

CHAPTER 11

HIGH EXPLOSIVES

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11 HIGH EXPLOSIVES

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11.1 AWARENESS SUMMARY

11.1.1 Application of High Explosives

High explosives are those, which detonate in their designed use and find defence application in warheads and demolition charges. In the commercial sector high explosives are employed in building demolition, quarrying and mining.

A detonating explosive has two outputs that can be used to create damage, the detonation shock pressure of the detonation shockwave as it passes through the explosive charge and the expanding hot gas products from the detonation. These outputs can be manipulated mainly through the choice of explosive formulation, that is, which explosive molecular type or types are present together with other reactive ingredients such as metal powders and binders.

Where metal driving applications are required as for fragmentation, shaped charge and explosively formed projectile (EFP) warheads the significant output is the detonation shock pressure. For warheads that have their effectiveness through airblast, underwater bubble pulse or cratering ability the significant output is the gas expansion or power effectiveness. Examples are given in Table 11-1. An artillery shell is effective mainly through fragment lethality with blast a useful secondary effect. Shaped charge and EFPs require optimum metal driving through a very high shock pressure and the gas expansion from these warheads is of little consequence. Both the air dropped 1000 lb bomb and the torpedo warhead require maximum gas expansion effects to create airblast/cratering and underwater bubble pulse respectively.

Table 11-1 Energy Optimisation for Some Warhead Types

Warhead	Shock pressure	Power
Artillery shell	High	High
Shaped charge/EFP	Very high	High
1000 lb bomb	High	Very high
Spearfish blast warhead	High	Very high

Commercial explosives normally will be breaking concrete or rock and as such do not need the performance of military explosives that fragment or drive metal. In general their shock pressure is very modest although gas expansion effects are quite reasonable as lift and heave are often the main requirement.

11.1.2 Choice of Explosive Type

There are a number of different explosives available to produce high explosive formulations as shown in Table 11-2. The choice for a particular application, however, may not be as simple as its detonation pressure or power values.

Table 11-2 Performance of Some Established Explosives

Explosive	TMD* ρ (g cm ⁻³)	m.p (°C)	Ignition temp (°C)	Detonation Pressure (GPa) at ρ	Power (TNT equiv.)	Rotter test (F of I)
NG	1.60	13	188	24 (1.60)	1.52	30
PETN	1.76	141	205	26.9 (1.56)	1.50	50
TNT	1.64	80	240	17 (1.57)	1.00	150
RDX	1.81	204	213	35 (1.81)	1.52	80
HMX	1.91	278	300	39.2 (1.89)	1.50	60
TATB	1.94	340	359	28.3 (1.88)	0.90	>200
HNS	1.74	318	325	20.8 (1.70)	0.98	>150

* Theoretical Maximum Density

Nitroglycerine (NG) would not be suitable for a military high explosive on several counts even though it is a very powerful explosive although with modest detonation shock pressure. Above 13 °C it is a liquid, it has a very low ignition temperature and has very high impact sensitiveness (see 20.2.1). PETN is little better from a safety perspective and is not employed in main high explosive charges. However, due to its ability to detonate in very small diameter charges it is used in detonating cord and the base charge of detonators.

To provide explosive charges with good detonation shock pressure RDX and HMX are good candidates and as such either one or the other will be found in most warhead formulations. The impact sensitiveness for both is not ideal and so they are desensitised by mixing with either TNT or an inert binder. TNT was a main filling of choice between the 1st and 2nd World Wars before RDX and HMX became available as it can be readily melt cast having a melting point well below its ignition temperature. This makes it suitable to desensitise RDX and HMX as it allows them to be slurried in crystalline form in molten TNT well below their ignition temperatures and melt cast in to warheads.

11.1.3 Formulation Requirements

Modern high explosive formulations are chosen to be suitable for the following performance requirements:

1. Metal driving/shattering for fragmentation warheads and demolitions
2. Metal driving for Shaped Charge and Explosively Formed Projectile warheads
3. Gas expansion effects for airblast and underwater weapons

Other factors also are important:

1. Acceptable levels of safety
2. Acceptable service life
3. Suitable for filling methods
4. Cost effective

With the exception of TNT, most high performance explosives have high melting points which are too close to their ignition temperatures to allow warhead filling by melt-cast techniques. Other solid additives may be required by the formulation, such as ammonium perchlorate or aluminium. A binder is therefore required to enable solid charges with favourable mechanical and safety properties to be made and be suitable for a filling process.

Initially, the binder that allowed explosive formulations to be manufactured with RDX and HMX during and following the 2nd World War was TNT. It provided safe explosives and a ready melt-cast filling method. Inert binders such as waxes followed and then in the 1960s the use of polymers. All of these are still to be found in UK defence explosives. Across all natures of ammunition containing high explosives in UK service around 40 % w/w contain TNT.

11.1.4 TNT Formulations – General Aspects

TNT has a melting point when pure of 80.65 °C. For UK military use, a melting point of at least 80.2 °C is required to ensure a sufficiently low contamination with its isomers and dinitrotoluenes to prevent exudation which, apart from constituting a fire-risk and explosion hazard, might penetrate into exploder systems and safety and arming units, thus preventing their proper functioning. An example of exudation is shown in Figure 11-1 where the TNT filling has exuded in to the threading of the fuze pocket. With a tetryl exploder, which may still be found in obsolete ammunition, a liquid eutectic of very high sensitiveness is formed with the exudate.

