

CONSIDERATIONS OF EXPLOSIVE TRAINS IN ARTILLERY ROUNDS DURING SERVICE LIFE AND USE.

Investigating the design features necessary to achieve the safe storage and transportation of a large calibre artillery nature during service life, and to assure safety during intended use.

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Principles of OME

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Abstract

Casted TNT has long served as the main-fill for most conventional HE large calibre rounds in service across the UK. This report aims to examine the chemistry of TNT, the principles of the explosive train and the MoD regulations that govern storage and manufacture of munitions both at home and on operations, to determine how a large calibre, TNT-filled munition is best placed to function as planned when fired in the field, and to determine whether TNT is still the best composition for the job in the modern-era, where most UK operations are carried out in extreme climates.

Introduction

The Explosive Train

The explosive train is defined as a 'sequential arrangement of explosive components with the fundamentals being an easily initiated primary explosive, a booster sensitive enough to be reliably initiated by the modest output of the initiator but also providing much higher output to initiate the relatively insensitive main charge' [1]. For safety reasons, most main charge explosives are reasonably difficult to detonate. It is required therefore that the explosive train can reliably achieve the desired detonation or ignition of a main charge when set in to motion. Understanding the explosive train, how it works and how to prevent accidental initiation is key to protecting in-service munitions throughout their life and ensuring safe and effective firing when called upon.

TNT

TNT, named fully as 2,4,6-trinitrotoluene [2], was first discovered by Julius Wilbrand in 1863 [3], where it was originally used as a dying agent. Germany was the first country to manufacture TNT commercially, towards the end of the 1800s, and by the turn of the 20th Century they had discovered

its use as an explosive composition, replacing picric acid as the conventional filling for military munitions in 1902 [2]. By the outbreak of the First World War in 1914, the United Kingdom and the USA had both abandoned picric acid TNT's more desirable properties – and TNT became, and still is, one of the most commonly used explosive compositions in military munitions worldwide.

Manufacture, Storage and Transport

Properties of TNT¹

TNT is a typical secondary explosive of the form $C_aH_bN_cO_d$, containing only the four elements of carbon, hydrogen, nitrogen and oxygen, having the chemical formula $C_7H_5N_3O_6$ [4]. The decomposition reaction of TNT produces a high amount of carbon (C) and carbon monoxide (CO) among the products of detonation [4], giving TNT its characteristic black smoke plume. This production of C and CO occurs because TNT is hugely oxygen deficient. In chemistry, oxygen balance refers to the amount of oxygen within a molecule compared with the amount of oxygen required to completely oxidise the carbon and hydrogen in the composition [4]. If there is an insufficient amount of oxygen available, then the composition is termed 'oxygen deficient' and has a negative oxygen balance. The oxygen balance of TNT is almost -74%, among the lowest of all commonly available military grade high explosives. Secondary explosives with such extreme oxygen imbalance suffer in performance. There is a direct correlation between oxygen balance and heat of explosion, as demonstrated in Figure 1 [4].

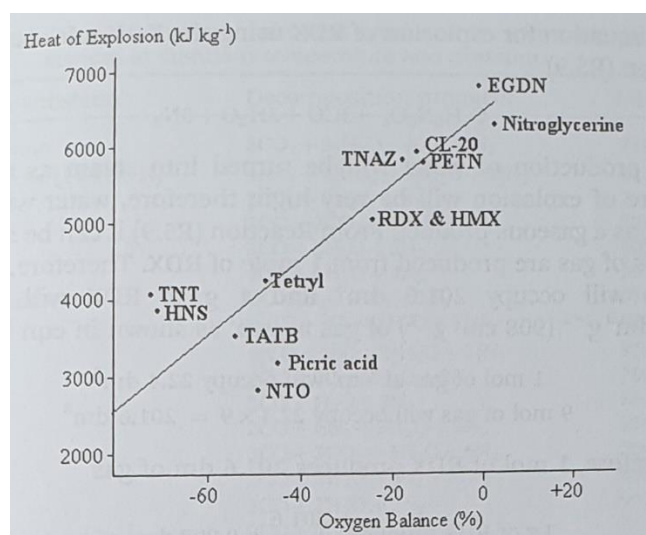


Figure 1: Graph comparing Oxygen Balance of explosive compositions and their associated Heat of Explosion

EGDN, which has an oxygen balance of exactly zero, meaning that the products of detonation are purely carbon dioxide and water, has a much higher heat of explosion than that of TNT. Table 1 shows the full list of properties associated with TNT.

