Explosives and Detonators

1 Types of explosive

1.1 Definition of explosives

An explosive is a substance which, when properly initiated, is very rapidly converted to gases at high temperature and pressure. This process is called detonation. A litre of modern high explosive will expand to around 1000 litres within milliseconds (ICI 1997), creating pressures in a blasthole of the order of 10,000 MPa (1,450,000 psi). Temperatures range from 1650-3870°C and the velocity of detonation (VOD) is so high (2500-8000 m/s) that the power of a single charge is around 25,000 MW.

1.2 Classifications of explosive

The speed of detonation is one of the parameters used to classify an explosive. The other main parameter is whether or not a standard detonator can initiate the explosive. Figure 3.1 illustrates the basic classifications of explosive.

![Figure 1: Basic classifications of explosive](image)

2 Explosive properties

The main parameters that influence the performance and selection of an explosive are:

- Effective energy
- Velocity of detonation
- Density
- Detonation pressure

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3.1 Effective energy

Some explosive energy is always wasted (vented to the atmosphere, lost as heat, etc) and so it is more realistic to express explosive strength in terms of the amount of energy a user can expect to have available to do useful work (ICI 1997). This parameter is termed the effective energy and is used by all major mining companies in Australia to compare explosive strengths. Effective energy is defined as the total energy released by the explosive gases as they expand and do useful work from the initial detonation down to a cut-off pressure of 100 MPa. A ‘cut-off pressure’ is used because it is recognised that the ability of a gas to do work diminishes as the confining pressure drops (ICI 1997).

a) Relative effective energy

Manufacturers tend to use their own methods for determining explosive energies and it can be misleading to compare quoted values from different suppliers. A more useful indication of the strength of an explosive is the relative effective energy.

Relative weight effective energy (RWEE). RWEE is defined as the effective energy of an explosive compared to the effective energy of an equal weight of standard ANFO (i.e. 94% AN, 6% FO, density = 0.8 g/cm³). RWEE is expressed as a percentage, with hat of ANFO being 100%.

b) Shock and heave energy

Energy is delivered by an explosive in two main forms, shock energy and heave energy. At detonation, the rapidly expanding gases compress the rock around the charge and cause a shock wave to travel through the surrounding rock mass. The gases continue to expand, forcing their way into fractures created by the shock wave, and displace the fractured rock outwards. This latter effect of the expanding gases is termed heave. The mechanism by which an explosive breaks rock is explained in more detail in section 4.

3.2 Velocity of Detonation (VOD)

The velocity of detonation (VOD) is the rate at which the detonation wave travels along an explosive column. The greater the VOD the greater the power or ‘shattering’ effect of an explosive. High VOD explosives are more suitable in hard rock and low VOD in softer rock. Generally, explosives with a lower VOD tend to release gas over a longer period and consequently have more ‘heave’. The VOD range in commercial explosives is 2500-7500 m/s.

3.3 Density

The density of a explosive determines the charge weight per meter of hole.

3.4 Detonation pressure
Detonation pressure is the pressure in the reaction zone as an explosive detonates. It is a significant indicator of the ability of an explosive to produce good fragmentation. A high detonation pressure is one of the desirable characteristics in a primer (Atlas 1987).

3.5 Sensitivity

Sensitivity is a measure of the ease with which an explosive can be detonated by heat, friction or shock and of its ability to propagate that detonation. As described in section 3.1.2, modern commercial explosives can be grouped into two main categories according to their sensitivity, detonator sensitive explosives and blasting agents. Some explosives with very high sensitivity, such as pure nitroglycerin or dynamite, can be detonated by mechanical impact or friction.

The sensitivity of an explosive has other operational implications. If the sensitivity is too low, the detonation within a blast hole can be interrupted if there are gaps or obstacles between the charges. An explosive that is too sensitive can result in propagation of a detonation from one blast hole to another (sympathetic detonation). There are various measures of sensitivity (Atlas 1987).

Minimum Booster
The smallest detonator or primer charge that will produce detonation.