There are additional safety hazards associated with TNT filled munitions particularly for those that will experience high g-force accelerations such as artillery shells. The melt-cast filling process is complicated by the shrinkage by about 10 % as the liquid TNT sets and becomes solid. Steps must be taken to control the cooling to avoid the development of cavities or low density areas and cracks in the solid charge. If cracks or cavities are present they can collapse

under the extreme g-forces on launch causing adiabatic compression of the air leading to ignition of the explosive and subsequent run to detonation within the shell. This can occur within the gun barrel. To avoid this the molten TNT is filled in to a pre-heated shell body with controlled cooling and a liquid TNT header maintained above the setting filling to fill any cracks or voids, a method known as the Meissner process.

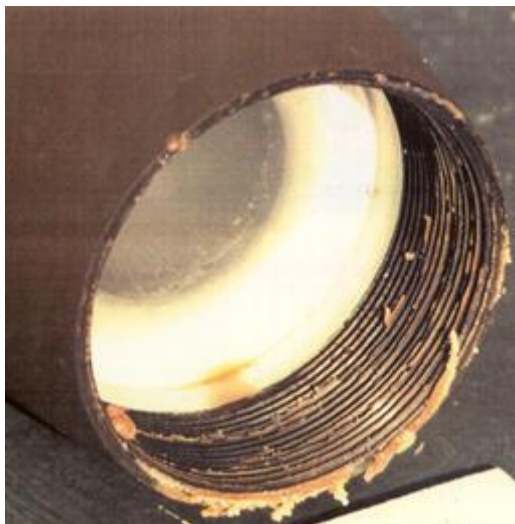


Figure 11-1 TNT exudation in a fuze pocket thread

The potential for cracks or voids to form is exacerbated by the propensity for TNT to crystallise in large crystals (Figure 11-2(a)) orientated in the direction of heat flow which forms planes of weakness in the explosive. To minimise this problem the crystal habit may be modified by adding a small quantity of hexanitrostilbene (HNS) to the melt giving smaller grains as can be seen in Figure 11-2(b). When added to compositions at the 0.3-0.5 % w/w it ensures that the TNT crystallises out as very small randomly orientated interlocking crystals. The strength of the cast charge may be increased as much as fivefold and its cracking resistance considerably enhanced.

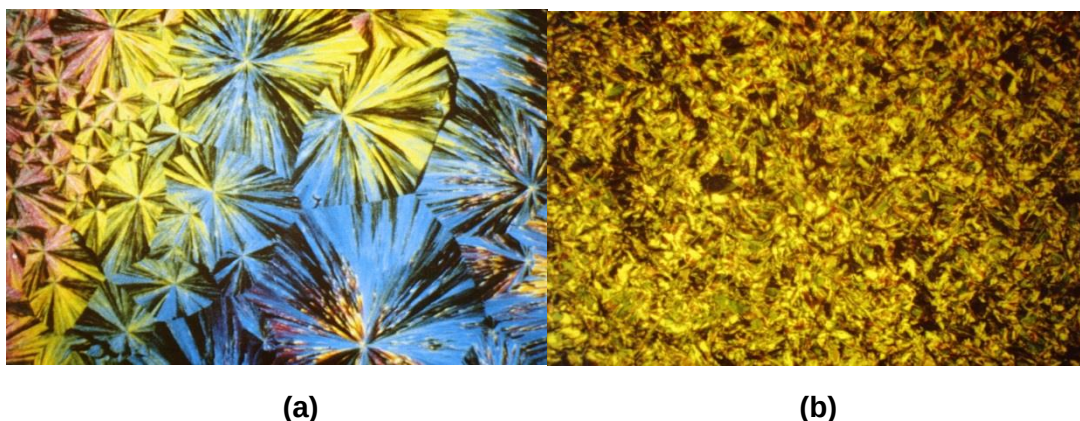


Figure 11-2 (a) Unmodified TNT, (b) TNT with 0.2 % w/w HNS

A similar effect can be obtained using 'creamed' TNT. Here the material is allowed to cool to its setting temperature with continuous agitation. When a slurry has formed, about 10 % w/w of finely powdered TNT is added to the slurry and the mix poured for immediate casting. These fine crystalline forms of TNT are more sensitive to detonation shock initiation than the coarser material although they are not unduly sensitive.

Another disadvantage in the use of TNT in warheads is the tendency for TNT formulations to have high explosiveness (see 20.2.1) making them unsuitable for Insensitive Munition (see 2.12) fills. This has been the main driving force for a move to polymer desensitised explosives. Formulations that use wax as a desensitiser in general also exhibit high explosiveness.

11.1.5 TNT Explosives in Service Use

TNT is of modest performance as a military high explosive as so is mixed with nitramines such as RDX and HMX to provide improved performance munition fillings. A common composition is RDX/TNT (60/40 % w/w) with a detonation pressure of around 25 GPa and an F of I of 120 (see 20.10.2.1). If greater detonation pressure is required then HMX is included in place of RDX with high solids content such as HMX/TNT (75/25 % w/w). If greater power is required then aluminium powder is added as in the Torpex type explosive such as RDX/TNT/Al (40/40/20 % w/w).

11.1.6 Other RDX and HMX Explosives in Service Use

Desensitisers other than TNT are used to produce formulations of suitable performance and safety. These include waxes and polymers where the non-explosive component is usually between 5 and 12 % w/w of the composition. Again, if high detonation pressure is required the explosive used will be HMX together with small amounts of the inert component such as HMX/polymer (95/5 % w/w).

A standard formulation with RDX would be RDX/binder (88/12 % w/w). Again, as for the TNT compositions, if high power is required then aluminium powder is added to produce the RDX/Wax/Aluminium (RWA) series of explosives.

