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ENGINEERING DESIGN HANDBOOK

PRINCIPLES OF EXPLOSIVE BEHAVIOR

HEADQUARTERS, U S ARMY MATERIEL COMMAND

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large diameter. In practice, however, it is found that in small diameter cylindrical charges the detonation front is curved, and its velocity depends upon the degree of charge confinement and charge diameter. Also it is observed that for each explosive there is a critical value of charge diameter d_c below which a steady-state detonation will not propagate. For example, d_c is about 1 cm for cast TNT, about 10 cm for ammonium nitrate, and about 160 cm for some types of rubber-base composite propellant. The explanation of these "nonideal" detonation phenomena relates to the effects of charge expansion and lateral energy losses on the rate of chemical reaction in the detonation reaction zone. "Nonideal" detonation behavior is discussed in detail in Chapters 9 and 11.

If we take a solid explosive such as cast TNT and set a match to it, it will probably burn (deflagrate) with a linear velocity of ≈ 1 cm/sec. However, if we strongly shock the explosive it will detonate at $\approx 7 \times 10^5$ cm/sec. It can also be observed that if a burning explosive is confined or if the explosive is porous, a deflagration to detonation transition will occur some place in the material. This brings up very practical questions such as what are the conditions which cause the initiation of detonation in an explosive, and why do different explosives, or even the same explosive at different bulk densities, react differently to initiating stimuli—e.g., shock, impact, friction, spark, heat, etc.? The need to design reliable detonation initiation devices and to prevent accidental initiations lent early impetus to studies devoted to characterizing the ease of initiation or sensitivity of explosive materials.

There is now substantial evidence that all detonation initiation processes are essentially thermal in origin. By this is meant that initiating external stimuli such as shock, impact, and spark cause heating of the explosive and the creation of thermal explosion—sometimes in small localized regions of the explosive charge, i.e., hot spots. The thermal explosion, if it is of sufficient intensity, will propagate a deflagration and/or shock wave which eventually leads to the formation of a detonation wave. The factors which determine whether or not the stimulus is sufficient to cause thermal explosion and whether or not the thermal explosion is of sufficient intensity to grow to detonation are

very complex, involving chemical kinetics, thermodynamics, mass and heat transport, and hydrodynamic flow. A detailed discussion of thermal explosion and its application to detonation initiation are given in Chapters 10-12.

As indicated earlier, one of the main applications of condensed explosives is as an energy source for blasting. The transmission of detonation energy to the medium surrounding an explosive relates not only to the properties of the medium but also to the properties of the explosive; e.g., detonation velocity, energy, pressure, product composition, etc. The theory of blast propagation in air and water from an spherical explosive charge is described in detail in Chapter 13. The theory is of significance in a book on explosive behavior since it sets the foundation and limitations of the concept of "TNT Equivalent" which is often used in evaluating explosive performance, as well as forming the basis of some of the experimental determinations of the energy of detonation (cf. Chapter 3).

Finally in Chapter 14 we discuss some of the equilibrium thermodynamic and time dependent hydrodynamic computer codes which are currently being used in calculating explosive properties and explosives' behavior.

1-3 TYPES OF EXPLOSIVE

It has become traditional to distinguish between various types of explosives. Most military explosives consist of pure compounds or of relatively simple mixtures of explosive compounds. In such compounds the oxygen is normally bound in nitro- or nitrate-groups, and the explosion reaction consists of the decomposition of the molecule of the explosive substance. Many commercial explosives consist of mixtures of various kinds. The mixture may consist of a substance which itself is an explosive to which are added various materials which may serve as added fuel, added oxidizer, or inerts. When inerts are present, their function is usually to serve as a thermal ballast and thus to moderate the energy available for useful work or the temperature of the gaseous products. If one or more of the ingredients of such mixtures is an explosive substance, it is useful to call the mixture a hybrid explosive. Commercial dynamites provide an example of explosives of

this type. A very large number of formulations exist, each of them tailored to meet a particular commercial need and to comply with safety requirements imposed by the particular use. Another type of explosive mixture may consist of two or more substances none of which of themselves are explosives. These may be called composite explosives. Typically they consist of mixtures of a substance serving as fuel and a substance serving as oxidizer. Mixtures of the oxidizer ammonium nitrate, which can only be exploded with great difficulty, and fuel oil are examples of this type which have recently become very prominent as cheap blasting agents.

