Explosives
Technology for
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Explosives Technology

For

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EXPLOSIVES TECHNOLOGY

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CHAPTER 1: INTRODUCTION TO EXPLOSIVES

BACKGROUND

An explosion may be defined simply as a rapid expansion of gas that can perform work on the immediate surroundings. However, another definition may be, a chemical or mixture of chemicals that is, or are, a self-contained source of energy. This latter definition allows pyrotechnics to be included within the category of 'explosives' as, indeed, they are. There are three distinct types of explosion:

Physical explosion;

Nuclear explosion;

Chemical explosion.

This course is concerned with the chemical explosion in but a brief mention of the other types is given for comparison, showing that all types create rapid gas expansion but by different mechanisms.

Physical explosion

As children we have all witnessed a balloon bursting. This is a simple example of a physical explosion. On a more damaging scale cylinders of compressed gas can explode. This may well happen in a fire. In this case the compressed gas is heated and increases the pressure inside the cylinder. Eventually the tensile strength of the cylinder is exceeded and the cylinder ruptures releasing the gas. The cylinder might break into a number of fragments, these will be propelled at speed and can damage buildings or personnel in the area. A physical explosion of this nature is the very rapid release of gas. In nature the extreme case of a physical explosion occurs when a volcano erupts. This is the sudden vaporisation of a liquid to a gas and can be devastating (Krakatoa, August 27th 1883).

Nuclear explosion

In a nuclear explosion uranium of plutonium is split releasing energy (atom bomb). This in turn may be used to fuse light elements (hydrogen isotopes) and release greater amounts of energy (hydrogen bomb). It is the very rapid release of heat which causes the explosion. Gas in the vicinity is raised to enormously high temperatures. This gas then expands rapidly. A nuclear explosion is the rapid release of heat.

Chemical explosion

A chemical explosion is caused by very rapid chemical reaction liberating both heat and gas. This is the type of explosion of concern for the remainder of this work.

THE DEVELOPMENT OF EXPLOSIVES

The Fuel-Oxidiser Mixture Concept

Generically, material that is burned to create heat is called a 'fuel' and most fuels consist of carbon and hydrogen (hydrocarbons). To burn a fuel, oxygen is required and normally this will come from the air. In a controlled reaction this chemistry is used to produce heat for cooking and space heating in homes and businesses and for industry. However, take a large quantity of hydrocarbon, which is a vapour or a gas, and pre-mix it with air, then an explosion is possible. This type of fuel-air explosion accident is common worldwide. There is merit in creating this effect for military purposes and there are many weapons that use this concept.

Solid explosives have been known since about 700 A.D., probably discovered by the Chinese. Black powder (or gunpowder) first was used as a propellant for rocket assisted lances. In the thirteenth century, the scholar Roger Bacon experimented with saltpetre and is reputed to have developed a workable explosive. A number of European scholars similarly discovered the secrets of explosives. By the end of the 13th century explosives were being used for wall breaching. There is evidence that, by 1320, black powder was being used in guns. Black powder is a mixture of charcoal, sulphur and saltpetre (potassium nitrate KNO_3), that is a mixture of fuel and oxidiser. The carbon fuel is burned by the oxygen held within the potassium nitrate thus producing carbon dioxide gas (together with nitrogen gas from the nitrogen in the nitrate) and heat. The speed of reaction and thus the performance of black powder as an explosive, will depend on the intimacy of mixing. With black powder, where all the components are solid, this is not as easily achieved. Early black powder simply was a mixture of the powdered materials. It was not until the introduction of corning, to ensure intimate contact of the fuel and oxidiser, that black powder would give reliable performance. Corning requires a mixture of the components and water to be milled together and then pressed and dried before being broken up into grains.

There are many explosives of this form, often these are found in improvised explosive devices such as sugar/sodium chlorate mixture or sugar/ammonium nitrate. Commercial examples would include ANFO, a mixture of **A**mmonium **N**itrate and **F**uel **O**il, which constitutes over 50% of all blasting explosive used in the UK.

Explosive Molecules

By the middle of the 19th Century the limitations of black powder were being found. More difficult mining and tunneling operations required a better explosive. The first modern explosive, nitroglycerine, was discovered in 1846 by the Italian Professor Ascanio Sobrero, who realised the hazards of this material and did not pursue its study. This was carried out by Immanuel Nobel.

1863 saw the production of nitroglycerine by Nobel and his family including Alfred (of the Nobel Prizes) at Helenebourg. The material, liquid nitroglycerine, whilst being a very acceptable commercial explosive, had several problems. These can be summarised as:

i) initiation of the nitroglycerine initially was unreliable (use of fire, etc)

ii) it was prone to accidental initiation

iii) it was a liquid

The first problem was solved in 1864 by the development of the mercury fulminate detonator.

Problem two resulted in the factory being destroyed, in 1864, by an accidental initiation of the material. This problem was, to an extent, solved by the Nobels by using kieselguhr (1867) as an absorbent, which led to the dynamites and later, gelignites. This solved, also, the problem of being a liquid.

Nitroglycerine, structurally, has a great advantage over the fuel oxidiser mixture, since it contains both fuel (carbon and hydrogen) and oxidiser element (oxygen in the nitro groups) in the same molecule. This gives a constant ratio for the oxidising element to the fuel elements and the most intimate contact for the fuel and oxidiser. There are 3 classes of these explosive molecules:

C-nitro compounds

When a nitro group ($-NO_2$) is attached to a carbon atom this is classified as a C-nitro compound. Materials such as TNT fall into this chemical classification. In general the C-nitro compounds are intrinsically the more stable of explosive molecules.

N-nitro compounds (nitramines)

The next most stable (i.e. more easily initiated) chemical class of explosives is the nitramine or N-nitro compound. RDX and HMX fall into this class.

O-nitro compounds (nitrate esters)

In general the least stable of explosive compound is the nitrate ester or O-nitro compound. Materials such as nitroglycerine (NG) and nitrocellulose (NC) are quite typical in this respect, needing stabilisers to be added if the material is to be stored for longer than a few months.

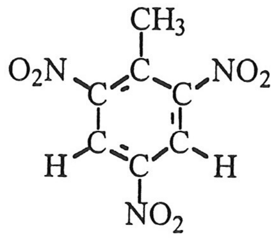
PETN is also a nitrate ester. It is somewhat more stable then NG and NC and has been found in high explosive formulations such as Pentolite.

STRUCTURES AND DATA FOR SPECIFIC EXPLOSIVES

Data for the most important explosive molecules is given below.

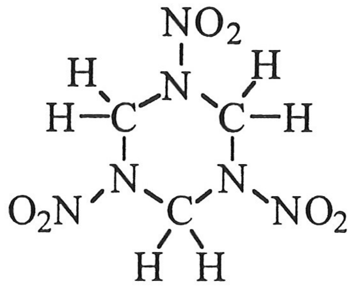
Key to Data:	Q	the heat output for one gram of explosive.
	V	the gas output for one gram of explosive.
	T_d	detonation temperature in Kelvin.
	m.p.	the melting point of the explosive.
	D	detonation velocity.

TNT (Trinitrotoluene)



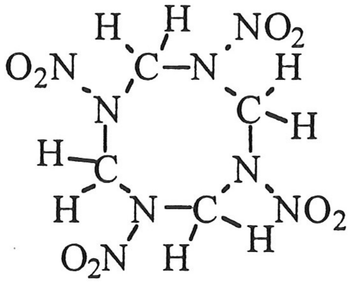
Formula	$C_7H_5N_3O_6$
Q	4080 Jg^{-1}
V	790 cm^3g^{-1}
T_d	2595 K
m.p.	80.7°C
D (@1.6gcm^{-3})	6900 ms^{-1}

RDX (Research Department eXplosive)



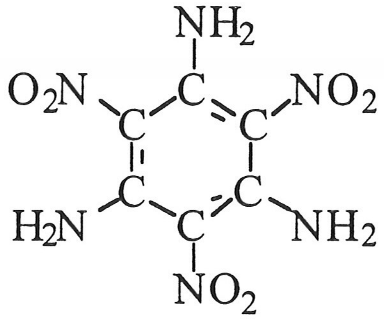
Formula	$C_3H_6N_6O_6$
Q	5130 Jg^{-1}
V	908 cm^3g^{-1}
T_d	4255 K
m.p.	204°C
D (@1.76gcm^{-3})	8750 ms^{-1}

HMX (High Molecular-weight eXplosive)



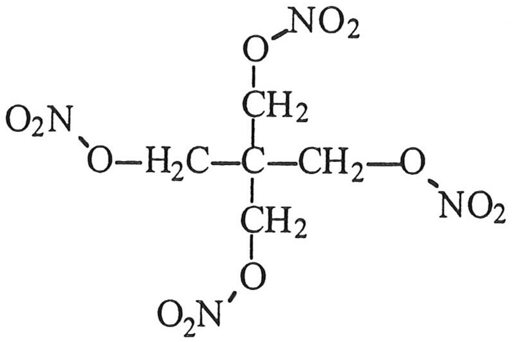
Formula	$C_4H_8N_8O_8$
Q	5130 Jg^{-1}
V	910 cm^3g^{-1}
T_d	4200 K
m.p.	278°C
D (@1.9gcm^{-3})	9100 ms^{-1}

TATB (1,3,5,-triamino-2,4,6-trinitrobenzene)



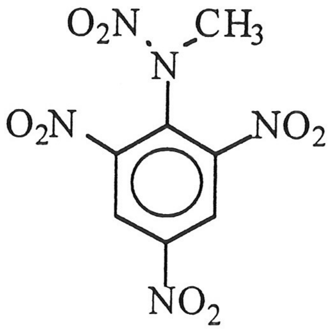
Formula	$C_6H_6N_6O_6$
Q	3496 Jg^{-1}
V	781 cm^3g^{-1}
T_d	2880 K
m.p.	340°C
D (@1.8gcm^{-3})	7350 ms^{-1}

PETN (PentaErythritol TetraNitrate)



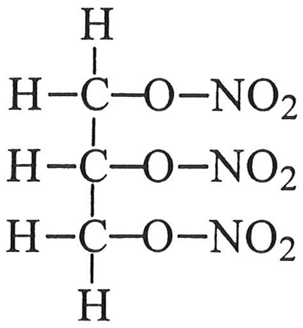
Formula	$C_5H_8N_4O_{12}$
Q	5940 Jg^{-1}
V	790 cm^3g^{-1}
T_d	4625 K
m.p.	141°C
D (@1.7gcm^{-3})	8400 ms^{-1}

TETRYL OR CE (Composition Exploding)



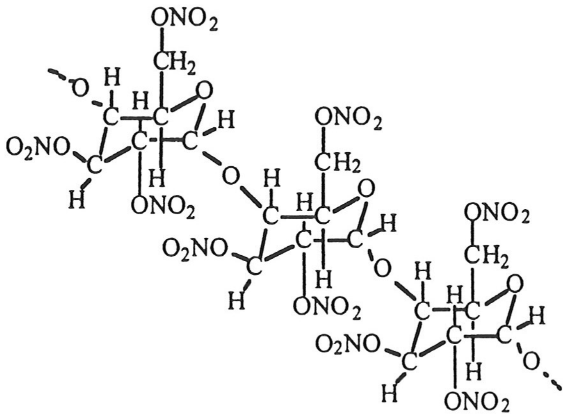
Formula	$C_7H_5N_5O_8$
Q	4350 Jg^{-1}
V	845 cm^3g^{-1}
T_d	3545 K
m.p.	130°C
D (@1.71gcm^{-3})	7570 ms^{-1}

NG (Nitroglycerine)



Formula	$C_3H_5N_3O_9$
Q	6275 Jg^{-1}
V	740 cm^3g^{-1}
T_d	3290 K
m.p.	13°C
D (@1.59gcm^{-3})	7600 ms^{-1}

NC (Nitrocellulose)



Formula	$(C_6H_7N_3O_{11})_n$
Q	3745 Jg^{-1}
V	880 cm^3g^{-1}
T_d	3290 K

CHAPTER 2: BURNING AND DETONATION

INTRODUCTION

When explosives function they can operate in one of two modes. These are burning and detonation and in many cases the explosive can function by either method depending on initiating stimulus. Thus, explosives are categorised as:

Low Explosives	Burn in their designed use
High Explosives	Detonate in their designed use.