11.1.7 Next Generation Explosives

New explosive molecules are now being considered as replacements of RDX and HMX to either improve performance or safety. A US explosive, CL-20 has greater detonation shock pressure than HMX, the previous best performer in this regard. NTO is considered a safer explosive component than RDX, which has very similar performance.

As replacement for TNT the explosive DNAN is now being considered as it can also be melt-cast for filling and provides compositions that have improved safety.

11.2 HIGH EXPLOSIVE FORMULATIONS FOR SHOCK PRESSURE

As noted earlier high explosives are chosen to be effective through either:

1. The shock pressure output that is used to create fragmentation, accelerate metal in shaped charges or EFPs or shatter structural materials in demolitions,
2. Gas expansion to produce airblast or underwater bubble pulse.

The pressure of the shockwave in a detonating explosive (p) depends on two variables, Velocity of Detonation (D) and density (ρ) of the explosive in a relationship shown in Equation (11-1).

$$\text{Detonation pressure } (p) \propto \rho \times D^2 \quad (11-1)$$

To formulate explosive charges with high detonation shock pressure explosive types are chosen that will maximise these characteristics. RDX ($D = 8750 \text{ m s}^{-1}$, $\rho = 1800 \text{ kg m}^{-3}$) and in particular HMX ($D = 9110 \text{ m s}^{-1}$, $\rho = 1890 \text{ kg m}^{-3}$) are ideally suited compared to TNT ($D = 6950 \text{ m s}^{-1}$, $\rho = 1640 \text{ kg m}^{-3}$)⁽¹⁾. Table 11-3 shows how this markedly affects the shock pressure.

11.2.1 RDX/TNT and HMX/TNT Formulations

The use of TNT as an energetic binder and desensitiser with the nitramines RDX and HMX produces formulations that have improved safety compared to the pure nitramines by reducing sensitiveness (see 20.2.1) values but still maintaining useful performance as shown in Table 11-3.

Table 11-3 Sensitiveness and Performance Data for RDX/HMX/TNT Explosives

Explosive	F of I	Mallet Friction Test	Shock pressure (GPa)
RDX	80	100/50/50	35 (1.80 g cm^{-3})
HMX	60	100/100/100	39.2 (1.89 g cm^{-3})
TNT	150	0/0/0	17 (1.57 g cm^{-3})
Composition B RDX/TNT (60/40 % w/w)	120	0/0/0	29.2 (1.71 g cm^{-3})
Octol HMX/TNT (75/25 % w/w)	90	0/0/0	32.5 (1.81 g cm^{-3})

In manufacture the nitramines as powdered solids are held in a liquid slurry in the molten TNT prior to casting. The UK uses air castable RDX/TNT Type A as a standard filling in artillery shell, large scale demolition charges and cratering munitions. A Type G variant is used in artillery shell and these compositions are shown in Table 11-4. UK service TNT compositions contain beeswax as an

extra desensitiser for the nitramines to that conferred by the TNT alone. The US equivalent to RDX /TNT Type A is Composition B which incorporates RDX manufactured by the Bachmann rather than the Woolwich process (see 10.3.3.1) and contains up to 10 % w/w HMX. The filling for Shell 155mm HE L15 is a modified RDX/TNT Type G with X28M plasticiser added comprising polyvinyl nitrate/mononitrotoluene (22/78 % w/w).

To increase the performance of TNT melt cast explosives, the solids loading can be increase or HMX substituted for RDX as shown in Table 11-5. This development has been seen with:

1. RDX/TNT compositions with higher RDX content e.g. RDX/TNT 75/25 % w/w developed in Germany
2. The development in the UK of EDC1 series of compositions, in which HMX replaces all but 4 % w/w of the RDX.
3. The development of HMX/TNT (Octol) compositions with high loadings of up to 85 % w/w HMX.

The viscosity of these compositions necessitates the use of vacuum casting, and in addition, for the highly loaded RDX and HMX compositions, pressure sedimentation as well.

Table 11-4 RDX/TNT Formulations

Formulation	TNT (% w/w)	RDX (% w/w)	HMX (% w/w)	HNS (% w/w)	Beeswax (% w/w)
RDX/TNT Type A	39.5	59.5	-	-	1
RDX/TNT Type G	39.3	55.5	4	0.2	1
CW 3	RDX/TNT Type G	99.7	-	X28M plasticiser	0.3

Table 11-5 EDC Formulations

Formulation	Composition
EDC1	TNT/RDX/HMX (25/4/70 % w/w)
EDC1A	EDC1/TNT (95/5 % w/w)
EDC1G	EDC1/HNS (99.8/0.2 % w/w)
EDC1S	EDC1G/X28M plasticiser (99.7/0.3 % w/w)

11.2.2 RDX and HMX Formulations with Inert Desensitisers

Another route to the production of formulations containing RDX and HMX that have acceptable sensitiveness (see 20.2.1) values and still maintain the required performance is to include waxes, greases or polymers in the formulation. Although these are non-explosive components the performance is not unduly lessened as a much smaller amount is required than the large percentages used for TNT desensitisation. These materials are often called phlegmatisers as a phlegmatic person is not easily excited, a good analogy to reduced sensitiveness.

11.2.2.1 Wax desensitised

The only formulation designed as a main charge utilising shock output that is wax desensitised in the filling of the High Explosive Squash Head (HESH) round (see 7.3.2.3). The filling is a mixture of RDX and Wax Special No. 8 88/12 (% w/w).

