

WASC 2307

Creating an
Explosion

J. A. Burgess
G. Hooper

CREATING AN EXPLOSION

The theory and practice of detonation and solid chemical explosives

J A Burgess and G Hooper

Recently in *Physics in Technology* we described the advances in containment of undesirable explosions. Here we look more closely at the physical phenomena of detonation and explosion, and how they can be tailored to practical advantage

Drs Burgess and Hooper work at the Propellants, Explosives and Rocket Motor Establishment (formerly the Explosives Research and Development Establishment), Ministry of Defence Procurement Executive, Powdermill Lane, Waltham Abbey, Essex EN9 1BP

The science of explosives, especially solid explosives, is a rather specialised subject and one rarely included in the physics and chemistry curricula of universities. The subject, though fascinating, has a limited applicability and in most seats of learning the provision of facilities suitable for practical work would pose serious problems. The purpose of this article is to define the terms 'explosion' and 'explosive', to describe the phenomenon of detonation and present a picture of the history, development and classification of explosives with regard to their (mainly military) applications.

'Explosion' is an evocative word and no doubt fires the imagination of different people in different ways. Nonetheless, it may be simply defined as 'the rapid expansion of matter, generally gas, into a volume much greater than it originally occupied'.

The term will, therefore, include both deflagration (rapid combustion) and detonation arising from chemical reactions giving gaseous products, as well as physical phenomena such as the sudden release of high-pressure gas which might result from the rupture of a gas cylinder or the puncture of a motor-vehicle tyre. In fact, the largest physical explosion in recorded history was the destruction of the volcanic island of Krakatoa in 1883, as a result of steam pressure generated by the contact of molten lava and sea-water.

It follows then, that an 'explosive' is any system which may be induced to explode. More specifically, a chemical explosive is a substance or mixture of substances which, when a suitable stimulus is applied, will decompose or react very rapidly, evolving heat and gaseous products.

Detonation is propagated by a shock wave while deflagration is propagated by means of heat transfer mechanisms. The velocity and the pressure of the shock wave in an ideal detonation are determined solely by the thermodynamics of the explosive and the exothermic reaction. In a typical solid explosive the velocity of the shock wave, known as the detonation velocity, will be several kilometres per second, and the pressure will be several hundred thousand atmospheres. It is this high pressure which gives detonating or high explosives their shattering power (brisance) and which gives rise to blast waves when a high explosive is detonated in air. Some detonation properties for a few typical high explosives are given in table 1.

Figure 1a shows the remains of a substantial steel tube which has been filled with an explosive

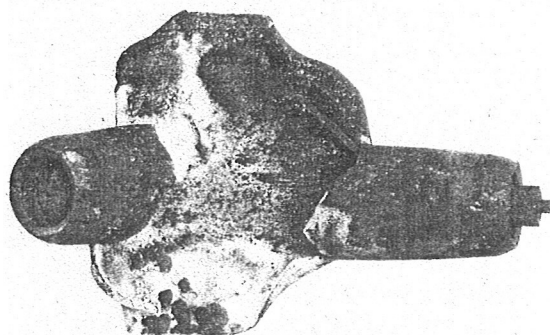
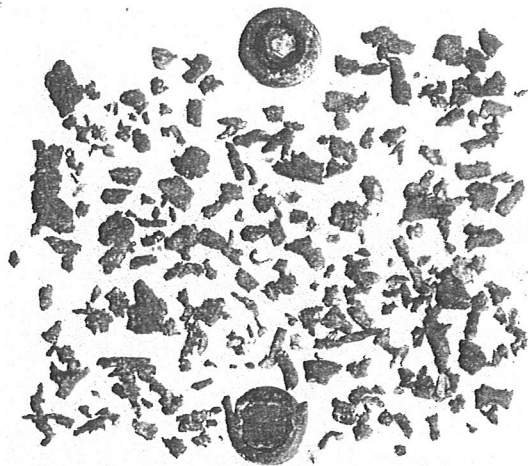


Figure 1 a – Remains of a substantial steel tube which has been filled with an explosive and detonated (large sealed-vessel test), **b** – Remains of a similar tube in which the explosive has been burned but not detonated (deflagration)

which detonated. The tube has been reduced to small fragments which, in an open space, would travel at high velocities. This forms the basis of fragmentation weapons such as hand-grenades. Figure 1b shows the remains of a similar tube in which the explosive has burned but not detonated. The burning explosive has produced gases which have reached a pressure exceeding the yield strength of the steel tube, which has split open but is still in one piece.