Properties of TNT	
Chemical Formula [4]	$C_7H_5N_3O_6$
Detonation Products (Kistiakowsky-Wilson) [4]	$3.5CO + 3.5C + 2.5H_2O + 1.5N$
Oxygen Balance [4]	-73.96%
Heat of Explosion [4]	4091.63 kJ/kg
Melting Temperature [5]	80°C
Ignition Temperature [5]	240°C

¹ All properties of TNT in this section are taken from [4] and [5]

Table 1: Key properties of 2,4,6 trinitrotoluene (TNT)

The melting and ignition temperatures of TNT form the basis for its widespread manufacture, but also its potential long term storage issues.

Manufacture and Vulnerability of TNT

The primary method of manufacture for TNT is melt-casting. This is because of its low melting temperature. TNT's melting temperature of 80°C is under half that of RDX and HMX, which are also commonly used as main charge explosives [6]. This means that TNT can be melt-casted without needing to produce exceedingly high temperatures, reducing cost and energy use during manufacture.

Melt-casting is a common form of processing for filling large shells such as a large calibre artillery round. Explosive compositions are heated up until they melt, and then poured in to large containers and left to cool down, which causes the composition to solidify. It is not safe to cast explosives that have an ignition temperature close to their melting temperature. With an ignition temperature of 240°C, TNT is a safe option for casting [5]. It is a cheap, effective and straightforward processing method.

TNT's ease of use for casting is a double-edged sword. The properties that make the composition so usable for melt-casting also pose risks for long-term storage in the field. With a melting temperature of 80°C, TNT melts at a temperature low enough to cause serious issues in many of today's modern combat theatres, with many modern-day theatres of war being in areas of the world liable to extreme temperatures.

It was identified on recent operations that temperatures of cased explosive compositions in well-ventilated storage on certain operations could still reach 78°C, and on a launcher under the effects of severe solar radiation could surpass 100°C – due to the effects of solar radiation, as detailed in table 2 [7].

Exposure to the sun	Temperature of explosive composition
Full exposure	Up to 50°C higher than ambient temperature
Tarpaulin covered (in contact)	Up to 52°C higher than ambient temperature
Shaded	Up to 27°C higher than ambient temperature

Table 2: Summary of the effects of solar radiation on the temperature of explosive compositions under different storage conditions.

TNT's low melting temperature poses a genuine risk to service personnel in the field when stored in unforgiving conditions, in environments where TNT would be reasonably expected to melt and recrystallise over and over again during its service life.

The repeated uncontrolled melting and cooling of TNT can cause long, sensitive 'needles' of TNT to form within the composition. If these needles crack, they are very liable to detonate. There is an increased risk of ammunition depot fires and explosions in combat theatres if there is a high proportion of TNT-based munitions in storage, which poses a serious risk to personnel [7].

Beyond the associated safety risks, there are also related performance risks linked to the stressing and melting and cooling of TNT.

Safe Storage and Transport Principles

In order for a large calibre, TNT-filled artillery round to fire successfully when the time comes, it is essential to uphold safe storage and transport behaviours at all times for the entire round.

Segregation of the All-up Round (AUR) components

An all-up artillery round consists of several energetic components in order to complete the explosive train. This will include the TNT-filled shell warhead, as well as a detonative explosive train featuring a detonator, fuze and potentially a booster, alongside a propellant to propel the round down-range, most likely in the form of a propellant bag-charge in UK operations. In line with regulatory and statutory requirements, all of these components, of different natures and displaying different hazard classification codes (HCC) and compatibility groups (CG), must be stored in line with mixed storage regulations as shown in figure 2 [8].

TABLE 1 COMPATIBILITY GROUP MIXING RULES FOR STORAGE													
CG	A	B	C	D	E	F	G	H	J	K	L	S	N
A													
B			Note 1	Note 1	Note 1	Note 1	Note 1						
C		Note 1				Note 2	Note 3						Note 5
D		Note 1				Note 2	Note 3						Note 5
E		Note 1				Note 2	Note 3						Note 5
F		Note 1	Note 2	Note 2	Note 2		Note 2&3						
G		Note 1	Note 3	Note 3	Note 3	Note 2&3							
H													
J													
K													
L											Note 4		
S													
N			Note 5	Note 5	Note 5								

Figure 2: Compatibility table for mixed storage of groups. Compatible groups are marked with a black square.

Notes 1 to 5 for the mixing rules are detailed below in figure 3 [8].