Formulations with significantly less desensitiser are employed as booster charges. RDX and Wax Special No. 8 are mixed in a 93/7 ratio. Other formulations including US compositions A3, A5 and CH6 are employed in UK munitions with details given in Table 11-6. The Debrix compositions are manufactured using a special process that gives a thin coating of Wax No.10 such that they have acceptable sensitiveness values for boosters but maximise the shock output to initiate a main charge.

Table 11-6 RDX/Wax Booster Compositions

Composition	RDX (% w/w)	Wax (% w/w)	Other (% w/w)	F of I ⁽¹⁾
RDX/Wax	93	7		
Composition A3	91	9		140
Composition A5	98.75 – 99.0	0	Stearic acid 1.25 – 1.0	110
CH6	97.5		Calcium stearate 1.5 Graphite 0.5 Polyisobutylene 0.5	100
Debrix 11	99	1		110
Debrix 12	95.8	4.2		120
Debrix 18 AS	95.3	2.7	Zinc stearate 1.5 Aerosil 0.5	120

11.2.2.2 Polymer desensitised

The title 'Polymer Bonded Explosive' (PBX) is applied to a variety of explosive mixtures which contain a large percentage of explosive powder in an intimate mixture with a polymeric binder. In some instances, a plasticiser is included in the composition to further modify the physical properties of the explosive charge. The polymer forms a matrix in which the solid components of the formulation are embedded.

Choice of polymer and plasticiser provides the possibility of achieving explosive charges with much higher melting temperatures than those employing TNT or wax as desensitiser. Their physical properties can be controlled, such as reduced brittleness, which reduces explosiveness (see 20.2.1). Good chemical stability, required explosive output and insensitiveness to handling, shock and thermal input, are all achievable with PBXs.

11.2.2.2.1 Polymeric binders

Properties required for a polymeric binder are:

1. Elasticity with a low modulus
2. Strain-rate and temperature insensitive
3. Low glass transition temperature
4. Good heat-sink
5. Good adhesion to particulate system
6. Easy to process

There is a wide range of commercially available polymers and they can be divided into three groups:

1. Thermoplastics
2. Thermosetting materials
3. Elastomers

Thermoplastics are stable polymers which soften and melt on heating, and can be moulded in the plastic state to yield products of varying degrees of hardness and toughness. Examples of thermoplastics are listed in

Table 11-7. All materials have reasonable mechanical strength at ordinary temperatures, but only Nylon, Terylene and PTFE remain hard and strong above 150 °C.

Table 11-7 Examples of Thermoplastic Polymers

Material	Softening point (°C)
Polyvinyl chloride (PVC)	82
Polyethylene (low density) (LDPE)	82 - 87
Polystyrene (PS)	82 - 103
Polymethyl methacrylate (PMMA)	85 - 115
Nylon (type 6)	220 (m.pt.)
Terylene	230
Polytetrafluoroethylene (PTFE)	above 250

Thermosetting plastics are processed from monomers or partial polymers, in the form of liquid resins or moulding powders. These are polymerised by heat, pressure and catalysts to yield hard plastic materials which cannot be melted or softened by heat. Examples of the thermoset materials are phenolics, polyesters, epoxy resins and polyurethanes. These materials provide varying degrees of hardness and toughness over a wide range of temperatures. They are stable at 200 °C. PBX compositions are conveniently prepared from thermosetting resins or moulding powders, by intimate mixing of the ingredients followed by polymerization under the influence of gentle heat, pressure and catalysts. Such preparations may be filled and polymerised directly in a weapon case. Alternatively, a charge may be machined from the plastic bonded product. The requirements of such castable binders are:

1. Compatibility with high explosives
2. Thermal stability
3. Low toxicity (isocyanates are therefore a problem)
4. Ready availability
5. Good processability (e.g. a low number of reagents)
6. Low viscosity - for room temperature and easy casting
7. Long pot life
8. Good curing at low (<60 °C) temperatures, no exothermic reactions, short cure period, low glassy temperature.
9. Predictable and controllable polymerisation

Elastomers are polymers containing crosslinks and undergo elastic deformation. The degree of hardness of an elastomer depends upon the number of cross links present. Elastomers include polyurethanes, polybutadienes, natural and synthetic rubbers. PBX compositions are prepared from elastomers by mixing the elastomeric resins with the particulate system. Crosslinking of the elastomer during curing will impart rigidity to the PBX.

Some polymer binders used in UK service explosives are given in

Table 11-8.

There is interest in using polymers that incorporate explosophores such as nitro groups in their structure. Such polymers can contribute to the explosive performance of a PBX formulation in their own right and are called 'energetic binders'. These materials are presently the subject of research a promising material being poly-NMMO (poly 3-nitratomethyl-3-methyloxetane).

Table 11-8 Some Polymer Binders in UK Munition Formulations

Binder	Type
Viton	Fluoroelastomer
HyTemp	Polyacrylate
Polyisobutylene	Elastomer
HTPB-IPDI *	Polyurethane
Estane	Polyurethane
Poly(dimethylsiloxane)	Silicone

*Hydroxyl-terminated polybutadiene/Isophorone Di-isocyanate cross linking agent

11.2.2.2.2 Plasticisers

The mechanical properties of a PBX e.g. glass temperature, hardness, may be modified by incorporating a liquid plasticiser into the polymer. Typical plasticisers are dioctyladipate (DOA), dioctylsebacate and di-2-ethylhexylsebacate with DOA being the most common.

11.2.2.2.3 PBXs in UK munitions

Table 11-9 gives examples of PBX explosives in UK service use. The US composition PBXN-5 is used in a number of munitions as a booster pellet. With a high percentage of HMX it will be sensitive to pick up from a detonator and have a high shock output to detonate the main charge. A similar composition PBXW-11 also is used as a booster charge.