Historical background and development

Until the middle of the nineteenth century, the only chemical explosive and propellant in use was gunpowder which, as most schoolboys know, is an admixture of saltpetre (potassium nitrate), charcoal and sulphur. The invention of gunpowder has been ascribed to the Chinese (*ca* AD 1000), and there is evidence that gun-powder was used by the Arabs

as an incendiary mixture in 1290. It is uncertain when and how gunpowder spread further west, but the monk Roger Bacon (*ca* 1250) is generally credited with its introduction into England. Whether Bacon discovered gunpowder as a result of his own researches or acquired the knowledge from the east by some means is uncertain. His writings on the subject were impounded by the Church, and it was not until early in the fourteenth century that the military significance of gunpowder was properly realised.

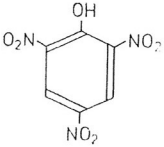
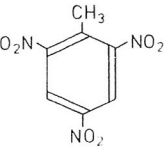
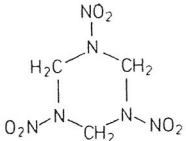
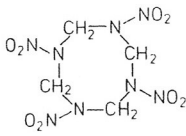
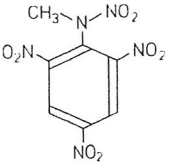
Over many centuries the basic ingredients of gunpowder have remained unchanged, but their proportions have altered considerably. However, since 1781 the composition has remained the same: saltpetre (75%), charcoal (15%) and sulphur (10%). Between the seventeenth and nineteenth centuries a complex technology and industry grew up around the manufacture of gunpowder as the influence of the grain size and bulk density upon the burning characteristics was gradually appreciated.

Gunpowder is not a high explosive (*i.e.* it will not detonate). The shells and grenades employed during the Napoleonic wars burst as a result of gas pressure generated by the burning gunpowder. Although some 'sensitive' chemical compounds such as heavy-metal picrates and fulminates were known before 1800, the phenomenon of detonation remained unappreciated until the advent of high explosives during the middle years of the last century.

The discovery of high explosives was a direct result of the technical developments in the field of chemistry which enabled nitric and sulphuric acids to be purified and concentrated. The treatment of many organic materials with a mixture of these concentrated acids (nitrating acid) yields organic nitrates and nitro-compounds, many of which have explosive properties. In 1846, Sobrero treated glycerine with cold nitrating acid and produced nitroglycerine (properly glycerol trinitrate). He quickly realised the dangerous nature of the oily liquid, and considered it too unstable to risk further development. Nonetheless, nitroglycerine was used for many years as a rock-blasting explosive, often being manufactured on site and often with disastrous results. A major step forward in 'taming' nitroglycerine was taken by Nobel, who discovered that kieselguhr (a diatomaceous earth) would absorb and retain a large proportion of the liquid explosive. The resulting material was much less sensitive than pure nitroglycerine and, being a solid, much easier to handle. In 1867 Nobel patented a mixture of nitroglycerine (75%) and kieselguhr (25%) as dynamite.

About the same time as nitroglycerine was discovered, gun-cotton (nitrocellulose, properly cellulose nitrate) was produced by treating cotton hanks with nitrating acid. For many years gun-cotton was used as a propellant and, in the form of wet compressed slabs, as a demolition explosive. Nobel found that nitroglycerine will dissolve nitrocellulose to

Table 1 Detonation properties of some common explosives

Explosive	Chemical composition or structure	Density (g cm ⁻³)	Heat of explosion (kJ g ⁻¹)	Detonation velocity (km s ⁻¹)	Detonation pressure (GPa)
Mercury fulminate	Hg(ONC) ₂	4.0	1.8	5.0	25.0
Lead azide	Pb(N ₃) ₂	4.93	1.5	5.1	39.4
Nitroglycerine	$\begin{array}{c} \text{CH}_2 - \text{O} - \text{NO}_2 \\ \diagdown \\ \text{HC} - \text{O} - \text{NO}_2 \\ \diagup \\ \text{CH}_2\text{O} - \text{NO}_2 \end{array}$	1.6	6.7	7.7	25.3
PETN	$\begin{array}{c} \text{CH}_2 - \text{O} - \text{NO}_2 \\ \\ \text{O}_2\text{N} - \text{O} - \text{CH}_2 - \text{C} - \text{CH}_2 - \text{O} - \text{NO}_2 \\ \\ \text{CH}_2 - \text{O} - \text{NO}_2 \end{array}$	1.77	5.9	8.3	30.5
Picric acid		1.63	3.7	7.25	20.0
Trinitrotoluene		1.6	3.9	6.95	19.0
RDX		1.8	5.7	8.64	33.8
HMX		1.9	5.6	9.11	38.7
Comp. B	RDX (60%) TNT (40%)	1.68	4.8	7.975	25.0
Tetryl		1.71	4.3	7.85	25.0
Torpex 2	RDX (42%) TNT (40%) Aluminium (18%)	1.74	6.7	7.20	22.5
Amatol (80/20)	Ammonium nitrate (80%) TNT (20%)	1.5	4.1	5.1	8.8

form a gel, which became known as blasting gelatine. The addition of inorganic nitrates such as ammonium nitrate and sodium nitrate to the nitroglycerine/nitrocellulose gel gave rise to gelignite blasting explosives. In 1888 Nobel further discovered that by mixing nitroglycerine and nitrocellulose under water and drying the filtered product by passing through heated rollers he could produce a tough horny material. This material formed the basis of what is now known as cordite.