Note the word 'designed' as virtually all explosives may be persuaded to detonate.

BURNING

Burning is a surface reaction and as it progresses successive layers are raised to their initiation temperature and ignite. This is due to the transfer of heat from the burning surface to the layer below. Most of the heat is lost to the surroundings, removed by the gaseous products. As the heat is transmitted to the next layer, mainly by conduction in a solid propellant or explosive, the temperature gradually rises. As the process continues the propellant layer reaches its ignition temperature and spontaneously ignites. This layer then starts to raises the temperature of the next layer etc. This process is shown in Figure 1.

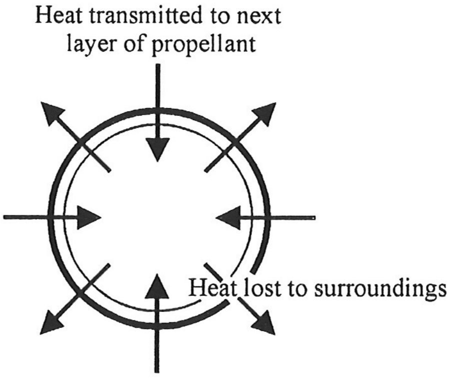


Figure 1: The Explosive Burning Process

As the burning only takes place at the surface, the rate at which a given mass of material burns is a function of the total surface area. For example in a gun we require the propellant to burn before the projectile is out of the barrel. That is we require a very fast mass burning rate. To achieve this, small grains with large surface areas used. Conversely in a rocket system the main motor is required to burn for a relatively long period of time (compared with a gun system) and single large grains tend to be used.

Pressure will also effect the rate at which a propellant burns. As the system pressurises it could be envisaged that the heat being transferred away from the propellant is now being held around the propellant and more heat will then be transferred into the propellant. This will raise successive layers to the ignition temperature quicker. In the open a propellant grain may burn for many seconds. However, in a gun breach, the pressure will increase considerably

(20-30 tons/sq. inch) and the propellant will burn in a few milliseconds. This gives linear burning rates of around 5 mms^{-1} in the open and 400 mms^{-1} in a gun.

An explosive that will burn in its normal mode of operation, e.g. a propellant, is said to be a low explosive. Low explosives do work through the expanding gas formed as the explosive burns.

DETONATION

Detonation is a bulk phenomena, that is, it occurs through the material not just at the surface. A shock wave passes through the material, breaking the bonds holding the explosive molecules together. The rate at which the process occurs is dependent, not on heat transfer, but on the speed at which the shock wave passes through the material.

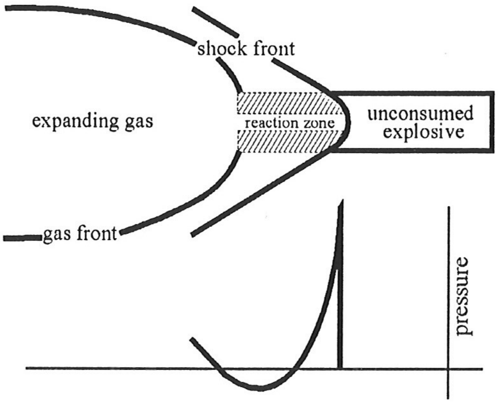


Figure 2: Detonation Passing Through an Explosive

As the shock wave passes through the explosive it will experience a very rapid rise in pressure. This creates high temperature and causes the explosive molecules to react. Behind the shock wave is a reaction zone in which the products of explosion are formed. Once formed the products of detonation then expand. This process is shown in Figure 2.

There are 2 major differences between the burning and detonation processes. One is the speed at which they proceed and the other is the effect known as BRISANCE, which can only occur with a detonation.

Velocity of Detonation

When an explosive is detonating it will achieve a steady state velocity (speed). This is known as the velocity of detonation. The range for military explosives is between 6,5000-8,500 ms^{-1}. This far exceeds the speed of sound in the material.

Critical Diameter

With any detonating material there is a minimum diameter for the material below which it cannot sustain detonation. PETN has a critical diameter less than 1mm and thus is employed in detonating cords. Pure TNT has a critical diameter of ~7 mm.

Effects of Detonation

Brisance is the ability of a detonating explosive to shatter strong materials, such as steel. It is caused by the pressure in the detonation shock wave, which may exceed 250,000bar (atmospheres). To be effective the explosive should be touching the material, for example the contact of an explosive filling with a shell case. Fragmentation munitions employ the brisance effect. The gas expansion from a detonation is extremely fast and can be used to create lift and heave for cratering or produce a blast wave.

TABLE 1
A Comparison of Burning and Detonation

Burning	**Detonation**
Burning is a surface reaction	Detonation is a bulk reaction
Burning rates are typically a few mms^{-1} to $500ms^{-1}$.	Detonation rates are typically 4,000 to $9{,}000ms^{-1}$.
Burning can lead to the build up of pressure on a container giving a pressure burst	Detonation causes fragmentation of a container if it is in contact with the explosive through brisance.
Burning is initiated by the action of heat on an explosive (direct flame, adiabatic heating, friction).	Detonation is initiated by the action of a shock wave on the explosive.
Burning rates depend on pressure.	Detonation velocity is dependent on the explosive, its density and, for small charges only, charge diameter.

CHAPTER 3: INITIATION OF EXPLOSIVES

ACTIVATION ENERGY

To initiate an energetic material it is necessary to input some energy, as heat, to create the chemical reaction of explosive to gaseous products. Some explosives will be easier to initiate than others thus they are classified as either primary or secondary explosives. This is best quantified by a property known as 'activation energy'. Figure 3 below shows pictorially this concept.

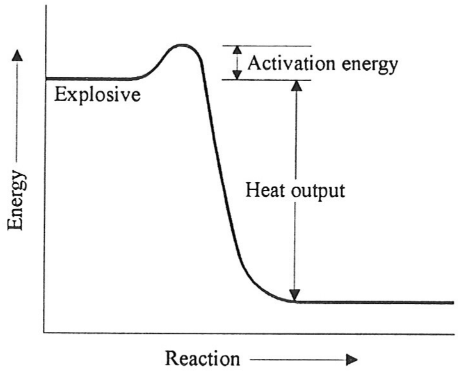


Figure 3: Energy Profile for Explosive Initiation

There are many mechanisms that can create heat in the explosive such as percussion, friction, flame and indeed the detonation shock wave. However, the key to producing explosive decomposition is to overcome the activation energy after which the process will be self-sustaining.

Thus, primary explosives have low activation energies and secondary explosives have larger activation energies. In other words, primary explosives are easy to initiate (sensitive) and secondary explosives are more difficult to initiate. For safety reasons it is unwise to say that secondary explosives are hard to initiate as it gives the wrong message.

EXPLOSIVE TRAINS

Most practical explosive devices will contain a series of materials starting with easily initiated compositions (primary explosive), booster compositions (secondary explosive) and main charge (very insensitive secondary explosive). This is used to achieve safety and reliability in performance. Many detonating devices will include a lead azide containing composition as initiator, which is separated from the booster charge by shuttering or being move out of line. Such a simple method affords protection in the event of accidental initiation of the primary explosive. The output of the primary explosive is small and will not propagate through the munition unless it is in almost direct contact with the booster. The movement to bring the initiator in line with the booster is called 'arming' and for this to happen in a detonating explosive train, the warhead must experience 2 independent environmental stimuli. These may include g-forces on launch, spin on launch, pressure in a rocket motor, a spinning vane for air dropped ordnance, etc.

Burning explosive systems such as propelling charges also have an explosive train of events. However, it is often found that the train is complete even in storage and arming is not required, for example in fixed artillery ammunition. However, in a tank gun the booster and initiator are present in the vent tube.

Below in Figure 4 is a diagrammatic representation of an explosive train.

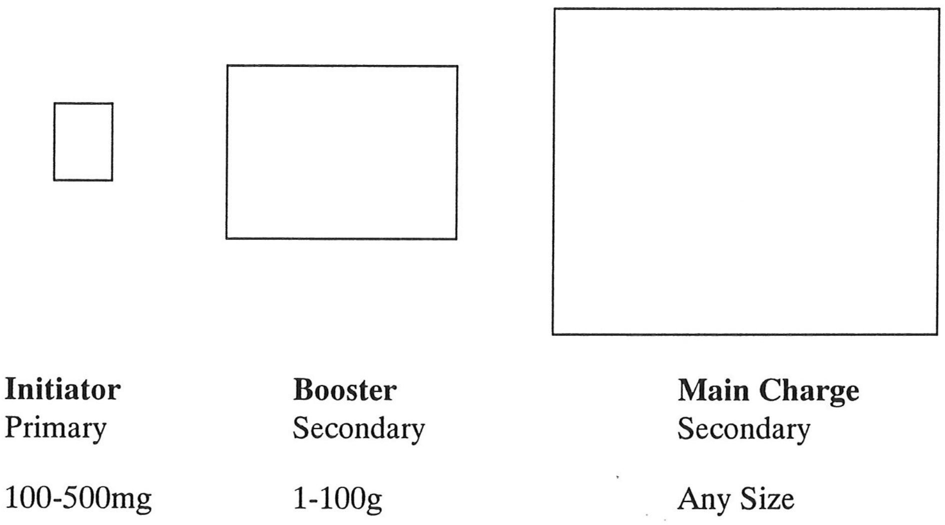


Figure 4: Make-up of an Explosive Train

INITIATION TO BURNING

Any method chosen purposefully to initiate explosives must be reliable, that is function as expected when we require the process to take place. However, it must not occur accidentally. To ensure reliability we require explosives that are easily initiated. For the second consideration we require explosives that are not readily initiated. In practice we use both types as demonstrated above. Thus, when considering initiation there are always 2 points of view, safety and reliability.

