad line. The following sections cover the basic physical properties of explosives, as listed below:

DENSITY
DETONATION VELOCITY
DETONATION PRESSURE
STRENGTH
ENERGY
BRISANCE
SENSITIVITY
FLAMMABILITY
PERMISSIBILITY
WATER RESISTANCE
FUME CLASSIFICATION

CHARGE SHAPE CHARGE CONFINEMENT PARTICLE SIZE

Assuming that the perfect explosive mixture has been generated and has an ideal geometric configuration, there exist a theoretical detonation velocity and detonation pressure. The theoretical detonation velocity will be dependent on chemical composition, bulk density, temperature, pressure, catalytic influences, and the velocity of the initiation process. The following equations establish a working relationship between detonation pressure, detonation velocity, and the density of the explosive mixture:

Equation 1

$$P_d = (2.325 \times 10^{-7}) \times \rho_e \times V_d^2$$

where: P_d = detonation pressure in kilobars

V_d = detonation velocity in feet per second

ρ_e = density in grams per cubic centimeter

Equation 2

$$P_d = (2.5 \times 10^{-6}) \times \rho_e \times V_d^2$$

where: P_d = detonation pressure in kilobars

V_d = detonation velocity in meters per second

ρ_e = density in grams per cubic centimeter

Equation 3

$$V_d = 3810 (0.392 + \rho_e)$$

where: V_d = detonation velocity in meters per second

ρ_e = density in grams per cubic centimeter

NOTE: To convert from bars to pounds per square inch (psi), multiply bars by 14.5.

DENSITY

The density of a substance is its mass per unit volume (m/V). In other words, a substance's density is its pounds per cubic foot, kilograms per cubic meter, or grams per cubic centimeter. In almost all references dealing with explosives material, the density of explosives is given in grams per cubic centimeter, which is labeled g/cc. It is important for the serious explosives engineer to realize that in almost all situations, density refers to initial density, ρ_i . As soon as detonation occurs, the density of the explosive begins to change throughout. To make this problem workable, however, density (ρ_e) will always be the initial density of the explosive charge.

From equations 1 and 2 it would appear that as you increase the density of an explosive you will increase the detonation velocity (V_d) and the detonation pressure (P_d). In reality, as you increase the density of a single-component explosive, you will increase the detonation velocity up until the component's crystal density is reached.

An easier way of looking at this is to take a large crystal, such as quartz, and break it into many small pieces. If you could magically scatter these pieces throughout a 1' x 1' x 1' box, the density for the quartz would be very low. Now if you bring the crystal pieces closer together so they are all touching one another, the density of the quartz increases. If you were to now put the crushed quartz into a press and squeeze it, you would increase the density as you increased the pressure. However, you could not reach a density greater than the original density of the quartz crystal (its crystal density) before you broke it.

Figure 9 illustrates the change in detonation velocity (km/sec) with change in density (g/cc) for some secondary explosives. Figure 10 illustrates the change in detonation velocity with change in density for some primary explosives. (Secondary and primary explosives will be covered later in the text.)

In some engineering applications, the engineer will not be using a single-component explosive but explosives

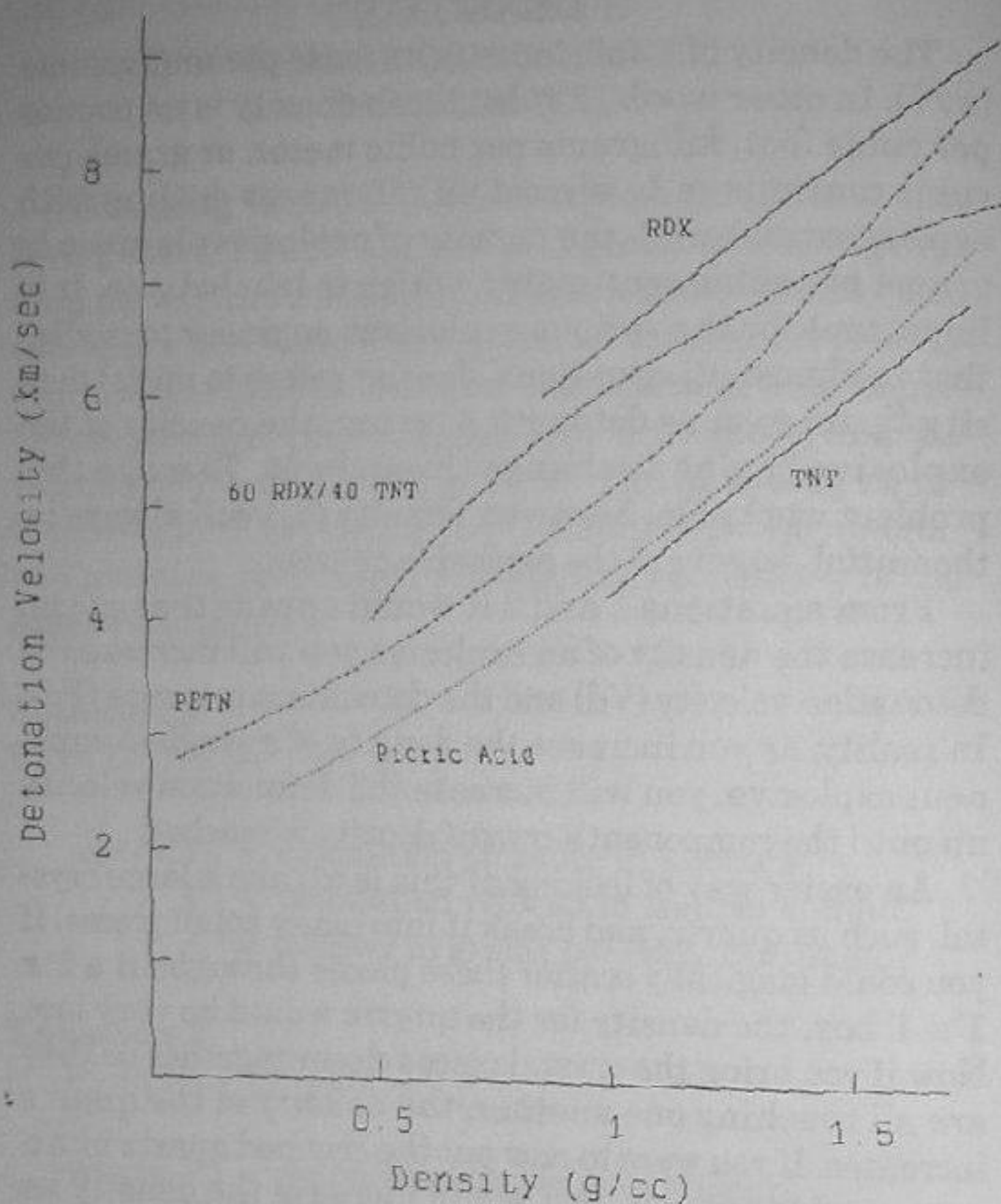


Figure 9. Detonation velocities for secondary explosives. (Adapted from Johansson and Persson, 1970.)

made up of two or more components. In most cases one component will be oxygen-rich and the other oxygen-deficient (or a fuel). When using multicomponent explosives, as you increase the density of the explosive you will increase the detonation velocity—up to a point. Further increase in density will result in a reduction in the detonation velocity (see Figure 11).