Organic nitrates such as nitroglycerine and nitrocellulose are unstable compounds. They are sensitive to impact, friction and heat, and they tend to decompose on storage, especially at elevated temperatures. The development of dynamite and the gelignites represented a major advance in the safe handling of these explosives, but neither of these materials is sufficiently stable physically or chemically to withstand the prolonged storage and extremes of environmental conditions required of a military shell filling and still remain in a safe and viable condition. The robbers of old were always plagued with 'sweaty gelly'.

The treatment of organic aromatic compounds with nitrating acid resulted in the discovery of nitro-compounds, and in 1841 Laurent synthesised picric acid (trinitrophenol). This is a yellow crystalline solid (melting point 122 °C) which is very much more stable and much less sensitive than either nitrocellulose or nitroglycerine. Indeed, because of this relative lack of sensitivity to impact, friction and heat, some time passed before the explosive properties of picric acid were realised. In 1885, Turpin filed a patent to cover the use of picric acid as a shell filling. In this role, fairly substantial quantities of a more sensitive detonating explosive, for example mercury fulminate, were required to provide a shock sufficient to ensure the detonation of the main picric acid charge. Picric acid was the first high explosive to be used extensively as a shell filling, and was in general use until after the outbreak of the first world war. Cast picric acid was known as lyddite, after the town of Lydd in Kent, where it was first made.

Picric acid suffers from two serious drawbacks. Firstly, it has a comparatively high melting point, and if heated much above this it tends to decompose. Although cast picric acid charges were produced, the material was often pressed dry or with small quantities of collodion or heavy oils – a fairly expensive process. A more easily cast composition (known as shellite) was obtained by the addition of a mixture of dinitrophenols, but the performance was somewhat impaired. Secondly, a more serious disadvantage lies in the fact that picric acid is a comparatively strong acid, and will attack many metals and their oxide coatings. Some of the salts produced, particularly the heavy metal picrates such as lead and copper, are very sensitive materials and it was necessary to take extensive precautions to avoid contact with metals both during manufacture and in the weapon. The inside surfaces of

shells to be filled with picric acid based compositions had to be coated reliably with an acid-resistant varnish.

Trinitrotoluene (TNT) was first synthesised in 1863, and it suffers from neither of the major disadvantages of picric acid. It is not corrosive and it has a fairly low melting point (80 °C). As the melt is stable to considerably higher temperatures than this, TNT is readily cast. Cast TNT is, however, a good deal less sensitive to shock and impact than picric acid and therefore requires to be well 'boosted' with a more readily detonated material to ensure detonation. It was this lack of sensitivity and the consequent need for a strong booster which was the main reason for the delay in its adoption in Britain until 1914 – the Germans were using it as a shell filling by 1903. A suitable boosting explosive was found to be tetryl (trinitrophenyl methyl nitramine) which was first produced in 1877 by the nitration of certain products of the synthetic dye industry.

Before discussing the chemistry of explosion and some of the more recent developments in explosives composition, we should mention two important explosive compounds introduced during the 1930s: RDX (cyclotrimethylene trinitramine) and HMX (cyclotetramethylene tetranitramine). These are both colourless crystalline solids, considerably more sensitive to impact and shock than either TNT or picric acid, but with higher performances. HMX is a by-product of RDX manufacture and is consequently the more expensive of the two. The higher density of HMX gives it a slight advantage over RDX on grounds of performance. It is perhaps worth mentioning that HMX can exist in several polymorphic forms, some of which are very sensitive. β -HMX, the least sensitive form, is the polymorph used.

Neither RDX nor HMX is castable, but they may be added to molten TNT to form a castable mix. A composition containing RDX (60%) and TNT (40%) formed the basis of one of the most important bomb and shell fillings of the second world war. This composition, known sometimes as Comp. B, is still used extensively.