External Heat

If an explosive were heated in a test tube we would not be able to predict how long it would take for the material to ignite. Thus, simply heating an explosive to create ignition is not useful from a practical viewpoint. However, if propellant were heated in a gun barrel, for example a round left in a hot gun breech it would eventually reach the point of initiating. This is known as cook-off, an accidental initiation, and has been witnessed with rapid fire weapon systems. A typical propellant will initiate with external heating at 180°C-200°C.

External heating is not used practically to initiate explosives, propellants or pyrotechnics to burning. It is, however a relatively common form of accidental initiation, for example, in fires.

Flash or Flame

The initiation of propellants and pyrotechnics by flash or flame is commonly employed. Thus, a burning composition is capable of transmitting flame to another component in an igniferous train. A flame consists of hot gases and, particularly in the igniferous train, hot particles. Both play a part in initiating other materials. The hot gases raise the temperature of the next component possible to its initiation temperature. The hot particles will produce hot spots in the acceptor material which lead to initiation. Black powder is particularly good at this type of initiation producing large amounts of hot burning particles. It is thus used in the primer tubes of many propellant initiation systems.

Percussion

In the initiation of small arms rounds a firing pin strikes a percussion cap to initiate the primary composition. When the striker pin hits the cap the composition is compressed between the firing pin and the anvil. The materials will be heated due to compression heating, known as adiabatic heating (like a diesel engine) and some friction as the particles rub against each other. The importance of the frictional heat contribution is increased by the addition of gritty material to the composition. A typical percussion cap is shown in Figure 5.

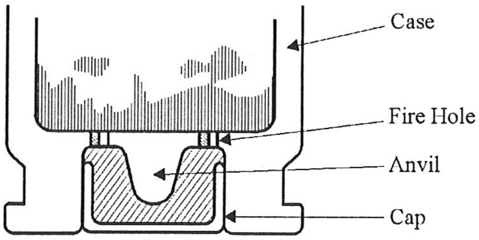


Figure 5: Percussion Cap Igniter

Friction

Friction is not a practical method of initiating military propellants or explosives. It is, however one of the most significant means of accidental initiation of powdered materials.

The thunder flash is one of the few devices where friction is used practically, in this case to initiate a pyrotechnic composition.

Stabbing

Friction, however, plays a major role in the initiation of primary explosives by the process of stabbing. The movement of the stabbing needle and subsequent movement of the composition will generate hot spots in the explosive. A typical stab sensitive compositions would contain lead dinitroresorcinate (LDNR), barium nitrate and tetrazene. Such a composition could be used as the first stage of a detonating system. The first step is to initiate the stab sensitive composition to burning, subsequently changing this to detonation with other material as discussed later.

Stab initiators require about 60 mJ of energy to initiate the primary composition. These are to be found in a very wide range of munitions e.g. aircraft bombs, anti-personnel mines, shell fuses, tank mines, etc.

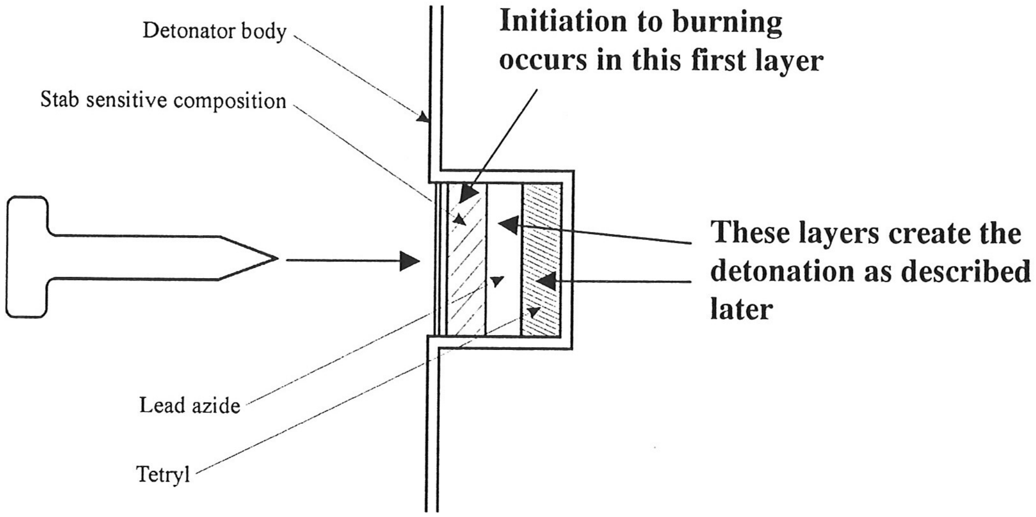


Figure 6: A Schematic Diagram for a Stab Detonator

Electrical

The most common system of electrical initiation uses a bridge wire, sometimes called an electric match-head. It consists of a resistance wire covered by a primary explosive composition. When a current flows, the wire heats and ignites the explosive. This creates a flash of flame that can be used to ignite the next component of an initiating system. It takes about 10 mJ to initiate the electric match-head. All fire currents of about 1-5 amps are typical for these devices which have a resistance of about 1Ω. Figure 7 shows such a bridge wire initiator as found in, for example, demolition detonators.

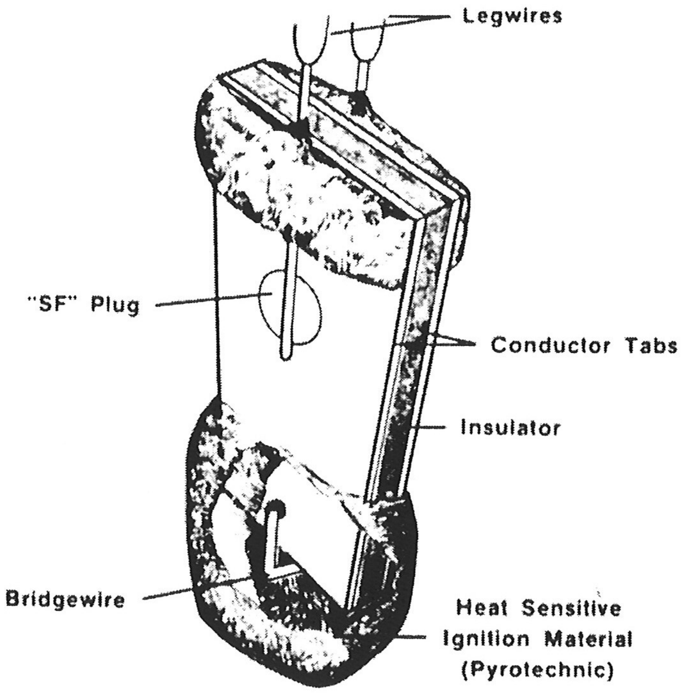


Figure 7: An Electric Bridge Wire (Match-head)

A variant of this is a conducting composition. Such compositions contain graphite to make the composition electrically conducting. Heating of the composition is due to resistive heating of the explosive itself. The low resistance makes devices initiated by fuze heads susceptible to induced and stray electrical currents.

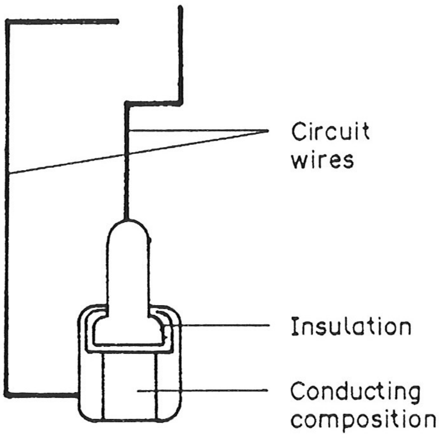


Figure 8: A Conducting Composition Initiator

One final method of initiating explosives electrically is a well known hazard. This is the discharge of static electricity. This may come from equipment, particularly that with moving brushes or belts. However, one major source of static electrical discharge is from humans. This level of discharge can initiate primary explosives.

Chemical Reaction

It must be remembered that explosives are reactive chemicals. If placed in contact with other reactive chemicals it may be possible to induce initiation to burning.

INITIATION TO DETONATION

Initiation to burning is probably much easier to achieve than a direct initiation to detonation. Hence many devices will be initiated to burning and then converted to detonation by a burning to detonation step.

Burning to Detonation

In a typical demolition detonator, an x-ray of which is shown in Figure 9, an electric match-head is initiated, the output from this is flashed onto a flash receptive layer of azide-styphnate-aluminium (ASA) composition. This initially will ignite but almost instantaneously the composition achieves a detonation velocity. Plain detonators use the flash from safety fuse in place of the electric match-head.

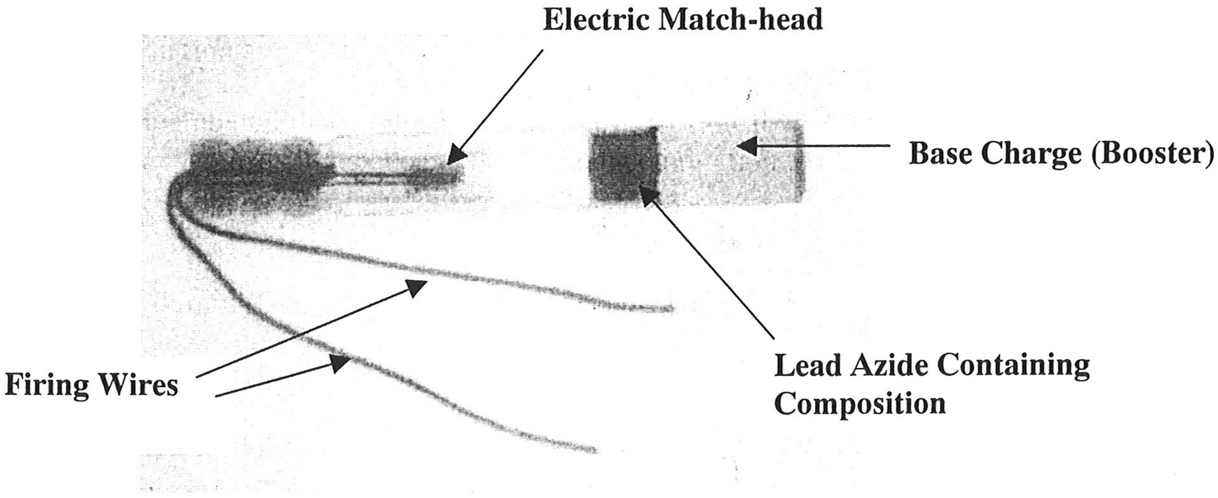


Figure 9: X-Ray of An Electric Detonator

Donor/Acceptor Initiation

All secondary explosives used as main fillings in munitions are initiated by a detonation shock wave produced by another detonating explosives. In a typical shell an ASA primary explosive will burn to detonation as described above afford the first detonating step. This now can act as a detonating donor charge and the shock wave is passed on to a tetryl or Debrix (RDX/wax) booster charge as acceptor. Similarly as the shock wave leaves the booster charge (donor) it will enter the main filling (acceptor) and repeats the process giving reliable detonation of the warhead.