Polymer binders have allowed a number of explosives with very high detonation shock pressure, through having HMX content of over 90 % w/w, to be accepted in to service. As shown in

Table 11-9 they find use in either shaped charge or high performance fragmentation warheads. Currently, PBX explosives are found only in warheads that do not experience high g-force loading.

Table 11-9 PBX Formulations in UK Munitions

Name	Composition (w/w)	Use
PBXN-3	HMX/Nylon (86/14 %)	Missile fragmentation warhead
PBXN-5	HMX/Viton (95/5 %)	Booster pellets and small shaped charges
PBXN-9	HMX/HyTemp/DOA (92/2/6 %)	Anti-armour shaped charge warhead
PBXW-11	HMX/HyTemp/DOA (96/1/3 %)	Booster pellets and anti-armour shaped charge warhead
PBXN-107	RDX/Polyacrylate (86/14 %)	Large unitary land attack warhead
LX-14	HMX/Estane (95.5/4.5 %)	Anti-armour shaped charge warhead
KS32	HMX/HTPB Polyurethane/DOA (85/14/1 %)	Missile fragmentation warhead

11.2.2.3 Mouldable and flexible formulations

Demolition and bomb disposal activities rely on the availability of hand mouldable and flexible sheet explosives known universally as plastic explosive. For a considerable time the cartridge and bulk PE4 and sheet SX2 have been the inventory explosives for these purposes. PE4 consists of 88.0 % w/w RDX, 1.0 % w/w pentaerythrite dioleate and 11.0 % w/w DG-29 lithium grease (2.2 % w/w lithium stearate and 8.8 % w/w paraffin oil BP). There is a legal requirement to add a chemical detectable by vapour detector to all plastic explosives. The taggant added is (2,3-dinitro-2,3-dimethylbutane, DMNB) at 1.0 % w/w. On very long term storage in paper wrapped cartridge form there is a tendency for the mineral oil to evaporate and the formulation becomes slightly crumbly. Sheet explosive SX2 is a mixture of 88.2 % w/w RDX, 8.2 % w/w polyisobutene, 2.2 % w/w di(2-ethylhexyl)sebacate and 1.4 % w/w PTFE hot rolled to a thickness of 3 mm.

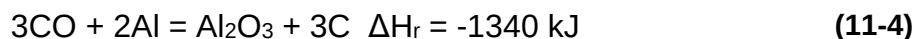
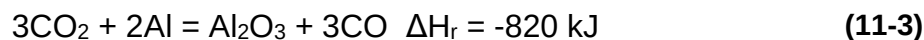
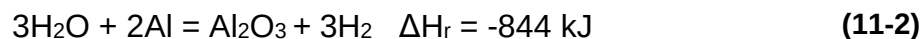
Both PE4 and SX2 have been replaced with the explosives PE8 and SX4 both using the formulations containing nominally 87 % w/w RDX, which is desensitised using polyisobutenes with dioctylsebacate plasticiser.

11.3 HIGH EXPLOSIVE FORMULATIONS FOR GAS EXPANSION

Since the 1st World War aluminium powder has been employed in explosive mixtures to provide heat for gas expansion as the combustion of aluminium is highly exothermic. Initially the compositions used an oxidiser such as ammonium nitrate to provide the oxygen such as in ammonal, which also included small quantities of TNT as the war progressed. The explosive was a powder and not suitable for munition fillings but perfectly suited to the large

mines placed in tunnels under enemy lines. During the 2nd World War this type of composition was used mainly to supplement the meagre stocks of TNT although its main use was in sea mines and had very good underwater explosion effects. Developments to specifically increase the gas expansion effects of high explosives began in this period and have relied on RDX as a major component of these formulations desensitised either with TNT or using PBX technology.

In modern formulations the aluminium does not need a specific oxidant such as ammonium nitrate to be added as it is capable of reacting with the initial products of explosion formed from the carbon, hydrogen and nitro groups. As the explosive molecules react they form carbon dioxide, carbon monoxide and water. The following reactions of these gases with aluminium can then occur:



As explosive power is proportional to Heat of Explosion $\times$ Gas Volume Equations (11-2) and (11-3) will increase the amount of heat produced but maintain the gas volume as one mole of any gas occupies the same volume (22.4 litres mole⁻¹). However, if reaction shown in Equation (11-4) occurs then heat energy is produced but as the product carbon is a solid the gas volume will decrease. This limits the amount of aluminium that can be added to a formulation if no other source of oxygen is present to between 18 % and 25 % by weight.

Other developments turned to the addition of large amounts of oxidants such as ammonium perchlorate with either TNT as binder, or an energetic binder such as PBX mixed with energetic plasticiser or wax and energetic binder/plasticiser. Although these have excellent gas expansion performance their sensitiveness (see 20.2.1) and explosiveness (see 20.2.1) preclude them from modern formulation requirements.