Gap Sensitivity
The ability of an explosive to propagate across an air gap. The test is conducted on unconfined cartridges.

Critical Diameter
The smallest diameter at which the detonation will propagate along a column of explosive.

Pressure Tolerance
The static pressure in a blasthole at which the explosive will fail to detonate.

3.6 Fume characteristics

The gases produced by the detonation of an explosive consist mostly of non-toxic carbon dioxide, nitrogen and steam. However, small amounts of toxic gases are also produced, the main ones being carbon monoxide and oxides of nitrogen.

a) Carbon monoxide (CO)

Carbon monoxide is produced by incomplete combustion of carbonaceous material. Some properties are:

- extremely toxic - 0.1% collapse, 1% immediate death
- colourless, odourless, tasteless
- highly flammable - burns with blue flame 12.5% to 74.2%
- explosive – maximum violence at 29% by volume in air

b) Oxides of nitrogen

The oxides of nitrogen are nitric oxide (NO), nitrous oxide (N2O) and nitrogen dioxide (NO2). Of these, nitrogen dioxide is the most toxic. The gas dissolves readily in the water in eyes and lungs to form both nitrous and nitric acids which cause irritation and, at higher concentration, corrosion.
of the eyes and respiratory system. At a concentration in the air of 100 ppm, coughing may commence and a concentration of 200 ppm is likely to be fatal (McPherson 1993, p382).

Fortunately, even under extreme conditions, the concentrations of these gases in explosive fumes are very small (of the order of 0.1%). Their effects are minimised by:
After blasting, wait a set time before re-entering the area to allow fumes to clear.
Provide sufficient ventilation to disperse the fumes.

3.7 Storage properties

Explosives deteriorate and shelf life is particularly affected by both climate and magazine conditions. Statutory authorities in each State and Territory are responsible for the approval and licensing of magazines used for storing explosives. The maintenance of explosives magazines is also subject to Statutory Regulations. Explosive manufacturers specify the storage properties or shelf life of their products, based on normal magazine conditions (ICI 1997).

Nitroglycerin products are the most susceptible to deterioration during storage. Dynamite undergoes a normal aging process which rarely affects the energy output but can affect the appearance and sensitivity.

3.8 Water resistance

Blasting often takes place in wet conditions, even underwater for special tasks. In these cases, the water resistance of an explosive is a very important consideration. ANFO has no water resistance whilst emulsions and slurries have excellent water resistance. The water resistance of an explosive can be classified by testing its ability to detonate after exposure to water for certain time periods (Atlas 1987).

3.9 Physical characteristics

The physical characteristics of an explosive can be important with respect to handling and loading into blastholes. ANFO is a granular material, which is loose and free-flowing. It can be readily poured into a blast hole from bags or blown in from a large container by means of compressed air. Bulk emulsions are gel-like in consistency and can be pumped into blastholes from large containers; other emulsions are more like putty and can be packaged in plastic sausage-shaped cartridges that are easy to load by hand into a blasthole.

4 Blasting agents

A blasting agent is an explosive that:
• Comprises ingredients that by themselves are non-explosive
• Can only be detonated by a high explosive charge placed within it and not by a detonator.

All blasting agents contain the following essential components (ICI 1997):
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<table>
<thead>
<tr>
<th>Oxidiser</th>
<th>A chemical that provides oxygen for the reaction. Typical oxidisers are ammonium nitrate and calcium nitrate.</th>
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</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>A chemical that reacts with oxygen to produce heat. Common fuels include fuel oil and aluminium.</td>
</tr>
<tr>
<td>Sensitiser</td>
<td>Provides the heat source ('hot spot') to drive the chemical reaction of oxidiser and fuel. Sensitisers are generally small air bubbles or pockets within the explosive.</td>
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The composition of explosives is balanced chemically to produce the desired effects in blasting.

Note: the orange fumes sometimes seen in open pit blasting indicate that there is water in the blastholes. The water desensitises a proportion of the fuel, upsetting the oxygen balance and resulting in the production of nitrous oxides.