Exploding Bridge Wire (EBW) and Slapper Detonators

Recent developments have made it possible to initiate secondary explosive materials directly to detonation without the use of a primary explosive that burns to detonation. Such devices require large energy inputs from high voltage capacitor discharge sources.

An exploding bridge wire (EBW) uses a current in the order of 700-1000 amps which is deposited in a fraction of a microsecond to vaporise a wire, which explodes violently creating a shock wave. The shock generated by this is capable of initiating low density PETN, a secondary explosive, directly to detonation. Such high energy inputs cannot be produced with out using the firing circuit. This makes the device safe from accidental initiation by induced electrical currents. Also, there is no sensitive primary explosive present, making this a very safe detonator.

Slapper detonators, also known as 'exploding foil initiators (EFI), use similar energy inputs to fire a disk of plastic into hexanitrostilbene (HNS) or PETN. Again this will produce a shock wave sufficiently large to initiate the secondary explosive directly.

CHAPTER 4: PROPELLANTS

INTRODUCTION

Historically, guns employed black powder (gunpowder) to propel a projectile. Black powder is a mixture of carbon, sulphur and potassium nitrate. This led to problems in mixing as the different components need to be in intimate contact to function correctly. In the late nineteenth century nitrocellulose (gun cotton) was perfected as a gun propellant. Further improvements in performance were made by the introduction of nitroglycerine to the nitro-cotton to give higher flame temperatures. This resulted in the rapid erosion of barrels and the formation of flash due to the hot fuel gases (hydrogen and carbon monoxide) igniting on mixing with the air. Nitroguanidine (picrite) has been added to propellants to give flashless propellants by reducing the flame temperature. The lower temperature results in lower performance but is mitigated to an extent by the larger volume of gas produced. In recent times high performance propellants have had RDX and/or HMX added to the formulation. There is some work being carried out to investigate the use of liquid propellants (LP) in guns and demonstration models available today may lead the way to LP guns for both direct and indirect fire applications.

SOLID GUN PROPELLANTS

Gun propellants have traditionally been fabricated from nitrocellulose based materials. The use of the fibrous material provides mechanical strength to the material and also affords a method of controlling the burning surface area. Typically the propellant, in a granular or stick form, is fabricated to have a controlled burning surface throughout the burn. Gun propellants have to be all burnt in a fraction of a second and as such have a large surface area.

Propellant Grain Shape

To ensure rapid consistent burning of propellants in a gun a large surface area is required. To achieve this various grain sizes and shapes are employed. Some of these are shown in Figure 10.

If the propellant grain has only an outer surface e.g. a cord or ribbon then the surface area decreases as the burning process takes place. This is known as regressive burning. When an inner surface is exposed and allowed to burn e.g. tube or slotted tube then the decrease in the outer surface area is compensated for by an increase in the inner surface and the two surfaces move towards each other. This is known as neutral burning. Finally if the inner surface increases faster that the outer surface decreases we have progressive burning. This is the case with a multi-tubular propellant. Multi-tubular propellants tends to be use in large calibre guns where the volume behind the projectile increases considerably as the projectile moves up the barrel.

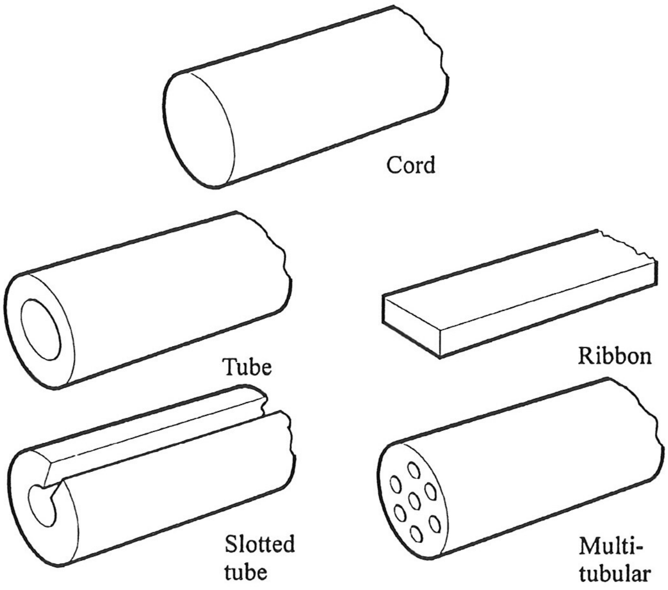


Figure 10: **Some Gun propellant Grain Shapes**

Single Base Propellants

Nitrocellulose on its own would be termed a single base propellant. The nitrocellulose can be manufactured, typically, to have between 12.5% and 13.2% nitrogen. As the nitrogen only appears in the nitro group within the molecule this gives a measure of the degree of nitration of the cellulose, a higher nitrogen percentage indicating more nitro groups in the molecule and hence more oxygen and a better oxygen balance. fully nitrated material would have a nitrogen content of ~15%. Single base propellants have application in small arms rounds, mortars and howitzers.

Double Base Propellants

The addition of nitroglycerine to nitrocellulose will give a double base propellant, the term double base indicating that there are two energetic materials in the propellant. Nitroglycerine has a positive oxygen balance producing a better oxygen balanced product than nitrocellulose on its own. This results in higher flame temperatures for the ,propellant which in turn will result in a higher pressure for the gas in the gun barrel and produce greater thrust. On the negative side higher temperature results in barrel erosion and hotter gases leave the barrel. The resulting muzzle flash caused by flammable gases exiting the barrel at high temperature and igniting can be used to locate the gun. Double base propellants are found in small arms and mortars.

Triple Base Propellants

To reduce muzzle flash, a third energetic material, nitroguanidine (picrite), is employed. These propellants are now termed triple base. The nitroguanidine molecule has a large nitrogen percentage having a formula $CH_4N_4O_2$. The introduction of over 50% nitroguanidine to the propellant will reduce the flame temperature but increase the gas volume. The overall effect is to reduce the performance slightly but to increase the barrel life due to less erosion and reduce muzzle flash. Triple base propellants are used in tank gun rounds and large calibre rounds.

High Energy Propellants

Recently higher velocities have been required for the attack of armour as with Armour Piercing Fin Stabilised Discarding Sabot (APFSDS) ammunition. This could be achieved by the use of a double based propellants with a high nitroglycerine percentage. However, this will result in the problems of NG exudation from the propellant - not something to be encouraged for long term storage. One method is the incorporation of the explosives RDX or HMX in place of some or all the nitroguanidine in a triple base propellant to give the improved performance without the problems of NG exudation. However, these high energy propellants can be vulnerable to fragment and/or shaped charge jet initiation.

PROPELLANT ADDITIVES

There are a large number of other chemicals added to a gun propellant formulation. These include:

Stabilisers to control the slow decomposition of the nitrocellulose and nitroglycerine, which could lead ultimately to spontaneous ignition in storage.

Plasticisers to aid in extrusion processes during manufacture and to resist cracking of the propellant grains during their burn.

Flash supressants (other than Picrite) to reduce muzzle flash.

Surface lubricants (graphite) particularly with very small grain propellant such as for small arms ammunition to moderate the initial burn.

Water repellants such as dinitrotoluene are used to prevent the propellant absorbing water from the atmosphere.

Table 2
Data for Some Propellants

Material	Contents %	Oxygen Balance	Flame Temp (K)	Q (Jg^{-1})	Gas Vol. (cm^3g^{-1})
Single base (FNH)		-51.3	2519	3140	855.4
NC (13.15%N)	84.0				
Diphenylamine	1.0				
Dibutyl phthalate	5.0				
2,4-dinitrotoluene	10.0				
Double base (NNN)		-28	3280	4300	810
NC (13.2%N)	90.2				
NG	8.0				
Carbamite	1.8				
Triple base (NQ)		-31.9	2810	3287	1195.6
NC (13.1%N)	20.8				
NG	20.6				
Picrite	55.0				
Carbamite	3.6				
High Energy		-31.7	3653	4415	984.8
NC (13.1%N)	21.3				
NG	17.7				
RDX	55.0				
Dibutyl phthalate	5.0				
Carbamite	1.0				

ROCKET PROPELLANTS

ROCKET GRAIN SHAPES

Rocket propellants generally burn on an inner surface. To achieve this the outer surface is either bonded to the body of the rocket or an inhibitor is applied to the outer surface. Rocket propellant grains tend to be large in comparison to the gun propellant grains as they are generally required to burn over a prolonged period of time. Shaping of the propellant grain can effect the type of burning by control of the burning surface areas. Very fast burning motors will have large surface areas and thin webs, which will burn up quickly. This is particularly important in an ABOL (all burnt on launch) motor as would be used in a shoulder launched weapon. A second longer burning motor may well be incorporated as well to give a longer range. There would need to be a delay between the ABOL motor burning out and the main motor igniting to prevent the operator being burnt by the hot gaseous exhaust.

A cigarette burn would only give combustion on a single flat face, giving a constant but low burning surface area. The tube will give a bigger surface area and as it is only the inner surface burning the surface area will increase as the burn continues, this is again known as progressive burning. The slotted tube could give a rapid initial burn followed by a cigarette burn giving boost and sustain motors in one grain. The star centre, multi-perforated and dendritic grains are all designed to give neutral burning. That is maintain a fairly constant surface area as the propellant burns. These are shown below in Figure 11.

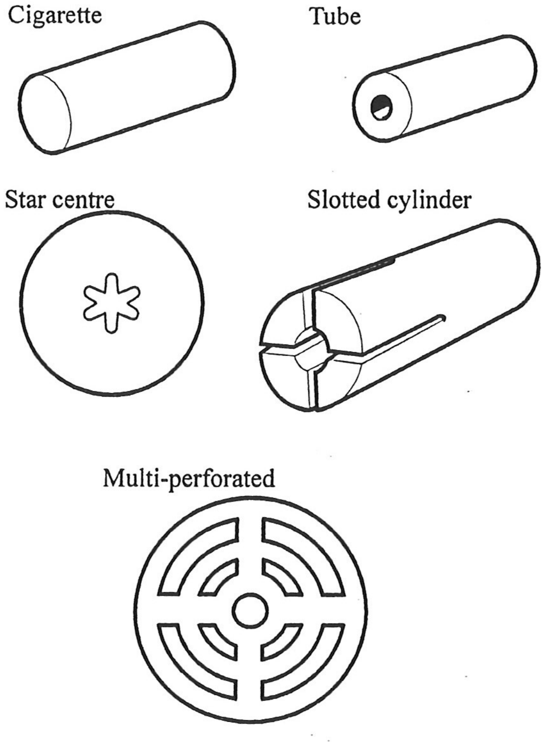


Figure 11: Shapes for Some Rocket Motor Grains

DOUBLE BASE ROCKET PROPELLANTS

Double Base rocket propellant compositions contain nitroglycerine and nitrocellulose similar to a gun propellant. However, as erosion by hot flame is less important, this formulation can contain much more nitroglycerine and be more energetic than the gun propellant. This type of propellant can have a number of advantages:

smokeless burning;

may be platonised;

can be cast or extruded in to complex shapes.