If the world were simple, equations 1, 2, and 3 would

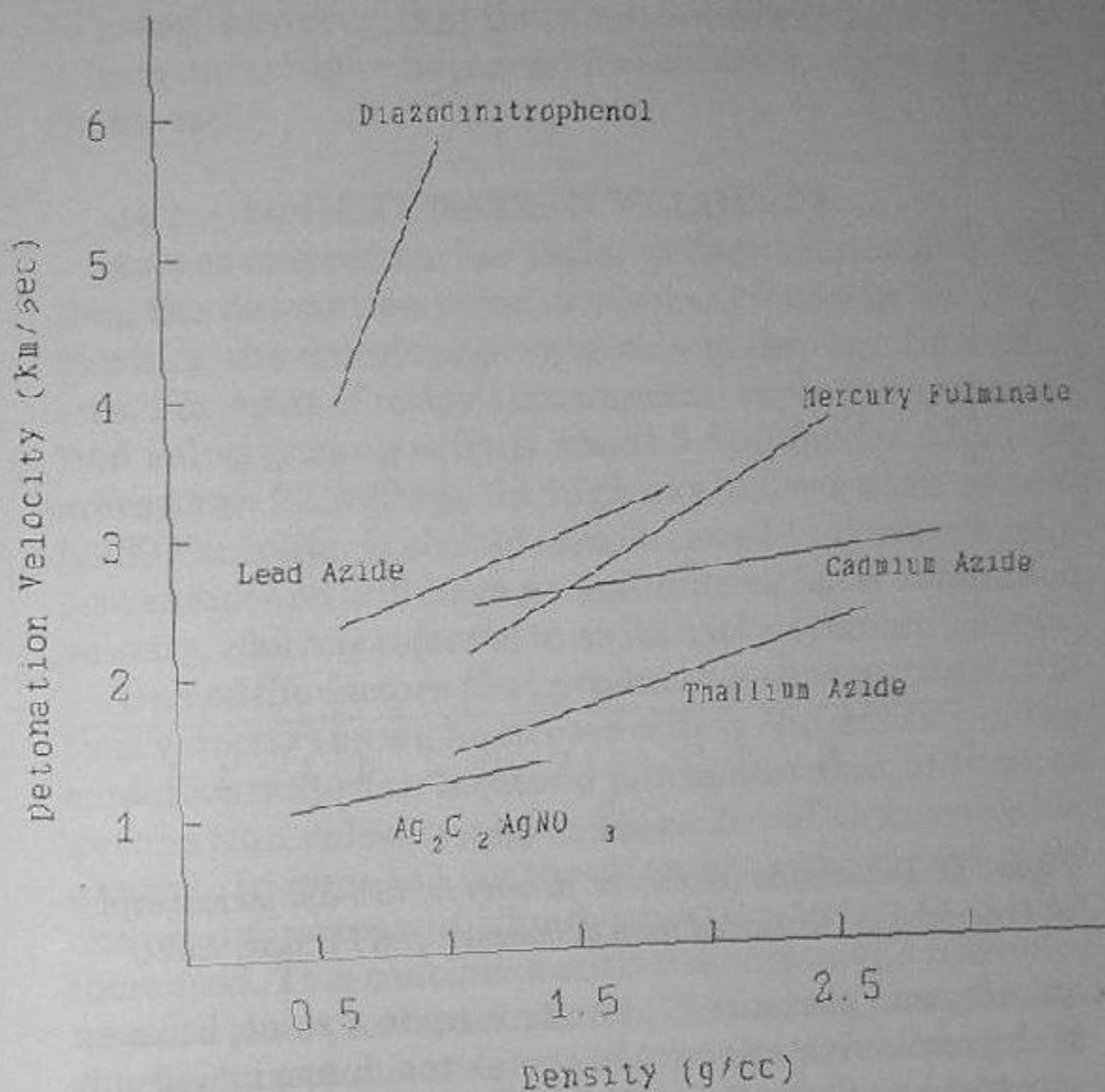


Figure 10. Detonation velocities for primary explosives. (Adapted from Johansson and Persson, 1970.)

provide all the physical data needed to design the perfect explosive charge. Unfortunately, the world isn't perfect, and the explosives engineer must take into account other parameters. For instance, the manufacturer's specified density may be changed when the explosive is compressed into a container or a hole. From the equation this would not appear to be a problem because as you increase the density you should be able to increase the detonation

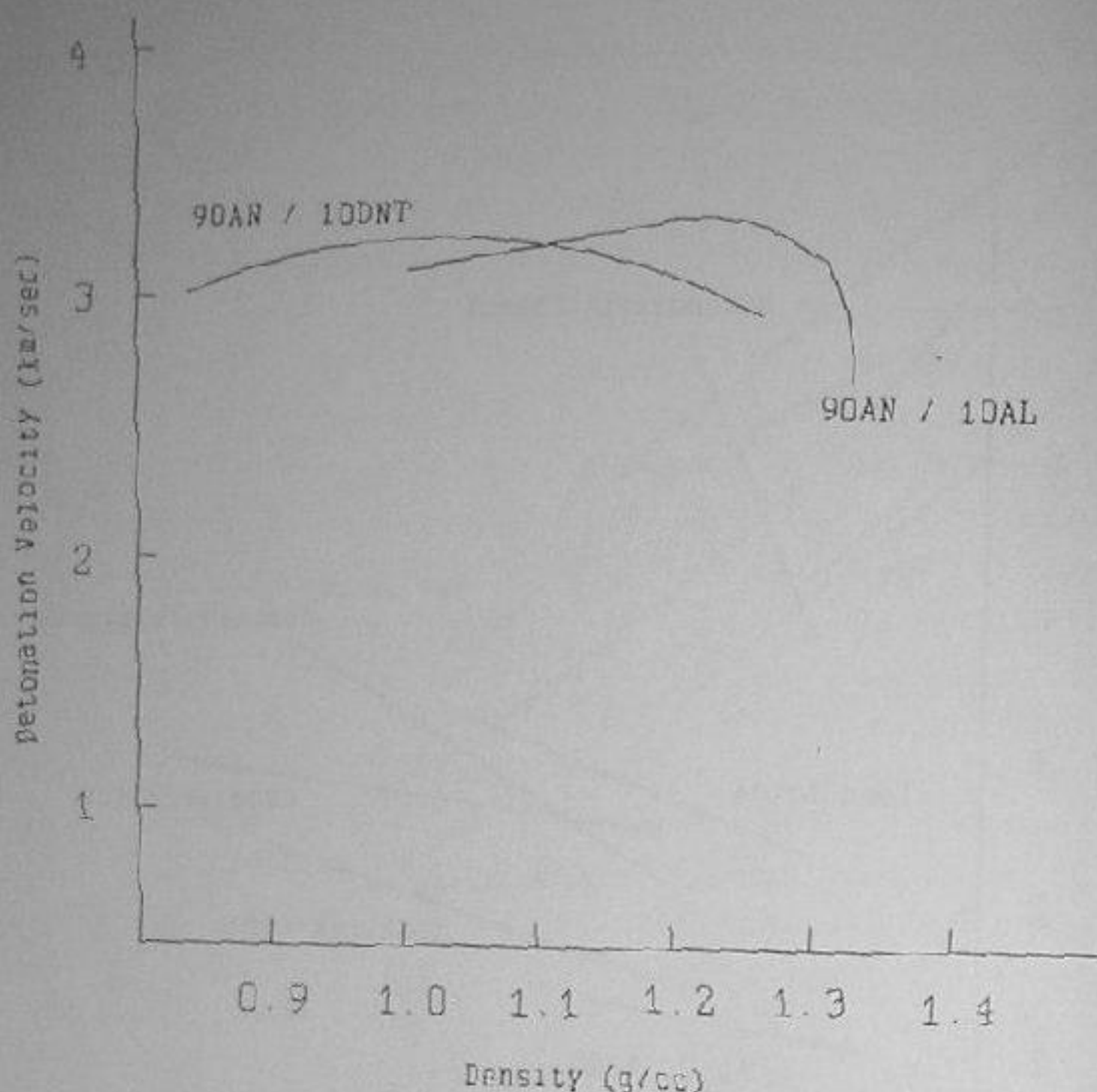


Figure 11. Detonation velocity vs. density for two-component explosive compounds. (Adapted from Johansson and Persson, 1970.)

velocity and pressure. This is true up to a point, because if the explosive mixture becomes too dense it will not support the formation of hot spots, and the mixture is said to be *dead-pressed*. In blasting this can happen dynamically when the earlier detonation of holes adjacent to a blast hole generates pressures in that hole that compress its explosive to the dead-press level.

One of the field applications of a knowledge of explosive density is to calculate the amount of explosives that will be used in blasting. The explosives engineer often must relate the explosive density (in g/cc) and diameter (in inches) of the blast hole to the amount (in pounds) of explosive per loaded foot of hole. Another field application of density is in the traditional density/stick count.

The density/stick count is a relationship between the density of the explosive and the number of 1 1/4-inch by 8-inch cartridges contained in a 50-pound case. It should be noted, however, that there are few if any 1 1/4-inch by 8-inch cartridges being manufactured in the United States today.

DETONATION VELOCITY

As was covered earlier under deflagration and detonation, the detonation velocity of an explosive is the speed at which the detonation wave moves through the explosive. For most of today's commercial explosives, detonation velocity ranges from about 5,000 fps for ANFO to more than 22,000 fps for high explosives such as cast 50/50 Pentolite. It should also be noted that every explosive compound will have a maximum or ideal detonation velocity, which is referred to as its *hydrodynamic velocity*.

One of the factors that produces a change in detonation velocity (as we have covered) is the density of the explosive material. A second parameter that influences detonation velocity is the diameter of the explosive charge. In general, as the diameter of an explosive charge is increased, the detonation velocity is also increased. This continues until the explosive's hydrodynamic velocity is reached. In the reverse case, as the charge diameter is reduced, the detonation velocity will be reduced to a point at which the charge can no longer support detonation. The point at which detonation no longer occurs is referred to as the explosive's *critical diameter* (D_c). Figure 12 illustrates the change in detonation velocity with change in charge diameter for common explosives.