Table 11-10 Enhanced Performance Formulations Containing Large Oxidant Percentages with Aluminium

Formulation	Ingredients w/w				
	TNT %	Binder/plasticiser	RDX %	Al %	Oxidant %
Minol-2	40	-	-	20	40(AN)*
CTX-1	14	-	15	24	41(AP)**
CPX-100	-	9 % HTPB*** / 21 % K10****	60	22	28(AP)
PBXN-105	-	4 % Wax / 13 % BDNPA/F*****	7	26	50(AP)

* AN = Ammonium Nitrate

**AP = Ammonium Perchlorate

***HTPB = Hydroxyl Terminated Poly Butadiene

****K10 = Trinitroethylbenzene/dinitroethylbenzene (35/65 % w/w)

*****BDNPA/F = Bis(2,2-dinitropropyl)acetal/formal

11.3.1 Aluminised RDX Explosives

The Torpex series of explosives, where RDX and aluminium are bound with TNT, have been in use since the 2nd World War. Examples of Torpex compositions and the US equivalent (H-6) are given in Table 11-11. With such large solids loadings TNT is not a perfect binder. Therefore a series of formulations with wax as binder was developed as the RWA series (see

Table 11-12).

Initially aluminised explosives were developed for underwater weapons and several current torpedoes and depth charges have either Torpex or RWA fillings as do large air dropped bombs. Aluminised PBXs also have been developed and employed in large air dropped ordnance including PBXN-109, where the aluminium content is similar to the TNT and wax desensitised compositions (

Table 11-13).

Table 11-11 Formulations with RDX, TNT and Aluminium

Name	TNT (% w/w)	Additive	RDX (% w/w)	Aluminium (% w/w)	Beeswax (% w/w)
Torpex - 2	39.7	-	41.6	18	0.7
Torpex - 4A	53.2	2.9 % w/w	19	24.3	0.3
H-6 (USA)	29	5 % w/w Wax	45	21	-

Table 11-12 Formulations with RDX, Wax and Aluminium

Name	RDX (% w/w)	Wax (% w/w)	Aluminium (% w/w)	Other (% w/w)
RWA-2	70.5	9	20	0.5
RWA-3	73	10	15	2
RWA-4	71	7	20	2
Hexal	55	5	40	-
Hexal W30	66.5	3.5	30	-

Table 11-13 PBX Aluminised Explosives

Name	Nitramine (% w/w)	Polymer/ Plasticiser (% w/w)	Aluminium (% w/w)
PBXN-109	RDX 65	14	21
PBXIH-18	HMX 64.4	5.6	30
DPX-6	HMX 50	4	46

11.3.2 Enhanced Blast Explosives

It has been recognised that if an aluminised explosive detonates in air then further reaction of aluminium with atmospheric oxygen can enhance blast output. This has led to the development of formulations with aluminium content well in excess of the previous limitations for underwater explosions. The Hexal compositions shown in

Table 11-12 can be found in medium calibre cannon rounds and formulations such as PBXIH-18 and DPX-6 in

Table 11-13 are listed as anti-structure or enhanced blast explosives, which are highly effective in enclosed spaces.

11.4 NEW FORMULATIONS

11.4.1 Potential Explosives for Future Formulations

There are a number of explosive molecules that are of interest to develop new explosives (Table 11-14). Some are already in use by other nations and some being studied in the UK as potential replacements for current formulations.

Nitrotriazolone (NTO) has for some time been considered as a replacement for RDX, particularly in formulations designed to produce munitions that pass the Insensitive Munitions (IM) tests. When NTO replaces RDX even in TNT containing formulations the IM properties are improved. However, the most recent development of specific interest in the UK is the replacement of TNT in melt-cast compositions with 2,4-dinitroanisole (DNAN).

Table 11-14 Explosives in Potential Future Formulations

Substance	Velocity of Detonation (m s ⁻¹)	Density (g cm ⁻³)	Impact sensitiveness	Temperature of Ignition (°C)
CL-20	9,380	2.04	20 (F of I)	220
TATB	7970	1.94	>200 (F of I)	320
DADNE (FOX-7)	8800	1.885	100 (F of I)	217
NTO	8430	1.91	80 - 90 (F of I)	>270
DNAN	5670	1.52	>100 (ERL Impact Test, RDX = 18)	244

The explosive hexanitrohexa-azaisowurtzitane (CL-20) has a detonation pressure of 44 GPa compared to a value of 39.2 GPa for HMX, the current explosive of choice in formulations that require very high shock pressure. There is international interest in developing formulation containing this explosive and it is commercially available.

11.4.1.1 New melt cast insensitive high explosives

In 2005, the US Army began a programme to replace TNT and Composition B in its artillery and mortar rounds to make them more IM compliant. An extensive down-selection process was undertaken, resulting ultimately in two formulations

being selected. The replacement for TNT was IMX-101, which comprises DNAN, NTO and nitroguanidine (NQ) and the replacement for Composition B was IMX-104, which comprises DNAN, NTO and RDX. The compositions of these formulations are given in Table 11-15 (for IMX-104 this is the range for Qualification).

Table 11-15 US Melt-Cast Explosives with Improved IM Suitability

	Ingredients (% w/w)			
	DNAN	NTO	NQ	RDX
IMX-101	43.5	19.7	36.8	-
IMX-104	29.7-33.7	51-55	-	13.3-17.3

The performance of IMX-101 and IMX-104 is very similar to TNT and Comp B respectively. The detonation performance of these explosives is given in Table 11-16.

Table 11-16 Performance of TNT and Composition B vs IMX Replacements

Composition	Density (g/cm ³)	VoD (m sec ⁻¹)	Detonation pressure (GPa) - calculated
TNT	1.60	6,900	19
IMX-101	1.64	6,900	19.5
Comp B	1.71	7,980	27.2
IMX-104	1.75	7,400	24

IMX-101 and IMX-104 have been subjected to IM acceptance tests with the results shown in Table 11-17. IMX-101 meets all the IM acceptance criteria. Whilst IMX-104 does not meet the criterion for shaped charge jet attack, it performs markedly better than Composition B.