The concept of platonisation is important, as it is possible by use of additives to create a pressure range over which the linear burning rate does not alter. If this pressure range can be engineered to be that at which the motor operates then a very stable burning system can be created.

Disadvantages of Double Base rocket propellants include:

prone to cracking at low temperatures;

prone to out-gassing;

limited maximum energy.

COMPOSITE ROCKET PROPELLANTS

The alternative to the Double Base type is a fuel oxidiser mixture typically ammonium perchlorate with a rubbery polymer as fuel/binder. This type of propellant is known as a composite propellant. They too have advantages:

very high energies can be achieved giving large thrust;

very large motors can be cast;

excellent physical properties.

The disadvantage of this type of propellant are:

the smoky exhaust plume generated, which is corrosive and toxic;

stress cracking can occur with large grains when setting during manufacture.

Typically cross-linked hydroxy terminated butadiene is used in rubbery propellants. Aluminium may be added to the formulation to increase the flame temperature. This cannot be used in Double Base propellant.

CHAPTER 5: HIGH EXPLOSIVE FILLINGS

INTRODUCTION

High explosive fillings are produced from a limited range of materials. The properties of these materials, both individually and in mixtures, assign the characteristics of the filling. The performance of the filling is determined by such properties as Power Index and Detonation Velocity. Similarly the sensitiveness of the filling is determined by Figure of Insensitiveness (F. of I.) and ignition temperature. Additionally the density of a filling composition will determine the amount of explosive placed into a given cavity. Table 3 lists some of the common explosives and their properties.

Table 3
Common High Explosives and Their Properties

Explosive	Density (g cm^{-3})	Melting Point (°C)	Ignition Temp (°C)	Detonation Velocity (m s^{-1})	Power index[1]	Rotter F. of I.	Detn. Pressure (kbar)
NG	1.60	13	188	7750	160	30	230
PETN	1.76	141	205	8300	161	50	300
Tetryl	1.73	130	185	7160	123	90	220
TNT	1.64	80	240	6950	117	150	190
RDX	1.81	204	213	8400	159	80	347
HMX	1.91	278	300	9110	159	60	393
TATB	1.94	340	359	7760	108*	>200	275
HNS	1.74	318	325	7000	109*	>150	208

Nitroglycerine

Nitroglycerine is not used for military high explosives, it is found in propellants and commercial blasting explosives. Being a liquid at room temperature it would easily fill military devices but a liquid filling interferes with the ballistic performance of a shell

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(slowing spin). Also, it is far too easily initiated to be used on its own. Commercially it is desensitised by absorption into Kieselguhr (dynamite) or by gelling with nitrocellulose (blasting gels), which reduces performance of the pure material. Even when pure, it does not have particularly good performance for detonation pressure when compared to others in the Table.

Pentaerythritol Tetranitrate (PETN)

PETN, although having good performance, is limited in its use by its sensitivity. The impact sensitiveness value of 50 and ignition temperature of 205^{0}C show it to be far less safe than RDX. Since RDX has better detonation pressure and is not significantly more expensive, then the UK tends to prefer RDX to PETN. The only use for PETN on a large scale is to fill detonating cord. This choice is because PETN detonates reliably down to very small diameters.

Tetryl (CE)

Tetryl was traditionally the military exploder (booster) composition in the form of pressed pellets. The Rotter F. of I. value of 90 is regarded as the lower limit for insensitiveness by the Ordnance Board for use as HE filling in British munitions. The toxic properties of tetryl are leading to its replacement with RDX/wax compositions (DEBRIX).

Trinitrotoluene (TNT)

TNT has been the most useful explosive for melt-cast filling due to its low melting point (80°C) compared to its ignition temperature (240°C). Alone, TNT has modest performance, however, it is a very insensitive explosive. In modern usage TNT is employed as an energetic binder to form melt-cast compositions with other materials such as RDX, HMX and aluminium powder (see below.

TNT has certain drawbacks, it is prone to cracking and, if impurities are present exudation. Both can create hazardous situations with munitions. Exudation is particularly dangerous, if TNT comes into contact with Tetryl a liquid eutectic of high sensitiveness is formed, another reason to not use Tetryl. Additionally, exudation may penetrate the safety and arming unit, preventing its proper function or find its way in to screw threads leading to a possible accidental initiation if the thread in undone..

RDX and HMX

RDX and HMX have melting points close to their ignition temperatures, so they cannot be melted safely for casting. They have too great a sensitiveness to be employed as munition fillings on their own. A desensitiser must be used and this is either TNT as discussed above or a binder such as wax or polymer. RDX is the workhorse of British munitions, found in shells, bombs, shaped charges, exploders, detonators and plastic explosives. The usual fillings are RDX/TNT (60/40) or RDX/inert (88/12). The detonation pressure for pure RDX is 347 kbar and this is reduced to ~250 kbar when desensitised. However, this is easily high enough to fragment steel and thus is used in fragmenting warheads such as shells, etc.

HMX, with its higher detonation pressure, would produce better performance but its general use is limited by the cost (currently about 4 times that of RDX). However, if detonation pressure is critical to the operation of the warhead then HMX is employed and formulations have been developed that have a large HMX content, for example HMX/TNT (85/15). The warheads that require this type of filling are shaped charges, EFPs and very high performance fragmentation warhead such as in missiles.

To increase power, aluminium powder is added to the formulations as this can increase the heat of explosion without reducing the gas volume produced, up to a certain level. Thus, addition of ~18-25% by weight of aluminium powder can increase the power (gas expansion) effects by 20%.

Tables 4, 5 and 6 give examples of such formulations.

Table 4
Formulations for High Detonation Performance

Formulation	**TNT%**	**Binder/ Plasticiser**	**RDX%**	**HMX%**
RDX/TNT	40	-	60	-
EDC1A	28	1% wax	4	67
RDX/wax	-	12% wax	88	-
EDC 24	-	5% wax	-	95
RDX/PU	-	16% PU	84	-
HMX/HPTB	-	7% HTPB	-	93
PU = Polyurethane, HTPB = Hydroxylterminated polybutadiene.				

Table 5
Enhanced Blast Formulations Based on RDX and Aluminium

Formulation	**TNT%**	**Binder/ Plasticiser**	**RDX%**	**Aluminium%**
Torpex-2	39.7	0.7	41.6	18.0

Torpex-4	53.2	3.2	19.3	24.3
RWA-2	-	9% wax	71.0	20.0
CPX-200	-	6% polyester/14% K10	60.0	20.0

PU = polyurethane, K10 = energetic plasticiser

Table 6
Enhanced Blast Formulations Based on Oxidant and Aluminium

Formulation	TNT %	Binder/Plasticiser	RDX%	Al%	Oxidant%
Minol 2	40	-	-	20	40 (AN)
CTX-1	14	7%	15	24	40 (AP)
CPX-100	-	9% HTPB/21% K10	20	22	28 (AP)
PBXN-105	-	4% Wax/13% BDNPA/F	7	26	50 (AP)

AN = Ammonium Nitrate; AP = Ammonium Perchlorate; K10, BDNPA/F = energetic plasticisers

PRACTICALITIES OF FILLING

Most service explosives rely on RDX as the main explosive component. TNT is the most common binder, with some use of wax or grease. Plastic bonded explosives are currently not common, though this may change in the future.

Melt Filling

The low melting point of TNT is used to good effect in the filling process allowing the molten filling to be poured into the shell (or what ever). As the TNT cools it will shrink. Figure 12 illustrates the effect of allowing a beaker of TNT to solidify without taking any precautions to prevent the effects of shrinkage at the liquid-container interface.

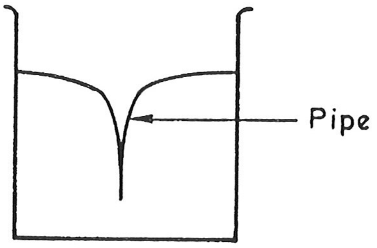


Figure 12: Piping Caused by Shrinkage of TNT When Setting

Pouring can also introduce air bubbles into the filling if precautions are not taken to avoid this problem. A filling tube can be employed to ensure that the liquid enters the shell below the surface of the molten explosive. This method is employed in the filling of 155mm HE shells. As the filling nears the top of the shell the funnel and tube must be withdrawn and the filling continued to avoid a central hole or pipe. Another possible precaution to avoid air bubbles is to work with the cavity under a partial vacuum.

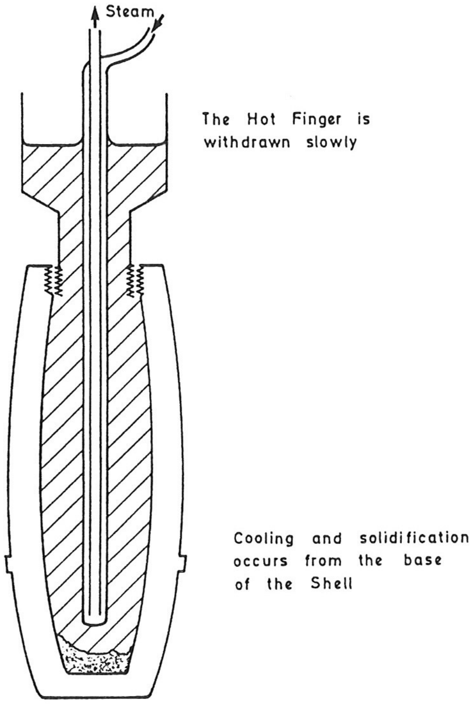


Figure 13: Filling by the Meissner Process

Once the shell is filled cooling can then take place to solidify the HE filling. This requires some degree of control if cracking and shrinkage problems are to be avoided. The molten filling will cool from the outside towards the centre. The effect of this contraction is often countered by the use of a header with additional molten filling. The Meissner process, shown in Figure 13, was one method employed to avoid rapid solidifying of the molten TNT. As the mixture reaches a little below the melting point (or freezing point) it will start to solidify and produce crystals. The size of the crystals depends on both the rate of cooling and the amounts of impurities added to the mixture. Too large a crystal size will allow the formation of cracks in the filling. Small crystals give a better strength to the HE filling. Small crystals can be formed by rapid cooling, but the main problem with this is the contraction on cooling leaving a series of shrinkage cracks. These are not filled by molten filling as all the material is solidifying at the same time. Slow cooling can result in a weak filling due to the formation of large crystals and a corresponding low total surface area. Other materials are incorporated into the filling to control the crystal size. Typically small amounts of HMX and/or HNS are added. Then slow cooling and small crystal size can both be achieved.

Table 7
Advantages and Disadvantages of TNT Formulations.

Advantages	Disadvantages
TNT is relatively cheap	The melt contracts by about 10% on setting and can lead to unacceptable charge defects if not carefully controlled
TNT is insensitive to friction and impact and will desensitise as well as bind more sensitive explosives	The charges crack easily and form dust in the cracks when the charge is vibrated. This may lead to accidental ignition
Formulations are pourable at temperatures attained with low pressure steam.	Exudation can occur at temperatures between 60°C and 80°C.