DETONATION PRESSURE AND EXPLOSIVE PRESSURE

Detonation pressure is that pressure experienced at the front edge of the initial reaction zone. Equations 1 and 2 establish a relationship between detonation pres-

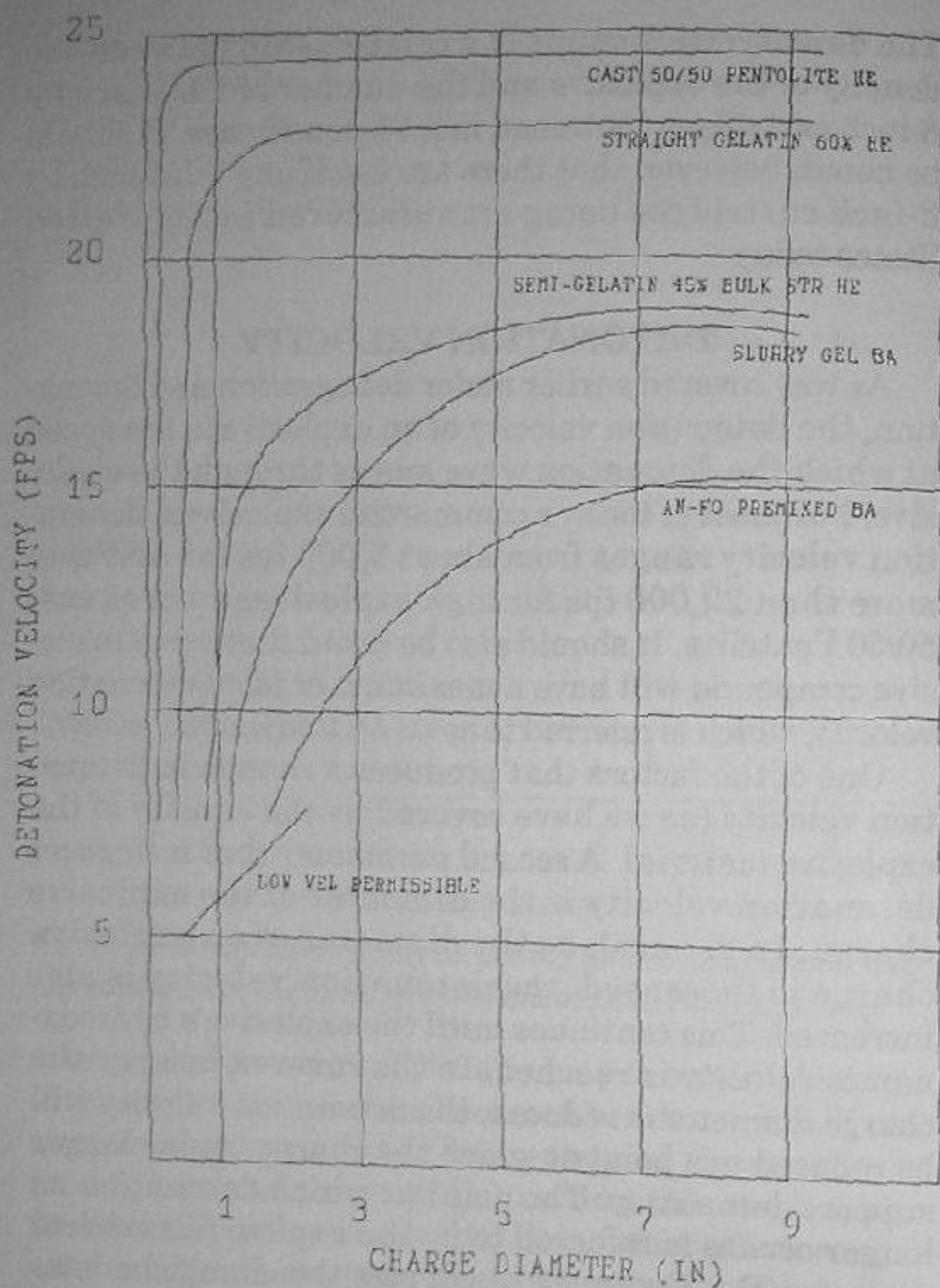


Figure 12. Detonation velocity versus charge diameter.

sure, density, and detonation velocity. There is another means of expressing detonation pressure in terms of detonation velocity and explosive particle velocity, as shown in Equation 4 below. Because it is almost impossible to determine the velocity of explosive particles in the air (it is hard to photograph due to dust and expanding gases),

V_e is determined from underwater detonations.

Equation 4

$$P_d = \rho_e \times V_d \times V_e$$

where: P_d = detonation pressure in kilobars
 V_d = detonation velocity in feet per second
 ρ_e = density in grams per cubic centimeter
 V_e = explosive particle velocity in inches per second

As was stated earlier, the detonation pressure will shatter objects rather than push them aside. A measure of this shattering potential is referred to as the explosive's *brisance*.

It is important not to confuse detonation pressure with explosion pressure. Explosion pressure is associated with the walls of the containing medium after the shock wave has passed. This is the pressure that enters cracks in the confining medium and pushes the material apart. It is also the pressure that expands hot gases outward, forcing material to be moved or thrown from the area where the explosion took place. The explosion pressure is about one-half of the maximum detonation pressure.

EXPLOSIVE STRENGTH

The strength of an explosive is defined as a measure of its energy content and the amount of work it is capable of performing. Historically, strength has had its greatest application in defining different grades of dynamite. In this role, strength rating was used as an identification marking on containers of explosives. In reality, however, there is no accurate means of measuring an explosive's strength, nor do strength classifications reveal how well an explosive will work under all conditions.

For all practical purposes, modern explosive nomenclature totally disregards the concept of strength classification.

cations; however, because it still has applications for some explosives, such as dynamites, we will review the two basic, traditional definitions. One definition is *weight strength*, or the percentage by weight of nitroglycerin in the dynamite. For more modern dynamites it is based on a comparison of the new explosive with the old, straight dynamite. The second definition is *bulk strength*, which was an attempt to take into consideration the influence of density.

The device used to develop strength classifications is the *ballistic mortar*. The ballistic mortar is a small cannon suspended on a pendulum. It is loaded with 10 grams of explosive, and the resultant swing of the pendulum, upon initiation of the explosive, is compared to the swing of the pendulum when 10 grams of straight dynamite is used. The limited flexibility of the test makes it difficult to compare an explosive whose density varies significantly from straight dynamite.

EXPLOSIVE ENERGY

Explosive energy is a measure of the energy released from the decomposition of an explosive mixture. One way to define explosive energy is to express it as calories per gram (cal/g). Different manufacturers may use different units, but they all are some form of energy per unit. This method of defining explosive energy is calculated directly from the mixture's formula.

A second method of expressing explosive energy is to equate the reaction of the earth's material (rock) to the detonation of the explosive. In simplistic terms, this method requires measuring how much material was thrown and how fast it was moving. This is not an easy task, and it is influenced by the nature of the rock being blasted. Also, this is not a widely accepted standard for measuring explosive energy, and thus most explosives engineers need concern themselves only with heat-of-formation values expressed in calories per gram.

BRISANCE

Brisance is a measure of a high explosive's ability to shatter a given material, usually sand. In the sand test, 0.40 grams of the explosive are buried in 200 grams of special sand. The explosive is detonated and the amount of sand that has been shattered is used as an indication of the brisance of the explosive. Other methods used to measure brisance are: the plate dent test, where the size of the dent produced by the explosive is used as an indication of brisance; the copper cylinder contraction test, where the reduction in length after the explosive has been detonated on top of the cylinder indicates brisance; and the explosive projectile test, where the number, size distribution, and fragment velocity of an exploded projectile are used to indicate brisance.

SENSITIVITY

In the introduction to this book, I stated that there are four basic methods of initiating or starting explosive decomposition. Because we are interested primarily in detonation, the preferred method for initiation is through a shock wave that is of sufficient velocity to cause our explosive charge to undergo detonation. Thus our interpretation of sensitivity is "the relative amount of shock energy required to cause an explosive to detonate." For basic applications, the source of the detonation shock wave is a standard blasting-cap-type initiation device.

In designing an explosive mixture, the aim is to make it sensitive to shock initiation from a blasting cap but relatively insensitive to other forms of initiation such as heat, friction, and impact. One of the most prevalent methods of identifying design sensitivity is to measure it by the size of blasting cap required to initiate the explosive. The standard in the United States is the No. 8 blasting cap. A more accurate laboratory means of determining sensitivity is to use a fixed amount of standard primary explosive such as PETN.