- (1) Articles of CG B are to be segregated in storage from other articles of CGs C, D, E, F and G by means which are effective in the prevention of propagation to those other articles, i.e. in a separate compartment, or by use of suitable traverses/barriers or simple distance separation. Fuzes of CG B may be stored with their parent explosive articles, but the NEQ must be aggregated and the whole treated as CG F.
- (2) Articles of CG F are to be segregated in storage from other articles of other CG by a means that is effective in the prevention of propagation of those other articles, i.e. in a separate compartment or by use of suitable traverses/barriers or simple distance separation.
- (3) Articles of CG C, D or E, or those articles of CG G which do not give rise to loose explosives powder, may be mixed in storage. Articles in CG G that may give rise to loose explosives powder will be given special consideration by ESTC through the relevant IE.
- (4) Articles of CG L are to be stored separately from all articles of other CG as well as from all other articles of CG L.
- (5) Articles of CG N are not normally to be stored with articles of other CGs except S. However, if articles of CG N are stored with articles of CGs C, D and E, the articles of CG N are to be considered as CG D.

Figure 3: Notes 1 to 5 from the Mixed Storage Table.

In the artillery round in question, the most probable compatibility groups for the components are:

- TNT Main-fill shell – CG D (Article containing a secondary detonating explosive substance without means of initiation of propelling charge)
- Fuze/Detonator – CG B (Article containing a primary explosive substance without two or more effective protective features)
- Propelling Bag Charge – CG C (Article containing propellant explosive substance)

These would have to be segregated in storage in accordance with figure 2 and 3 from [8] to protect natures from synthetic detonation and large scale fires, which would be an increased risk in combat zones that are vulnerable to extreme temperatures that can denature explosive compositions.

Safe Storage of Components in Conventional Storehouses

As well as segregation of the round in to its component parts to protect from synthetic detonation, each component needs to be stored according to strict regulation to avoid performance and safety issues.

An ideal temperature for an explosives magazine is between 5°C and 25°C. Keeping to this temperature range is imperative for many reasons. In the case of the TNT fill, for the reasons already alluded to, it is important to prevent the composition from melting and cooling uncontrolled.

Propellants are incredibly susceptible to degradation due to environmental effects. Any propellants containing nitro-glycerine or other nitrate esters must not be stored in environments where there is the possibility of sustained drops below the minimum temperature limit. This is to prevent the release of nitro-glycerine from the charges, and the prevention of physical changes to any propellant charges [9].

High temperatures can also have serious adverse effects on propellants. The shelf-life of propellants can decrease rapidly due to exposure to high temperatures, due to the impact it has on nitrate esters [9].

Guidelines state that, as a general rule, a standard gun propellant under ideal conditions would see its shelf-life deteriorate by half for every incremental increase of 10°C in storage [7]. Figure 4 breaks down the rule for propellants of differing ideal shelf-lives.

Temp in degrees C	Projected Shelf-Life in years/Months				Remarks
30	15.0	20.0	30.0	40.0	The design shelf-life
40	7.5	10.0	15.0	20.0	
50	3.75	5.0	7.5	10.0	
60	1.83	2.5	3.75	5.0	
70	0.92	1.25	1.87	2.5	
80	0.42	0.62	0.92	1.25	
90	0.21	0.31	0.46	0.62	

Figure 4: Breakdown of the effects of high storage temperatures on the shelf-life different propellants [7].

Humidity and moisture is another factor that must be taken in to consideration when storing explosives. Moist, humid environments will contribute to explosive deterioration, particularly, again, in propellants – most notably composite and double-base propellants [9].

The effects of allowing the ingress of moisture in to explosive compositions are severe. Particularly at high temperatures, moisture ingress can have the following effects [7].

- **On initiation systems:** initiation systems are susceptible to failure due to moisture. Their role in the explosive train means that failure in use in the field would prevent the AUR from firing.

- **On propellants:** the process of hydrolysis² can cause the breakdown of propellant compositions. This reduces the efficiency of a propelling system on firing.
- **On all explosive compositions:** chemical reactions, particularly corrosion by oxidation due to water presence, can degrade explosive compositions, with the potential to sensitise and de-sensitise. The effects of corrosion on compositions are varied, and all negative, posing performance and safety issues.

Ministry of Defence guidelines dictate that packages should be stored so as to achieve optimum airflow around stacks. Stacks must be raised off the floor using battens, and should be kept a minimum distance of 50cm away from the nearest external wall [9].