Release of energy

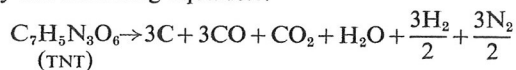
It is appropriate at this point to consider the source of energy latent in the detonating explosives mentioned so far. The molecules of these explosives all contain the atoms carbon, hydrogen, nitrogen and oxygen, and the heat of explosion is released as the explosive compound decomposes to yield finally a mixture of nitrogen, hydrogen, water, oxides of carbon and solid carbon. If the proportion of these products is known, together with their heats of formation and the heat of formation of the original explosive, the heat of explosion per unit weight of explosive, H_e , may be given as:-

$$\Delta H_e = \sum_1^n \frac{\Delta H_{p,n}}{m_n} - \frac{\Delta H_f}{M}$$

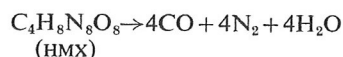
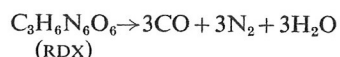
where $\Delta H_{p,n}$ is the molar heat of formation and m_n

is the molecular weight of the n th product, and ΔH_f is the molar heat of formation of the explosive and M its molecular weight.

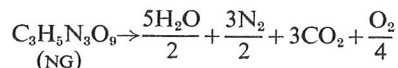
The composition of the reaction products resulting from the detonation of a particular explosive depends upon the chemical equilibria which exist between the molecular species present, and upon the degree of 'confinement' under which the explosive was detonated. The overall decomposition of TNT by detonation under heavy confinement (e.g. in a massive metal case) may be represented by the following equation:



In fact, by whatever means TNT decomposes, the products will always contain unburnt fuel, i.e. free carbon and/or hydrogen. Picric acid is also fuel rich. If it is assumed that RDX and HMX decompose on detonation to give mainly water, carbon monoxide and nitrogen, then they are perfectly balanced:



Even if it is assumed that all the carbon in nitroglycerine is burnt to carbon dioxide, nitroglycerine still remains oxygen rich:



As the molecules of these explosives contain both fuel and oxygen, they are often termed homogeneous explosives. HMX is the most energetic solid homogeneous explosive in service.

It was appreciated during the first world war that more energy could be made available if a separate oxidant, such as an inorganic nitrate, were added to TNT to supply the extra oxygen required to burn the excess fuel. For example, compositions containing ammonium nitrate and TNT were called amatols. An alternative means of increasing the heat of explosion is to add a fuel which oxidises more exothermally than carbon or hydrogen. Powdered aluminium is a particularly suitable fuel, as aluminium is readily available and the heat of formation of aluminium oxide is high; furthermore the inclusion of a metal raises the overall density of the explosive. The first explosive in service to use aluminium powder was ammonal, a mixture of TNT, ammonium nitrate and aluminium. During the second world war, Torpex 2 (40% TNT, 42% RDX, 18% Al) was developed as a filling for mines and torpedoes; it is still in use. In contrast to homogeneous explosives, explosives which contain separate chemical species as fuels and/or oxidants are termed composite explosives.

It may be seen from table 1 that although the heats of explosion of composite explosives such

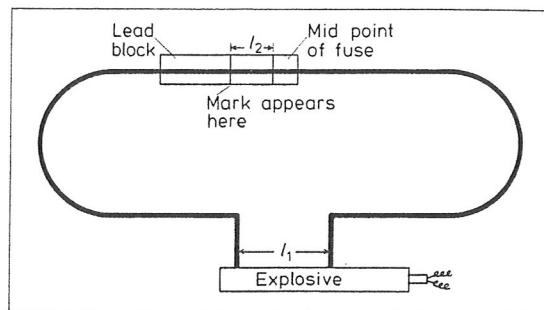
as amatol and Torpex 2 are higher than some homogeneous explosives, their detonation velocities and pressures are lower than might be expected. In a homogeneous explosive, where the oxidant and fuel are present in the same molecule, it is probable that the initial detonation reaction is principally *intramolecular*, so that the reacting components are relatively close together and the rate of reaction and rate of energy release is high. A large proportion of the available energy will be released sufficiently quickly to support the detonation wave. In a composite explosive the reactions are largely *intermolecular*. Several time-consuming processes may have to occur before the full quota of energy available is released. For example, a separate solid oxidant will have to vaporise (or decompose) to produce oxygen-rich species which will then have to interdiffuse with the fuel molecules in order to react.

Because of the relatively slow release of energy in composite explosives, only a proportion of the total energy available is released in time to support the detonation wave. Thus, the detonation velocities and detonation pressures of composite explosives are low. In general, homogeneous explosives with high detonation velocities and pressures (high brisance) are the most suitable for fragmentation and cutting purposes.