A close relative to explosive sensitivity is explosive sensitiveness. Explosive sensitiveness is a measure of an explosive's ability to propagate detonation across an air gap. One way of measuring this is to divide a 1 1/4-inch by 8-inch stick of dynamite in half and separate (end to end) the two halves by a fixed distance. One of the halves is then initiated and a determination is made if the second half was initiated over the air gap. This is continued at varying distances until the maximum distance (in inches) over which the initiated half stick will cause the second half to detonate is determined. This maximum distance is a measure of the explosive's sensitiveness.

FLAMMABILITY

Flammability is much like sensitivity; it is a determination of an explosive's sensitivity to being ignited by heat. This is a relative measure of the amount of heat it takes to cause the explosive to burn but not detonate. There is a level of heat that, if reached, will cause the explosive to detonate; it is referred to as the *critical temperature* of the explosive.

PERMISSIBILITY

Permissibility is a go/no-go measure of an explosive's ability to be used safely in underground gaseous mines. That is to say, an explosive is either a permissible or it is not a permissible. Permissible explosives are designed to minimize the temperature, volume, and duration of their flames. By reducing the explosive's flame parameters, it reduces the likelihood of the flame igniting gas or dusts in the mine. Permissibles find their greatest application in coal mines, where methane gas and coal dust are a real hazard.

WATER RESISTANCE

The water resistance of an explosive is a measure of how many hours it can remain submerged in still water and still be detonated. Basically, this is a measure of how

well an explosive keeps water from penetrating its ingredients and decaying their sensitivity. In this test, both the explosive package or wrapper and the composition of the explosive itself are employed in keeping the water from penetrating the explosive. This measurement is in relative terms of good, fair, poor, etc.

It is important to realize that the test to determine an explosive's water resistance is conducted in still, relatively pure water and at low pressures. In the field, the water that fills blast holes may be acidic and, at the bottom of the hole, the hydrostatic pressure may be very high (depending on the depth of the water).

FUME CLASSIFICATION

In the industrial application of explosives, the gaseous by-products of an explosion are referred to as *smoke* and *fumes*. Smoke is made up primarily of steam and solid products of combustion. Fumes, on the other hand, are the gases of combustion such as carbon monoxide. Those of interest in generating fume classification are toxic (see Fig. 8).

There are two classification schemes for industrial explosives—one for permissibles and the other for nonpermissibles. Permissibles are classified as Class A if they produce 0-53 liters of noxious gases per 1 1/2 pounds of explosive. Permissibles are classified as Class B if they produce 54-106 liters of noxious gases per 1 1/2 pounds of explosive. Nonpermissibles are classified as Class 1 if they produce 0.00-0.16 cubic feet of noxious gases per cartridge of explosive. Nonpermissibles are classified as Class 2 if they produce 0.17-0.33 cubic feet of noxious gases per cartridge of explosive. Nonpermissibles are classified as Class 3 if they produce 0.34-0.67 cubic feet of noxious gases per cartridge of explosive.

CHARGE SHAPE

So far in our treatment of explosives, all explosive mixtures were taken to be cylindrical. In this geometric

configuration, there is a definite relationship between charge diameter and length. This relationship is controlled by the reaction products' lateral expansion and therefore their need for room to expand appropriately. It has been shown experimentally that most commercial explosives require a charge length that is four to five times the charge diameter to support optimum detonation. This is another of the key parameters in designing an explosive train.

In 1883, C.E. Munroe discovered a second area where the charge shape influences explosive performance. By indenting one end of a column of explosives and igniting the opposite end, Munroe was able to obtain a high-velocity plasma. This plasma proceeded from the indented end of the charge at speeds greater than the detonation velocity of the explosive. This phenomenon is referred to as the *Munroe Effect*, or a *shaped charge*. If a metallic material is used to line the surface of the indentation, the plasma generated will be of higher density and thus possess far greater energies. Good explosive parameters for the explosive engineer to know and understand.

CHARGE CONFINEMENT

Another factor that can influence explosive performance is the degree of confinement of the explosive charge. In the equations for detonation pressure and velocity, it is assumed that the charge is totally confined. This means that in the equation no allowance is made for loss of heat or the release of explosive products. In just the reverse of the confinement assumption, the equation assumes that there are no lateral confinements to the passage of the detonation wave. In essence, these confinement factors tend to cause the real world values of detonation pressure and velocity to be less than those produced by the equations.

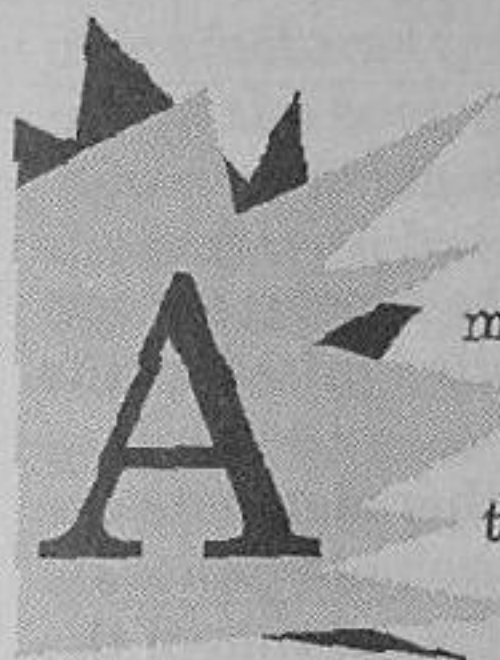
PARTICLE SIZE

A last parameter that influences explosive perfor-

mance is the particle size of the explosive. If you reduce the particle size but maintain the same density, the detonation velocity will increase. This is because as you decrease the particle size you introduce more particles to the mixture and in so doing increase the surface area available for decomposition.

One area where this phenomenon is quite prevalent is in the use of ANFO. The shipping, mixing, and loading of ANFO can cause reduction in overall particle size. It is also interesting to note the influence of reduced particle size on the sensitivity of ANFO, which is a key parameter for the explosives engineer.

EXPLOSIVE MATERIALS



number of explosive characteristics have been introduced to aid in distinguishing between differing explosive materials. In this chapter, explosive materials will be addressed under four groupings, based primarily on their utilization. The first contains the high explosives, which are commonly referred to as *primary explosives*.

The second group is made up of those high explosives that are called *secondary explosives*. The third group are those high explosives used in industry. The fourth covers a few of the more common military explosives.

PRIMARY EXPLOSIVES

Primary explosives are energetic materials that are sensitive to initiation by heat, spark, impact, or friction. Their primary application is as the first element in an *explosive train*, which is a sequence of explosive materials varying in sensitivity. The first element, called the *primer*, is the most sensitive and is used to initiate the second element, often called the *booster*. The booster adds energy to the detonation wave generated by the primer and is used to initiate the main charge of the

PRIMARY EXPLOSIVE PARAMETERS							
PRIMARY EXPLOSIVE	HEAT OF DET (KJ/GM)	SENSITV (G/CM)	VELOCITY (IMPACT) (DIST & WEIGHT)	5 SEC EXPLOSIVE TEMPERATURE (600 C)	STATIC DISCHARGE (100/100)	WISAMU (X AT 100)	DET VELOCITY (1000)
Lead Azide	0.367	4.66	0.75	315-345	0.01	40	5.400
Mercury Tribromate	0.427	4.17	0.2	210	0.025-0.078	27.3 - 59	5.400
DDNP	0.620	1.63		195	0.26	94 - 105	7.100
Lead Styphnate	0.460	2.90	0.25-0.5	282	0.01	22 - 53	5.200
Tetrazene	0.658	1.05	0.02	160	0.01	40 - 70	

Figure 13. Primary explosives.

explosive train. The main charge and the booster are secondary explosives and are not as easily ignited as the primer, which is a primary explosive.

There are times when one or two other elements are added to the explosive train. One such element is a *delay*, which is designed to prevent detonation of the booster for a specific period of time after the primer has been fired. The other is a *relay*, which may be needed to strengthen the shock wave of the delay so that the booster or secondary explosive can be initiated.

Although primary explosives are by far the most dangerous energetic materials because they are so easy to initiate, they do have applications in other areas. For example, most matches make use of friction-sensitive compounds in the match head. Also, many toy caps, toy torpedoes, and similar devices used for generating noise make use of primary explosives. To some extent, one might say that these applications of primary explosives existed before they were used in the explosives industry. It should be noted, however, that in all of these nonindustrial applications, the primary explosive is used in very small amounts.

There is a vast array of energetic materials that falls under the sensitivity classification of primary explosives. When the complexity and extent of primer explosives are multiplied by all the different ways manufacturers use initiation devices, the subject becomes extremely voluminous. Rather than cover all these materials and their applications, we will concentrate on only those most commonly used in the construction of such initiation systems as blasting caps and primers. Figure 13 contains some of the physical attributes of common primary explosives.