Table 11-17 IM test Results for IMX101 and IMX104

	IM TEST					
	Fast Cook Off	Slow Cook Off	Bullet Impact	Fragment Impact	Sympathetic Detonation	Shaped Charge Jet
IM Passing Criteria	V	V	V	V	III	III

	IM TEST							
	Fast Cook Off	Slow Cook Off	Bullet Impact		Fragment Impact		Sympathetic Detonation	Shaped Charge Jet
155mm TNT	III	III	IV		IV		I	I
155mm IMX-101	V	V	V		V		III	III
81mm Comp B	II	II	III		III		I	I
81mm IMX-104	V	V	IV (a)	V (b)	III (c)	IV (d)	III	I
120 mm Comp B	II	I	I		I		I	I
120 mm IMX-104		V	IV		V		III	

a - 0.50" Cal, b - 7.62 mm, c - 8300 ft s⁻¹, d - 6000 ft s⁻¹

11.5 COMMERCIAL EXPLOSIVES

Apart from military formulations which have commercial equivalents, for example plastic explosives, the common commercial explosives divide into 4 types:

1. Ammonium Nitrate/Fuel oil (ANFO) mixtures
2. Emulsions and emulsion blends
3. Nitroglycerine gelatines and dynamites
4. 'Permitted' explosives

Over the last 20 years emulsion explosives have become the dominant commercial explosive together with ANFO as they have developed in to a range of bulk delivered explosives for quarrying and mining and cartridged explosives that have largely replaced nitroglycerine equivalents.

The performance of commercial explosives, particularly the detonation pressure (see 11.2), is inferior to military explosives based on RDX, TNT and HMX as highly brisant (shattering) explosives would be unsuitable for commercial activities. Quarrying, for example, requires sufficient shattering capability to start the rock fracturing, which then is acted on by the expanding gasses with a heaving effect. The rock produced (the muck pile) must have rock pieces that can be handled by quarry plant including crushers. For rock such a limestone this does not need high detonation pressure.

Commercial explosives manufacturers express the performance of their products in terms of strength. This is measured by comparing the work done by an explosive with that done by either an equal weight (weight strength) or an equal volume (bulk strength) of a standard explosive. The standard chosen initially was blasting gelatine although it is common in recent times to use ANFO as the standard. Care must be taken when considering a quoted strength as blasting gelatine is around 25 % more powerful than ANFO. Table 11-18 provides data on the performance of commercial explosives compared to typical military explosives.

Table 11-18 Performance of Some Commercial and Military Explosives

Explosive	TNT equivalence	Detonation pressure (GPa)	Velocity of detonation (m s^{-1})
ANFO mixtures	0.8 – 0.9	2 - 3	2000-3500
Emulsion/emulsion blends	0.8 – 1.0	5 - 9	4000 - 6000
Gelatine dynamites	0.8 – 1.1	6 - 11	4500 - 6000
TNT	1.0	17	7000
RDX/TNT (60/40)	1.3	24	7800

Another difference between military and commercial explosives is that the cost of the explosive is of much less concern for the manufacture of ammunition than for commercial blasting operations. The vast majority of commercial explosives used worldwide are based on ammonium nitrate as the major component, which is a very cost effective ingredient. In comparison TNT, RDX and HMX are very expensive explosive ingredients.

11.5.1 ANFO Type Explosives

ANFO is a mixture of 94.5 % w/w pure (>98 % w/w) ammonium nitrate and 5.5 % w/w fuel oil (diesel oil), or closely similar percentages. The ammonium nitrate is used in the form of prills, which are smooth spheres about 2 mm to 3 mm in diameter, which are made by allowing the molten nitrate to fall inside a high tower. Porosity is achieved by driving out the last few percent of moisture from the material after it has been prilled, and this enables the prills to soak up the oil more efficiently. The crystal density of ammonium nitrate is 1.7 g cm^{-3} , but the bulk density of prills is only about 0.8 g cm^{-3} and the addition of the comparatively small percentage of oil makes little difference to this figure.

ANFO can be obtained ready-mixed from explosives manufacturers, or alternatively the prills and oil can be purchased separately and mixed on the blasting site. For large operations ANFO can be truck mixed and augered in to bore holes. ANFO is not resistant to water and must be kept dry. It cannot be initiated by a detonator alone or by standard detonating cord. A primer with

good shock pressure output is used to initiate ANFO. The detonation velocity of ANFO will be in the range of $2000\text{--}3000\text{ m s}^{-1}$ unless it is loaded pneumatically in to bore holes as this increases the filling density, which can increase the detonation velocity to nearly 4000 m s^{-1} . This can improve the shattering ability of the explosive.

11.5.2 Emulsion Explosives

The term 'emulsion explosive' is taken to mean a high internal phase, water-in-oil emulsion of a concentrated (often supersaturated) solution of nitrate salts in water emulsified into an oil base. Emulsion explosives have unusually high rates of detonation for such a heterogeneous explosive (Table 11-18).

The velocity of detonation depends on maintaining an intimately mixed liquid system. The emulsified droplets are of the order of $1\text{ }\mu\text{m}$ in diameter separated by an oil film of the order of 3 mm thick. The use of water is limited because it inhibits detonation. The production of an oxygen balanced explosive requires a large quantity of oxidising salt. The emulsion is a supersaturated meta-stable solution, typically containing $70\text{ }\%$ w/w ammonium and sodium nitrates, $20\text{ }\%$ w/w water emulsified in oil or oil/wax phase.