Reject store can easily be steamed out for recovery and reuse.	Unintentional initiation can occur by: fire, impact of high velocity fragments, mechanical shock (dropping), cook-off, or by set back forces.
Formulations can be cast into charges with unusual shapes.	

Press Filling

Where the viscosity of the filling or the small size of the devices precludes the use of melt-casting process, press-filling is often employed. In this the material may be pressed at high pressure into the munitions using hydraulic ramming. To achieve a good fill, the solid particles should have a suitable crystal grist, i.e. a combination of differently sized particles in the order of 1 to 10 to 100 in linear dimension, so that the middle sized crystals will fit into the gaps between the largest crystals. This will leave even smaller gaps, which can then fill with the smallest crystals. The correct distribution of these crystal sizes can have considerable effect on the performance of the filling by giving increased density.

Direct pressing

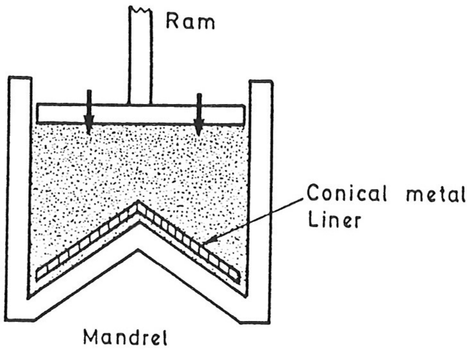


Figure 14: Press filling of a Shaped Charge Warhead

A simple device could be press-filled by placing the required composition into the body of the munitions and pressing the material. This would give rise to density differences throughout the filling due to the frictional losses, the material nearest the ram having the higher density and the material further away having a lower density. This effect may be beneficial if the initiation takes place at the lower density material as this will pick up by shock more readily than higher density material. The figure illustrates the pressing of a shaped charge. Note the use of a mandrel to prevent distortion of the copper liner.

Incremental pressing

The pressing of the filling can produce a reversed density gradient if incremental pressing is employed. In this technique part of the filling material is placed into the device and pressed, further material is then added and pressed at a lower pressing pressure etc.

Hydrostatic and isostatic pressing

In pressing the explosive composition there are limits of density achievable. The theoretical maximum density for a HMX based explosive is in the order of 1.9 gcm^{-3}. Typical fillings using direct or incremental pressing will not achieve this level of compaction. Hydrostatic pressing utilises a rubber membrane to hold the explosives which is pressed in oil. This gives pressing from all directions and will increase the density of the filling. Isostatic pressing takes the process one further step by evacuating the rubber bag at the same time as pressing. Isostatic pressing can produce explosive very close to the theoretical maximum density. The lumps of explosive then require machining to produce the required shape for the charge. This will make the filling an expensive item to produce and the technique is only utilised for special devices.

Extrusion filling

Many small devices can be filled by extruding the filling directly into the munitions. This is similar to press-filling but will employ a lower pressure. RDX/wax, for example can be directly extruded in to small shaped charge devices.

QUALITY ASSURANCE OF THE FILLING

After the filling process is complete a melt-cast shell is cleaned up, by removing excess HE filling removed from the top and the outside of the shell case. A cavity is then machined into the top of the filling to take the fuse assembly. At this stage normal UK practice is to X-ray a sample (or even all) of the production run to check for cavitation and sectioning of a sample of the devices will be carried out. During manufacture there will also be checks on the size of the metal shell, which will be changing due to the temperature changes. This is carried out with a gauge plate.

Filling Faults

The filling of an explosive device is a carefully controlled process. In the normal production and storage of munitions Quality Assurance procedures are employed to avoid the problems cited below. However poor storage conditions, mishandling etc. can induce problems. For this reason accelerated ageing of the munitions is carried out, including temperature cycling, humidity cycling, vibration testing etc.

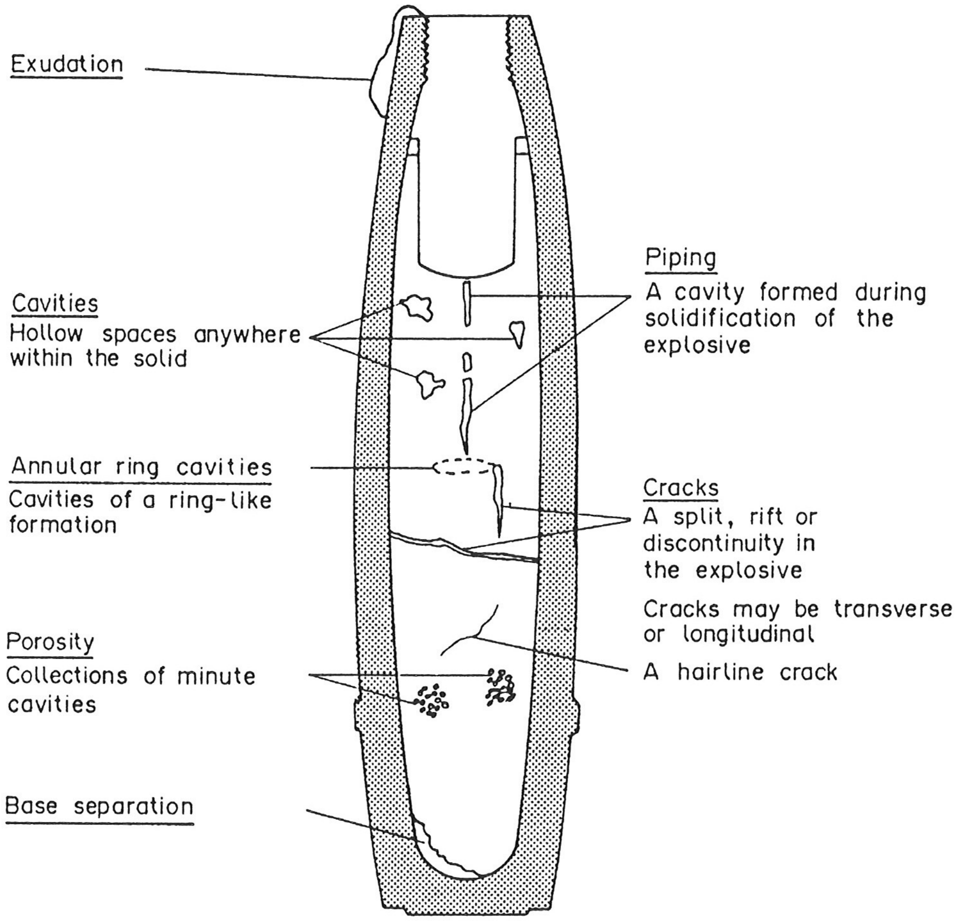


Figure 15: Possible Filling Faults for an Artillery Shell

CHAPTER 6: SAFETY AND RELIABILITY OF EXPLOSIVES (INCLUDING TESTING)

INTRODUCTION

Explosives are substances which can be easily initiated to rapid burning or detonation. They are handled and processed during manufacture and filling. In the form of explosive stores they are subjected to rough usage during transit and in the field. Finally they are required to function with complete certainty in moments of crisis. The user requirements for explosives are therefore as follows:

- Safety;

- Reliability;

- Adequate performance.

Safety and reliability are clearly vital requirements. To some extent they conflict, since it is sometimes difficult to produce an explosive which is completely safe and yet totally reliable.

FACTORS AFFECTING SAFETY AND RELIABILITY

- Purity of the Explosive

- The explosive must be free from contaminants and from by-products of manufacture.

- Storage Stability

The explosive must have an adequate shelf life under varying climatic conditions. To ensure this, stabilisers are sometimes added to the explosive.

- Compatibility

The explosive must be compatible with materials in contact with it. Metals and plastics may give rise to incompatibilities on prolonged contact.

- Mechanical Strength

Adequate strength over a wide range of temperatures is needed in explosives whose performance depends on geometrical factors (eg hollow charges and propellants).

- Sensitiveness

The explosive must have a sensitiveness which is matched to the role in which it is employed and which remains fairly constant in all conditions of use.

SENSITIVENESS OF EXPLOSIVES

An essential characteristic of explosives is their tendency to ignite or detonate when a local stimulus is applied. This stimulus can be quite small in some cases. An explosive which is easily initiated by a given type of stimulus is said to have high sensitiveness to that means of initiation.

Sensitiveness of explosives is a vital factor in safety considerations, where explosives must not be too sensitive to process, handle and transport safely. Sensitiveness of explosives is also important in relation to reliability. In this case explosives must have adequate sensitiveness to be initiated in a reliable manner. Explosives differ widely in their sensitiveness to a given stimulus. The sensitiveness of an explosive depends on many factors; it cannot be calculated from chemical theory. The only satisfactory determination of sensitiveness is by experiment, using a reliable technique. There are six mandatory powder tests required before a Safety of Certificate can be issued:

- Rotter Impact Test;
- Mallet Friction Test;
- Temperature of Ignition;
- Ignition by Flash;
- Train Test;
- Electric Spark Test.

These methods are supplemented by more specialised tests as required, eg Fragment Attack, Fuel Test, Gap Test, Susan Test, Spigot Intrusion, etc. These are all charge tests but are not classed as sensitiveness tests.

IMPACT SENSITIVENESS

The usual method for determining the impact sensitiveness of an explosive is by the Rotter impact test. This method utilises a falling weight technique to determine the minimum amount of kinetic energy needed to ensure reliable initiation of the explosive by percussion. The explosive is confined in small caps on to which a weight is dropped from various heights up to 3 metres. The objective is to determine the medium drop height required for a statistically significant percentage (50%) of trials, which result in ignitions. A parallel series of trials is carried out using pure crystalline RDX for comparison. Then, since sensitiveness is related inversely to drop height, a result known as the figure of insensitiveness (F. of I.) is obtained thus:

$$\text{F. of I.} = \frac{\text{Median drop height for initiation of test explosive}}{\text{Median drop height for initiation of pure RDX}} \times \text{F. of I. of pure RDX*}$$

*The F. of I. of pure RDX is taken to be 80.

Comparison of Impact

It is important to remember that Rotter test results are figures of insensitiveness, ie the higher the figure the less sensitive is the explosive. Using these results, it is possible to classify explosives into three groups:

- Very sensitive,F.of I. <50.
  These explosives must be handled with extreme care in small quantities only;
- Sensitive, F. of I. 50 - 100;
- Comparatively insensitive, F. of I. >100.

Factors which Affect Sensitiveness to Impact

- Chemical composition and structure, and hence the heat of explosion and thermal stability;
- Sensitiveness heat of explosion (Q);
- Sensitiveness rate of thermal decomposition (kT);
- Crystalline form;

For crystalline explosives which exhibit polymorphism, the forms which are least stable at normal temperature are generally the more sensitive;eg. α lead azide is more sensitive than the βformand βHMX are more sensitive than αHMX.

- Presence of air in explosive;

Granular charges are more sensitive than cast charges;

At high loading densities, sensitiveness may decrease;

Cracks and cavities increase bulk sensitivity of cast explosives;

- Presence of inert materials;

Soft or viscous components (waxes, grease, oils, polymers) reduce the sensitiveness of explosives. They are called phlegmatisers;Examples: RDX/Wax, PE4 (RDX + grease) and SX2 (RDX + polyisobutene).