For most explosives engineers, the information in Figure 13 is of little use outside of academic interests. The average explosives engineer will use commercially manufactured ignition systems specifically designed to ignite the booster or secondary explosive being used. However, for those who may find the need for designing the entire explosive train themselves, the information in Figure 13 is of great value.

For example, in designing the primer explosive compound, it is important to know which secondary or booster explosives can be initiated by which primary explosives. Figure 14 illustrates the relative efficiency of various primary explosives in initiating some of the more frequently used secondary explosives. From Figure 14 it is evident that if the secondary explosive is PETN, then mercury fulminate would be the optimum primary explosive. The least desirable primary explosive, if PETN is the secondary, would be tetracene.

Of course it is also important to know which triggering mechanism or initiation method is optimum for the primary explosive. That is to say, it is important to know how you plan to initiate the primary explosive—by flame, shock, spark, or friction. In the previous example, mercury fulminate is used as the primary explosive to initiate PETN. Based on Figure 15, mercury fulminate is most sensitive to impact, which would be the ideal triggering mechanism.

There are other explosive mixtures used at the head

PRIMARY EXPLOSIVES' RELATIVE
ABILITY TO FUNCTION AS AN INITIATOR

EXCELLENT	Tetryl	Tetryl	Tetryl TNT		
GOOD	TNT	TNT			
FAIR		PETN			
POOR	PETN		Ammonium Picrate	PETN	
FAIL	Ammonium Picrate	Ammonium Picrate			PETN TNT
	LEAD AZIDE (D.L.A. - U.S. TYPE I)	MERCURY FULMATE	DIAZODINITROPHENOL (DDNP)	LEAD STYBNATE	TETRACENE

Figure 14. Primary explosives' utility.

of a train of explosives. These mixtures may or may not include primary explosive ingredients. Because they are at the head of an explosives train, however, they are included in this text. The two most common initiation systems that fall into this category are *friction primers* and *percussion primers*.

Friction primers

Friction primers are any device composed of an energetic material which is capable of producing a flame from frictional energy. A frictional primer material common to all households is the kitchen match. When used in field-expedient applications, the kitchen match does have explosives application as a primer. However, the friction-

al primers of interest here are those used to light fuzes, pyrotechnics, or propellants.

The most common friction primers are those that translate push or pull energy into frictional energy. This is accomplished by movement of a rod or wire through a friction-sensitive compound. To accent the production of friction, the rod/wire may be roughened or granular material may be added to the explosive compound. Listed below are the percentage of composition and parts composition for three typical friction primer compounds.

Two-Component Mixture:

Potassium Chlorate = 66.6 percent (about 2 parts)

Antimony Sulfide = 33.4 percent (about 1 part)

Four-Component Mixture:

Potassium Chlorate = 56.2 percent (about 6 parts)

Antimony Sulfide = 24.6 percent (about 3 parts)

Sulfur = 9.0 percent (about 1 part)

Ground Glass = 10.2 percent (about 1 part)

Five-Component Mixture:

Potassium Chlorate = 44.6 percent (about 12 parts)

Antimony Sulfide = 44.6 percent (about 12 parts)

Sulfur = 3.6 percent (about 1 part)

Ground Glass = 3.6 percent (about 1 part)

Metal Powder = 3.6 percent (about 1 part)

Percussion Primers

Percussion primers contain an energetic compound that is impact sensitive and, when struck by a firing pin or similar device, produce a very hot flame. Most percussion primers have the explosive compound contained in a small metallic cup. The primer compound is wet mixed and pressed into the cup. If needed, an anvil foil is inserted into the cup and then the primer cup is set aside to dry. This type of primer is most often referred to as a *Boxer primer*. If the primer does not contain an anvil it is called a *Berdan primer*.

PRIMARY EXPLOSIVE'S RELATIVE SENSITIVITY TO BEING INITIATED

HIGH SENSITIVITY		Impact	Impact	Spark	Impact Heat
		Friction	Heat Friction	Friction	
	Friction				
	Spark	Heat		Impact	Spark
	Impact	Spark		Heat	
	Heat		Spark		
LOW SENSITIVITY					
	LEAD ACIDE (DLA - U S TYPE I)	MERCURY FULMINATE	DIAZODINITROPHENOL (DNBP)	LEAD STYPHATE	TETRACENE

Figure 15. Primary explosives' sensitivity.

For the Boxer primer, a stiff, convex, two- or three-leaf circular metal foil is pressed into the cup after the primer material. This metal foil is bent so that the center is in contact with the primer material and the outer edges of the leafs are secured to the rim of the cup. In this way the center of the foil acts as an anvil when the outer surface of the cup is struck by a firing pin.

To utilize the percussion primer, the primer cup is pressed into a well designed to hold it. When Boxer primers are used, the primer well has a hole drilled in its bottom center. This hole provides an avenue for the hot primer flame to pass through to the booster charge or to

the explosive powder of a small arms round. If the primer does not contain its own anvil (Berdan primer), the center of the base of the primer well is raised to function as the anvil. In this case the flame ports in the primer well are located off-center. Figure 16 illustrates the basic Boxer percussion primer design.

Four typical percussion primer explosive mixtures are listed below:

PRIMER TYPES	PRIMER INGREDIENT			
	A	B	C	D
Mercury Fulminate	48.8%	11.0%	...	...
Potassium Chlorate	25.0%	52.5%	53%	50%
Antimony Sulfide	26.2%	36.5%	17%	20%
Lead Thiocyanate			25%	...
Lead Peroxide			...	25%
TNT			5%	5%

SECONDARY EXPLOSIVES

If a delay and/or relay is not used in the explosive train, the explosive most often following the primer is a booster, which is a secondary explosive. The booster is less sensitive to initiation than the primer but is more sensitive than the main or, as it is sometimes called, *bursting charge*. The booster's role is to add detonation energy to that of the primer, thus bringing it up to a level sufficient to initiate the main charge.

Both the booster and the main charge are secondary explosives. As a secondary explosive they differ from primary explosives in three basic ways. The first is the secondary explosive's insensitivity relative to the primary explosive. In other words, it takes more initiation energy