4.1 ANFO

a) Description

Ammonium nitrate is relatively insensitive, and wasn’t even recognized as an explosive until some decades after it began to be used as fertilizer. Major disasters which have been blamed, retrospectively, on ammonium nitrate include the Galveston Harbour and Halifax explosions. Sadly, the North Americans hadn’t learned from an earlier disaster at Oppau, Germany, in 1921. There, the ammonium nitrate was considered so safe it was stacked outdoors. It would cake from the rain, and set hard. When loading became a problem, the stack was broken up using dynamite …. There is now a lake and a plaque where the town stood.

Ammonium nitrate fuel oil (ANFO) consists of small granules of ammonium nitrate (AN) called prills, coated with a special grade of fuel oil (FO). There are 3 types of ingredient.

Oxidiser | Ammonium nitrate
---|---
Fuel | Fuel oil/distillate
Sensitiser | Entrapped air

ANFO can not be initiated on its own by heat, shock or by a detonator. It must be detonated by a primer, a cartridge of high explosive with detonator and the detonation pressure of the primer should be greater than that of the ANFO.

b) Mixing

One of the great advantages of ANFO is that it is convenient and inherently safe to use. ANFO can supplied pre-mixed in 10-25 kg bags, which are simply poured into blastholes (Figures 3.2 & 3.3). In large surface operations, quantities of correctly proportioned and mixed ANFO are charged quickly and efficiently by bulk ANFO mix trucks. The AN prills are blown out of a tank by means of a compressed air, through a nozzle at which fuel oil is added from a separate small tank, and into the blast hole (Figure 3.3). For small operations a hand-operated concrete mixer can even be used. In large underground mines, ‘special charge-up vehicles’ are fitted with a AN tank (‘kettle’) and compressed air supply. To distinguish between a mixed ANFO and straight AN, the fuel oil is often coloured blue or pink with a dye.

Mixing of ANFO constitutes the manufacture of an explosive and a license or permit must be obtained from the appropriate statutory authority.
c) Properties

Fuel oil content  The proportion of FO is 5.5-6.0% by weight, a mix that gives maximum energy and VOD. Too much FO increases the production of carbon monoxide and too little increases the proportion of oxides of nitrogen. The most efficient, perfectly oxygen-balanced mix is at 5.7% FO (Atlas 1987, ICI 1997).

Density  Loose-poured ANFO has a density of 0.8 to 0.85 g/cm³. This low density means that the bulk strength is relatively low. The density can be increased up to about 1.0 g/cm³ by pneumatic loading (‘blow-loading’). Blow loading increases the relative effective energy and the VOD.

Water resistance  Ammonium nitrate readily absorbs water from its surroundings. ANFO which contains more than about 10% water usually fails to detonate (ICI 1997). Under conditions of high moisture content the prills will cake. ANFO can only be used in dry holes, unless it is packaged in a suitable waterproof container.

Performance  • moderately high VOD - around 3660 m/s  
• moderately high detonation pressure - 2700 MPa  
• high gas production, therefore excellent heave  
• large amounts of post-blast fumes  
• Easy to handle and load  
• In bulk form it fills the complete cross-section of blasthole and provides 100% coupling with the rock; i.e. there is no gap between the explosive and the hole walls  
• Problems of separation between explosive cartridges are eliminated

Costs  • Easy to manufacture  
• Around $570/tonne (1999)

4.2 Emulsion blasting agents

a) Components

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Emulsions are the newest form of commercial explosive and have excellent performance characteristics and flexibility of use. An emulsion blasting agent is a water-in-oil emulsion consisting of a super-saturated solution of microscopic AN droplets suspended in an oil, wax or paraffin fuel and stabilised with emulsifying agents (figure 3.4). Entrapped air, in the form of either ultra-fine air bubbles, dispersed throughout the emulsion, acts as a sensitiser (Mather 1997). On initiation, the explosive shock wave causes the air bubbles to compress at high speed, thus creating hot spots and causing the emulsion to detonate. The amount of entrapped air controls the sensitivity and can be varied to create a product that is either a high explosive or a blasting agent.