Hard components (glass, sand, grit) increase the sensitiveness of explosives, eg powdered glass formerly used in cap compositions;

PETN and RDX are grit-sensitive;

Sensitiveness increases with temperature (rapidly, as ignition temperature of explosive is approached).

SENSITIVITY OF EXPLOSIVES

Sensitivity relates to the ease of initiation of an explosive charge by its designed stimulus. This term normally is used in relationship to detonating explosives and thus to shock initiation.

EXPLOSIVENESS

Explosiveness is a measure of the violence of an explosive event created by an unplanned stimulus. Thus it is a measure of the potential hazard from an explosive charge.

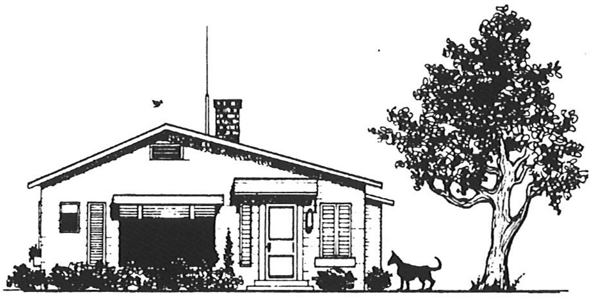
CHAPTER 7: EXPLOSIONS IN AIR

INTRODUCTION

When an explosive charge detonates in air its damage capacity relies on two factors: the propulsion of fragments of its container and other nearby material at high velocity, and the disturbance of the surrounding air, known as blast. The word blast is an ambiguous one; it is used by journalists as synonymous with explosion on any scale of magnitude, and by engineers in the mining quarrying and demolition industries for any explosion set off in pursuance of their operations. In the latter case detonation usually occurs deep inside earth rock or concrete, so the disturbance of the surrounding air is minimal and does not contribute to the required effect. In this distribute the word blast denotes the shock wave caused in the air by an explosion, more particularly at a distance sufficiently remote from the charge for its characteristics to be distinguishable from the detonation shock wave which precedes it in time.

An explosion may be caused with the deliberate intention of inflicting damage by blast. Some military weapons rely largely on blast for their effect; vulnerable targets include personnel in the open, buildings, unarmoured vehicles, ships' superstructure and aircraft, the latter either parked or in flight. A bomb planted in a city street by a terrorist causes damage primarily by blast effect; the windows of shops, offices and houses are particularly susceptible to blast and disintegrate into fragments which can then cause injuries to people nearby as a secondary effect. Alternatively, the effects of blast have to be taken into account in safer matters. The presence of stored explosives involves potential accident hazards and the damage capacity of a quantity of explosive must always be assessed in determining the safest location and design of a manufacturing or storage facility. For all these reasons the theoretical and experimental study of blast has proceeded continuously for many years. It is a complex subject and involves phenomena which neither theory nor practice is always adequate to predict.

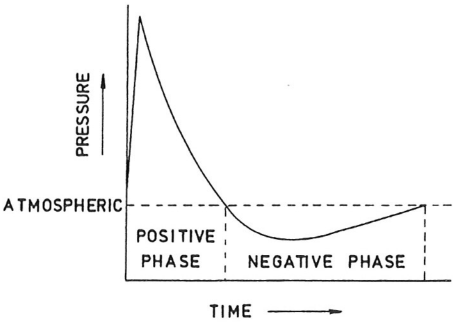
THE NATURE AND FORMATION OF THE BLAST WAVE



When an explosive charge is detonated in air the detonation shock front travels away from the charge faster than the expanding gaseous products. However it is not long before the hot and expanding gaseous products become environmentally unfriendly.

The air surrounding the charge is first heated by the passage of the shock wave and is then immediately pushed outwards by the expanding hot gases.

After a short distance of travel a new shock front is formed in the air; it has a lower peak pressure and initial velocity than the detonation shock wave but a longer profile, and has a zone of rarefied air immediately behind the high-pressure area. This wave is called the blast wave.



On formation it travels supersonically then, losing velocity and amplitude, it decays into an acoustic wave. Because it decays more gradually than the detonation shock wave, the blast wave travels much further and exerts its effects to distances hundreds of charge diameters from the explosion centre. For the purpose of some theoretical approaches, the blast wave can be treated as the decaying detonation wave, but it is more usual to consider it as a related but separate phenomenon. blast waves can, of course, be created by explosions which do not involve detonation conditions including gunshots and also physical explosions. Pressures in the shock front of blast waves, being much lower than detonation pressures which obtain close to the charge, can be measured experimentally by employing piezoelectric transducer gauges of high natural frequency connected to a transient recorder. The gauge produces a profile of the wave which can be stored by the recorder. This profile shows the compression phase in the form of a steeply rising pressure pulse which then decays rapidly with time.

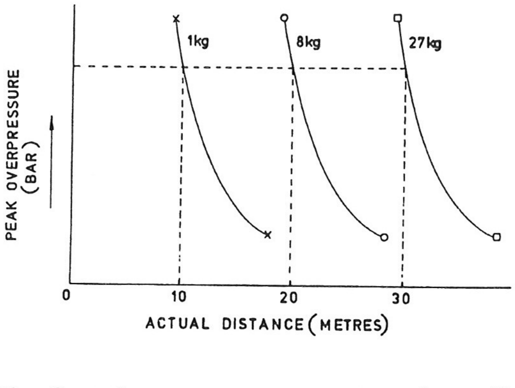
Blast pressures are usually quoted as overpressure, i.e. the excess of pressure over the ambient atmospheric pressure, about 1000 bar. Behind the high pressure front the elasticity of the air causes the formation of a rarefaction or negative pressure phase, and this is of somewhat longer duration than the positive phase. The cycle of compression and rarefaction is then repeated at decreasing amplitudes but the oscillation is quickly damped out in air, and for all except extremely large charges only a single cycle need be considered. The two main parameters of a blast wave are the peak overpressure at a given distance and the impulse. The latter involves both the overpressure and the time during which it exists at a given distance; this time depends in turn on the profile and velocity of the wave.

FACTORS AFFECTING THE FORMATION AND MAGNITUDE OF THE BLAST WAVE

The chief factors which govern the magnitude of the peak overpressure in a blast wave from an uncased charge in free air at sea level are;

- the distance of the wave from the centre or the explosion.
- the explosion parameters of the charge.
- the weight of the charge.

The Scaling Of Blast Parameters



The fact that overpressure at a given distance is proportional to the cube root of the charge weight for a given explosive is consistent with the principle of similarity which was propounded by B. Hopkinson in 1915. This states that the pressure and other properties of shock waves are similar if the scales of distance and time by which they are measured are changed by the same factors as the dimensions of the relative charges. In practice it is more convenient to use the weight of the charge than its dimensions for the purpose of scaling the blast overpressure and other parameters. It is assumed that the shape of the charge is compact and symmetrical. Now, if we take, for example, a spherical charge and double its diameter, the volume will be increased by the third power, and provided the density remains constant, the weight will also increase by the third power. Thus, according to Hopkinson's principle, by cubing the charge weight we have increased only two-fold the distance at which the charge will produce a particular overpressure. The concept is shown more clearly above, where it is seen that a transducer mounted at 10 metres from a 1 kilograms charge will register the same overpressure as one mounted at 20 metres from an 8 kilograms charge of the same explosive, or one at 30 metres from a 27 kilograms charge.

CHAPTER 8: EXPLOSIVE TOXICITY

INTRODUCTION

Although most people are more concerned with dangers associated with the accidental initiation of explosive materials it must be remembered that explosives are chemicals. All chemicals have the inherent ability to be poisonous. During World War I there were 24000 cases of TNT poisoning of which 580 were fatal. Here we are considering occupational hygiene where there is a fundamental requirement to protect the workforce. This protection is given by defining an acceptable level of risk for exposure to chemical substances (including explosives). The toxic risk depends upon:

- The toxicity of the substance to man;
- The duration of exposure;
- The intensity of exposure.

PRINCIPLES OF TOXICOLOGY

"All substances are poisonous; there is none which is not a poison; it is the dose alone which matters".

This was quoted by a famous medieval physician, Paracelsus (1493-1541). We must consider therefore that all materials have the ability to be harmful if taken in sufficient quantity.

EXPOSURE

To be toxic the material must interact with the body. The main routes of entry are:

- By ingestion;
- By inhalation;
- Through the skin;
- Through the eye.

Ingestion

Entry via the digestive tract should be the easiest to control. However, it is possible that if cleanliness routines are not followed then material may be transferred from dirty hands to food. This is why it is important to wash hands before eating at work.

Inhalation

Inhalation of toxic materials is probably the major toxic hazard. The material may be present as a fine dust (particulate) or as a vapour. Vapours can form by evaporation of solid directly into the atmosphere. Absorption into the body via the lungs is extremely rapid due to the nature of the lung. Vapours and gases penetrate easily into the internal structure but particulate matter penetration depends upon particle size.

Through the Skin

The skin is considered as an important organ of the body (16% by weight) and can allow passage of materials which have come in contact.

Factors affecting skin penetration are:

Properties of the material;

Damage to the epidermis;

Swelling of the epidermis;

Area of contamination;

Time of contamination.

Through the Eye

The eyeball socket and associated tear ducts give a good site for the absorption of particulate matter or liquid splashes.

Blood Distribution

Once a toxic substance has entered the body it may be distributed by the blood or lymph system. Transport via the blood is very rapid. All the blood in the body passes through the heart in less than two minutes. Thus entry of a toxic material at a point source, lung, patch of skin etc. results in rapid distribution throughout the body. During this distribution process the material may be metabolised to a relatively harmless substance. It may be rapidly excreted before it can have a harmful effect.

Harmful Effects

If the toxic material has a harmful effect at the site of exposure then this is called a local effect. If, however, the material enters the body and reaches its site of toxic action after distribution within the body this is a

systemic effect. An effect which occurs after short exposure to the toxic substance is described as an acute effect. When effects are seen only after repeated long term exposure this is called a chronic effect. Whether an effect is acute or chronic may depend on both substance and quantity absorbed. Local effects include the reaction of skin to applied materials - soreness, eczema, chemical burns, ulceration and dermatitis. Allergic sensitisation is also possible. Another important local effect is that of inhaled material on the lung. Irritation or damage of the lung tissue can lead to oedema. Non-reactive particulate matter can produce long term effects e.g. asbestosis, silicosis etc. Systemic effects of importance include the reduction in oxygen carrying capability of the blood and effects on the peripheral and central nervous system.