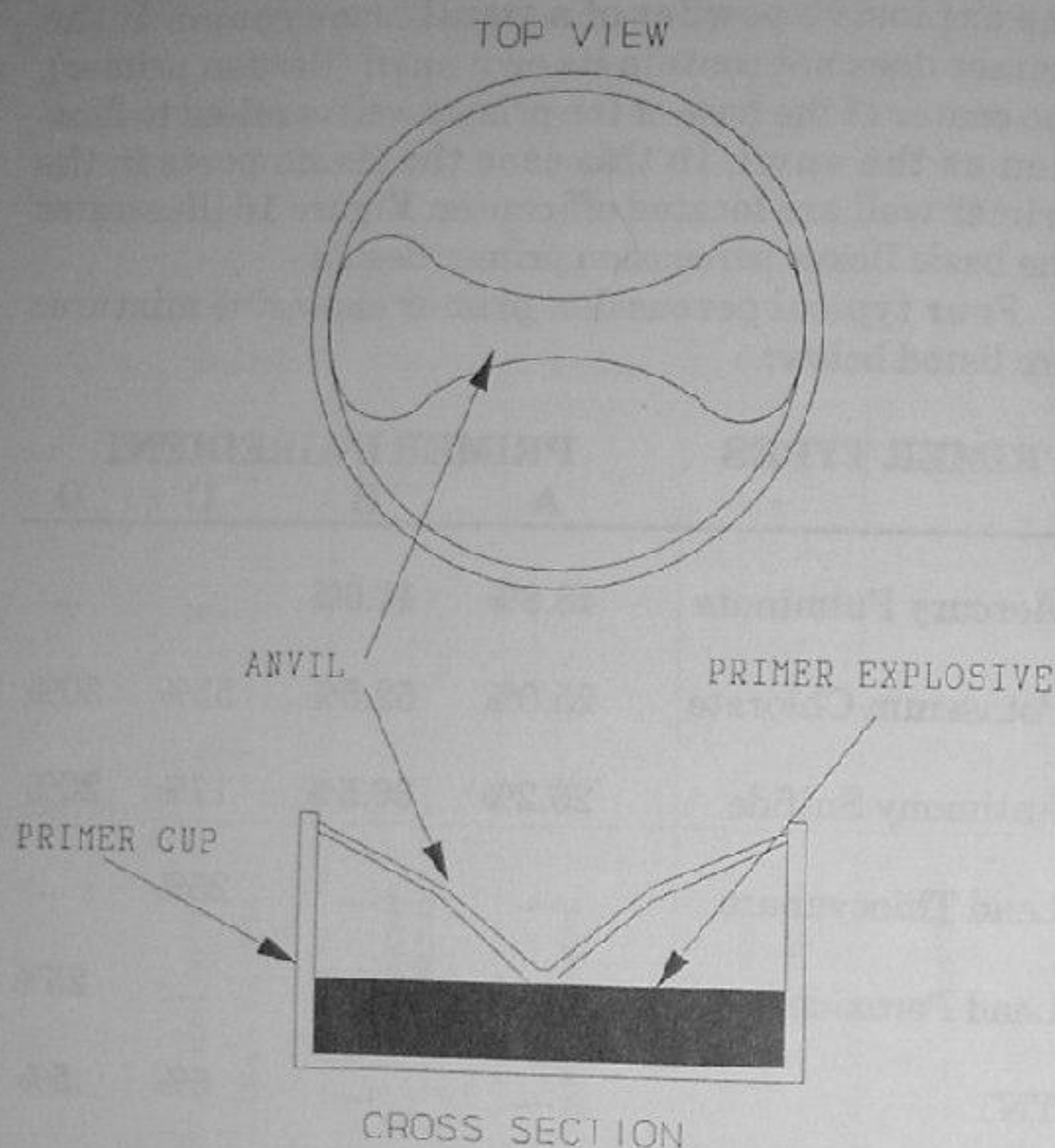


Figure 16. Percussion primer.

to get secondary explosives to detonate than it does primary explosives. A second difference is that secondary explosives do not normally undergo a DDT (remember: a deflagration to detonation transfer). Secondary explosives' relative insensitivity to ignition by electrostatic spark is the third difference between secondary and primary explosives.

There is an extremely large range of energetic materials that fall into the category of secondary explosives, too many to list all of them. In general, however, secondary explosives can be divided into seven basic groups. Each group and examples of representative explosives are listed below.

1. *Aliphatic Nitrate Esters:*
nitroglycerin
PETN
2. *Nitramines:*
HMX
RDX
tetryl
3. *Nitroaromatics:*
ammonium picrate
TNT
4. *Ammonium Nitrate*
5. *Binary:*
amatol
C4
6. *Ternary*
7. *Quaternary*

COMMERCIAL HIGH EXPLOSIVES

There are numerous domestic and foreign manufacturers of explosives. Often their products are identical in performance, even though they may have differing names. To try and reduce the complexity of describing commercial explosives, individual manufacturer's names will not be used in the following section. Instead, the explosives will be grouped into classes based on their overall general properties.

Dynamite

Dynamite originated when Alfred Nobel mixed nitroglycerin with clay, sawdust, and a mixture of the two. Since that time the composition and nature of dynamite have changed dramatically. Many ingredients have been incorporated into the composition, producing dynamites that today are safer and better designed to cover a multitude of missions.

If you do not include all of the various individual manufacturer modifications, dynamite can be subdivided into three basic classes. The first class is referred to as

granular dynamite due to the granular texture of the material. This class does not contain nitrocellulose. The second class of dynamite is called *gelatin dynamite*. This class of explosive does not have a granular texture but it does contain nitrocellulose. The third class is a granular dynamite (ammonia dynamite) that contains a small amount of nitrocellulose, called *semigelatin dynamite*. Figure 17 shows the relationship between the ingredients of dynamite and the resulting dynamite type, and Figure 18 lists typical commercial dynamite parameters.

Water Gels

Water gels are high explosives that do not contain nitroglycerin. First manufactured by Du Pont in 1958 under the trade name *Tovex*, water gels offered a considerable increase in safety over dynamites. As water gels became more popular they took on the industrial name of *slurry explosives*.

In general, slurry explosives are made up of four basic ingredient types. The oxidizer for slurry explosives is most often AN or AN + NO₃, and the fuel is TNT, aluminum powder, nitric acid, or nitromethane. The gelatin substance in water gels is guar gum, a sugar derivative. These ingredients are then held together as a mixture by the cross-linking agent potassium dichromate.

For the most part, water gels are of a lower density than most dynamites and have a lower detonation velocity. They are much safer, however, and when compared to most blasting agents they have higher density, higher detonation velocity, much higher detonation pressure, and better water resistance.

Blasting Agents

Blasting agents are explosive compounds that cannot be initiated by blasting caps and are made up of two basic nonexplosive ingredients. That is to say, the two basic ingredients of a blasting agent are by themselves not explosives; when you mix them together, however,

THE DYNAMITE FAMILY TREE

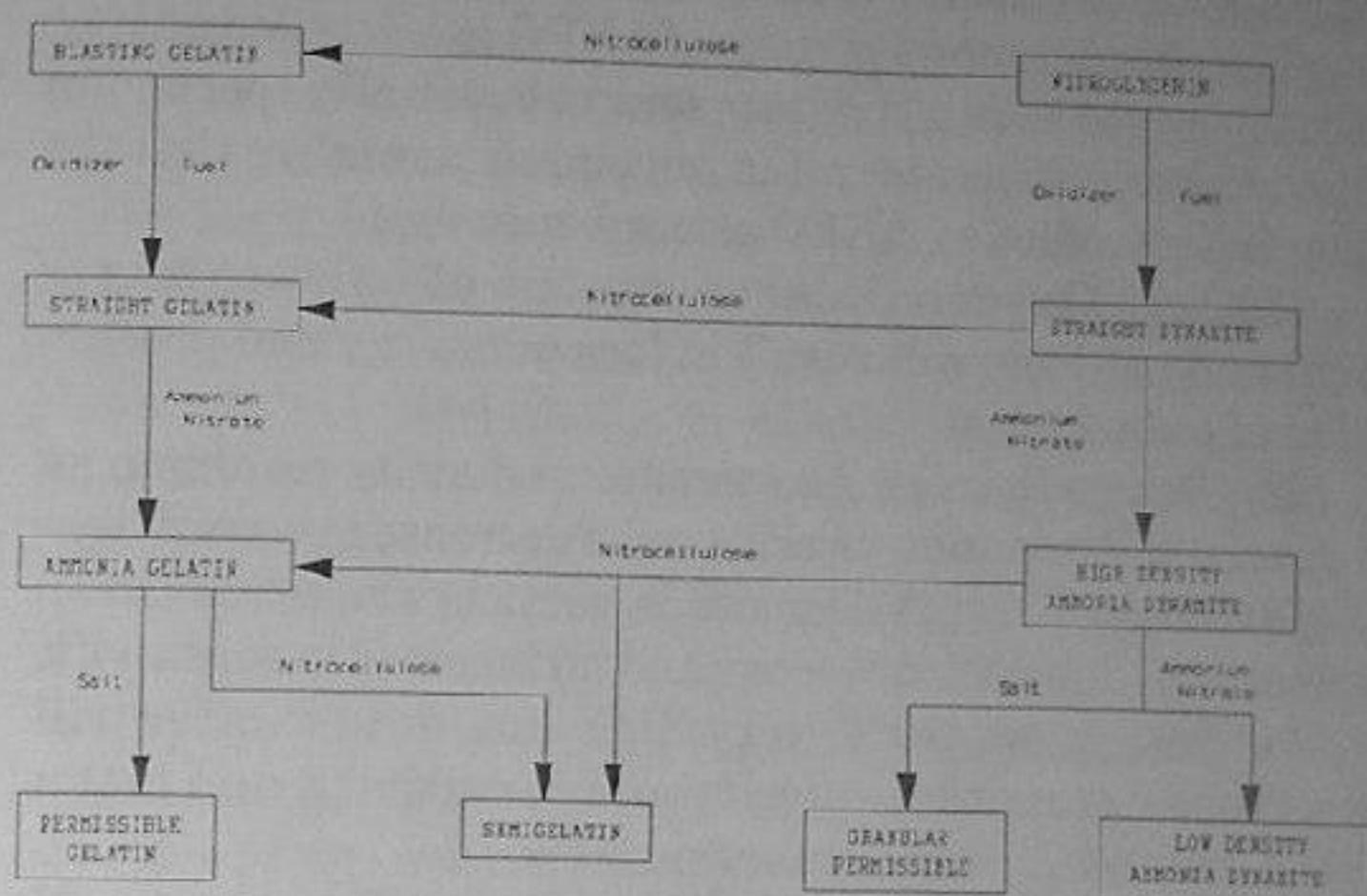


Figure 17. Dynamites and their composition.