Most explosive charges contain a main charge which is designed to accomplish the particular task for which the explosive is intended. The common explosives with a sufficiently high energy and pressure of explosion are normally somewhat difficult to initiate. These materials are called secondary explosives. Typical of this class are the military explosives TNT, RDX, and the commercial dynamites. To provide reliable initiation, the charge will contain an initiator employing a substance easily initiated by a thermal source or by mechanical shock but whose energy and pressure of explosion are too low for use as a main charge. These materials are called primary explosives. Lead azide and mercury fulminate are well-known examples. A typical explosive device (see Fig. 1-1) consists of a train composed of an initiating charge of primary explosive, a main charge of secondary explosive, and a booster charge which is initiated by the primary explosive and which accomplishes the initiation of the main charge. The booster, therefore, serves as an intermediate step in the detonation of the main charge. The more sensitive secondary explosives are employed as boosters. Tetryl and PETN are frequently used for this purpose. Blasting caps are themselves explosive trains, containing a small amount of primary explosive and a booster charge which today is often PETN.

Some typical explosive compounds are listed in Table 1-1. Table 1-2 gives the compositions of some explosive mixtures.

1-4 SOME DEFINITIONS

We wish here to define the meaning of several terms that are employed in the discussion of the

properties and behavior of explosive substances. Some of these terms are in everyday use with meanings that are in varying degrees of imprecision. Some are not even capable of precise definition but are in such common use as to have a more or less established meaning through usage. The word "explosion" is in this category, as is, for example, the word "fire". Some terms are susceptible to exact definition but are frequently misused; such as the word "detonation", which should only be used in the case of reaction by a detonation wave.

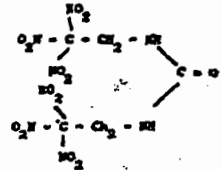

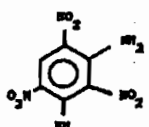
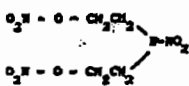

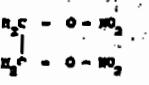
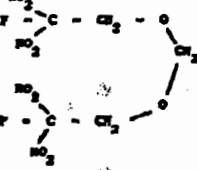
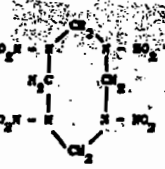

An *explosive* can be loosely defined as a substance capable of undergoing an explosion. More precisely we shall employ the word as we have in par. 1-2 to designate a substance or mixture of substances capable of undergoing exothermic chemical reaction with the evolution of gaseous products at an extremely high rate. Explosives may be in the gaseous, liquid, or solid state of aggregation. In this handbook we shall be mainly concerned with condensed explosives that are either liquid or solid.

An *explosion* is literally the sudden outward projection of a quantity of matter. The term is, for example, applied to the event following the rupture of a steam boiler in which steam and possibly boiler case fragments undergo a rapid excursion. The term is also applied, for example, to the event that follows the sudden admixture of liquid water to molten materials at a temperature substantially in excess of the boiling point of water. As a final example, the term applies to the event resulting from the overpressurization of any container. All of these meanings are endorsed by everyday use. However, in this handbook we shall employ the word in a more restricted sense to refer to the overall process by means of which an explosive is suddenly converted to gaseous products which, as will be shown, are at high temperature and pressure. We shall frequently refer to the chemical products of this process as explosion products.

It may be noted that explosives may undergo slow reactions to gaseous products (cf. Chapter 3). If the rate of these reactions is so slow that high temperature and high pressure are not obtained; the process is not an explosion.

The term *thermal explosion* is used in a special sense that is fully discussed in Chapter 10. It is the result of runaway exothermic chemical reaction which occurs when the rate of

TABLE 1-1 TYPICAL EXPLOSIVE SUBSTANCES

(Code)	Name	Elemental Formula	Structural Formula	Principal Use
(AN)	Ammonium nitrate	$N_2H_4O_3$	$NH_4^+ NO_3^-$	solid oxidizer
(AP)	Ammonium perchlorate	$N_2H_4Cl_7$	$NH_4^+ ClO_4^-$	solid oxidizer
(RDX)	2,4,6-trinitroresorcinyl urea	$C_3H_5N_6O_{12}$		secondary high explosive
(D)	Ammonium picrate	$C_6H_5N_7O_{12}$		secondary high explosive
(DATM)	Diaminodinitrobenzene	$C_6H_4N_4O_4$		secondary high explosive
(DINA)	Diethylamine dinitrate	$C_8H_{16}N_4O_8$		secondary high explosive
(EDNA)	Ethylene dinitramine "Nalate"	$C_2H_4N_4O_8$		secondary high explosive
(EGDN)	Ethylene glycol dinitrate	$C_2H_4N_2O_6$		liquid explosive
(FPO)	2,2-dinitro-2-fluoroethyl formal	$C_2F_2O_4N_2$		secondary high explosive
(HMX)	Cyclotetramethylene tetranitramine	$C_4H_8N_8O_{16}$		secondary high explosive
	Lead Azide	Pb_3N_6		primary explosive