Assessment of detonation parameters

Detonation velocity and detonation pressures are important properties of an explosive. As detonations are very rapid events, special techniques are needed to measure the parameters associated with them. There are three principal techniques for determining the detonation velocity of an explosive. The first, due to Dautrich, is used commercially and claims the advantages of requiring no very special equipment and no great expertise on the part of the experimenter. Two ends of a length of detonating fuse are inserted into a length of the explosive under test, a measured distance apart (l_1 , see figure 2). The midpoint of the detonating fuse

Figure 2 The Dautrich technique for determination of detonation velocity. The detonation velocity of the explosive D is given by $D = dl_1/2l_2$ where d is the detonation velocity of the fuse



is marked and a length of the fuse in the vicinity of this point is placed in a groove cut in a thin lead plate. When the test explosive is fired, the detonation wave initiates one end of the fuse before the other. Where the two detonation waves in the fuse meet, a dent is produced in the lead plate. The position of this dent with respect to the midpoint of the detonating fuse (l_2) may be related to the detonation velocity (D) of the unknown explosive. The disadvantage of the method is that the detonation velocity of the detonating fuse must be known and assumed to be constant. The final result is, of course, an average detonation velocity for the unknown explosive over the distance l_1 .

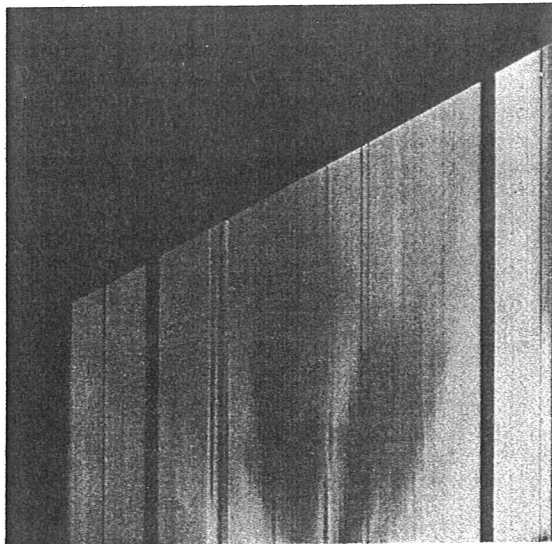
Another technique involves the placing of electrical probes on the surface of the explosive charge at intervals along its length. Most explosive compositions are good electrical insulators, whereas the reaction zone in a detonation is of almost metallic conductivity. This transition from insulator to conductor can be used to complete an electrical circuit, and the signals obtained from a series of probes can be fed into an electronic or oscillographic recording system from which arrival time of the wavefront at successive points along the explosive charge can be derived, in turn giving the velocity of detonation as a function of distance along the sample of explosive. The technique is particularly applicable to heavily cased charges.

One of the simplest and most effective methods for the measurement of the velocity of detonation of uncased explosive charges involves the use of a rotating-mirror streak camera. The explosive charge is imaged on to a narrow slit whose long axis is parallel to the direction of propagation of the detonation. The image of the slit is swept via a

rotating mirror of known angular velocity along a captive film track, giving a time-resolved streak record. In general the detonation front appears luminous, so that the photographic record will consist of a line inclined to the length of the film track at an angle which depends on the detonation velocity of the explosive and the speed of rotation of the mirror, as shown in figure 4. For explosives with a low velocity of detonation the wavefront may not appear luminous, and in such cases the surface of the explosive is coated with reflecting paint, and the whole illuminated externally. The detonation front will progressively destroy the reflecting surface, so that the passage of the detonation wave is recorded as a transition from light to dark as shown in figure 3.

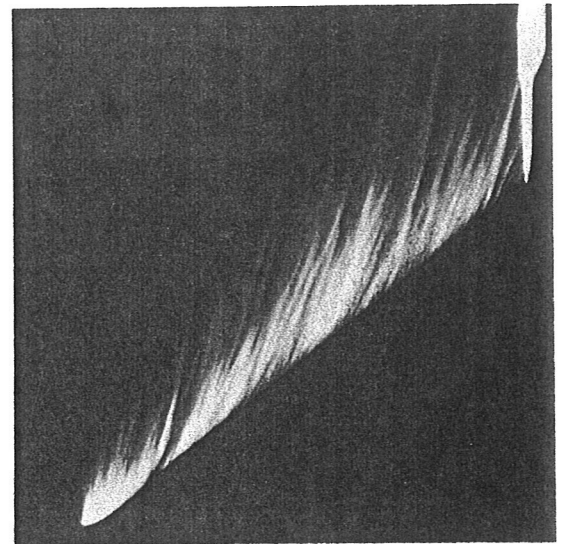
Detonation pressure is much more difficult to determine experimentally, and very often use is made of the relationship $P = \rho D^2/4$, where P is the detonation pressure in megabars, ρ is the density of the explosive in g cm^{-3} , and D is the detonation velocity in $\text{cm } \mu\text{s}^{-1}$. It is not generally possible to measure the detonation pressure of an explosive directly; it is generally inferred from the interaction of the detonation wave with a material whose equation of state is reliably characterised up to high pressures. Probably the most precise method for detonation pressure evaluation currently in use is the measurement of the free-surface velocity imparted to a metal plate which is in contact with the detonating explosive. The free surface velocity of the plate is measured by recording the time of arrival of the metal surface at a series of contactors or pins. The use of plates of varying thickness enables the entire pressure profile behind the wavefront to be derived. The technique does, however, require a

Figure 3 Detonation of a cylindrical charge coated with reflecting paint and externally illuminated (streak-camera record). Time vertically and distance horizontally



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Figure 4 Detonation of a cylindrical explosive charge where the detonation front is self-luminous (streak-camera record). Time is the vertical axis and distance is the horizontal axis



high standard of machining of both the explosive and the metal plates, and is beset by a number of other experimental difficulties, so that in general recourse is made to the 'aquarium' technique for detonation pressure measurement.