EXPLOSIVE	MANUFACT	DENSITY (G/CC)	DET. VELOCITY (FT/SEC)	WATER RESISTANCE	TEMP CLASS
STRAIGHT DYNAMITE		1.37	16,100	Good	Very Poor
		1.40	20,000	Excellent	N/A
STRAIGHT GELATIN		1.32	19,700	Excellent	Poor
		1.50	20,000	Excellent	N/A
HIGH DENSITY AMMONIA DYNAMITE		1.29	13,200	Very Good	Very Good
		1.29	12,000	Fair	1
AMMONIA GELATIN		1.26	19,500	Excellent	Very Good
		1.36	18,000	Excellent	1
SEMIGELATIN		1.29	13,100	Very Good	Very Good
		1.28	15,000	Good	1
GRANULAR PERMISSIBLE		1.15	9,000	Very Good	A
		0.94	10,500	Poor	P
PERMISSIBLE GELATIN		1.37	16,500	Excellent	A
		1.33	17,900	Excellent	P

Figure 18. Commercial explosives' characteristics.

they form an explosive mixture. The most common blasting agent is ANFO, which was covered in Chapter 3.

The chemistry and physics of ANFO are detailed enough that it would take a separate text to cover all aspects. For the explosives engineer it is important to realize that the key factors affecting ANFO performance are:

(1) Zero Oxygen Balance. An out-of-balance mix of fuel and oxidizer will result in loss of energy and production of toxic fumes.

(2) Charge Density. An increase in density results in an increase in detonation velocity and a decrease in sensitivity.

(3) Particle Size. A decrease in particle size results in an increase in detonation velocity and an increase in sensitivity.

(4) Percent water. A very little amount of water will decrease detonation velocity and sensitivity, and just a little water will stop detonation.

(5) Confinement. An increase in confinement will result in an increase in detonation velocity and an increase in sensitivity.

(6) Charge Diameter. An increase in charge diameter of up to 9 to 10 inches will result in an increase in detonation velocity. An increase in charge diameter will result in a decrease in sensitivity up to about 5 inches.

(7) Primer Strength. An increase in primer strength will increase detonation velocity up to a point.

Emulsions

One of the newer commercial explosives now on the market is the family of explosives called *emulsions*. An emulsion is a liquid that is a mixture of two liquids. That is to say, the two liquids in the emulsion are mixed together but remain separate. One of the easiest ways to visualize this is when a small amount of oil is put into a jar of water and the jar is shook. The oil forms small round beads that are mixed throughout the water. If the beads of oil could be made very small and if they could be kept dispersed throughout the liquid, you would have an emulsion. An emulsion explosive is made up of a liquid

oxidizer internal phase (like the small oil beads) suspended in a liquid continuous fuel phase (like the water).

One of the unique physical properties of emulsions is that they do not have to be a liquid as we think of a liquid. Because the continuous phase is the predominate ingredient, it dictates the physical nature of the emulsion. Thus an emulsion may flow like a thick liquid or it may be made like a stiff putty. Also, because of the nature of the ingredients in an emulsion, their physical nature remains the same over a rather wide range of temperatures.

One of the advantages of emulsions is the fact that they are quite insensitive, yet once initiated have good detonation velocities. One reason for the good detonation velocities is the fact that the emulsion is made of very fine particles that are in a very uniform distribution. This means that the detonation process is more uniform than with granular or solid explosives, wherein the material is not uniform.

Military Explosives

The military use of explosives ranges from ANFO to exotic experimental explosives with high molecular densities. Because we have already covered many explosive types, only those explosives with a unique military use will be discussed.

(1) *Military Dynamite*. Military dynamite is unique in its high RDX content (75 percent), which results in a detonation velocity of around 20,000 fps. Because of the difficulty in obtaining this grade of dynamite, it probably will soon be phased out of the inventory of military explosives.

(2) *Trinitrotoluene (TNT)*. Trinitrotoluene is the most widely used military explosive. Its primary use is as a booster charge or as a demolitions charge.

(3) *Amatol*. Amatol is an explosive mixture made up of ammonium nitrate (80 percent) and TNT (20 percent). It is used as a more economic substitute for TNT. Because of its poor water resistance, however, it does not have as

wide an operational mission area as TNT.

(4) *Composition Explosives*. Composition explosives are a unique form of military explosive consisting of two or more materials:

A3 = 91 percent RDX, 9 percent wax. Used as a booster charge in demolition devices and as a main charge in some projectiles.

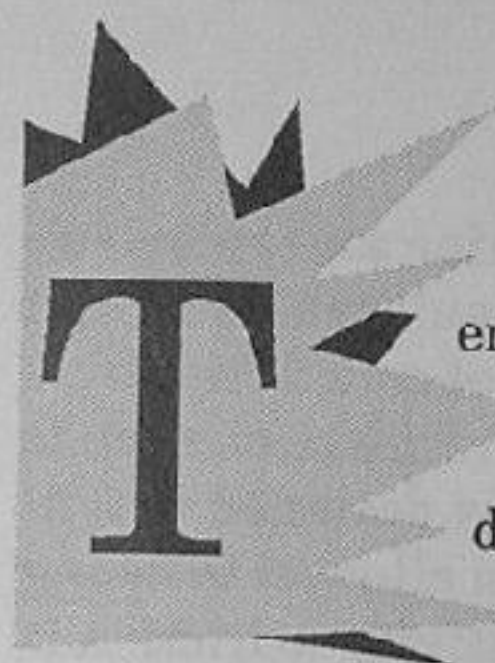
B = 60 percent RDX, 39 percent TNT, 1 percent wax. Used most often as the main charge in shaped charges.

B4 = 60 percent RDX, 39.5 percent TNT, and 0.05 percent calcium silicate. Used in shaped charges and other demolitions devices.

C4 = 91 percent RDX, 9 percent nonexplosive plasticizers. Used as a burster charge and as a main demolitions charge where high detonation velocities are required.

(5) *Tetrytol*. Tetrytol is made up of 75 percent tetryl and 25 percent TNT. It is most often used as a demolitions charge that is more powerful and brisant than TNT.

TESTING



he testing of explosives is a difficult and somewhat dangerous undertaking. Throughout history the explosive engineer has sought methods for analysis of his explosive concoctions. The methods devised by engineers are as diverse as the engineers themselves.

Rather than go into all types of testing, only those tests most frequently used by industry will be covered in this chapter.

IMPACT TEST

The impact test consists of placing a fixed volume of material on a solid surface (anvil) and then dropping a known weight from a known height onto the explosive. Variables in this test are how much the weight weighs and how high the weight is above the anvil.

For the most part, all of the variables in the impact test are well controlled, especially when the test is conducted on an Explosive Research Laboratory (ERL) or Picatinny Arsenal machine. The minimum height that causes the explosive to detonate or the product of the minimum height and the weight's weight is used as a measure of impact sensitivity.

Another impact test is called the *flying plate test*. In this test a metal plate is explosively driven against an explosive sample. The velocity of the plate is a measure of the explosive's sensitivity to high-velocity impact.

SPARK (ELECTROSTATIC) TEST

The spark test is used to determine the sensitivity of an explosive to a spark. In this test the explosive is separated from an electrode by an air space or gap (there are many different devices to do this). The energy from a capacitor or other device is discharged through the electrode, resulting in an arch or spark jumping to the explosive. The explosive's sensitivity is a measure of the energy dumped into the electrode.

FRICTION TEST

The friction test is used to determine an explosive's sensitivity to friction, which is of considerable interest during manufacturing. One method of conducting this test is to use a pendulum and anvil. The explosive is spread out on the anvil, and a specially designed weight (shoe) attached to a pendulum arm is allowed to swing back and forth across the anvil. Sensitivity to friction is measured by the number of snaps, cracks, ignitions, or explosions resulting from the interaction of the pendulum shoe and the explosive.