The emulsion is not in itself an explosive and can be stored and transported as a product known as emulsion matrix with a Hazard Classification Code of 5.1 (Oxidising substances). To convert it to a detonable material voids are introduced either in the form of hollow glass or plastic spheres, by air beaten in to the mixture or by a chemical reaction. These voids provide a mechanism for the conversion of energy in the shockwave from the detonation to heat energy necessary to produce chemical reaction and to sustain detonation. The sensitivity and velocity of detonation of the explosive are dependent on the quantity and size of the bubbles. Emulsion explosives can be made to be detonator sensitive in small critical diameters and with a velocity of detonation in the range 4000 m s^{-1} to 6000 m s^{-1} . The energy of the explosive, increasing power (strength), can be further enhanced by incorporating aluminium powder as in military explosives. The consistency of emulsion explosives ranges from that of thick cream to a stiff paste. Shelf life for cartridge, also known as packaged, emulsions is usually 1 year.

It is now common practice for large scale use of emulsion explosives such as in quarrying and mining to have a range of emulsions to match the local requirements that can be fine-tuned at point of use. The explosive company will provide bulk emulsion trucks known as 'Mobile Manufacturing Units' (MMUs) or 'Mobile Charging Units' (MCUs) that contain the emulsion matrix in a tank but also carry prilled ammonium nitrate and a gassing agent. The gassing agent is mixed with the emulsion matrix as it is pumped in to the borehole and reacts to form gas bubbles sensitising the matrix to shock detonation. This reaction can take some hours before sensitisation occurs but will remain usable for up to 2 weeks or more. This is called the 'sleep time', that is how long between borehole loading and detonation. The ammonium nitrate prills are mixed with

the emulsion matrix as the borehole is loaded a typical mixture being 70 % w/w matrix and 30 % w/w prills. The ratio is adjusted for the specific requirements of the blast.

11.5.3 Nitroglycerine Explosives

Nitroglycerine (NG) (see 4.2.2) based explosives dominated the commercial explosives scene until the mid C^{20th} when explosives based on ammonium nitrate became available. The ingredients for nitroglycerine explosives divide into two parts, the explosive molecular components NG, ethyleneglycol dinitrate (EGDN) and nitrocellulose (NC) and secondly an oxidant/fuel mixture (see 4.2.1) known traditionally as 'dope'. The oxidant is ammonium nitrate and the fuel woodmeal and this acts as a base material to absorb the liquid NG and EGDN. NC is present to further bind or gel with the liquid explosives and provides a rigid gelled solid if sufficient NG/EGDN is present. This led to the generic name being a gelatine dynamite or gelignite. As the liquid component is reduced the term semi-gelatine is used and finally at low amounts the mixture is not a rigid solid and is called NG powder

The EGDN originally was added to the mixtures to prevent the NG freezing in cold conditions. NG has a freezing point of 13 °C and so temperatures below this may be encountered when in use. Frozen NG is far more sensitive than when in the liquid state and so the EGDN mixed with the NG lowers the freezing point of the mixture. EGDN has a freezing point of -22 °C and the mixtures with NG values that are significantly lower. In modern gelatine explosives the EGDN is the major component compared with NG. With a zero oxygen balance (see 4.3.1) EGDN is actually more powerful than NG.

Table 11-19 Performance of Nitroglycerine Containing Explosives

Type	Weight Strength vs BG (%)	Density (g cm ⁻³)	Velocity of Detonation (m s ⁻¹)
Blasting Gelatine (BG)	100	1.6	7000
Gelatine Dynamite	80 – 65	1.5 – 1.4	6600 - 5500
Semi-gelatine	65 – 50	1.3	6000 – 5000
NG Powder	<50	1.15	4000

The true gelatines are rubbery and are filled into cartridges by extrusion. Because of their physical homogeneity they have good water resistance and shelf life. Their sensitivity falls with storage time, however, due to the loss of occluded air. Blasting gelatine has little or no dope with some mixtures containing up to 93 % w/w NG mixed with NC and an antacid stabiliser. It is very sticky to handle and is rarely if ever used. The commonly used explosives are the gelatines, semi-gelatines and NG powders, the gelatine types as paper wrapped cartridges and the powder in cardboard or plastic tubes as it has no

water resistance. The NG content reduces from gelatines through to the powders, the latter containing around 20 % w/w NG and 80 % w/w dope. The performance of these explosives is shown in Table 11-19.

11.5.4 Permitted explosives

A Permitted Explosive is one that has passed the tests required for use in coal mines where there is a risk of explosion caused by ignition of flammable gases such as methane or of coal dust. The main requirement is that it produces a flame of lowest possible temperature for the minimum possible time. The explosive is tested in a gallery into which flammable gases can be introduced. In the UK these are known as the Buxton Tests. The explosive contains components that are flame suppressants and flame coolants such as sodium chloride and sodium bicarbonate (

Table 11-20). The first British list of permitted explosives was published in 1899. Typical detonation velocities range from 3800 m s^{-1} for a gelatine type to 1800 m s^{-1} for some NG powders.

Table 11-20 Some Formulations of Permitted Explosives

	Gelatine (% w/w)	Semi-gelatine (% w/w)	NG Powder (% w/w)
NG/EGDN	27.00	16.00	10.0
NC	0.75	0.25	-
AN	30.50	42.75	64.00
Sodium Chloride	28.50	26.00	16.50
Kaolin	3.00	2.00	-
Carbonaceous fuel	1.25	2.00	8.50
Barytes (barium sulphate)	5.00	5.00	-
Calcium sulphate	-	4.00	-
Other	4.00	2.00	1.00

11.6 REFERENCES

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