As with ANFO, emulsion blasting agent can be loaded in bulk from trucks. Bin capacities in the trucks can be varied to carry different proportions of AN and emulsion phase. Data loggers are also available to record the quantities of each blend of product used in each hole in a blast (Mather 1997).

b) Properties

**Physical properties**  An opaque gel similar in viscosity to light grease or heavy oil (similar to vaseline)

**Performance**
- very high VOD - up to 6000 m/s
- high detonation pressure: 10-12,000 MPa
- energy output can be varied by altering the blend of the explosive
- less chemical energy per unit weight compared to ANFO, due to water content.

**Water resistance** Excellent

**Stability**  Blasting agent stable for about 4 days in holes.

**Cost**  Approximately $800/tonne (1999)

### 4.4 Bulk explosive trucks

In operations such as open pit mines and quarries, blasting agents can be mixed on-site, at the point of delivery into the blasthole. Figures 3.5, 3.6 and 3.7 illustrate the layout of such bulk explosives trucks, termed mobile manufacturing units (MMU).
5 Detonator (‘cap’) sensitive explosives

5.1 NG-Based Explosives (Dynamites)

a) Composition of Dynamite
There is a very wide range of dynamite compositions based on:

- nitroglycerine
- nitroglycol
- nitrocellulose
- oxidising salts
- fuel ingredients

The liquid portion of all dynamites consists of a blend of nitroglycerine and nitroglycol, known collectively as ‘NG’. Nitroglycerine is usually the minor % of the two as nitroglycol has a lower freezing point (-22°C), better heat stability and is cheaper. NG content varies from 5-90%.

- **Nitrocellulose**
  A ‘gelling’ or thickening agent which binds the liquid NG to the other ingredients and prevents its exudation. Typically only a few % of the total.

- **Oxidisers**
  Mainly ammonium nitrate and/or sodium nitrate.

- **Fuel ingredients**
  These components balance the oxidisers and may also contribute to water resistance and density control. Typical fuels are sawdust, wax or aluminium.

Typically, NG-based explosives are packages in waxed paper cartridges (figure 3.8). Dynamite can be supplied in straight, ammonia, and gelatin forms.

![NG-based explosive cartridges](image)

**5.2 Packaged emulsion explosives**

Emulsion explosives can be made detonator-sensitive by increasing the amount of air pockets in the mixture. Currently, cap-sensitive emulsions are produced by using glass microballoons (GMBs) as a sensitisier instead of chemical gassing (Bellairs 1999). Although they can be initiated by a No. 8 detonator, this type of explosive has extremely low sensitivity to impact and friction and are therefore much safer than NG-based explosives.
5.3 **High energy primers**

High energy explosives have been developed specifically for the efficient initiation of blasting agents. Their composition is based on military high explosive compounds such as TNT (trinitrotoluol) and PETN (pentaerythritol tetranitrate).

The ICI range of such explosives is named Anzomex and the primers are made principally of cast pentolite, a mixture of TNT and PETN. The explosive is packaged in rigid plastic containers that are usually cylindrical in shape (Figure 3.10). These plastic containers generally incorporate a form of hollow tube or attachment for the connection of a detonator, detonating cord or shock tube (see section 3.6).

ICI Anzomex products have a density of around 1.65 g/cm$^3$, a VOD of about 7500 m/s (ICI 1997) and a shelf life of about 5 years. Cast primers must be handled very carefully; for example, they can detonate if dropped from 15 m onto sharp rocks (Bellairs 1999). At present, Orica has the only cast booster plant in Australia, which manufactures the same product for both Orica and Dyno Nobel labels.