In the aquarium technique, the velocity of the shock wave imparted by a sample of explosive to water surrounding it is measured by means of a rotating-mirror streak camera. The measurement of the transmitted shock velocity (U_s) into the water permits one to ascertain the particle velocity (U_p) and hence via the conservation equation,

$$P_{\text{wat}} = \rho_{\text{wat}} U_s U_p,$$

the shock pressure in the water. The detonation pressure in the explosive is then derived from the impedance match equation:

$$P_{\text{HE}} = P_{\text{wat}} \frac{\rho_{\text{wat}} U_s + \rho_{\text{HE}} D}{2 \rho_{\text{wat}} U_s}$$

where D is the detonation velocity of the explosive.

In practice the shock velocity in the water is not a sensitive function of the shock pressure and so extreme precision is required in measuring this velocity in order to obtain a reliable estimate of the detonation pressure.

Special applications of explosives

There are some special applications in both the military and civil fields where the physical properties of an explosive are particularly important. It may be readily imagined that a putty-like explosive with a high brisance would be a valuable item in a demolition kit. Such explosives have been developed. The plastic explosive most commonly used today contains RDX (88%) and a hydrocarbon binder (12%). It is readily malleable and safe to handle. A material of similar composition is available in the form of thin, flexible sheets (sheet explosive), ideal for cutting girders and railway lines!

In the civil field, quarrying explosives have changed dramatically over the last twenty years. In very large quantities, ammonium nitrate (a common fertiliser) will detonate. When mixed with fuel oil the sensitivity is greatly increased, and during the early 1950s ammonium nitrate/fuel oil (ANFO) was used as a blasting explosive. The composition most commonly used is ammonium nitrate 94%, fuel oil 6%; the mixture does not readily separate and is roughly stoichiometric. The main advantages of ANFO are the absence of nitroglycerine, cheapness and the availability and relative safety in handling of the ingredients.

In more recent years ANFO has been largely replaced by slurry explosives. These materials are based on strong solutions of mixed inorganic nitrates, usually those of calcium, ammonia and sodium, which may be thickened or gelled with natural gums such as guar. In to this matrix may be introduced aluminium powder, organic fuels and solid oxidants. Some slurry explosives will flow sufficiently well to establish good contact with the walls of a bore hole

and to envelop rock debris. Most slurry explosives are only detonable under 'heavy confinement' or in large quantities. They are composite explosives with low detonation velocities (3–4 km s⁻¹) and correspondingly low brisance. In fact, it is generally undesirable to use an explosive of high brisance for rock-blasting since it is preferable to break the rock into manageable blocks rather than to pulverise it.

Slurry explosives are rapidly replacing nitroglycerine-based blasting explosives for large-scale quarry work, especially in the USA, where they are produced in enormous quantities, often on site. The sensitivity of slurry explosives may be increased by the incorporation of small air or gas bubbles. Air bubbles may simply be introduced during the mixing of the explosive, or gas bubbles may be added in a more permanent form as small gas-filled silicate spheres, which are a by-product of coal-burning power stations. It is thought that the bubbles provide 'hot-spots', as the gas they contain is adiabatically compressed by the advancing detonation front, and that these hot spots assist propagation.

Another special type of explosive with both military and civil applications is detonating fuse. This consists of narrow flexible tube (4–5 mm diam.) of plastic or plastic-coated textile material which is filled with high explosive (generally PETN, pentaerythritol tetranitrate). A common commercial detonating fuse (cordtex) has an explosive loading of about 10 g of PETN per metre, and a detonation velocity of 6.5 km s⁻¹. Detonating fuse may be used as a cutting explosive, but in quarrying it may be used to connect and initiate charges in a pattern of bore-holes, reducing the number of detonators required and ensuring an almost instantaneous initiation of all the charges.