Safe Storage of Components on Operations

On operations, it is more difficult to maintain the ideal conditions for storage as set out in [9]. Instead, [7] lays out the rules and guidelines for storage on operations, adding that ‘every effort must be made to reduce the effects of high temperatures and moisture on explosives held by units or in bulk storage.’

Some of the regulations in place to help prevent issues of this nature include the requirement to never store explosives in direct contact with the ground. They are required to be stored a minimum distance of 10cm away from the floor to help ventilation. Sand, earth and vegetation are not permitted to shroud the palletted stores and prevent air-flow.

The effects of radiant heat should be mitigated with the use of tarpaulins or camouflage nets. These are not permitted to be in contact with explosives, and there should be a gap of between 30 and 50cm between munitions and any temporary cover, as direct contact between covers and stacks can lead to the highest temperatures of all, as mentioned in table 2.

Explosives in the field, and in all storage, should be retained in their proper, original packaging for as long as possible, and then returned to packaging as quickly as possible.

There is a priority list for covered storage if not all munitions can be reliably covered in the field. This list is given in figure

- (1) Water Activated Explosives.
- (2) Guided Weapons, Torpedoes and Rockets.
- (3) Anti-Tank, Ranging and Spotting Ammunition. One shot ammunition.
- (4) Propelling Charges.
- (5) Pyrotechnics.
- (6) Mortar Ammunition.
- (7) Grenades.
- (8) Boxed Shell.
- (9) Small Arms Ammunition.
- (10) Loose Shell.

Figure 5: Priority list for covered storage, in the event that not all stock of ammunition can be stored under cover in the field, according to [7].

Ensuring Functionality on Use

The ideal function of the explosive train in a munition is essential to the successful firing of the system. To ensure functionality of a large calibre munition on firing, as well as adhering to the guidelines in

² The chemical breakdown of a compound due to reaction with water [13].

place for safe storage of explosive components, the correct design choices need to be made during the manufacturing stage to allow the best chance of a successful fire. Figure 6 shows an example of a typical three stage detonative train that would need to be replicated in order for the successful detonation of the round once in contact with the target, in which primer sets off a detonator containing a primary explosive, which in turn provides enough energy to transfer a detonation wave through a main charge, either with or without the aid of a booster charge. A booster charge will usually always contain a secondary explosive, and a main fill likewise, but the use of a booster can allow for the filling on a main charge with insensitive, tertiary explosives, that will only detonate with a large input of energy.

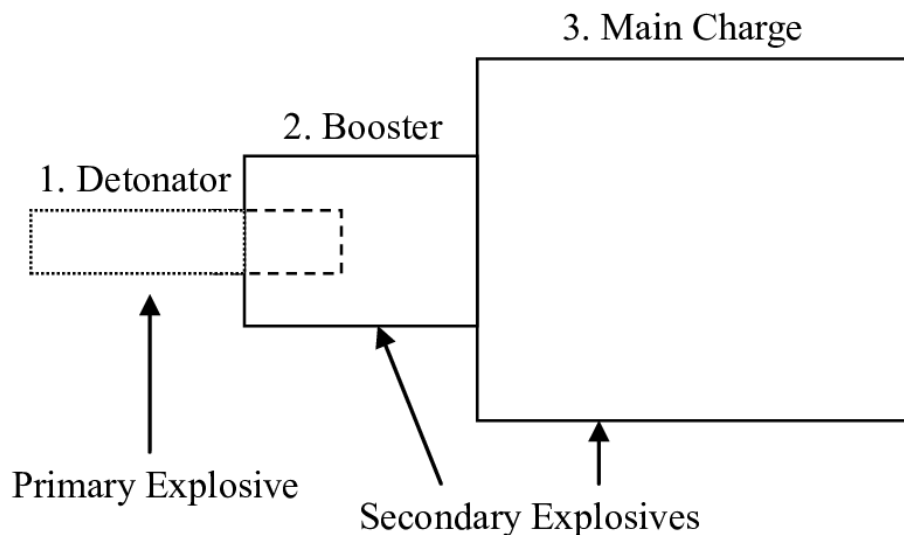


Figure 6: A typical three-step detonative train [10].

During firing, there will also be an igniting train in place to ignite the propelling bag charges. An ignition train works differently from a detonative train, but many of the principles remain the same. An igniter containing a sensitive substance is ignited by a primer, and transfers its energy to a less sensitive, higher energy main propellant charge in order to achieve a full deflagration of the main fill. This typical ignition train would need to be replicated in order to achieve successful propulsion of the round down-range.