6 **Initiating explosives**

Initiating explosives are designed to safely activate larger explosive charges at a controlled time and in a pre-determined sequence ('delay blasting'). Initiating explosives can be broadly classified into *electric* and *non-electric* types. In electric systems, a device that can generate or store
electrical energy transmits that energy to the initiating explosives via a circuit of insulated conductors. Blast sequences can be controlled by means of electric timing systems but delay timing is usually achieved through pyrotechnic delay elements incorporated inside detonators. Non-electric initiating systems use reactive chemicals to store and transmit energy by controlled burning, detonation, or shock waves. (ICI 1997.)

6.1 Detonators

Detonators are compact devices that are designed to safely initiate and control the performance of larger explosive charges. They contain relatively sensitive high explosives which can be initiated by electrical or shock energy from an external source. All detonators contain components that can be initiated by sufficient impact, heat, friction or electrical energy. These characteristics make them the most dangerous explosive products in industrial application and they must be stored, transported, handled and used according to set procedures, specified in codes and regulations.

6.3 Electric detonators

a) Construction

Electric detonators are widely used to initiate blast sequences but are rarely now used inside the blastholes themselves (ICI 1997). Electrical energy is introduced into the detonator from the exploder (battery, hand-driven magneto or charged capacitor) via a primary circuit wire (shotfiring cable) and detonator leads. In the detonator (Figure 3.11), the current heats up a high resistance wire which then ignites a fusehead (similar to a match). The resulting flash ignites a delay element which burns through to a primer charge that detonates the base charge. The timing of the pyrotechnic delay element is accurate to within 8 ms (White 1999).

![Construction of Electric Detonator](image)

Fig. 11: Construction of electric detonator (Hustrulid 1999)

b) Electric circuits
The simplest and most convenient way to connect electric detonators is in series. If one or more detonator connections are faulty then the entire circuit will not fire, eliminating the possibility of having explosive in the broken rock after firing. Connection in series allows the entire circuit to be tested for continuity and resistance from a safe place. In a parallel circuit, in which each detonator is connected across two common wires, each detonator is independent of the others. The circuit resistance is lower but even if one connection of faulty the remainder will fire, resulting in unexploded charges in the muck pile. Each individual detonator must be tested for continuity.

When connecting a round of charged blastholes, the ends of the detonator leads are coupled in series and the two free ends of the detonator circuit coupled to a firing cable, often via a short length of twin twist wire. The recommended minimum firing current is 1.5 amps DC or 2.5 amps AC for each series circuit (ICI 1997) and it is often necessary to calculate the circuit resistance to determine if the firing current is sufficient.

**c) Accidental firing hazards**

Electric detonators may fire if electrical energy from outside enters the blasting circuit.

**Lightning**

A lightning strike close to a blasting circuit can initiate some of the detonators; a direct hit will cause the entire circuit to fire. Lighting can also initiate non-electric systems. If an electrical storm approaches a blast site, charging operations must stop and the site be evacuated.

**Static electricity**

The build-up of static charge on an object can be sufficient to initiate an electrical blasting circuit. The most likely cause is by blow-loading of ANFO in dry conditions. Charging equipment should be properly earthed and a semi-conductive charging hose should be used (ICI 1997).

**Stray currents**

Stray currents from faulty electrical equipment can initiate electric detonators. The most serious hazard is faulty insulation of high voltage cables. All electrical equipment should be properly earthed and detonators leads and firing cables should be placed well clear of any power lines.

**Electro-magnetic radiation (radio, TV, etc)**

If a powerful radio frequency transmitter is close enough and the length and orientation of the lead blasting wires is correct, the radio waves may induce sufficient current in the blasting cables to initiate detonators. Mobile radio transmitters and telephones must therefore be kept away from electrically primed blastholes. Alternatively, signs should be posted instructing persons to switch off their communication devices when entering a blast site. (ICI 1995.)