A summary of explosives with special applications would be incomplete without a brief mention of permitted explosives. Fire and explosion hazards are endemic to coal mines, where quantities of methane (fire-damp) and fine coal dust are often present, and permitted explosives are designed for underground blasting with the minimum risk of initiating a methane-air or dust-air explosion. Methane-air mixtures show a finite induction period before they will ignite, and a stimulus must be applied for at least this period before there is a reaction. Deflagrating explosives such as gunpowder are unsuitable for use in mines as their burning time is too long. On the other hand, many high explosives will also initiate methane-air mixtures by virtue of the high pressures and temperatures reached. Modern permitted explosives are high explosives with low detonation temperatures and pressures, but with detonation velocities sufficiently fast for the reaction to be over before the critical induction period for initiation is exceeded. There are, of course, many permitted explosives available each with their own specific properties, but by and large the required properties are obtained by diluting blasting explosives based on nitroglycerine and/or nitro-

cellulose with considerable quantities (sometimes more than 40%) of an inert diluent such as common salt.

The shaped charge

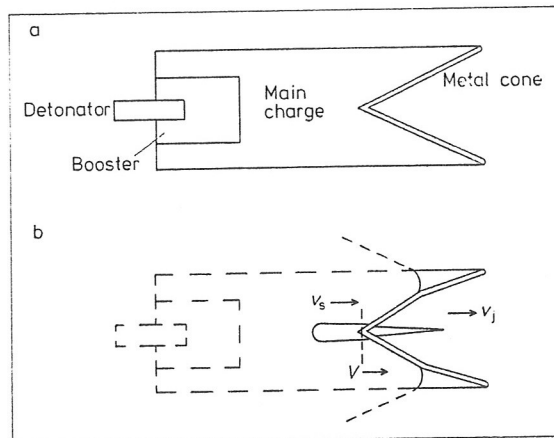
One of the most striking special applications of explosives is the shaped charge. This consists of a volume of explosive into which is recessed a hollow metal cone diametrically opposite the point of initiation, as shown in figure 5a. When the detonation wave reaches the conical liner, the metal is subjected to a pressure so high that the strength of the liner can be neglected and the flow field treated hydrodynamically. For instance the pressure from the explosive may be as high as 3×10^{10} Pa (300 000 atm) whereas the yield strength of the liner may be of the order of 8×10^8 Pa (8000 atm). The manner in which the cone collapses is shown in figure 5b.

Analysis shows that a jet will be formed moving at a velocity V_j greater than the velocity V_l given to the collapsing liner, and in addition a slug will be formed which propagates at a velocity V_s , less than V_l . A velocity gradient will develop along the length of the jet, being greatest at the head. This jet has great penetrating power. Typically, a shaped charge will penetrate a block of steel to a depth of five cone diameters, the penetration and cross-sectional area of the hole being directly related to the angle of the liner cone and the velocity of detonation of the explosive. Figure 6 shows the cross-section of a block of steel attacked in this way. The shaped charge is used extensively in military applications to defeat heavy armour, and is also used commercially to tap blast furnaces.

Classification of explosives

It is clear from what we have said that detonating explosives differ widely in their sensitiveness to external stimuli, and it is reasonable that they should

Figure 5 a – A shaped charge, where a hollow metal cone is recessed into the explosive opposite to the initiation point. **b** – Shows the manner in which the cone collapses



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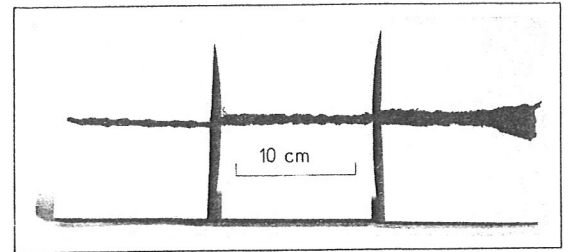


Figure 6 The penetration in steel (three pieces placed in contact) by a 63.5 mm cone diameter shaped charge

be classified according to the hazards associated with their handling, transport and storage. On this basis there are two classes into which detonating explosives may be divided – primary (initiator) explosives and secondary explosives. Primary explosives are very sensitive to impact, friction and in some instances electrostatic discharge. Consequently they are very dangerous to handle and special precautions and great care must be employed in their manufacture. Because of the comparatively small stimulus required for initiation, primary explosives are used in caps, detonators and primers. Two typical primary explosives are mercury fulminate (which was used in shell fuses from the mid 1880s to long after the first world war) and lead azide, which was used in the second world war and is still in use. There are many others.

Secondary explosives are comparatively insensitive to external stimuli, but once initiated are capable of releasing more energy per unit weight. Secondary explosives require, therefore, a fairly large stimulus to initiate detonation, such as that provided by the detonation of primary explosive. Another important difference between the two classes of explosive is that primary explosives can be made to detonate in a very small diameter charge (typically less than a millimetre) whereas for a secondary explosive much larger quantities are required. For example a cast and unconfined TNT charge will not sustain a detonation in a diameter of less than 25 mm.