GAP TEST

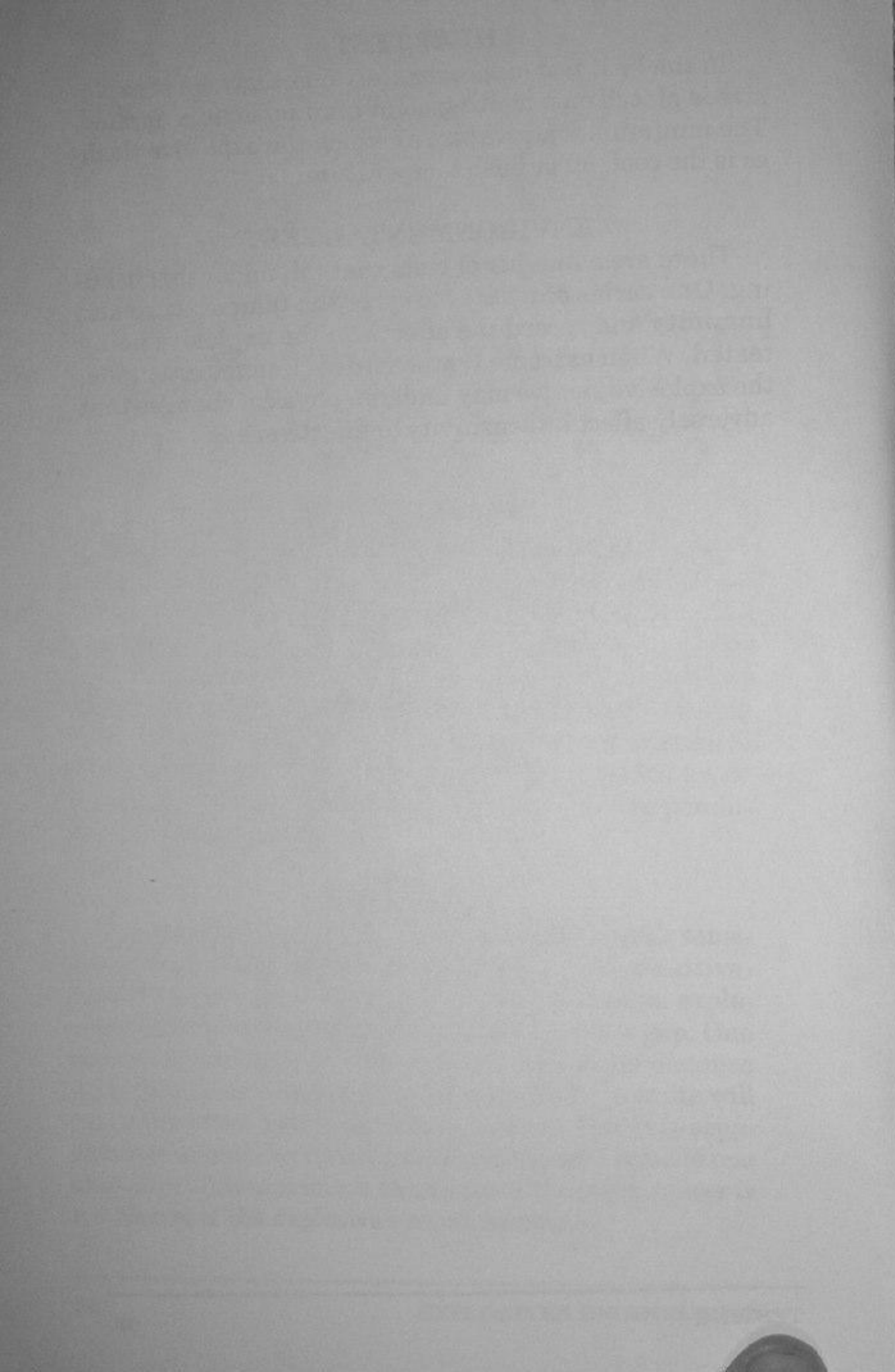
The gap test is used to determine an explosive's sensitivity to shock or, as was related earlier, its sensitiveness. Explosive sensitiveness is a measure of an explosive's ability to propagate detonation across a gap. One method of testing is a measure of the maximum distance (in inches) over which one half of a stick of dynamite will cause the other half to detonate. Another test is to separate two explosives by an inert material and initiate one explosive. The maximum thickness of the inert spacer is a measure of the explosive's sensitiveness.

HEAT TEST

In the heat test, approximately 5 milligrams of explosive is placed on a melting point bar and heat is applied. The minimum temperature at which the explosive flashes is the cook-off or flash temperature.

ENVIRONMENTAL TEST

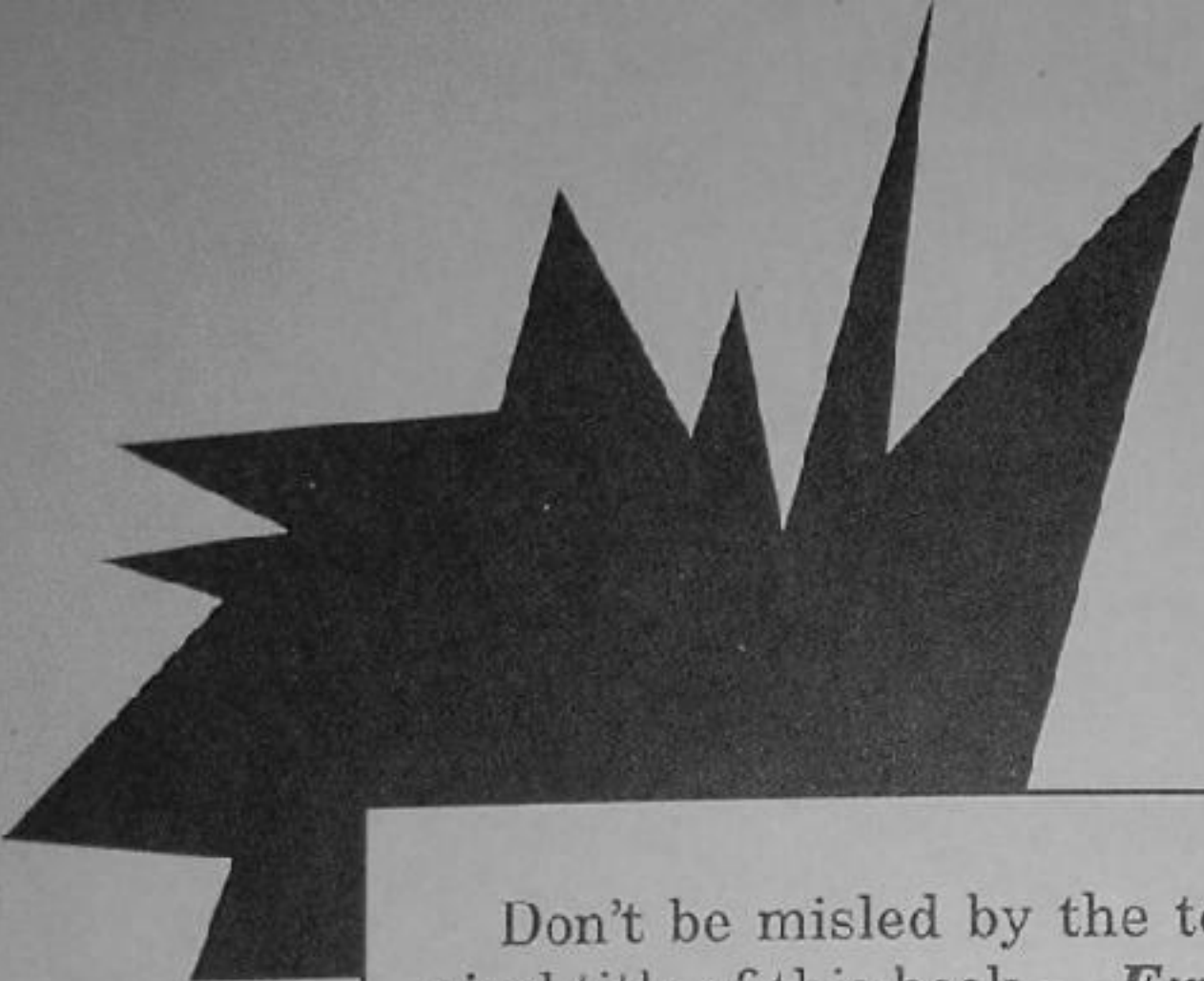
There are a number of tests that fall under this heading. One series of tests is to cycle the temperature and humidity and record the effects on the explosive being tested. When extreme temperature changes are made, the explosive sample may undergo physical changes that adversely affect its sensitivity or effectiveness.



CONCLUSION



My intent has been to present in as concise a manner as possible an introduction to the complexities of explosives. The purpose of this text is to educate those who have a serious interest in working or experimenting with explosives. It is my observation that there are many individuals who claim to be explosives experts, yet in truth they are only dangerous people. If all you want to do is see dirt fly and hear a loud noise, these so-called experts can probably get the job done—just be careful around them. However, if you are someone who truly wants to understand the properties of explosives, then I hope you will use what you have learned in this text as an introduction to the world of explosives. Continue to study what true experts have to say and make it a point to apply this knowledge in a safe manner. Killing yourself because you failed to take the time to understand explosives and their proper handling is stupid, but killing or harming someone else with explosives is unforgivable.



Don't be misled by the technical title of this book — ***Explosive Principles*** is a readable, easy-to-understand primer on the nature of detonations, as well as a concise look at the basic but often overlooked techniques that professionals use to maximize the performance of primary and secondary explosives to get any job done right. A must for demolition personnel, amateur "powder monkeys," or anybody interested in things that go bang.

For information purposes only.

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