### 6.4 Detonating cord

Detonating (figure 3.12) cord is a strong, flexible linear explosive which consists of a continuous core of high explosive, covered by a plastic ‘jacket’ and is often overwrapped with textiles (ICI 1997). The high explosive used is PETN, at a content of 3.6 to 70 g/m. When initiated, detonating cord will detonate along its entire length at a VOD of between 6.0 and 7.5 km/s and with very high shock energy. This shock energy is sufficient to initiate a detonator-sensitive explosive or a signal tube (see section 3.6.5). Cord is usually initiated by means of an electric detonator.
The great advantage of detonating cord is that it is an effective, but violent, means of transmitting energy for explosives initiation. Detonating cord trunklines can be laid out between rows of holes, with signal tube connection to individual blastholes or to a single row of blastholes. Delays can be introduced into det cord lines by means of millisecond connectors (MSCs). MSCs consist of two plastic blocks, each containing an identical delay detonator, linked by a short length of signal tube.

6.5 Signal (shock) tube

The signal tube system consists of narrow plastic tubes coated on the inside surface with a very thin layer of high explosive, typically HMX or PETN (Figure 3.13). One kilometer of tube will contain about a teaspoon of HMX. Signal tube can be initiated by an electric detonator, detonator cord or mechanical shot shell starter device. The resulting shock wave travels at high speed (= 2000 m/s) down the tube and sets off a detonator at the other end. (Because of the way in which the tube works it is sometimes known as ‘shock tube’.) The ‘explosive shock wave’ in the tube is not sufficient to break the tube, indeed, a length of tube can safely be held in the hand when it is initiated.

The main advantages of this initiation system are (ICI 1997):

- it is not susceptible to stray electric currents
- separate lengths of signal tube cannot initiate each other through direct contact, knots or other simple connections
- the tube is robust, having a high tensile strength and abrasion resistance
- it is very difficult to ‘kink’
- the initiation is virtually non-violent compared to detonating cord and is hence much safer to use
6.6 Electronic systems

The latest development in explosive technology is the electronic delay detonator (EDD) (Russell 1997, White 1999). Each detonator incorporates a micro-processor chip, contained within a lengthened version of the PVC end plug, which controls the time at which the fusehead ignites and therefore the delay. An electronic console is used to test and program the delay time for each detonator. Delays can be set in increments from 1 to 6000 ms. The circuit can be fired either manually or by computer. With the manual system, each detonator is programmed individually using the console. In computerised firing, each detonator is assigned an 'order number' from the console. (White 1999) A pre-determined firing pattern is then downloaded from a laptop.

The main disadvantage at this time is that the cost of detonators is up to four times per unit that of other types.

7 Explosives storage and handling

Explosives, by their very definition, are potentially unstable compounds. They will deteriorate if exposed to unsuitable conditions such as heat or humidity. Different types of explosives have a varying shelf life, depending on how they are stored and used. The approval and licensing of magazines is subject to State and Territory Regulations, which are usually based on the relevant Australian Standard (AS).

7.2 Classifications

All ‘dangerous goods’ are formally classified by Statutory Authorities, according to the main type of risk that they present. Detonators, blasting agents and detonator-sensitive explosives are classified in hazard Division 1.1 - mass explosion hazard (one which effects the entire load instantaneously). Bulk ammonium nitrate and emulsion are in Division 5.1 – hazardous goods.

7.3 Magazines

a) Licenses

A Magazine license is required to store detonators and explosives. The license is subject to the construction and location of the proposed magazine being granted approval. There are regulations governing operation, including separate storage of detonators, and keeping of records.

Ammonium nitrate and bulk emulsion are relatively harmless until mixed with a sensitiser. They are also used in very large quantities. Construction of storage facilities is, therefore, subject to less stringent Regulations.

7.4 Transportation
The specifications relating to explosive transportation depend mainly on the type and quantity of explosive. The Australian Explosives Code details requirements relating to: transportation licenses, documentation, personnel (driver, person in charge, passengers), vehicle, warning signs and fire extinguishers.

References


Jimeno, C.L. and Jimeno, E.L., 1995, Drilling and Blasting of Rocks, A.A. Balkema, Rotterdam.