Oxygen is carried in the blood by attachment to haemoglobin in the red blood cells. The haemoglobin can be blocked from carrying oxygen. Some chemical species convert the haemoglobin to methaemoglobin which cannot bind oxygen. Carbon monoxide converts haemoglobin to carboxyhaemoglobin. Up to 15% loss of haemoglobin can be tolerated but above this cyanosis sets in. At 30% loss severe symptoms occur including severe headache and dizziness. Death may occur once 60% loss is exceeded. Effects on the nervous system are less well understood particularly when considering the central nervous system (brain and spinal cord). Even industrial solvents can affect the nerve fibre coatings causing temporary paralysis. It is now accepted that heavy metals such as mercury and lead have chronic effects within the central nervous system. A third important systematic type of toxicity is the attack on the cellular mechanisms which provide energy for the cell. If these are affected the cell shuts down and depending upon which cell type is affected the body will deteriorate to the point of death. This is how cyanide acts as a poison

MEASUREMENT OF TOXICITY

If a large population of people are subjected to a toxic material which can cause lethality then the percentage response against dose would be that shown below. This is called the dose-response curve.

The figure often quoted to compare the toxicity of different substances is the dose at which 50% have responded. Where the response is death this is called the median lethal dose (LD50). It is usually expressed in mg kg-l of body weight. Note that oral LD50 may be different to percutaneous LD50. For toxic substances inhaled from the atmosphere it is usual to measure toxicity by a measure of exposure. That is the concentration in the atmosphere (mg $m\text{-}^3$) multiplied by the time of exposure (min). Thus, this gives LCt50 (mg min $m\text{-}^3$). In the workplace effects less severe than lethality must be considered. The quoted figures for LD50 and LCt50 give relative toxicities even though this level of exposure may never be reached. Any exposure to such substances must be controlled and so standards have been set and regulations produced to this end.

PROTECTIVE MEASURES

Exposure of employees to Hazardous Substances, by any route, should either be prevented or, where this is not reasonably practicable, adequately controlled. Prevention or adequate control of exposure should be achieved by measures other than the use of personal protective equipment, as far as reasonably practicable. One of the main aims of good Occupational Hygiene practice is to ensure that atmospheric contamination levels in the workplace are maintained low enough by administrative or engineering means so that respiratory protection is not needed. The use of protective clothing and respiratory protection should be seen as a last resort to protect staff. Processes and procedures where toxic materials are handled should be designed to keep environmental levels below those stipulated by Occupational Exposure Standards (OESs). This may be achieved by local exhaust ventilation or preferably by process design e.g. avoid the use of fine powdered solids which may pose an inhalation hazard. Particular note must be made of protecting eyes and hands.

Remember that the skin is not a barrier to chemicals and many operations involving explosive item manufacture are performed manually.

TOXICOLOGY OF SOME EXPLOSIVE MATERIALS

Most explosives, propellants and pyrotechnics contain ingredients which include nitrates, nitro compounds, nitrate esters, or nitramines. These act in the body generally by formation of nitrite ion through metabolism following absorption. Nitrite ion gives rise to the formation of methaemoglobin described earlier. Symptoms of severe poisoning include cyanosis, headache, nausea and dizziness. There is evidence that these materials can also cause liver damage.

Nitrate esters

Organic nitrate esters such as nitroglycerine found in some propellants are highly potent vasodilators. This ability has found use in the treatment of cardiovascular illness. Those exposed to nitrate esters of this type experience a severe headache known as nitro-head or jelly-head (from gelignite). Nitroglycerine has a reasonably high vapour pressure and thus can produce a significant vapour hazard when present in a composition.

TNT

Inhalation, ingestion or absorption through the skin of TNT dust is a major toxic hazard. Poisoning has been observed in persons exposed to a concentration as low as 3 mg $m\text{-}^{3}$.

Tetryl

Tetryl is hazardous by inhalation or skin contact of the dust or solid material. This chemical is noted for its ability to cause severe dermatitis. Concentrations of 1.5 mg $m\text{-}^{3}$ in the atmosphere will cause symptoms to appear subsequently (2-3 weeks). These are insomnia, loss of appetite and giddiness.

Propylene Glycol Dinitrate (PGDN)

Propylene glycol dinitrate (PGDN) is a major (76%) constituent of OTTO Fuel II and is responsible for virtually all the toxic problems associated with exposure to OTTO Fuel. OTTO Fuel II has been used as a monopropellant for torpedoes for many years. Animals exposed to PGDN vapours exhibit lethargy, prostration, anoxia and methaemoglobinaemia, reduced response to external stimuli and, at high doses, death. PGDN is a potential health hazard to man by inhalation, ingestion or by absorption through the skin. Most of the symptoms produced by exposure to this compound are typical of the nitrate esters. Ingestion of liquid OTTO Fuel can cause gastrointestinal disorders as well as the usual systemic effects. Both the liquid and the vapour are known to cause mild eye irritation. The vapour pressure of PGDN is small but not negligible and toxic vapour inhalation is a health hazard posed by OTTO Fuel. The most significant route of entry for absorption of OTTO Fuel in normal use is likely to be skin absorption following accidental spillage or splashing. The acute systemic effects of mild OTTO exposure are nasal congestion, headache, nausea, eye irritation, lowering of blood pressure, dizziness and laboured breathing. The most common acute symptom is the well known nitroheadache, which can be very severe and last for several hours after exposure; as usual repeated exposure leads to a tolerance of the minor symptoms. Most of the effects of OTTO on individuals can be attributed to the cardiovascular action of PGDN. Dizziness and a marked impairment in balance can be induced by concentration levels of 2 to 3 times the OEL of 0.2 ppm.

A comprehensive study of 87 workers chronically exposed to OTTO Fuel in their working environment, some for as a long a period as 11 years, revealed a history of minor acute PGDN toxic symptoms but no serious effects. No evidence was found of any chronic physical or neurophysiological ill effects. No human deaths or other major toxic accidents due to PGDN have been reported. The low vapour pressure of PGDN is one of the main reasons why it presents much less of a practical industrial hazard than other similar compounds. It seems likely that under normal working conditions, with good ventilation, peak PGDN concentrations are usually far below the OEL of 0.2 ppm.

Phosphorus

There are two major types of phosphorus; red and white. White phosphorus (WP) is one of the most highly toxic materials used in the pyrotechnics industry. Severe symptoms have been recorded with a dose as little as 15 mg. The LD50 is considered as 1 mg kg^{-1} in man. WP can be absorbed into the body through skin, the respiratory system and by ingestion. Skin contact results in painful burns which can penetrate deeply into the underlying flesh. Chronic effects of WP are well documented from early industrial use. The major effect is to cause bone necrosis (phossy jaw) with severe weakening of the bones. Secondary infection in the jaw area is then common and extremely painful. Fatty degeneration of tissue is also evident particularly in the liver. If a person is contaminated with WP they must be placed immediately under an emergency shower until appropriate medical assistance arrives. This is to exclude air from the WP. Red phosphorus (RP) is considered to be much less of a toxic hazard than WP.

CONTROL OF SUBSTANCES HAZARDOUS TO HEALTH (COSHH)

In 1984 the Health and Safety Commission published its proposals on occupational health in a consultative document. The proposals aimed to achieve six goals. These were:

to provide one set of Regulations to cover occupational health risks;

to set out the principles which should be followed in occupational health (including those in occupational medicine and hygiene);

to make provisions for future changes to alter standards of control necessary to meet any new hazards hitherto unsuspected or underestimated;

to enable EC Directive 80/1107/EEC concerned with the protection of workers' health to be implemented;

to enable HM Government to ratify ILO Convention No. 139 on carcinogens;

to enable existing obsolete legislation to be revoked.

Following extensive consultations with interested parties the Control of Substances Hazardous to Health Regulations 1988 (S.I. No. 1657) (COSHH) were made.

CHAPTER 9: ELECTRICAL HAZARDS

THE THREAT

The threat from electrical hazards is that of raising the temperature of a small portion of the explosives to its ignition temperature or by inducing an electrical current greater than the no fire threshold. This can manifest itself by:

- Electrical Current;
- Static Electricity;
- Electromagnetic Radiation.

ELECTRICAL CURRENT

The application of an electrical current is one of the most common ways of deliberately initiating explosives as seen in the electrical primer cap or electrical detonator. In the working environment standard electrical practices should eliminate the risk from accidental initiation from what could be referred to as mains supply. If a store is designed to be initiated by current flow then any contact with wiring carrying an electrical current may result in the designed event occurring. The work place should be checked also for galvanic action that may result in current flow.

However the other two sources of electrical excitation static and induced emf from electromagnetic radiation, are more insidious in their approach and as a threat, not so readily identifiable.

STATIC ELECTRICITY

This is due to a surplus or deficiency of electrons in a material, and arises from an obstructed flow of current electricity, or from non-conducting surfaces or particles moving past each other. When the potential difference is large enough the current will pass from the object to earth or to an oppositely charged object, it momentarily becomes an electrical current. Should the flow pass through an explosive material or into the electric circuit then it may absorb sufficient energy to reach its ignition point or initiate the EED.

The significant hazards from. static electricity arise from:

- Lightning;
- A charge on the person or the operator;
- A charge in granular explosive material caused by friction;
- A charge on equipment.

Al of these can be eliminated by the correct earthing of equipment and personnel and environmental control such as artificially high humidity levels. Personal Test Meters are of extreme importance. Little can be done to protect munitions from a direct lightning strike; when dealing with currents between 10KA and 300KA (a typical flash is considered to be 30KA) with a core temperature of 15000°C detonation is inevitable. Explosives can only be protected by the external use of lightning protection systems, as prescribed in British Standard Code of Practice BS 6651 of 1985. Compared with lightning, the other electrostatic hazards are far less in terms of magnitude of energy but must be guarded against. In general the risk from low level electrostatic charges is greatest in manufacture during mixing, sieving, pouring operations, in for example the preparation of ANFO. Similarly individual static charges in excess of 0.02J can be generated by operatives.

ELECTROMAGNETIC FIELD INDUCED CURRENT (RADHAZ)

When an EED is passed through an electromagnetic field there is a probability that a current can be induced to flow through the circuit. This is often called 'Radiation Hazard' or RADHAZ. The extent of the hazard is governed by:

- the energy of the transmission;
- distance of transmitter to target;
- the aerial effect of the EED wiring;
- the type of transmission (axial/radial, directional /omni-directional);
- use of screening and shunts in the EED;
- screening with a Faraday Cage.

It is possible to screen out the hazard from these energy currents, however in doing so the initiation system becomes more complex and expensive. High power ground transmitters radiate frequencies from between 0.2NHz to 35GHz. The propensity for induced current hazards in such an environment is significant.

Normally, it is not possible to effectively screen a process facility from electromagnetic radiation. Protection must be afforded by:

- External and internal packaging;
- Enclosure of risk components within the munition;
- The use of shunts and systems requiring high level activation energy.

A fully continuous metal covering will protect the contents from RADHAZ. However it must be borne in mind that any windows within the protection do not only reduce the risk, but may exacerbate the hazard by focusing the entry of the radiation. Whilst it may be possible to fully protect within the packaging, once removed most ordnance systems have some external discontinuity. As the risk is in essence one of currents being induced into conductive components inducing heat into the initiation system, the use of EEDs with Cap Conducting Compositions and Exploding Bridge Wire requiring higher energy levels are preferable to the traditional, but cheaper and simpler Bridge Wire devices.