The approach to assessing the sensitiveness of an explosive is essentially practical. Some of the tests carried out, particularly the preliminary tests, might appear rather crude and arbitrary, but their results for each class of explosives display a surprising consistency which, in the light of the data accumulated over many years, enables a broad picture of a new explosive's nature to be formed with some confidence. It would be tedious to describe all these tests in detail, and it is sufficient to state that their object is to assess the response of the explosive to impact, friction (between different types of surface, e.g. steel-steel, steel-brass, wood-wood, wood-stone), heat (temperature of ignition or explosion) and electrostatic discharge. The readiness with which a small quantity of the explosive will ignite when brought in contact with a burning gunpowder fuse, and the ease with which a train of the explosive will propagate combustion, are

also determined by small-scale tests.

The Rotter impact test is regarded as one of the most significant small-scale sensitiveness tests, and as its results clearly demonstrate quantitatively the difference between primary and secondary explosives, it is perhaps worth a brief description. The test involves dropping a weight (5 kg) from different heights upon small samples of the explosive under test contained in metal capsules. The figure sought in this test is the height from which the weight must be dropped to give an even chance of the explosive sample reacting. This figure is often termed the 'figure of insensitiveness', and a list of these for a variety of explosives may be found in table 2.

The results quoted in this table fall clearly into two main categories corresponding to primary and secondary explosives. The secondary explosive category may be subdivided, calling the more sensitive materials 'booster' explosives and the less sensitive materials 'main charge' explosives. This division depends upon the readiness with which the secondary explosive may be initiated by a charge of primary explosive (e.g. a detonator) alone. The distinction between primary and secondary explosives has a real and physical significance within the context of 'safety and arming' mechanisms in shells and bombs. Before such a weapon is armed, i.e. made ready for use, a barrier or 'shutter' exists between the fuse (primary charge) and the booster and main charges, so that if the fuse is detonated by accident the main charge will not be initiated and comparatively little damage will be done. On arming the weapon the shutter is removed. A typical safety and arming mechanism is shown in figure 7. The centrifugal bolts retaining the striker are disengaged as a result of the rotation of the projectile, and the detonator is aligned with the striker.

The small-scale tests mentioned so far are but a few of those currently employed. In addition, large-scale trials using real or simulated weapons filled with explosives are conducted to determine their

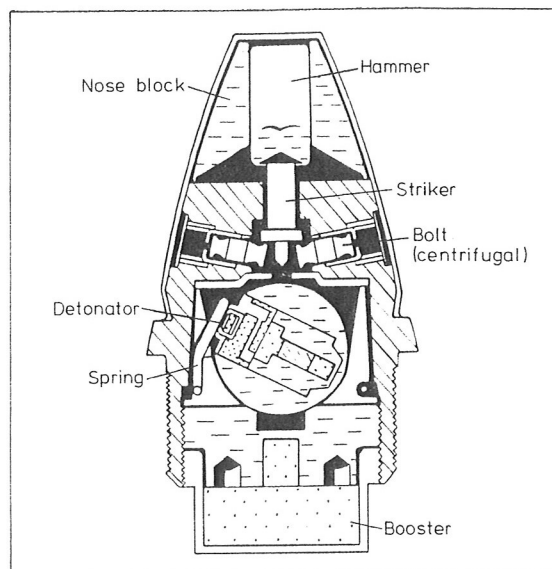


Figure 7 A safety and arming mechanism in an explosive shell

response to all aspects of bad handling, climatic storage and fire. Information from trials of this type is valuable in deciding whether an explosive store is a detonation and fragmentation risk or 'simply' a fire risk. The conditions allowed for packaging, transport and storage will depend upon such a decision.

It is beyond the scope of this article to dwell further upon the complexities of sensitiveness and hazard, but it is comforting to know that the whole question of explosive hazard in all branches of the military services and industry is under constant review. It is not necessary for a detonation to occur for a great deal of damage to be done, and criteria in addition to detonation and deflagration are being sought and defined which may be more readily correlated with real damage.

Where next?

Over the past fifteen years a wide variety of composite systems have been examined as explosives and propellants with a view to improving performance. There comes a point however, when increase in output is matched by an increase in sensitiveness and a decrease in chemical stability which are unacceptable from the point of view of storage and handling. Whilst it is possible that there may be a breakthrough in performance, there is no evidence at present that it will occur.

Advances may be made in the field of special applications. For example space research has created a demand for explosives and propellants (for explosive bolts and gas generators) which are able to resist high temperatures for protracted periods and still remain serviceable. Compounds such as diamino-trinitrobenzene and triaminotrinitrobenzene have been considered.

Table 2 The impact sensitiveness of some common explosives

Explosive	Class	Figure of insensitiveness
Mercury fulminate	Primary	10
Lead azide		20-30
HMX	Booster explosives	60
PETN		50
RDX		80
Tetryl		90-100
Picric acid	Main charge explosives	120
Comp. B		140
TNT		150
Torpex 2B		170