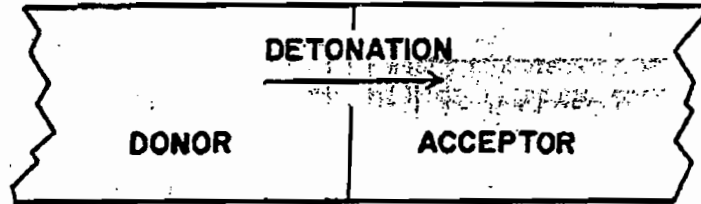


Figure 11-1. Transmission of Detonation From a Donor to an Acceptor Charge

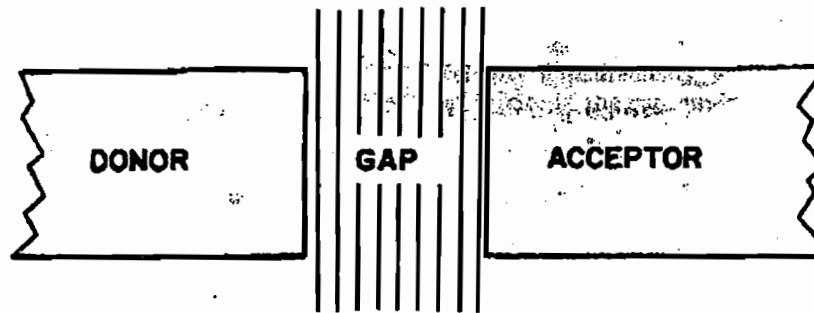


Figure 11-2. The Gap Test

illustrated in Fig. 11-3 and is described as follows: "a 5.08-cm length of pressed tetryl ($\rho_0 = 1.51$ g/cc) to supply the shock; Lucite, or the equivalent cellulose acetate, as the shock attenuator; a moderately confined acceptor charge of 3.65-cm diameter by 13.97-cm length; and a mild steel witness (test) plate 0.952-cm thick. The criterion of 'detonation' used is the punching of a hole in the witness plate. The measure of charge sensitivity is the length of attenuator (gap length) at which there is 50 percent probability of detonation according to the above criterion."

Gap test results become more significant when they are equated not simply to the number of cards or thickness of the gap but to the strength of the shock wave at the critical "go, no-go level". The Naval Ordnance Laboratory has "calibrated" the NOL test to make it possible to interpret the results in this manner. The method is described in the paragraph which follows.

11-3 SHOCK-PRESSURE MEASUREMENTS IN THE GAP TEST

By means of simultaneous shock wave velocity and free surface velocity measurements, such as those described in Chapter 5, the "Hugoniot adiabat" for Lucite has been determined. (The method of erecting the Hugoniot curve from the experimental data is explained in Chapter 8.) With this basic information the shock wave strength at the end of the gap can be determined from either shock wave velocity or free surface velocity measurements, with various thicknesses of Lucite in the gap, under actual conditions of the test, i.e., with the donor charge shown in Fig. 11-3. This kind of determination was carried out at NOL, with the results shown in Fig. 11-4, i.e., axial shock pressure at the end of the Lucite gap in kbar (1 kbar = 987 atm) vs thickness of gap.

The shock pressure at the end of the Lucite

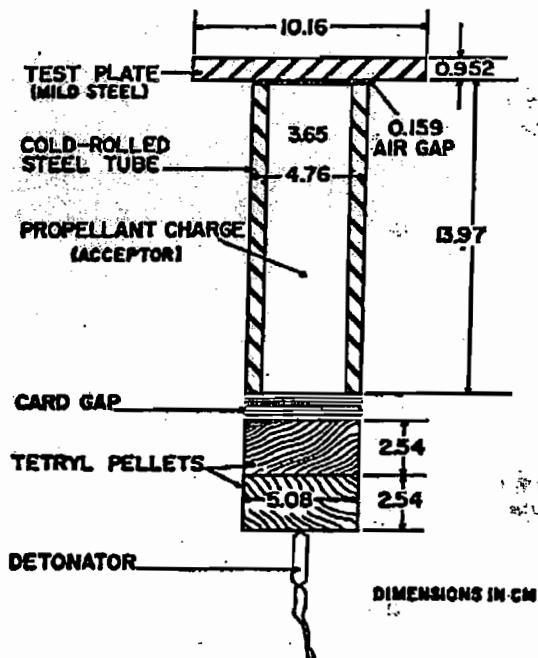


Figure 11-3. Charge Assembly and Dimensions for NOL Gap Test

gap, however, is not in general equal to the shock wave pressure transmitted to the acceptor explosive because there is usually an acoustic impedance mismatch between Lucite and the test explosive. The transmitted shock wave pressure can be readily determined from the Hugoniot adiabat of the acceptor. Experimental shock Hugoniots (or Hugoniot adiabats) have been determined for many of the military explosives (see Ref. 2). However, the impedance mismatch with Lucite does not differ very much for many of the common high explosives in the cast or pressed condition; therefore, the transmitted shock pressure in the explosive is approximately proportional to the incident pressure in the Lucite. Fig. 11-5 shows this relationship, the data points being the critical 50 percent explosion points for nine explosives for which sufficient equation of state data were available to calculate the initial pressure in the transmitted shock. It may be observed that for these materials no error would be made in ranking the explosives for shock wave sensitivity if one were to use incident pressures in the Lucite rather than transmitted pressures in the

explosive. This statement would not necessarily apply, however, if explosives differing widely in density were being compared, e.g., a loose crystalline powder and a cast material.