In the specific case of the described large calibre shell, the detonative train would need to consist of a reliable, sensitive primary explosive that will burn to detonation within the detonator after being ignited either by electrical inputs or by a flame generated by a primer. Typical examples such materials being used in UK operations to good effect are mercury fulminate or lead azide. It may not be necessary to use a booster in order to initiate a TNT main fill. If a booster were to be used, a typical choice would be a secondary explosive with a low figure of insensitiveness relative to the main fill. RDX and PETN are both secondary explosives with a higher sensitivity than that of TNT with values of 80 and 51 compared with TNT's 152 [11], but both have higher energies of explosion associated with them relative to TNT [4], and this would need to be considered when looking at the size of the booster, if it should be required.

At the back of the gun, where the propelling charges are located, the ignition train would need an igniter which would be lit by an electrical input, or by the flash from a primer. Common compositions for igniters include potassium nitrate or black powder. The energy provided will be enough to light the propelling charges which, depending on the energy output required from them, will be a composition that is nitrocellulose (NC) based, with either nitro-glycerine (NG) added for maximum energy (double-

based propellant), or an additional adding of nitroguanidine (NQ) (triple-based propellant) for an intermediate level energy above that of a homogenous NC composition (single based). Precisely how the propellant is made up depends on the desired range of the round.

There are also other factors not directly related to the energetics themselves. The firing system must match the calibre of the munition being fired. This is essential for the safe firing of the munition system. The firing system must be adequately maintained. This includes checking for any cracks, cavities or rusting of the barrel, as well making sure all mechanical and hydraulic components are fully working.

Future Alternatives to TNT

The performance and safety issues brought on by the uncontrolled melting and cooling of TNT, as well as the leeching of isomers from within the munition (which can occur as a direct consequence of this melting and cooling in the summer), means that there is a sizeable risk of density drops across the material, as well as the risk of isomers making their way to the screw threads of the munition and detonating if they are cracked or ignited during unscrewing [12]. The hugely negative oxygen balance, and associated low heat of explosion and undesirable products of detonation also mean that work has taken place for years to find reliable alternatives to TNT in future munitions.

RDX and HMX have both been considered widely as replacements for TNT. They are a common main-fill component in modern munitions, and have the advantages of having higher melting points and more desirable oxygen balance compared with TNT. These are properties which, relative to TNT, make RDX and HMX less susceptible to deterioration in the field, and also more effective, higher energy compositions with more desirable combustion products. HMX has the higher melting and ignition point, and chemical stability, compared with RDX, but has a worse oxygen balance and therefore a lower explosive power. Both, however, are harder to cast than TNT due to their high melting points, and both are considerably more expensive to produce and use in the manufacturing of munitions [12].

In fact, the more common alternative method to a TNT filled charge is to take advantage of its own desirable properties and mix them with other, more powerful explosives in order to create a mixture. RDX is difficult to cast, and casting is a cheap form of manufacture. TNT is easy and cheap to cast. Mixing RDX with TNT creates a castable explosive mixture, and also leads to a composition with a higher melting temperature, and a higher explosive power than simply TNT alone [12]. This mixture would, in all likelihood, be a more suitable composition for use in the large calibre artillery round described if the desire was to fill it by casting, and also to deploy it in a battlefield where there was a genuine possibility of extreme weather conditions.

Conclusion

Ensuring that a large calibre munition, upon firing, will function correctly, is the result of a long, multi-stage process that begins at design and continues all the way through manufacture, in to storage, transportation to the field, maintenance whilst on operations all the way through to maintenance of the system that will ultimately be responsible for firing.

The correct design choices, based on the science and regulations available, must be made to ensure that the munition, once manufactured, has the best chance of surviving testing storage conditions whilst on operations with the military.

TNT has long been the filling of choice for casting of large calibre shells, but questions persist in the modern day over the safety and performance of the composition relative to more modern, more powerful, and more stable explosives such as RDX and HMX. More and more, TNT is instead used

partially within mixes with RDX and HMX to take advantage of those chemical and physical properties to maximise safety and performance, whilst also considering cost and scale.

As well as just the main fill, the whole explosive train needs to perform as desired on the day. This means making the correct design choices throughout the munition system, including the detonators, fuzes, propellants, igniters and boosters (if required). All will need to function as planned at the time of firing, and all must be assessed at the design stage to take advantage of the properties of different compositions to achieve the desired effect. All components will also need to be subject to same strict storage and transportation guidelines to ensure that they are not deteriorated beyond use when they are called in to service from storage.

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