Table 11-1 lists some of the results obtained on solid rocket propellants at the Naval Ordnance Laboratory. The term "loading pressure" in the table refers to the pressure of the incident wave at the end of the Lucite gap. A notable feature of the measurements is the effect of voids in composite propellants. (These propellants are based on ammonium perchlorate as oxidizer with an organic, rubber-like binder.) Composite propellants in their service condition and containing no high explosives such as HMX are generally nondetonable in this test, even when the tetryl donor charge is in direct contact with the propellant (zero gap). However, a negative result of the gap test cannot be taken to imply that a propellant is nondetonable under all conditions of initiation charge diameter and confinement. When the propellant is shredded and recompressed, leaving some air-filled voids, it becomes very sensitive to initiation. Voids, therefore, appear to influence sensitivity very markedly in this case.

11-4 EFFECTS OF SHOCK WAVES IN CONDENSED EXPLOSIVES

In a homogeneous material, lacking voids or discontinuities of any kind, a shock wave raises the pressure, density, and temperature uniformly in the plane immediately behind the front. Condensed media are, of course, very much less compressible than gases; therefore, the increases in density and temperature that accompany a given rise in pressure are much smaller than in gases. However, the pressures developed in the detonation of condensed materials are in the order of 10,000 times the detonation pressures of gaseous mixtures at an initial pressure of one atmosphere—e.g., 200,000 atm pressure for condensed explosives compared to 20 atm for gaseous explosives. Under such tremendous forces, even seemingly incompressible materials are highly densified and heated by the compression. It is perhaps not surprising to find, therefore, that the detonation front in a condensed explosive detonation heats the medium to a temperature in the neighborhood of 1,000°C or higher, a temperature quite high enough to start

TABLE 11-1 SHOCK SENSITIVITY OF SOLID ROCKET PROPELLANTS IN THE
NOL GAP TEST

<u>Propellant</u>	<u>Physical State</u>	<u>Loading Pressure at the 50 percent Point, kbar</u>
various composites	service condition; nonporous	no-go
double base	service condition; nonporous	80-47
composite with 17-18 percent high explosive	service condition; nonporous	69-58
composite	shredded and pressed; 16-22 percent connected pores	11-7

the Taylor expansion described in Chapter 8) is small for a time period of some microseconds.

(3) Large enough diameter in the donor shock wave production system so that lateral expansion effects (described in Chapter 9) do not seriously affect the planarity of the shock wave or decrease the period of sustained high pressure behind the front.

(4) Variable attenuation of the donor shock wave. This is produced by inserting between the donor and acceptor charge a gap filled with an inert material of various composition and thickness.

A number of different experimental arrangements were used to elucidate various aspects of the phenomena. These cannot be described in detail here. Typical arrangements—taken from Refs. 5,6—are shown in Fig. 11-6(A) and 11-6(B), and illustrate how the various requirements previously enumerated were met in these experiments.

The major aspects of initiation phenomena in homogeneous and nonhomogeneous explosives as derived from a long series of experiments with liquid and solid explosives can be stated as follows:

(1) *In Nonhomogeneous Explosives.* If the entering shock wave is above a critical strength, it begins to accelerate at the point of entry, gaining strength relatively slowly at first, but ever more rapidly until steady-state C-J velocity is reached. The development of

detonation in this case may be described as a smooth transition from a shock wave at first only weakly supported by chemical reaction to a fully supported steady detonation. The final stages of acceleration to detonation, in which the greater part of the increase in shock strength occurs, comprise only a small fraction of the total time between the initial entrance of the wave and the final achievement of full detonation. Material lying in the region between the point of entry of the shock wave and the region between the point where detonation first starts remains essentially unreacted, and retonation (a detonation wave moving back toward the point of shock entry) is often observed.

(2) *In Homogeneous Explosives.* The entering shock behaves as would a chemically unsupported shock in an inert material, decaying slightly and losing speed as it travels forward because of normal dissipation. After an induction period—which bears a strong inverse relationship to the strength of the entering shock—detonation starts, not at the shock front but at the entering face of the acceptor. This detonation wave is characteristic of the explosive medium in the precompressed (and heated) condition created by the initial shock, and it travels at a hypervelocity (higher than the C-J velocity at normal density) characteristic of these conditions plus the velocity of forward motion imparted to the medium by the initial